A number of 8-10m class telescopes are now in operation, the latest of these, the GTC, is starting to produce scientific data on a routine basis. Meanwhile, the next generation of large telescopes is now on the drawing boards both in Europe and the USA. Also the James Webb Space Telescope (JWST), the successor to the Hubble Space telescope, is on its fast track to launch in 2014. With this panorama in mind, the GTC inauguration offered an ideal occasion for the Instituto de Astrofísica de Canarias (IAC) to organise an exchange of ideas on the role of the 8-10 m telescopes when the new generation of giant telescopes and space observatories comes on line. Other topics debated included the professional future of young astronomers confronted with the extremely competitive access to these giant telescopes, and the implications of the scarcity of observing time available to the astronomical community at large.

An elite group of influential astronomers gathered on the Island of La Palma to discuss the above points, as well as present their views on the future trends of astronomy that will be allowed by the current and the extremely large future facilities, and to join the celebration of the GTC's Inauguration by H.M. the King of Spain on July 24, 2009. Their talks and conclusions have been collected together in this volume, which has been published by the Ramon Areces Foundation.

The conference was organized by the Instituto de Astrofisica de Canarias (IAC) with the support of Red de Infraestructuras de Astronomía (RIA), Fundación Ramón Areces and "Encuentros Blas Cabrera", Grupo Banco Santander.

Science with 8-10m telescopes in the era of ELTs and the JWST

FUNDACIÓN RAMÓN ARECES

Science with 8-10m telescopes in the era of ELTs and the JWST

Seminar Proceedings: 25/26 July 2009, La Palma

Science with 8-10m telescopes in the era of ELTs and the JWST

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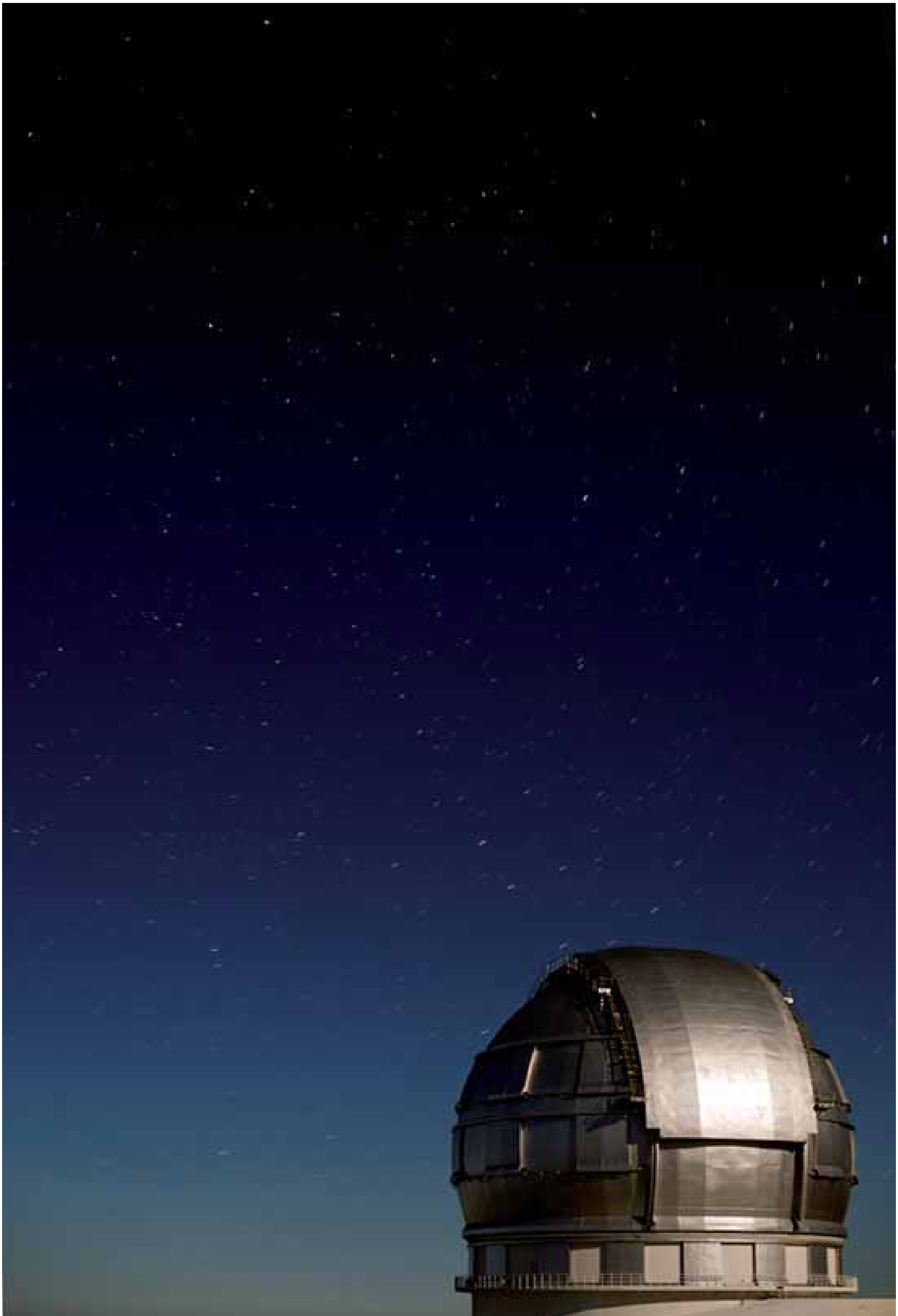

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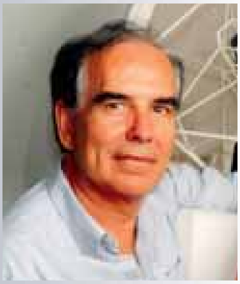

Preface

The inauguration of any state of the art telescope is always a matter of joy for the astronomy community. That is also the case for the Gran Telescopio Canarias (GTC), currently the World's largest IR-optical telescope. Such an inauguration is also a good place to meet colleagues, experts, friends, etc. So we asked the directors of the large telescopes currently in operation, as well as to the leaders of the future extremely large telescopes, that they join us for such an event. Then, we also thought, what a waste bringing together all these great minds, all these great people, for just a few hours. And here is the solution, a Workshop on the Future, when we just had finished inaugurating the "past". We thought it was important to grab the opportunity to think about the science to be done with the current facilities, to offer a space to ponder on strategies in preparation for the extremely large facilities of the future. The response to our invitation was great, and I can only be thankful to the many participants for your generosity both with your time and with your ideas.

We knew that the GTC, a 10.4m, segmented primary mirror telescope, was the last to join this exclusive club of large telescopes already in operation. We knew that Spain had never built even a medium size telescope of its own. For these and other reasons, the GTC, the most advanced telescope of its class, represents a great achievement by Spanish Astronomy, so you will understand that we feel very proud of it.

Indeed the GTC was designed to achieve excellent image quality, to be operationally efficient and very robust against failures. We have already seen the high image quality, the rest is still to be seen… Yes, we knew that the GTC was a late addition to the club, for this reason the GTC was also meant to pave the way for the future extremely large telescopes. Indeed, telescopes larger than about 8 m in diameter will always be built using segmented mirror technology. The GTC has refined the state of the art in segmented mirror production and in the optical control of the image quality of segmented telescopes.

One aspect was clearly undisputed during the meeting. The 8-10 m telescopes will be the most demanded and used tools by the astronomy community in the next 10-15 years. In fact many of the people participating in the Workshop will likely finish a successful career in astronomy using these telescopes. It was realised that the shear number of 8-10 m telescopes, with their phenomenal suit of state of the art instrumentation, spread across both hemispheres, represents the most powerful astronomical facility ever available to the current community of astronomers. So indeed, for the time being, and for at least the next 15-20 years, the right approach is to exploit the current large telescopes to produce the best astronomy.

For two days we had thought provoking presentations, and lively discussions. For instance, the question as to whether the 8-10 m telescopes should devote their capacities to catering for their respective communities, or whether they should agree and complement each other in the offer of instrumentation, was extensively discussed. Some successful ongoing collaborations were presented as examples to be followed.

Inevitably however, the new facilities loom over the horizon. Larger and larger telescopes are now on the drawing table. New and imaginative solutions are being thought out with regards to the size of the telescopes in the making, with regards to the new instrumentation, to the operational aspects, etc. Then on top of it there is the James Web Space Telescope, the successor to the extremely successful Hubble Space Telescope. The strength of the new projects is high. The enthusiasm too! The TMT, GMT, E-ELT, the LSST, etc. are here to stay. Their leaders showed us the power of their projects and the smartness of their solutions to difficult technological problems. These facilities are meant to be the drivers of Astronomy in the 20's and beyond.

This book, I hope, captures the essence of what was said and discussed during the meeting and we are very grateful to each of the contributors for their manuscript. I also hope that the book is useful to the current and future users of the 8-10 telescopes so that they realise the huge potential of the facilities they have within their reach. I also hope the book prepares the path for the new generation of telescopes, and most of all, sets the mood for cooperation amongst the 8-10 m facilities, as well as between these and the new extremely large telescope projects now on the horizon.

Finally I should acknowledge and thank the sponsors of the meeting; the Fundación Ramón Areces, the Red de Infraestructuras de Astrofísica, the Grupo Santander (by means of the Encuentros Astrofísicos "Blas Cabrera") and of course the hard work of Campbell Warden in organising the meeting and publishing these proceedings.

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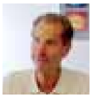
IAC Director



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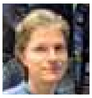

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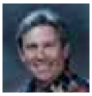

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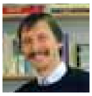

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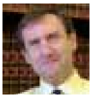

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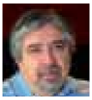

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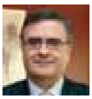

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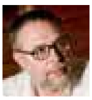

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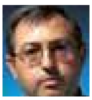

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William S. Smith, Jr.

Association of Universities for Research in Astronomy

Strategies for Optimizing Scientific Productivity for Future Observatories:

A "Flat World" for Astronomical Research

"...the world needs you to be forever the... generation of strategic optimists, the generation with more dreams than memories, the generation that wakes up each morning and not only imagines that things can be better but also acts on that imagination every day."
Thomas L. Friedman

Abstract:

During the course of an observatory's life, the strategy adopted for maintaining productivity must change as scientific ideas evolve, technologies change, and other observing facilities evolve. This paper examines the convergence of trends that may lead to a "flat world" for astronomical research and a landscape dominated by factors other than aperture size. These trends include: a data enabled research capability fueled by rapid technology advances which will democratize access to information; shifting telescope economics that focus new investment strategies, and an evolving trend towards larger highly multiplexed research teams that cross institutional lines and national affiliations.

1. Introduction

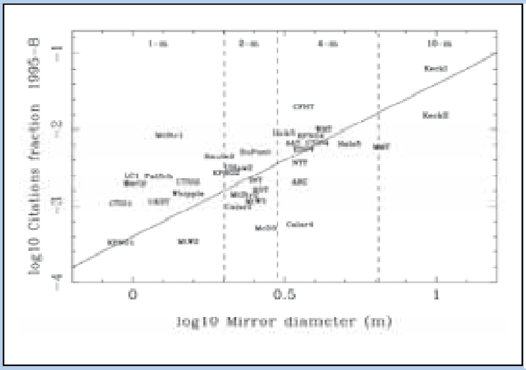
This year we celebrate both the 400th anniversary of Galileo's use of the telescope, and the 150th anniversary of the publication of Darwin's *"On the Origin of Species"*. Two of the most fundamental issues facing astronomers today also involve questions of origins but on an even grander and more profound scale – how did the Universe originate and what conditions are necessary for the origin of life. It is fitting, then, that we welcome the Gran Telescopio Canarias (GTC) in this dual anniversary year as a powerful new tool in what is the ultimate search for Origins.

The commencement of science operations for the GTC offers an exciting opportunity not only for Spanish and European astronomers, but for the world. And it comes at a time when observatories in the 8-10 m class are examining their own strategies for future growth. This paper is intended to examine strategies that have been employed in the past, and consider factors that may influence the future landscape.

Including the GTC, there are now 16 telescopes of aperture 6.5 meters and larger. The over-subscription rate on them is high - typically a factor of 4 or more. One decade from now there may be three extremely large telescopes-the Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and the European Extremely Large Telescope (E-ELT). The key science questions posed to justify the construction of each of these three ELTs are similar and are also concerned with origins and evolution: the origin of the universe and life within it and the evolution of the universe's structure and content. The ambitious science programs being defined to address these key questions will take up much of the available time on all three telescopes for a number of years.

As the generation of 2 m telescopes gave way to 4 m telescopes and the 4 m telescopes to 8 m telescopes, there has been a recurring debate over how to optimize the science role and productivity of those that were "superseded". Indeed, the recent ASTRONET Strategic Plan has called for reviews of operations modes of existing telescopes in the E-ELT era. Such reviews, carried out both in the US and Europe, will need to make a reasoned judgment about, not only the continuing support of smaller telescopes, but their fundamental scientific role.

Understanding what makes an observatory productive is fundamental to developing such strategies. There are several measures of scientific productivity, although no generally accepted standard. The most common is to examine the publication rates. In a 2000 paper when large telescopes were just coming on line, Benn and Sanchez examined the scientific productivity of a wide range of ground and space-based observatories over the prior decade. They found a correlation between telescope productivity and aperture size (and capital costs). Additionally they found that 1-4 m class telescopes accounted for a significant (~15%) fraction of the top cited papers. They stated that "The strong showing by 1-m and 2-m telescopes in the 1990s augurs well for the continued scientific impact of 4-m telescopes in the era of 8-m telescopes."



High-Impact Observatories

Rank	Facility	Citations	Participation
1	SDSS	1892	14.3%
2	Swift	1523	11.5%
3	HST	1078	8.2%
4	ESO	813	6.1%
5	Keck	572	4.3%
6	CFHT	521	3.9%
7	Spitzer	469	3.5%
8	Chandra	381	2.9%
9	Boomerang	376	2.8%
10	HESS	297	2.2%

1990's 2000's

Figure 1: Telescope Productivity Patterns Over the Past Two Decades

In a 2009 paper, Madrid and Macchetto carried out another review of the highest impact observatories in the mid 2000s. Although 8-10 m class telescopes clearly made an impact, they found changing patterns of scientific use emerging that have equal importance. Specifically, large public data sets such as from the Sloan Digital Sky Survey (SDSS), the Hubble Deep Field, and other large-scale surveys have had impacts comparable to or greater than high impact niche programs and large aperture telescopes. The clear correlations found by Benn and Sanchez had begun to change. The aim of this paper is to examine several traditional approaches to maintianing the productivity of observatories during their evolution, particularly as larger facilities become operational, and to compare these approaches with the emerging trends underlying Figure 1. The "Flat World" described herein will result from the convergence of technology, economics, and sociology.

2. Strategic Paths for Observatory Development

There is a great deal of well-justified optimism about the enormous contributions that 8-10 m class telescopes can make over the next decade. The advent of adaptive optics (AO) on these telescopes allows them to image objects in the near-IR with a spatial resolution at or close to their diffraction limit and with greatly increased sensitivity. AO also greatly adds to the synergy between these telescopes and space observatories such as the Hubble Space Telescope. Properly equipped, these telescopes can now tackle problems that would have been impossible even a decade ago. These range from studies of close-by objects within our own solar system to high redshift galaxies near the edge of the visible universe. Such enhanced capabilities mean that 8-10 meter telescopes will be much more than handmaidens to the few ELTs to be built; the GTC and its similarly sized companions will remain powerful tools for research and exploration in their own right. A few examples of areas that are prime candidates for such research and exploration by these telescopes are:

• High resolution studies of satellites of the giant planets as well as of asteroids and the larger Kuiper belt objects. This work will add to our knowledge of planetary atmospheres and the formation and early evolution of our Solar System.

• Near-IR AO observations from the ground combined with optical observations from space at the same spatial resolution provides a powerful new tool for studying resolved stellar populations within our own galaxy as well as in other nearby galaxies. Such a greatly expanded wavelength baseline permits detailed comparison with models in order to determine star formation histories.

• Near-IR AO observations are revealing previously hidden details of circumstellar disks and planet formation outside of our solar system.

• Observations of the Galactic Center have been able to closely define the properties of the central black hole and investigate star formation in its vicinity.

• Integral Field Spectrographs operating behind AO systems can now spatially resolve the dynamical structure of galaxies that formed only a few billion years after the big bang. Such knowledge adds greatly to our understanding of galaxy formation, mergers, and accretion in the early universe. As is the case of resolved stellar populations, observations from space in the visible at the same spatial resolution can, when appropriate, provide additional insight to galaxy formation processes.

Despite the exciting science that will be done on 8-10 m class telescopes, it is appropriate to examine their role in the era of 30 m telescopes and advanced space based observatories.

One classic view towards maintaining observatory scientific productivity has been that the scientific role of an observatory transitions from one of discovery (of unknown objects or processes) to one of exploration (of known objects or processes) as it is eclipsed by telescopes of larger aperture classes. Beyond this, observatories have often attempted to optimize their scientific productivity and service to their user in a variety of different ways. The most successful strategies have been the ones that have remained flexible and able to take maximum advantage of new discoveries and new technologies. Many times these strategies have not been the ones originally envisioned.

There have been three approaches, in general, that observatories have adopted as their world view.

• Type I: Full Service a well-resourced observatory seeks to offer a full range of services and acquire a broad range of capabilities, both workhorse and niche, that meet the widest range of needs for its user community.

• Type II: Vertically integrated observatory seeks to optimize its value by establishing a synergy with other major observing facilities, for example a larger aperture class of ground based telescopes, or space missions.

• Type III: Laterally integrated observatory seeks to establish strategic relationships with observatories in its own class and leverage broader participation for its user community.

AURA manages a wide range of observatories and telescopes with successful and unsuccessful experience in all of these strategies.

2.1 Type I: Full Service

Undoubtedly, a full service observatory will acquire the most dedicated and loyal community that will advocate for its best interests, optimal budget, and play a central role in making it scientifically productive. The Space Telescope Science Institute, established in 1983, was from the outset, a full service observatory that incorporated imaging and spectroscopic capabilities in the UV to the near-IR, robust data archiving, data pipelining, and observer grant support. By most measures, HST is one of the most productive observatories, and one of the most productive science missions NASA has ever undertaken.

With a staff of 400 including nearly 100 astronomers, a $45M/yr operating budget, a $20M/grant program, and over 700 users per year, STScI's role extends far beyond operating HST. STScI and HST have become one of the major sustaining sources of funding and science for the entire US community. STScI/HST users have also emerged as a powerful political force and were instrumental in achieving a series of Shuttle servicing missions for HST including the one just completed.

The U.S. National Optical Astronomy Observatory (NOAO) was originally conceived as a classic full service observatory offering access in the north and south, state of the art telescopes with a diverse suite of instrumentation, data reduction tools, and a large and diverse science staff. NOAO was a major source of instrumentation nationally. By the year 2000, however, it had become clear that the resources would not allow this as a sustainable model. Increasingly, alternative access to state-of-the-art telescopes became available to roughly half of US astronomers. AURA and the community found that a different strategy was needed for NOAO as illustrated in the following.

2.2 Type II: Vertically Integrated

There are many well documented examples of powerful synergies that have been achieved in the field of astronomy. One of the most prominent of these is the discovery of "dark energy" in which ground-based telescopes such as the Blanco 4 m provided an initial data base for Type I Supernovae which were subsequently measured with great precision by HST. Yet, this stunning achievement was not a part of the strategic vision for either HST or the ground based telescopes that contributed to this discovery. Thus the question is whether such synergies can be predicted with enough reliability to form a long-term basis for a strategic development plan incorporating engineering choices and instrumental development.

In the US, the Gemini project received its start as one of the high priority recommendations of the Decadal Survey carried out by John Bahcall. The decade of the 90s was to be "The Decade of the Infrared" and exploited with a grand strategy that was based on complementary observations from what was then known as the Space Infrared Telescope (now, the Spitzer Observatory), the SOFIA airborne observatory, and an IR optimized Gemini observatory.

The need to provide imaging and spectroscopy in IR atmospheric windows with a low IR background telescope became a major engineering driver for Gemini's telescope structure, mirror coating, and instrumentation. Current Gemini instrumentation envisioned to exploit this scientific phase space included Michelle in the North and T-ReCS in the South, both operating in the mid IR. Yet, many of the synergies that were envisioned have not materialized.

In general, the interests of the ground-based astronomical community have remained strongly rooted in the visible. Michelle and T-ReCS are by no means the most subscribed instruments and the more common follow-up for Spitzer observations are deep optical and near-IR imaging and spectroscopy as well as radio observations. Ground based mid-IR is rarely used for follow-up because of a lack of sensitivity or need for high resolution to resolve bright sources. SOFIA has not yet entered scientific operations and it is unknown whether this will renew interest in Gemini Mid IR capabilities. For Spitzer, productive synergies have been found in other "Great Observatories" .

As another example, in the early 2000s, NOAO telescopes were envisioned to provide the scientific basis for optimizing the use of Gemini for the major part of the US community. Although there was clearly a case to be made for NOAO telescopes as an essential gateway to Gemini and other large aperture telescopes on the horizon, this linkage never emerged as a strong feature of the NOAO landscape, nor of Gemini. For the most part, observing proposals for Gemini are self-contained science cases.

Comparison of Different Recommended Infrared Facilities	
Facility	Most Important Attributes
SIRTF	Unequaled sensitivity for imaging and moderate-resolution spectroscopy Broad wavelength coverage from 2 to 700 μm 7.5 (λ/30 μm) arcsecond imaging of faint sources at $\lambda > 30$ μm
Infrared-optimized 8-m telescope	0.7 (λ/30 μm) arcsecond imaging for $\lambda < 30$ μm High-resolution spectroscopy in atmospheric windows For $\lambda < 30$ μm Evolving instrumentation
SOFIA	High-resolution spectroscopy at $\lambda > 30$ μm 2.5 (λ/30 μm) arcsecond imaging at $\lambda > 30$ μm Training of instrumentalists

Figure 2: Original Role for Gemini as envisioned by 1990 US Decadal Survey

Despite some of these known shortfalls in achieving full vertical integration as a sustainable strategy, the potential for achieving synergy with the new generation of space and ground telescopes is compelling. A detailed scientific case for synergy between a thirty meter class telescope and the James Webb Space Telescope was developed by AURA's Giant Segmented Mirror Telescope Science Working Group.

2.3 Type III: Laterally Integrated

A laterally integrated strategy seeks to optimize scientific productivity by pooling and leveraging observing capabilities across observatories, many times in the same class. This provides a user community with a richer array of observing capabilities. For example, management and integration of the U.S. "system" of telescopes is now the central organizing principle for NOAO. Access to 6-10 m class telescopes is now successfully under way through the NOAO managed Telescope System Instrumentation Program (TSIP).

Within the U.S., as well as other countries, there has also been a re-emergence of interest in small and mid-sized telescopes. Motivated by a desire to better characterize how 1-6 m class telescopes could maximize their scientific productivity as part of a hierarchy of telescopes that could support 8 m and 30 m class telescopes, NOAO undertook a focused study referred to as ReSTAR (Renewing Small Telescopes for Astronomical Research). This can be seen as another effort to better define a vertical integration strategy.

The surprising result of the ReSTAR study, however, was that, in addition to this anticipated support role, these small and mid-sized telescopes retained an important niche in the hierarchy that was not related to larger telescopes, but simply to exploit science that was suited to this class of telescopes (a finding consistent with the Benn and Sanchez paper mentioned earlier). Some examples of this science include:

- Synoptic and time-critical observations of rapidly moving solar system objects such as comets and asteroids.
- In the rapidly growing field of exo-planet studies, these telescopes are well-suited for time domain studies of exo-planets transiting in front of their parent stars and for follow up of microlensing events.
- Studies for Star forming regions and of the inter-stellar medium via wide field imaging in both broad and narrow-band filters.
- Stellar interferometry and astero-seismology for detailed two and three dimensional studies of individual stars.
- Synoptic imaging and spectroscopic studies of variable stars and stellar clusters.
- Synoptic photometric and spectroscopic observations of extra-galactic compact objects to study the physics of accretion disks.

• Wide field surveys for medium to high redshift galaxies to study large scale structure in the Universe (Big-BOSS, Dark Energy Survey, etc.

At present, NOAO is pursuing several paths to optimize the suite of small to intermediate class telescopes in the US. The next logical step will be to engage the international community to examine the possible benefits of federating small and intermediate class telescopes on a larger scale.

Another example of an emerging lateral integration is the time exchange program the Gemini Observatory is pursuing with the Subaru Telescope and with Keck. Both of these agreements involve the exchange of classical nights on Gemini with classical nights on Keck and on Subaru. The instruments involved are those that are unique to the specific telescopes and would not otherwise be available to their respective communities, all of whom benefit.

3. Strategies for the Future: A "Flat World" for Astronomical Research

Thomas Friedman, in his book The World is Flat, has described the decline of traditional economic institutions and the emergence of a level playing field global economy. The economies of the past dominated by nations, and later by corporations, then multi-national corporations, have given way to one dominated by individuals armed with information and information technology. This was enabled by the convergence of technology, social factors, and political events, the net result of which was the creation of a global, web-enabled playing field that allows for multiple forms of collaboration and the sharing of knowledge and work. More importantly this could be done in real time, without regard to geography, distance, or even language.

It is now commonly recognized that every new technology creates new opportunities to conduct the basic activities of management and organization. Traditional management activities that have relied on hierarchical organizations (i.e. someone being in charge) such as:

• accumulating and allocating resources
• coordinating and controlling activities
• motivating and aligning efforts

are increasingly being redefined and overtaken by technological innovations. A flat world is a world without hierarchy but not a world without shape. Leaders in all fields, including science, will be successful only if they can perceive this shape and capitalize on it.

- Aided human eye
  - Large information content, low recording rate
- Photographic Plate
  - Large information content (1 MB/cm2, ~3 GB/plate)
  - Moderate recording rate (QE ~2-4%)
  - Analysis and distribution limited
- 2-d photon counting arrays (4kx4k)
  - Large information content (30 – 300 MB)
  - High recording rate (high QE)
  - Analysis can be automated
  - Distribution widespread (tape, CD, internet)
- 3-d energy resolving arrays
  - Enormous information content & data rates
  - 12k x 12k x 100(l) x 2 Bytes: 100 GB

Figure 3: Evolution in Information Technology

This has a strong parallel in the field of astronomy. Despite the successes and failures of the three world views characterized above, these are all linear strategies based on a static landscape, a landscape that is now changing. There is now a convergence of technology, economics, and sociology that is creating a new (level) playing field which is no longer dominated by institutional status nor aperture size alone.

The observatory today is a hierarchical ecosystem involving a complex array of technical and sociological factors that go far beyond glass collecting area. The vision of the Director and scientific staff, form of organizational governance, culture of its user base, structure and practices of the Time Allocation Committee, choices of operating modes, etc., all dramatically affect the approach to doing research and resulting output of an observatory.

The past has been dominated by a structure in which observatories have cultivated user communities expected to not only exploit technical and scientific advantages, but to advocate and remain loyal. The reward for the astronomer was the receipt of data. Astronomers fortunate enough to gain access to cutting edge facilities and acquire these data prospered; this hierarchical world was accepted. The observatory played a central role with the largest telescopes providing the most valuable data.

Figure 1 suggests a dramatically changing landscape for the role of observatories in the future. A level playing field for science productivity has begun to emerge that is independent of the size of the telescope, or the hierarchical status of the astronomer. This landscape has begun to "flatten" for several reasons including:

- Information: the ability to produce, transmit and use astronomical data,
- Economics: a dramatic shift in the economics of telescopes vis-à-vis their instruments, and,
- Sociology: an emergence of large scientific teams versus lone astronomers.

4. Information

The increasing ability to collect, transmit, and understand large volumes of information has caused a paradigm shift from one in which the focus of investment was the telescope itself, to one in which a highly multiplexed instrument has become the focus of investment, with the telescope being a minor partner. Technology for producing data has progressed at an astonishing rate from photographic plates to two dimensional photon counting arrays, to three dimensional energy resolving arrays. From figure 4, the relative increase in mega-pixels used in astronomical observations has increased substantially faster than the growth in glass collecting area. This has focused the need to establish workable public archives and effective tools for accessing and using this increasingly massive amount of information.

The Virtual Astronomical Observatory in the US and the International Virtual Observatory are intended to provide an array of such tools. As shown in table 1, within the US alone known archives account for over 500TB with a growth rate of nearly 250TB/yr. The onset of future observatories such as ALMA will add considerably to this. The Large Synoptic Survey Telescope (LSST) will generate 30 TB per night over ten years of operations.

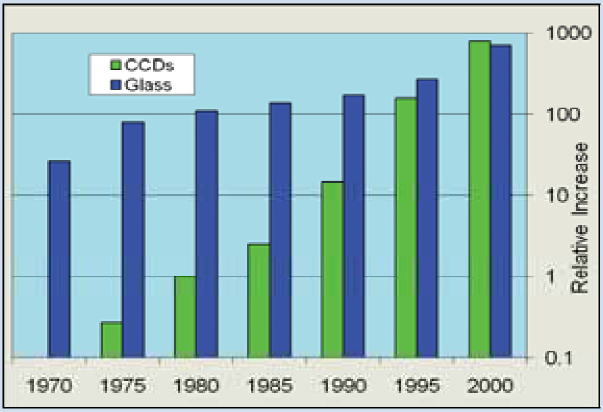


Figure 4: Relative increase in cumulative Glass and Megapixels for all telescopes

Public data bases from surveys have enabled research by astronomers from all institutions, at every stage of their careers. It is no longer necessary for a small institution to be marginalized as a minor partner in a big project. The Sloan Digital Sky Survey accounts for nearly 2,500 publications thus far. Of these, nearly 2/3rds are authored by astronomers not part of the SDSS consortium. As seen in figure 5, Hubble Space Telescope accounts for about 700 publications per year, half of which are from archival data. To date, there are nearly 1,400 publications using Hubble Deep Field data.

US Archives	2010 Holdings (TB)	GROWTH RATE (TB/yr)
Space Telescope Science Institute	113	65
Goddard (HEASARC)	70	12
Chandra Science Center	14	1.5
Spitzer Science Center	26	6
NASA/IPAC (IRSA)	50	50
NASA/IPAC (NED)	5	0.2
SAO Astrophysics Data Sys	10	0.5
TOTAL SPACE	288	135.2
NOAO	47	10
NRAO	70	50
GEMINI	7	0.9
KECK	4	1.5
SMA	4	0.6
Arecibo	40	55
Sloan Digital Sky Survey	88	--
TOTAL GROUND	260	118

Table 1: U.S. Data Holdings and Growth Rates

This trend also addresses a major need in the US and other countries to ensure that investments in research have the broadest possible impact and achieve social goals that are perceived to be part of the contract between the science community and public funding institutions.

Large utilitarian, well-constructed, and well calibrated data sets in accessible archives such as has been the example of the Great Observatories, and future dedicated survey telescopes such as the Large Synoptic

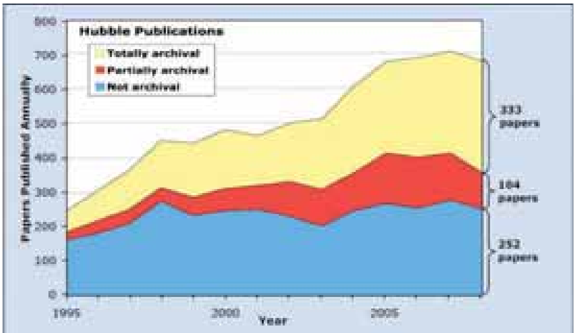


Figure 5 HST Publication Statistics

Survey Telescope have vastly diminished the value of raw data, the currency of the past on which the present hierarchical structure is based. An expectation is rapidly growing that astronomical data should be considered a public good and freely and immediately provided to all. This surely will democratize the future sociology of astronomy. The former paradigm in which an observatory depended on a community of strong advocates and users that identified with the telescope and guided its scientific development may give way to new culture.

NOAO, the US national observatory, is also in the process of making a transition from its traditional role to serve a broad segment of investigators to one that will utilize its venerable Blanco telescope to conduct a Dark Energy Survey to use over 500 nights over a 5 year period. Under consideration also is to use the Mayall 4 meter telescope to undertake the BigBOSS survey of a similar magnitude. It is significant that these projects are strongly influenced by the interests of the US Department of Energy and the high energy physics culture.

For Gemini, the present time allocation system is currently divided among six partners, two hosts, and the Gemini staff making it exceedingly difficult to allocate large blocks of time that would support surveys of the type that could enhance its productivity.

5. Economics

It is significant to note that for the highest impact entry in Figure 1, SDSS, the 2.5 m telescope itself was a minor partner in its success. The creators of Sloan focused their attention at the outset on the camera and the mass of data it would produce. While the telescope itself cost about $6 million, the imaging camera and spectrograph was in excess of $7.5 million. In annual operating cost for operating the telescope and managing the data was over $5 million per year, well in excess of the “standard” 10% of capital costs.

This reversal of traditional observatory economics poses great difficulties in the context of the present funding system which has been strongly focused on financing and building the telescope itself rather than building instruments and the collecting and processing of large data sets. The Wide Field Multi Object Spectrometer (WFMOS) which was under consideration by the Gemini Observatory would have cost as much as a Gemini telescope itself. Unfortunately the extent of this shifting landscape was appreciated only too late and the effort was cancelled.

Figure 6 illustrates some instruments and their relationship to their host telescopes. These consist of instruments beyond the resources of the host observatories and funded through the Telescope System Instrumentation Program, some recent Gemini instruments, and present and future instruments, some of which are on older NOAO telescopes. Those on the right hand portion clearly redefine traditional telescope economics (see end notes for instrument descriptions).

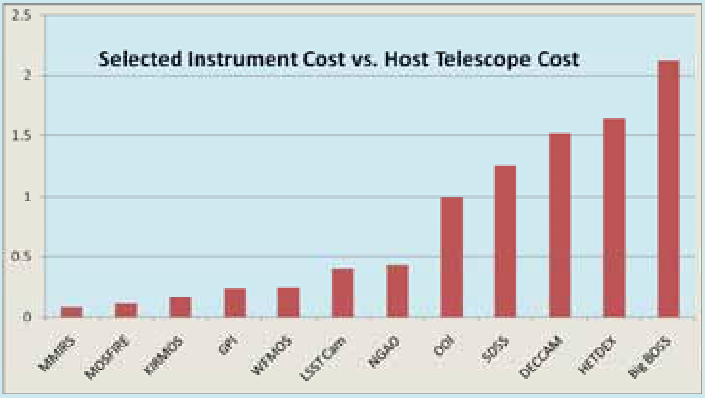


Figure 6: Selected Instrument vs. Telescope Cost Ratios

There are many factors that can account for this shift in the economics of astronomical instruments. Figure 7 is the result of a 2005 survey conducted by Simons et al. which shows the increasing trend towards number of planned NIR instruments out of the traditional optical regime. The most important reason is related to the science drivers for future discovery.

Figure 7. Survey of Planned Instruments

First, fundamental cosmological questions require the discovery and study with imaging and spectroscopy of large numbers of very distant objects. One of the key science cases for larger telescopes is based on observations of objects whose spectrum is shifted into the near-IR. Second, observations of dust obscured regions, such as the center of the galaxy, regions of star formation, and extra-solar planetary systems, also require infrared observations at the highest spatial resolutions that will be supplied by AO systems. Equally important are multiplexed detectors that are only available from industry. Given that the market for these detectors does not extend far beyond the astronomical community, their cost remains high, as does the cost of AO systems and related laser hardware.

	Optical	Infrared
Current	$400,000	$3,750,000
Future	$6,600,000	$5,000,000

Table 2. Current and Future Median Instrument Costs (From Simons, et al)

Another major science driver is the increasing emphasis on ultra wide-field surveys which need Giga pixel CCD mosaic focal planes in the visible. Comparable large infrared focal planes are currently beyond the resources of most astronomers, but would drive this economic trend even more strongly. Table 2 shows the current and anticipated costs for optical and infrared instruments for all telescopes from the Simons et al survey. Clearly, the costs of optical instruments with large multiplexed arrays are anticipated to increase by more than an order of magnitude. Infrared instruments are already costly and will continue to be so due to the limited market for array suppliers.

The transition from building instruments for 4 m telescopes to building instruments for 8 m telescopes was a difficult one in the US community. The old management paradigm which depended on the talents of one or a limited number of instrumentalists, most times located at universities, is giving way to one based on sometimes dispersed teams involving many institutions. For detectors, the core of the discovery potential for an instrument, astronomers are becoming increasingly dependent on commercial industrial suppliers which are rooted in the aerospace culture. Thus the interface between these two cultures must necessarily adapt to the aerospace standard.

The cost of the management approach is now significant, but proving itself necessary as the instruments increase in size and complexity. There is not yet experience in going from 8 m class instruments to 30 m class instruments, however the TMT and GMT projects within the US are concerned with fielding a usable class of first light instruments that can provide an initial science potential, with consideration of second generation instruments to truly take advantage of the larger apertures.

The era of 30 m class telescopes and James Webb Space Telescope will strongly affect the economics of astrophysical research and the public perceptions of its costs and benefits.

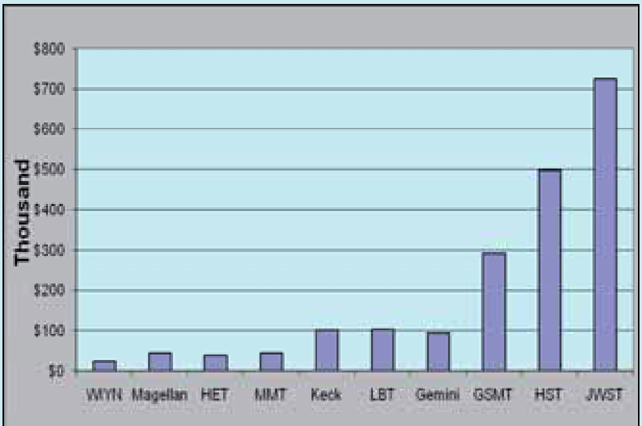


Figure 8: Opportunity Cost per "Night" for Selected Telescopes

Figure 8 compares the cost of current 6-10 m class observatories in the US with the "nightly" cost of operating the Hubble Space Telescope at present and the James Webb Space Telescope in the middle of this decade. Also included is the anticipated cost of operating the 30 m class Giant Segmented Mirror

Telescopes under consideration. Clearly, there is a reasonable gradation given the relative scientific contributions these are expected to make. However these costs are large and there is a need to ensure that the 6-10 m class telescopes are optimized in their use.

In the US, the community is undertaking Astro2010, its decadal survey. One initiative under discussion is a "National Treasure Program" for the next generation of 8 m class instruments. Recognizing the high cost of the new generation of instruments, this initiative seeks to place the highest leverage instruments on the most compatible and useful telescope, whether this is a public telescope or one operated by an independent or private entity. Public access would be granted on a competitive basis.

6. Sociology

In addition to information and economics, an equally important trend is taking place with the rapidly growing prevalence of "teams" in astronomical research. Unlike Friedman's flat world in which the information empowered individual emerges as the evolutionary end state, the astronomical world began with the individual and is evolving in the opposite direction. Not only are the investigator teams growing larger, they cross observatory lines and rely more and more on facilities across the electromagnetic spectrum and from space and ground. This can be quantified by looking at how many authors have contributed to the 100 most cited astronomical papers each year. Figure 9 shows that over a six year period the total number of authors for the top 100 papers has doubled, going from an average of 10 per paper in 2001 to 20 per paper in 2006. Figure 10 shows that such large team publications have large impacts in terms of citation rates. This same analysis also suggests a dramatic increase in the number of highly cited publications based on data from multiple facilities. The astronomy community itself is undergoing a lateral integration that crosses the boundaries of observatories, institutions, and countries.

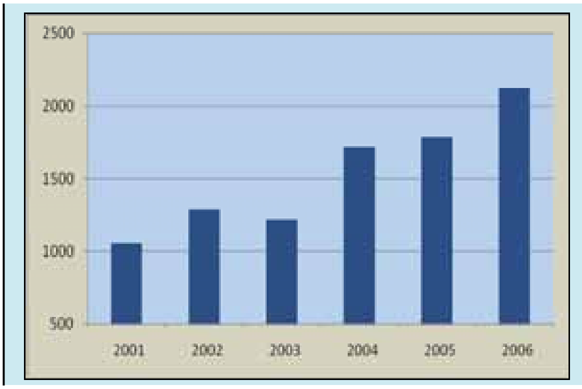
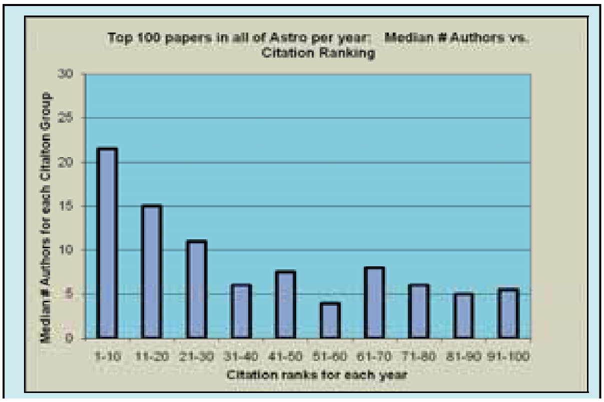


Figure 9: Author Count for top 100 papers.
Figure 10: Citacion Rates vs. Author Count.



7. New Directions

The convergence of these three factors—a data enabled research capability fueled by rapid technology advances, shifting telescope economics that focus new investment strategies, and an evolving trend towards larger highly multiplexed research teams—will flatten the world of astronomy. With regard to observatories, these factors could also lead to a stronger integration of observing capabilities across all present telescope classes and eventually for 30-40 m class telescopes. In order to achieve a full exploration potential, complementary instruments, time trading between observatories and a more facile way of forming collaborative teams will be needed.

While there will still be a need for efficient and rapid follow up with capable instruments, a more important role could be fulfilled. Rather than becoming just a support telescope for JWST and ELTs, the GTC could become a powerful element of a broader array of 8-10 m telescopes that can offer the collective community capabilities not otherwise available.

Scientific drivers for this exploration role are as likely to be derived from rich databases such as the LSST as any extremely large telescope, and will be carried out by groups of astronomers from many different institutions. It is crucial to remove barriers that might affect the competiveness of new observatories in this new landscape.

In this future landscape, astronomers will not be impeded nor advantaged by the present institutional structures, but will exploit the available phase space for optimizing their research capabilities. The astronomer of the future may well envision a research program that includes an observing program on Keck (through NOAO's TSIP program), object monitoring by a global network of 2 meter telescopes (through the ReSTAR program), observing programs on VLT and GTC (through research team colleagues), a queue scheduled target of opportunity on Gemini, access to JWST and HST archives, and access to a vast LSST real-time database. Focusing a broad range of observing tools on a single problem will define this landscape. None of this requires that such an astronomer be part of an institutional partnership, nor even that the astronomer be at some top-ranked institution, simply that the astronomer be creative.

Such a shift will surely affect the loyalties and political support expected of user communities towards their observatories, and the strategies that astronomers will use in justifying funding from governments and private funding sources. The very concept of judging the productivity of "an" observatory and comparing its ranking with others will be moot in this highly integrated environment.

Within this environment, the GTC has an opportunity to define its future and that of its user community. Who are its user community and what will they want? What linkages will they want with other observatories, user communities, and elements of the new landscape? The "flat world" scenario offers opportunities and challenges as never before.

Instruments

MMIRS—The MMT and Magellan Infrared Spectrograph is a wide-field near-IR imager and multi-object spectrograph built by SAO, based on the FLAMINGOS and FLAMINGOS 2

MOSFIRE—Keck Multi Object Spectrometer for Infrared Exploration will provide NIR multi-object spectroscopy over a field of view of 6.1' x 6.1', one atmospheric band at a time: Y(0.97-1.12µm), J(1.15-1.35µm), H (1.46-1.81µm), or K(1.93-2.45µm).

KIRMOS—Keck Infrared Multi Object Spectrograph, intended to provide an 11.4 x 11.4 arcminute FOV for imaging and approximately a 4 x 11.4 arcminute FOV for multi-object spectroscopy (R ~ 4000) with a multiplex of 100 to 150 objects.

GPI—Gemini Planet Imager, will provide diffraction limited images between 0.9 and 2.4 microns. The system will be able to see objects ten million times fainter than their parent star at separations of 0.2-1 arcsecond in a 1-2 hour exposure. The science instrument will provide spectroscopy of any object observed.

WFMOS—Gemini Wide Field Fiber Multi Object Spectrograph, intended to be installed on Subaru, would provide Gemini/Subaru with the capability of simultaneously obtaining moderate to high-resolution (R=1,000-40,000) spectra of ~4500 targets in a field of view of 1.5 degrees in diameter.

LSST CAM—The LSST camera will be a large-aperture, wide-field optical (0.3-1 µm) imager designed to provide a 3.5° field of view with better than 0.2 arcsecond sampling. The image surface is flat with a diameter of approximately 64cm. The detector format will be a mosaic of 16 Mpixel silicon detectors providing a total of approximately 3.2 Gpixels.

NGAO—Keck Next Generation Adaptive Optics system will incorporate multiple laser guidestar tomography to increase the corrected field of view and remove the cone effect inherent to single laser guide star systems. The improvement will permit higher Strehl correction in the near-infrared and diffraction-limited correction down to R band.

ODI—One Degree Imager on the Wisconsin Indiana Yale NOAO 4 m telescope on Kitt Peak. The focal plane of the optical imager will be sampled with 0.1" pixels, or 1 Gigapixel in total. The sharpness of images will be actively improved by correcting images for tip/tilt image motion during the integration corrections will be done over the entire field of view, using an Orthogonal Transfer Array CCD.

SDSS—Sloan Digital Sky Survey camera and spectrograph. The camera includes 30 CCDs arranged five to a column. Each CCD is made up of more than four million pixels.

DECCAM—Dark Energy Camera on the NOAO Blanco 4 m telescope, a 3 sq. deg. mosaic camera consisting of a large mosaic CCD focal plane, a five element optical corrector, five filters (g,r,i,z,Y)

HETDEX—An upgrade of the Hobby Eberly Telescope in order to measure Dark Energy. The project has three parts: upgrade of the HET to have a 22 ′ diameter field-of-view, deployment of the VIRUS integral field spectrograph, and completion of a wide field survey to constrain the evolution of dark energy.

BIG BOSS-- The BigBOSS experiment is a proposed ground-based dark energy experiment on the NOAO Blanco 4 m telescope to study baryon acoustic oscillations and the growth of structure with an all sky galaxy redshift survey. A 4000-fiber R=5000 spectrograph covering a 3-degree diameter field will measure BAO and redshift space distortions in the distribution of galaxies and hydrogen gas spanning redshifts from $0.2 < z < 3.5$.

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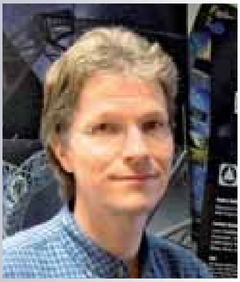
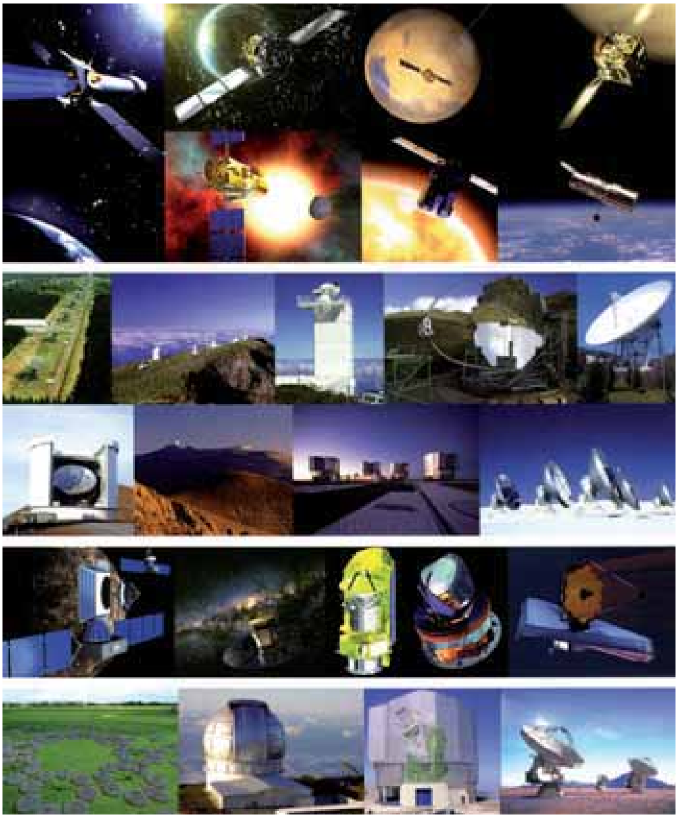


Astrophysics for the next decade

Abstract
Astrophysics has entered a 'golden age' with access to the complete electromagnetic spectrum through a combination of ground- and space-based observatories. Scientific results of the past decades have revolutionised the view of the universe and placed the solar system in a new context. Plans for the observational facilities of the next decade are drawn up defining the future of astrophysics. The current evolution of the existing and planned ESO facilities is used as a case study to address some of the most prominent science questions.



A selection of observing facilities accessible to European astronomers. Taken from the ASTRONET Roadmap (Bode et al. 2008).

1. Introduction

Every generation of astronomers has tried to define the most exciting research topics and to forecast what the new facilities will bring and where they should concentrate their efforts. Planning for the future with the existing telescopes and instruments, and the enabling opportunities of new observatories remains a critical task. Observational astrophysics also depends on large facilities and regular planning on national as well as European levels appears appropriate. The major research themes have been, and still are being, collected in science vision documents, roadmaps, decadal reviews and other planning documents. An incomplete collection includes the European ASTRONET Science Vision (de Zeeuw and Molster 2007), the ASTRONET Roadmap (Bode et al. 2008), the ESA Cosmic Vision (Bignami et al. 2005), the series of working group reports commissioned by ESA and ESO (Exoplanets – Perryman et al. 2005; ALMA-Herschel Synergy – Wilson et al. 2006; Fundamental Cosmology – Peacock et al. 2006; Galactic Populations, Chemistry and Dynamics – Turon et al. 2008), several national decadal reviews in Europe (a list of national plans can be found on the ASTRONET home page: http://www.astronet-eu.org/-Science-Vision-) and other parts of the world, astroparticle roadmaps (e.g. the European ASPERA roadmap: Spiering et al. 2008), and specific publications. An ESO conference on Science with the VLT in the ELT Era was held recently (Moorwood 2009). It is not too surprising that the scientific goals and themes of new facilities often read fairly similar. Examples are the characterisation of dark energy and dark matter, observations of the light from the first objects in the early universe, the objects responsible for the ionisation of the intergalactic material, the formation and evolution of galaxies as well as the formation of stars and planets are present in most science cases.

The full electromagnetic spectrum is now accessible to observations. We are currently in a situation where we can observe photons of energies from a few hundred TeV (corresponding to a wavelength of $1.2 \cdot 10^{-20}$ m) to wavelengths of several meters (or an energy of $1.2 \cdot 10^{-8}$ eV), i.e. over 20 orders of magnitudes can be monitored. The combination of space and ground observatories provides access to the sky never enjoyed before. The 'spectrum' is now extended to other particles ('messengers') through cosmic ray research, astrophysical neutrinos, the prospect of detecting gravitational waves and discovering dark matter particles in underground laboratories. This combination of fantastic observing capabilities and some of the dramatic discoveries of the past decades have led some to proclaim a 'Golden Age in Astrophysics'. The International Year of Astronomy 2009 is a fitting celebration of the achievements and the promises of astrophysics, the role it plays in our world view and the universe we live in. Engaging the public's interest in the world we inhabit and the cosmos engulfing us brings enhanced visibility and responsibility.

2. Research themes

The most prominent astronomical results over the past decades are leading to new questions. The following sections give a personal view of the achievements of past years and the prospects for the coming decade. Predicting the future is notoriously difficult and I will not venture too far. However, I believe that clear lines of research can be discerned and are the basis for several instruments in development or planning. I will mostly concentrate on the ESO programme for VLT instruments and future facilities.

3. What matters in the universe?

The discovery of dark energy and the long-standing enigma of dark matter remain major puzzles to be resolved. If the past decade is any guidance, then we are expecting large surveys and concerted efforts using many telescopes to achieve a further decrease in the uncertainty on the equation of state parameter of dark energy and to map out the gravitational growth of structure in the universe. The requirement to collect very large samples over large sky areas results in major projects of global scale and distributed efforts. Five main astrophysical methods are currently discussed to further improve our understanding of cosmology: Baryonic acoustic oscillations (BAO), weak lensing, supernovae, galaxy clusters and redshift space distortions. With the exception of distances derived from supernova observations all methods determine a combination of the expansion history and the growth of structure, i.e. dark matter concentrations. Examples of BAO surveys are the 2dF survey with the Anglo-Australian Telescope (Cole et al. 2005) and the Sloan Digital Sky Survey (Eisenstein et al. 2005). These are now followed by the WiggleZ survey (Drinkwater et al. 2009) and the Baryonic Oscillation Spectroscopic Survey (BOSS; Schlegel et al. 2007). One of the first massive weak lensing surveys is part of the Canada-France-Hawaii Telescope Legacy Survey (Hoekstra et al. 2006). The CFHT Supernova Legacy Survey (SNLS), the ESSENCE project and nearby supernova searches have now provided a sample of about 1000 Type Ia supernovae useful for cosmology. A summary of supernova surveys can be found in Leibundgut (2008). Galaxy clusters principally have been based on X-ray surveys and have been followed up from the ground to establish the redshifts, cluster membership and cluster dynamics. Redshift distortions can also yield measurements of the growth rate of mass agglomerations.

All these surveys have made use of 4 m and 8 m telescopes over several years. Telescopes equipped with large multiplex facilities (either wide-field imagers or multi-object spectrographs) have been essential. The commitment of large fractions of observing time has also been critical for the success of such surveys. Due to their small field of view and the massive amount of observing time necessary, it is to be expected that extremely large telescopes will contribute mostly specific information on individual objects. Instruments at 8 m telescopes for wide-field surveys are Suprime-Cam and the FMOS multi-object spectrograph at Subaru. The 4 m LAMOST telescope is in commissioning with a very high multiplex spectrograph and is fully dedicated to wide-field spectroscopy. It will certainly be used for cosmological surveys. Plans for the extremely high multiplex spectrograph VIRUS are in an advanced state for the Hobby-Eberly Telescope (HET) to be used for the HETDEX project (Hill et al. 2008). VIMOS at the VLT has already provided a first measurement of the redshift distortion (Guzzo et al. 2008) and the VIPERS survey is currently being executed (http://vipers.lambrate.inaf.it/).

An extremely large telescope can make a unique contribution by measuring the temporal change of redshifts and hence directly map the dynamics of the cosmic expansion (Liske et al. 2008). The CODEX experiment on the European Extremely Large Telescope (E-ELT) would be able to perform such a measurement. The fundamental requirement here is the very high spectral resolution and stability (to be achieved with laser combs, Steinmetz et al. 2008), sufficient photon collecting power and a long time line. This is clearly a measurement that is beyond any existing telescope facility.

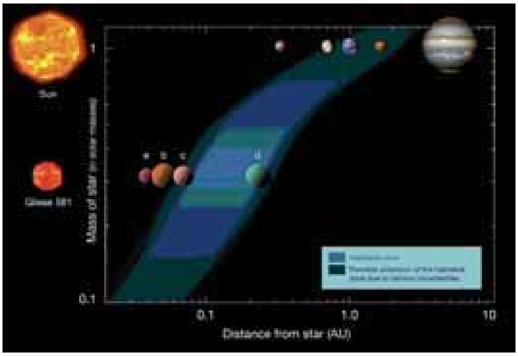
Further progress could be achieved through a dedicated space mission covering the whole extra-galactic sky. ESA is currently studying EUCLID, which would measure the equation of state parameter of dark energy to 1% accuracy. Such a mission will require ground-based support for calibration.

4. Planets, planets, planets

Our place in the universe can only be understood, if we have a better picture of how the solar system compares to planetary systems around other stars. This has been the most rapidly growing field of astronomy over the past decade and has produced several hundred known exoplanets in about 15 years (Udry and Santos 2007). There are three major ways to detect and characterize exo-planets: radial velocity changes in the parent star, direct imaging and detection of planetary transits as extremely faint eclipses of stars. Three additional methods are discovery by the periodic modulation in a pulsar signal, gravitational lensing by a foreground star (Beaulieu et al. 2006) and the astrometric movements of the parent star. Only one planetary system (with three planets) around a pulsar has been discovered (Wolszczan and Frail 1992). These systems must be extraordinarily rare as it is not obvious how a planetary system can survive the formation of the neutron star. Microlensing measurements have the impediment that it is very difficult to obtain additional information about the parent star or the planet after the lensing event. So far, the optical/infrared interferometers have not been powerful enough to measure the reflex motion in the astrometry of star, although the VLTI might be in a position to do this once PRIMA has been fully commissioned (Delplancke et al. 2003). A complete "discovery tree" for exo-planets can be found in Perryman et al. (2005).

The most important goals for the coming years are the characterization of planetary systems (rather than individual planets), a complete census of the mass distribution of planets, as well as their chemical composition and temperatures. Several planetary systems, i.e. stars which are known to harbour two or more planets, have been found so far. Currently, the measured mass distribution is highly biased as massive planets in short orbits are strongly favoured by the radial velocity method. Only the combination of several discovery schemes and increased sensitivity will provide a more complete picture. The measurement of chemical composition of planets has been done through differential spectroscopy in transiting systems. Direct spectroscopy of planets that can be separated from their host star will provide a significant improvement in the analysis.

A real industry of radial velocity projects has sprung up making use of many telescopes from 1 m to 10 m diameters. The observational requirements here are high spectral resolution and extended time series to measure at least a large fraction of an orbit or several orbits. Since planets at large distance from their host star have large periods, they can only be discovered by patient people. The currently most successful instruments are HARPS at the ESO 3.6 m telescope and HIRES at Keck. HARPS has recently found the least massive planet known with only twice Earth's mass (Mayor et al. 2009). The combination of planet transits with host star radial velocities is especially precious as masses, sizes and mean densities of the planet can be determined. The CoRoT satellite has already found several such planets and their masses have been determined through HARPS measurements (e.g. Moutou et al. 2008). The addition of HARPS North at the William Herschel Telescope will provide a full sky coverage and in particular supply the radial velocity measurements of transiting planets found by the Kepler satellite. The future of the radial velocity method will see the extension to fainter magnitudes with the ESPRESSO instrument on the VLT (Pasquini et al. 2009) and CODEX at the E-ELT.



The planetary system around Gliese 581. The innermost planet has a mass of only 2 M♀. The outermost planet is within the habitable zone around this star. Adapted from Mayor et al. (2009; ESO Press Release 15/09).

Direct imaging has mostly been done in the near infrared where the contrast between the host star and the planet is strongest. In particular, young planets are still cooling and are more easily detected in the near-IR. A high spatial resolution calls for adaptive optics (AO) instrumentation on large telescopes or imaging with space telescopes. It is no surprise that all current 8m telescopes have invested in AO. Keck, Gemini, Subaru and the VLT possess the capability to correct for image distortion caused by atmospheric turbulence and all these telescopes have found exo-planets and exo-planetary systems recently (Marois et al. 2008, Lagrange et al. 2008). These observatories are also investing in the next generation adaptive optics systems with several laser guide stars. At the same time several new instruments are developed for direct imaging of planets close to their star.

At ESO the SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) instrument is being built to directly observe and analyse planets around nearby stars. It will concentrate on young star associations, stars with already known planets from other detection methods and stars younger than 1 Gyr, when the brightness contrast between star and planet is high. A contrast of 14 to 16 magnitudes and very high angular resolution down to 0.1 arcsecond separations plus sensitivity to H≈24 mag are essential for this instrument. In addition, low resolution spectroscopy is included to characterise the planetary atmosphere. SPHERE will contain an optical and a near-infrared channel. Extreme adaptive optics combined with a coronagraph and dual-beam design for accurate image subtraction are employed to achieve the demanding requirements. The optical channel will be equipped with a polarimeter to separate the reflected light close from the star and hence further increase the contrast. A description of the instrument can be found in Beuzit et al. (2006). SPHERE should become available at the VLT in 2011.

A completely different option is to use interferometry for the characterisation of planetary systems. The MATISSE instrument for VLTI is in the preliminary design phase. Through its capability of combining up to four beams, it will be able to directly image planets at mid-infrared wavelengths.

A natural evolution in this field is to explore the increased angular resolution provided by larger telescopes and hence it is no surprise that direct imaging for planetary systems is one of the ELT core programmes. At ESO the EPICS instrument study is exploring the possibilities for the E-ELT.

5. How did stars and planets form?

The very early stages of star formation are hidden in the cores of dense molecular clouds and hence not directly observable at visible or near-IR wavelengths. The transition from the cloud collapse to the initial ignition of the nuclear burning has still not been observed. This field will profit most from the increased wavelength coverage that ALMA offers. The combination of angular resolution – to separate the individual sources in the crowded fields of their birth places – and the sensitivity at mm wavelengths is crucial to detect collapsing clouds and the increased heating of the surrounding gas by the nascent star. As the temperature increases and the surrounding material becomes ionised the object is revealed at progressively shorter wavelengths. The combination of different facilities to map the complete picture of star formation is essential. The disentangling of the different emission sites of the forming star and its environment are critical to improve our understanding of this process. The planetary disks and the later stages of the debris disks hold the signatures of forming planets. The chemistry of such disks is largely unexplored (although see the first results from MIDI at VLTI by van Boekel et al. 2004), but will become accessible with increased angular resolution and extended wavelength coverage. Matching angular resolution at all these wavelengths will yield the full picture. JWST is ideally suited to observe the warm disks and clouds, but the increased angular resolution of the extremely large telescopes will supply further details of the disks and possibly forming planets.

Since large telescopes are essentially diffraction limited in the thermal infrared the achievable angular resolution directly depends on the aperture. The advantage of the 8 m telescopes even over JWST for this type of research is obvious. CanariCam on the GTC will be ideally placed to explore the nearest star formation regions like Orion and Taurus. MATISSE at the VLTI will also be able to map star forming regions in great detail and an unchallenged angular resolution.

ALMA will have the potential to resolve many young circumstellar disks and detect gaps of planets. Combining this spatial information with the knowledge of the chemistry in the disk will provide unique details. The contribution of Thomas Henning has further details on the advances expected in this field in the coming years.

6. The Milky Way - our home

The solar neighbourhood and the structure of the Milky Way remain interesting fields of research. Astrometric missions, like HIPPARCOS and GAIA, are adding the proper motion information to the radial velocities and chemistry of the stars. The study of 14000 F and G stars over nearly two decades has provided a clearer picture about the dynamical evolution of these nearby stars (Nordström et al. 2004). The necessary sample size requires such very long studies. In this case, the objects are sparsely distributed on the sky and needed to be observed individually.

The structure of the Milky Way can only be understood through such coordinated, long-term efforts. The report by the ESA-ESO working group on stellar populations outlines what should be done in the coming years to make best use of the GAIA results combined with ground-based telescopes (Turon et al. 2008). The need for spectroscopy of thousands of stars is stressed in that report. Highly multiplexed facilities or observatories willing to invest large amounts of observing time will be in an excellent position to make such contributions.

The Galactic Bulge remains an active area of research. The exact composition and formation of this important galactic structure, observed through the Galactic bar, are the topic of many ongoing studies. The potential to separate stars according to their proper motion and a better isolation of the bulge stars from the foreground further improves the knowledge on the composition of the Milky Way.

Combining the information from gas flows, the stellar dynamics and the chemical composition of the various components holds the promise to fully disentangle the evolution of the Galaxy. The SDSS has found many dwarf galaxies around the Milky Way and provided clues to understand the growth of our Galaxy and the dark matter distribution around us. At the same time the existence of the densest and most massive star clusters near the centre of the Milky Way (Genzel et al. 2003a) together with high-energy phenomena like the observed 511keV electron-positron annihilation γ-ray line near the centre (Churazov et al. 2005) show that there is still a lot to be learned from this unique region on the sky and in our Milky Way.

7. Our own black hole

The accurate mapping of the innermost stellar orbits has proven beyond doubt that a super-massive black sits at the centre of the Milky Way (Schödel et al. 2002). The detection of infrared flashes from the position of Sagittarius A* (Genzel et al. 2003b) is the first evidence of matter falling into the black hole. This latter detection was only possible through adaptive optics. Multi-wavelength studies show the time behaviour of these flares. They ultimately will allow probing for the rotation of the black hole itself.

Probing the Galactic Centre has been a long-term undertaking and it is easy to predict that this research will continue for several years to come with the largest available telescopes. The exact measurement of the stellar orbits requires several years to map sufficient trajectories. In the future, precession of the peri-bothron (closest approach to the black hole) of the stellar orbits will provide even more details on the structure of the gravitational field around the black hole. Gemini South with the multi-conjugate adaptive optics system GEMS and also Keck with its next generation adaptive optics system NGAO will be well suited for these observations. ESO is developing the adaptive optics facility (AOF), which should provide further improved AO capabilities to the already existing AO-supported instruments NACO and SINFONI. All these observatories also use laser guide star facilities.

The goal now must be to explore the space-time geometry in the strong gravity regime. The black hole at the centre of the Milky Way is the nearest object, where we can hope to study many of the predictions of general relativity in detail. The Schwarzschild radius of the black hole is about 9 microarcseconds as seen from Earth and resolving emission from material on this angular scale should show many of the GR effects. Since the Galactic Centre is hidden behind several magnitudes of optical extinction, the only way to observe it is in the infrared. The resolution required for the above study can only be achieved through interferometry with the VLT unit telescopes. An instrument to explore this parameter space, GRAVITY, is currently in the design phase. It should allow astronomers to astrometrically probe this innermost region of our Galaxy. It may even be possible to determine the astrometry of individual flashes as a function of time. This would provide information on the very last moments of the matter falling into the black hole.

8. How did galaxies form and evolve?

There are four different redshift ranges of interest to track the evolution of galaxies. The galaxy population at $z>3$ needs to be mapped in more detail than is available today. These objects are mostly found through the Lyman-breaks in their spectrum, although one needs to be aware that this represents a selection. At higher redshifts galaxies are found through their Lyman-α emission. At redshift $1<z<2$ there is a population of massive galaxies with old stars. These ‘red and dead’ galaxies seem to have formed and exhausted their gas early. They form a significant fraction of the known mass in galaxies. A summary of the current knowledge of these objects is available in Bergeron (2009).

The build-up of the morphological Hubble sequence over cosmic time is a major topic in this field. The separate tracks of star-forming and passive galaxies need to be followed and possible crossings explored. The galaxies need to be identified in deep, wide-field imaging surveys and followed with massive spectroscopic surveys. Suprime-Cam on Subaru has made major contributions in this field and the upcoming survey telescopes VISTA, VST and later on LSST will provide plenty of objects.

At the moment the only spectropgraphs capable of such massive surveys are mounted on 4 m telescopes. The exceptions are VIMOS on the VLT and FMOS on Subaru, which is currently in commissioning. The large samples to be collected by these spectrographs will help understand the statistics of the different galaxy types.

The characterisation of internal dynamics of these galaxies needs to be explored to understand their evolutionary state. This requires high angular resolution as well as spatially resolved spectroscopy. Integral field spectrographs supported by adaptive optics are essential for this research. HST is a prime resource, but ground-based telescopes with adaptive optics can provide important contributions as well. There are many instruments currently mounted at 8 m telescopes. The VLT offers NACO and SINFONI, both supported by laser guide stars. The first GTC instrument, OSIRIS, with the important tunable-filter mode, which allows covering many galaxies in a field and quickly scan for emission-line objects, should be able to make important contributions. Future VLT instruments for this research will be KMOS as well as HAWK-I and MUSE supported by the adaptive optics facility. Of course, this is also one of the primary science cases of JWST. The future ELTs will provide even higher angular resolution, but will have to restrict themselves to small samples.

Objects at the highest redshifts are the scientific goal of almost all new facilities. The search for Lyman-α emitters and the detailed investigation of the intergalactic medium through the study of quasar absorption lines are the domain of large telescopes. JWST will have the advantage that the infrared background in space is limited to zodiacal light only. Subaru's Suprime-Cam has delivered most of the highest redshift galaxies (see Masanory Iye's contribution) and large sky areas need to be scanned to find these extremely rare and faint objects. LSST and EUCLID will provide many candidate objects, which will need to be followed up by optical and infrared spectroscopy. X-shooter and NACO at VLT, OSIRIS at the GTC, LRIS and DEIMOS at Keck and GMOS on the Gemini telescopes will be the instruments of choice to identify the nature of these objects. In the future AO-supported HAWK-I and MUSE together with KMOS on the VLT, MOSFire on Keck and EMIR on the GTC will provide tools to further investigate this rare population. Bergeron (2009) gives more details for VLT and ELT observations relevant for this field.

9. Fashions and other transient phenomena

Supernovae and Gamma-Ray Bursts (GRBs) have become very fashionable objects. Supernova cosmology (e.g. Leibundgut 2008) has provided evidence for dark energy and the connection of supernovae with the GRBs have sparked strong interest. While there is a lot of interesting physics to be learnt from these most energetic events, one should be careful not to overestimate their importance for astrophysics. Supernova explosions, both types – the core-collapse and the thermonuclear explosions – present some of the most fascinating physics, but at the same time also present some of the most challenging puzzles. It will remain to be seen how much the different observational methods will be able to contribute to these fields. In any case, the introduction of the rapid response mode at ESO (and Gemini) has provided the community with the capability to use 8 m telescopes to observe fast astronomical phenomena with the appropriate speed. In some cases GRBs could be observed within 10 minutes of the γ-ray detection by SWIFT (e.g. Vreeswijk et al. 2007). It is such types of specialisations, which can contribute dramatically to some observational fields.

On the other hand, there are scientific topics, which 'resonate' with instrumental capabilities. An example might be the study of active galactic nuclei (AGN) with low-resolution spectrographs at 4 m telescopes. The 8 m telescopes have contributed relatively little to the understanding of AGNs. However, accessing the innermost parts of AGN with interferometric observations, as is currently being done with the VLTI, will open up a new window into these astronomical power houses. The increased angular resolution has allowed the study of the inner torus of AGN_s(Jaffe et al. 2004).

Another spectacular success of 8 m telescopes has been the abundance studies of metal-poor stars (e.g. Cayrel et al. 2004). However, it is not clear in which direction this field is moving. It might well become part of the general studies of the stellar populations and the elemental distributions in our Galaxy described above.

All observatories need to be aware of emerging scientific trends and assess how they can position themselves to make an optimal contribution. ASTRONET is currently investigating how the 2 m to 4 m European telescopes can be coordinated to provide the most efficient resource for astronomy. A global coordination for 8 m telescopes is not planned, but it might be useful to discuss synergies between different observatories as it is done by the 8 m and 10 m telescopes on Mauna Kea.

10. When opportunity knocks

Nature occasionally provides us with unique and singular opportunities. SN 1987A was the nearest stellar explosion for several hundred years and has an uninterrupted observational record with HST and the VLT. This spectacular event continues to be observed with the major telescopes and remains a most interesting astrophysical object (for a summary of what has been learnt from SN 1987A see Fransson et al. 2007).

It is not possible to predict such events but observatories should be prepared to make best use when they occur. Flexible operational modes and the willingness to quickly identify and invest in such opportunities are instrumental for success. As the inauguration of the GTC on La Palma took place all major telescopes were observing Jupiter to follow up on an impact of a large body on the planet. This is now the second time such an impact can be studied in detail after Shoemaker-Levy 9 bombarded Jupiter in 1994. The solar system regularly offers surprising events.

We do not know what nature has in store for us, but we should be prepared to recognise the chance when it arises.

11. Telescopes of the future

The plans for extremely large telescopes need to be seen in context with the existing telescopes. There are now 13 telescopes operating with a diameter of more than 7 metres. Another 22 telescopes with diameters between 3 m and 7 m are available to astronomers. The bulk of the observations continues to come from these telescopes and it will be nearly a decade before any of the ELTs will start operations. The current suite of telescopes remains the basis for observational optical and infrared astronomy in the coming decade. Major additions in this size category will be JWST, LSST, VISTA, LAMOST and the Lowell Observatory's Discovery Telescope.

There are three ELT projects in advanced planning or with the first elements being procured, but they will clearly be outnumbered by the already existing 8 m to 10 m telescopes. The instrumentation on the ELTs will also be limited and will have to suit their strengths – light gathering power and angular resolution. Many scientific topics can very well be continued with the current telescopes and applications, which need large samples or long time series, will be better suited by the 8 m telescopes with state-of-the-art instrumentation.

The 8 m telescopes will remain the work horses of observational astronomy for the coming decade and beyond. They represent a distributed resource, which provides access for many different communities, and have a full instrumentation complement. The instrumentation on the VLT alone nearly covers the full available parameter space in term of wavelength coverage, spectral resolution, spectral multiplex and angular resolution combined with relatively large fields of view. Given this competition, it will be important for the observatories to decide where they want to put their resources and how they can optimally use the strengths of their telescopes. Examples of projects, which will most likely be preferably done with 8 m telescopes, are time series, collection of large samples, wide-field imaging and spectroscopy, and the search for rare objects. The 8 m telescopes will also be well suited to follow many space projects or complement ALMA observations.

The use of 4 m telescopes over the past decade can help to decide which strategies worked well. Several examples of successful specialisation of 4 m telescopes can be mentioned here: the exploitation of the wide-field capability of the AAT to produce the 2dF survey, the deep, wide-field imaging surveys of MegaCam on CFHT, UKIDSS, which made use of UKIRT, or the Mosaic2 camera on the CTIO Blanco telescope have produced important scientific results. The HARPS survey on the ESO 3.6 m telescope has made a clear difference in exo-planet research. It should be noted that these investments always were leveraged with dedication of large amounts of observing time. The time will come where the 8 m telescopes will benefit from such specialisations as well.

As mentioned several times already, there was and still is an important rôle for 8 m telescopes in complementing and enhancing surveys done with 4 m telescopes. The follow-up observations of UKIDSS, VST, VISTA, LSST and PanSTARRS will need a lot of 8 m time. Investigating rare objects found by such surveys in great detail with the large telescopes will be critical. The full exploration of the electromagnetic spectrum means that the 8 m telescopes will supply the optical and infrared photometry and spectroscopy to follow-up sources detected by Herschel, Fermi, XMM/Chandra, JWST and eROSITA. In many cases polarimetry will also be used to further investigate the light emission. Of course, ALMA and the SMA will be strong partners of the 8m telescopes for several decades to come.

12. ESO's next decade

ESO currently operates the La Silla Paranal Observatory, constructs ALMA and designs the E-ELT. It now receives well over 1000 observing proposal per (half-year) scheduling period. This means that ESO is handling over 2000 proposals per year for four 8 m VLT unit telescopes, the VLTI array, APEX, 3.6 m, NTT and the MPG 2.2 m telescope. Overall, it offered 23 different facility instruments plus a visitor focus on these telescopes for Period 84. Six instruments are undergoing upgrades of various forms and there are six VLT instruments in construction, under development or planning. In addition, the laser guide star facility went through a major upgrade programme recently and the adaptive optics facility providing a deformable secondary mirror is under development. Finally, the VLTI will be equipped with the phase referencing system PRIMA. All ESO data become publicly available through an extensive archive. Over 700 refereed publications based on data from ESO telescopes are published every year.

ESO is the European partner in the ALMA project and is responsible for several major deliverables. ALMA will start operations in 2013 with four receiver bands and 66 antennae. ESO is currently building up the ALMA Regional Centre with several nodes in member states.

At the same time ESO is finishing the design study for the European Extremely Large Telescope and pending Council approval will construct this telescope and instrumentation in the coming decade.

13. La Silla Paranal Observatory

The successful operations of the La Silla Paranal observatory remain a top priority for ESO. The VLT had reached its full instrument suite some years ago. In 2009 the first second generation instrument, X-shooter, has been commissioned and will start operating. Hence the VLT provides 11 facility instruments covering the whole optical and infrared electromagnetic spectrum plus adaptive optics support including laser operation. A visitor focus is maintained for highly specialised instruments. In addition, the VLT Interferometer with its auxiliary telescopes is operating about 200 nights per year. It is equipped with two instruments and is being upgraded with the Phase Reference Imaging and Micro-arcsecond Astrometry (PRIMA) facility.

The VLT on Paranal remains the prime observatory for European astronomers in the Southern hemisphere. Instrument upgrades and improvement of the facilities, like the laser guide star shown in this picture, are crucial for the continued success of the observatory.

PRIMA will give allow to observe much fainter sources than is currently possible and should make many interesting objects accessible to interferometry.

The instrumentation programme for the VLT continues with upgrades to existing instruments (e.g. detector upgrades for FLAMES/GIRAFFE, UVES, VIMOS, VISIR), upgrades of optical components (filters, gratings, grisms) and new instruments. In a few years the infrared multi-object spectrograph KMOS will be commissioned. It will be followed by MUSE, which will provide a massive integral field in the optical and will have many astrophysical applications. The planet finder SPHERE will make use of extreme adaptive optics to achieve the best possible angular resolution. The Adaptive Optics Facility will combine an adaptive secondary mirror with multiple laser guide stars to support HAWK-I and MUSE. A dedicated AO instrument is currently under discussion. VLTI is augmented with PRIMA and the future instruments GRAVITY and MATISSE to provide dual-feed fringe stabilisation, microarcsecond astrometry and closure phase observations. Detailed information on the VLT instruments can be found at http://www.eso.org/sci/facilities/paranal/instruments/ and http://www.eso.org/sci/facilities/develop/.

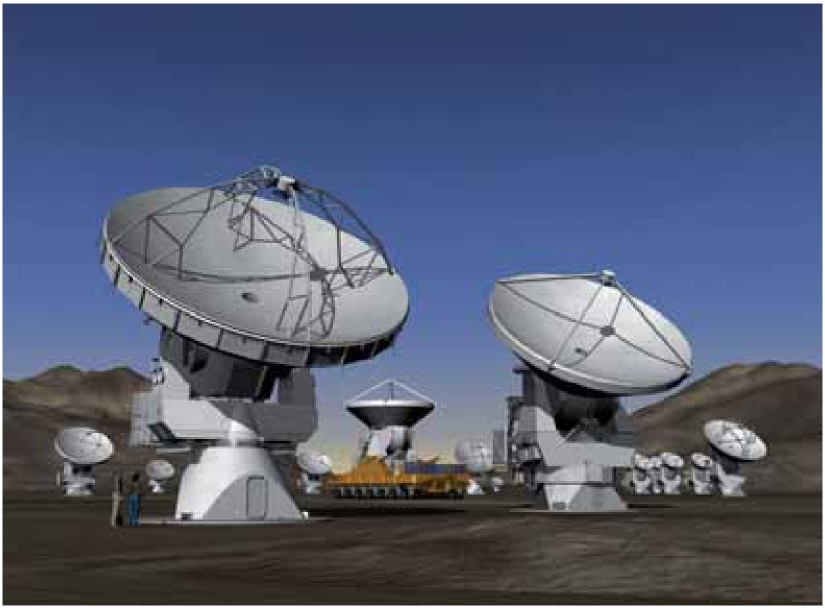
The 3.6 m telescope and the NTT on La Silla continue operations with extended long-term large observing programmes. HARPS is in strong demand and provides the most accurate radial velocity measurements globally. An upgrade to improve the spectral stability further and include a spectropolarimetry mode is ongoing. EFOSC2 and SOFI are the instruments on the NTT and afford access to general purpose projects. They are now in strong demand for multi-year supernova and solar system studies. The NTT also receives visitor instruments regularly for specialised observing methods. The wide-field imager WFI and the high-resolution spectrograph FEROS continue to be offered on the 2.2 m telescope.

In the next year the wide-field telescopes VISTA and VST will start operations and be used for massive public imaging surveys.

14. ALMA

The completion of the construction of ALMA within the next years is another primary goal of ESO. This global observatory is being built by a collaboration of Europe, North America and East Asia. The 66 antennae (50 with 12 m and 16 with 7 m diameter) at an altitude of 5000 meter will open a new window to the universe with the mm and sub-mm capabilities of the antenna array. The science requirements include the detection of carbon monoxide and the forbidden [C II] line in galaxies at a redshift of about 3, the dust emission and gas kinematics in proto-planetary disks and exploration of forming exo-planets. The resolution that ALMA can achieve will be comparable to the one from HST, JWST and AO-supported 8-10 m telescopes. ALMA's science goals are described at http://www.eso.org/sci/facilities/alma/science/goals.html where a link to the community-based design reference science plan can be found.

ALMA will offer four receiver bands at the start, but four more bands are under development. Eventually ALMA will offer a wavelength range from 84 GHz (3.6mm) to 950 GHz (320µm). The flexible array configuration will allow angular resolutions of better than 0.1 arcseconds. ESO provides the European access to this facility and is setting up the support of its community through the ALMA Regional Centre (ARC) and various national nodes. The scientific programme is strengthened through nine additional postdoctoral fellow positions funded by the European Union Marie-Curie scheme.

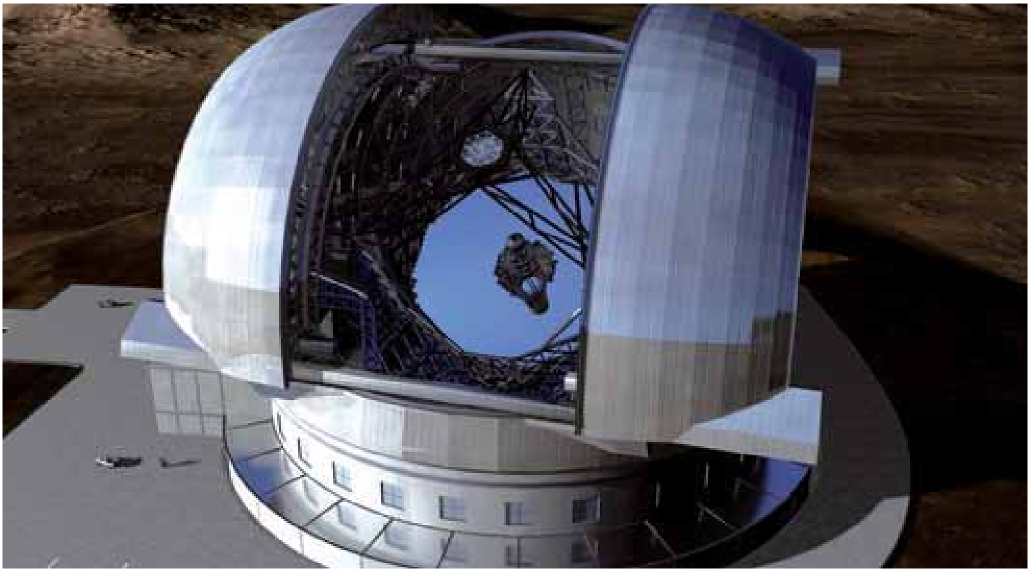


Artist impression of the ALMA observatory on Chajnantor. ALMA operations are planned to start in 2013 making this picture a reality.

ALMA synergy with the VLT and other optical/infrared telescopes is an important element for ESO. The coverage of the spectral energy distribution of many objects between the optical, which is typically dominated by the hot plasma of stars and the emission from cool gas and dust at mm wavelengths, is a very strong tool to disentangle complex and composite objects. Early science with ALMA is planned for late 2011 and full operations for 2013.

15. E-ELT

The detailed design study for a European Extremely Large Telescope of 42 m diameter will be finished in 2010 and a proposal for construction of the E-ELT will be presented to the ESO Council. It is ESO's next big project. The telescope has a revolutionary 5-mirror design which fully incorporates adaptive optics through a deformable mirror and a tip-tilt correction on a separate mirror. The science case for the E-ELT has been developed together with the community through the OPTICON network (e.g. Hook 2009) and will be delivered with the telescope proposal. The major themes are the same as described above. In addition, the E-ELT will have great power to resolve stellar populations beyond the Local Group. Eight possible instrument concepts for the E-ELT are being studied with the community (D'Odorico et al. 2009) together with two adaptive optics modules. There are currently 36 individual institutes from 10 member states involved in the instrument studies.



The E-ELT is the next large project for ESO. The study phase will be finished in 2010.

The E-ELT will strongly depend on synergetic observations with other facilities in space and on the ground. It will be a critical component in the telescope landscape with ALMA, JWST, survey telescopes and the Square Kilometre Array. Of course, the new parameter space accessible with the E-ELT will almost certainly reveal new phenomena, which are inaccessible to current telescopes. Despite the expected discovery potential of the E-ELT, the selection of the interesting objects will happen with the smaller telescopes and the 8 m telescopes will play a critical role for the effective and optimal use of the E-ELT.

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TMT: the next generation of segmented mirror telescopes

1. Introduction

The Thirty Meter Telescope (TMT) is a project to build and operate a ground-based thirty-meter telescope for optical and infrared astronomy. The primary mirror is segmented (492 segments) and follows the general design approach of the Keck Observatory. The telescope is compact (f/1 primary) and can accommodate multiple science instruments on either of two Nasmyth platforms.

1.1. Organization

The partnership that forms the TMT consists of the University of California, Caltech, Canada (HIA), Japan (NAOJ) and possibly other international partners. It is our desire that the National Science Foundation join the Project in order to provide a significant share of the telescope for use by the broad USA community of astronomers.

The headquarters of the project are in Pasadena, CA, but work is carried out as well by partner institutions at other locations. A number of industrial firms are involved in the design of the observatory.

The project began officially in 2004 with the hiring of its Project Manager, Gary Sanders. Jerry Nelson is the Project Scientist.

1.2. Site Selection

Finding the best site for such a large telescope is essential, and an extensive study of potential sites all over the world was initiated. Satellite studies of cloud cover and water vapor were used to reduce the candidates to five (Armazones, Tolar, Tolanchar in Chile, San Pedro Martir in Baja, and Mauna Kea in Hawaii). At these sites extensive testing equipment was installed to measure various weather and atmospheric conditions. Of greatest importance was the measurement of the seeing, and the vertical profile of atmospheric turbulence. Based on over two years of data at the five sites, two were judged highly meritorious on the basis of their science potential and were our final candidate sites (Armazones, Mauna Kea). After carefully reviewing the science potential, likely construction and operating costs, staffing issues, and other partner interests, we have recently selected Mauna Kea as the site for TMT. The actual site on Mauna Kea is a region known as 13N, somewhat lower than the summit ridge, at an altitude of 4000 m. This high site has particular potential for infrared astronomy due to its low precipitable water vapor and low temperature.

1.3. Schedule

The preliminary design phase has run from 2004 to 2009. We are now in the preconstruction phase, and expect that construction will start in the fall of 2011. The construction project includes the telescope as well as a very capable adaptive optics

(AO) system and three first-light science instruments. These will be discussed later. First light is expected in late 2018, with all the above systems operational and science operations underway, including AO.

1.4. Cost

The cost of the Observatory in FY2009$ is estimated at $970M which includes a 30% contingency. Cost is based on a detailed work break down structure, often going 7 layers deep and each WBS element costed bottoms-up. A formal risk analysis is employed for each of these elements. These risks are then rolled up to form the final percentage contingency for the Project. Of course the Project cost depends on what year $ it is calculated in, and will ultimately be sensitive to when actual construction starts.

2. Telescope Overview

Telescopes have grown gradually over time, from the 5 m Hale telescope completed in 1948 to the 10 m Keck telescope, put into operation in 1993. The Keck telescope uses a radical technical departure to achieve this size. The primary mirror is not a monolithic mirror, but is composed of 36 hexagonal segments whose positions are actively controlled. This allows the primary to behave optically as though it is a monolithic mirror.

Figure 1: The TMT shown with its enclosure and support facilities as it will appear on Mauna Kea

The TMT is built on the principles established by the Keck Observatory. The TMT primary mirror is segmented, with 492 hexagonal segments. The primary focal length is 30 m, allowing for a very compact enclosure. The optical configuration is a Ritchey-Cretien (RC) design, providing a 20 arcminute field of view with images < 0.5 arcsec. The telescope with its enclosure is shown in Figure 1. The optical layout is shown in Figure 2.

The primary mirror with its 492 hexagonal mirror segments is shown in Figure 3.

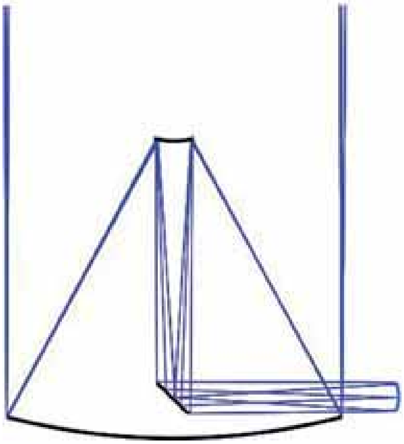

Figure 2: The Ritchey-Cretien design of the TMT with an f/1 primary and an f/15 final focal ratio. All instruments will be on the Nasmyth platforms, fed by the articulated tertiary.

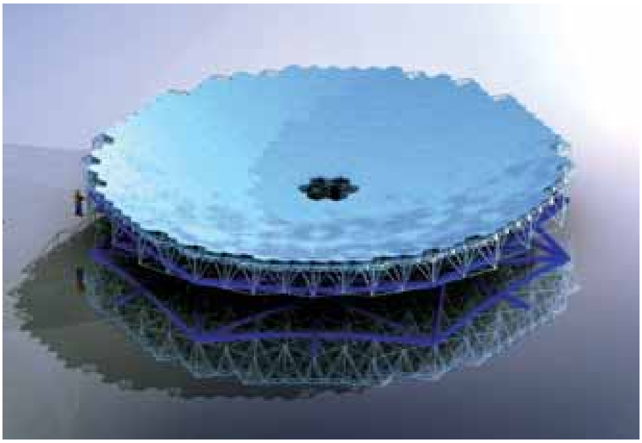

Figure 3: The TMT primary mirror with 492 1.45m diameter hexagonal segments, 45mm thick. Each is supported axially by a 27-point whiffletree system, and laterally by a diaphragm imbedded in the center of the segment.

The telescope as a whole is shown in Figure 4. The major components are labeled in the figure. The telescope can be moved to the horizon but science observations are limited to zenith angles above 65°.

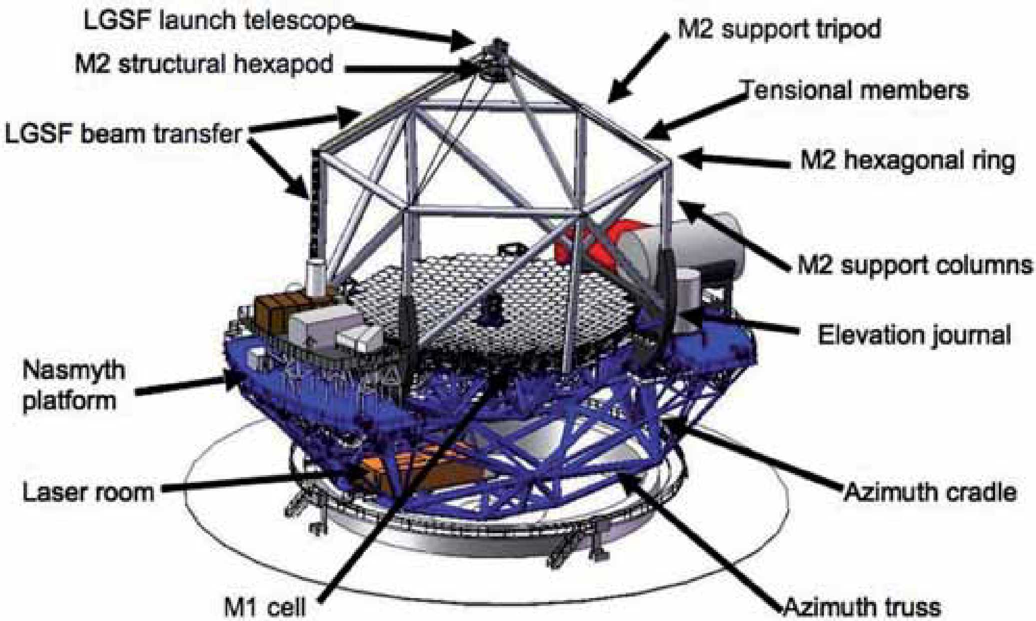

Figure 4: The telescope, showing its main structural features and the instrument facilities

The enclosure is a calotte design, with a fixed 31.25 m opening and an inclined rotation axis on top of a vertical rotation axis. This affords excellent protection of the telescope from wind and at the same time the enclosure system is balanced, so tracking the telescope does not require performing any work against gravity.

3. Key Features of TMT

The RC design provides excellent image quality over a 20 arcmin field of view. The optics are sized to provide an unvignetted 15 arcmin field of view and with <10% vignetting over the full 20 arcmin.

The tertiary mirror is articulated to allow it to direct starlight to any of the instruments placed on the Nasmyth platforms. Instruments along the elevation axis itself do not require motion of the tertiary, but instruments off the elevation axis require modest rotations of the tertiary as a function of zenith angle.

This feature allows all instruments to be stationary on the platforms and instruments will be live and ready for observations at all times. Each instrument will point towards the tertiary. This will allow the astronomer to switch between any instruments, and be ready to begin integration on a new target in under 10 minutes. This interchangeability is shown schematically in Figure 5.

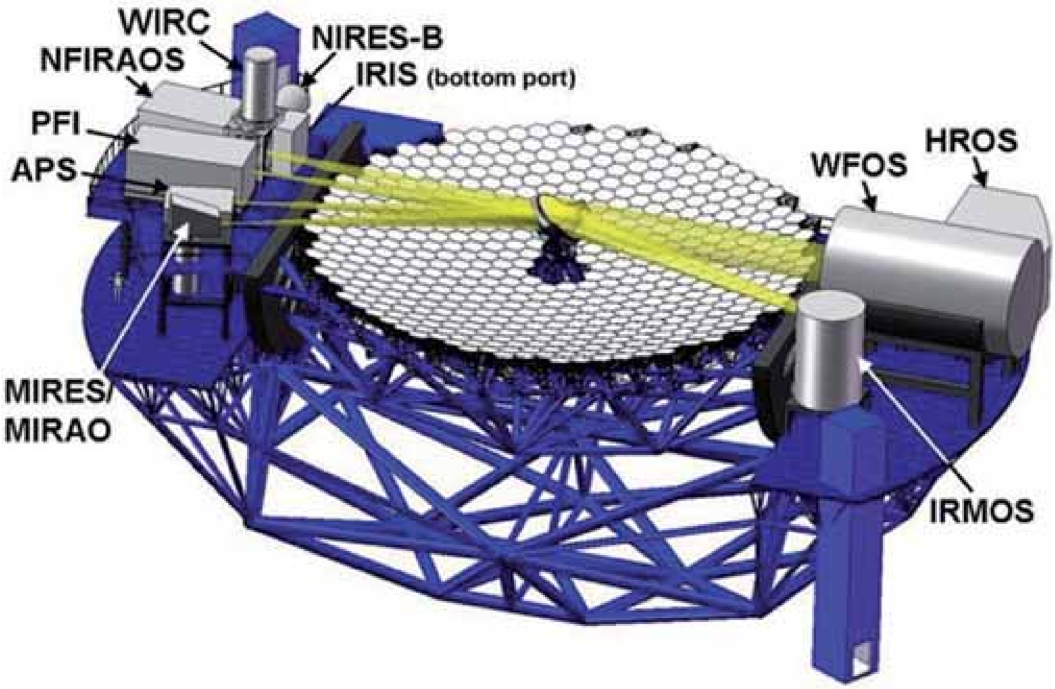

Figure 5: All science instruments and the AO system are located on the Nasmyth platforms and will be available at all times. Starlight can be directed to each instrument by rotation of the tertiary mirror.

The AO system for TMT includes a sodium beacon system with six laser beams launched from a telescope located behind the secondary mirror. This will form an asterism of six spots that is used to measure the turbulence of the atmosphere.

4. Major Science Goals

4.1. *Scaling laws*

A thirty-meter telescope obviously offers great gains over smaller telescopes, particularly when diffraction-limited. It is useful to consider the science metric of 1/time needed to make an observation. For seeing limited observations of background limited point sources the metric is sensitivity~ ηD^2 where η is the throughput of the system.

For background-limited observations of point sources in the infrared, AO is available to greatly improve the image quality. Here this metric is sensitivity~$\eta S^2 D^4$ where S=Strehl =1/exp(σ^2) and σ is the rms wavefront error in radians. With perfect optics S=1, so it is generally < 1. The D^4 gain is remarkable and is a major motivation for the science where TMT will excel. By this metric, reducing the wavefront error for AO is clearly very beneficial as well, and it will be limited by available technology. This narrow metric ignores the obvious benefit of improving image quality itself, so one can better understand the morphology of the targets of interest.

4.2 *Broad Science Areas*

TMT has generated detailed science cases for a diverse range of science opportunities and we will not review them in any detail here. The interested reader can find documentation on the TMT web page. Excellent opportunities include solar system studies, direct imaging of planets around nearby stars, detailed study of stars and stellar evolution, black holes and galaxies, nearby galaxies, distant galaxies and first light, and many more.

5. Science Instruments

5.1. Adaptive Optics

Because of the enormous science potential, diffraction-limited image quality (7mas at 1µm) will be available at first light of TMT. The adaptive optics system for initial science is NFIRAOS and will deliver wavefront errors ~ 190 nm rms over a 10 arcsec field of view, and only modest degradation over a 2 arcmin field of view. This will be achieved by having a dual conjugate AO system, with one deformable mirror (DM) conjugate to the ground, and a second DM conjugate to 11km height. This greatly increases the corrected field of view. The operating range of NFIRAOS will be from 0.8 to 2.6µm.

Light is needed to sense the ever-changing atmospheric wavefront errors. Generally, sufficiently bright stars for this are rare, thus sky coverage using natural stars to measure the wavefront errors is very limited. As a result we will have 6 sodium lasers that make bright spots in the sodium layer in our atmosphere. These artificial beacons will be used to tomographically reconstruct the three-dimensional turbulence structure of the atmosphere. From this three dimensional knowledge one can determine the optimal correction to be applied to each of the two deformable mirrors. Future systems may take further advantage of this knowledge by correcting the atmosphere in specific directions (using a deformable mirror for each direction) suited to the locations of the science targets. A schematic showing the principles of the tomographic measurement and correction is shown in Figure 6. To generate enough return light to measure the atmosphere at speeds of ~ 800 Hz we will have six 25W lasers generating Na light. The lasers will be mounted on the base of the telescope and with beam transfer optics the light will be shipped up to the launch telescope that is behind the secondary mirror.

Given the six measured wavefronts, actually reconstructing the atmosphere and generating commands to the deformable mirrors is extremely computationally intensive. We have studied various efficient iterative algorithms to solve the equations, and reviewed the use of specialized computational hardware (digital signal processors or DSP's). We have established that this computation can be done with existing hardware.

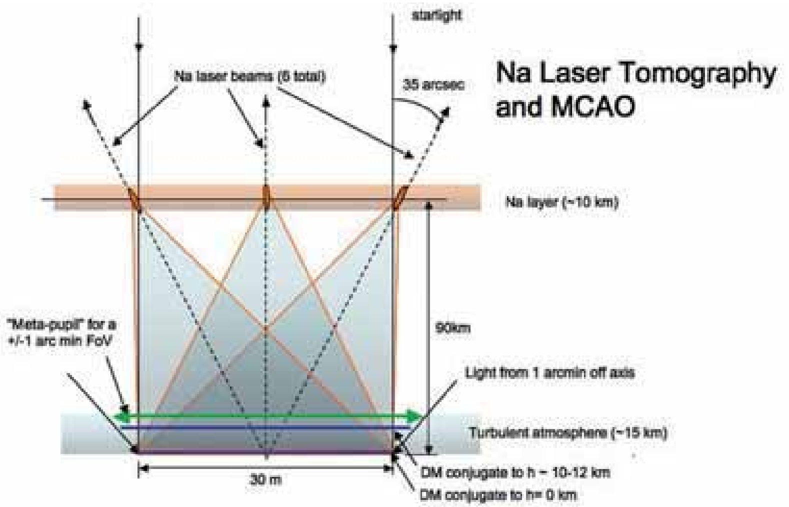

***Figure 6** This schematic shows the Na spots ~90km up and the illumination path of each spot through the atmosphere. The turbulent atmosphere of interest is only the lowest ~ 15km of atmosphere. The two DM's are conjugate to 0km and 11km for NFIRAOS.*

Laser beacons to measure the atmospheric distortions will measure the high order wavefront errors but cannot measure the tip, tilt, or focus errors. These must also be measured and stabilized. This will generally be done by measuring the locations and defocus of three natural guide stars that are within the 2 arcmin field of view. These will be measured in the near infrared to take advantage of the AO correction on these images. They will have a diffraction-limited core that will allow accurate centroiding. Because of this core, very faint guide stars can be used, and the resulting sky coverage at the galactic poles will be > 50%.

We have commented on the great improvements in angular resolution (factor of 100) that can be achieved with AO. One way to visualize the potential impact of such improvements is shown in Figure 7. A typical galaxy is shown at the resolution of the Hubble Space Telescope and then at the resolution of TMT with AO. This shows the gains by improving the angular resolution. The other measure we previously discussed was the gain in point source sensitivity.

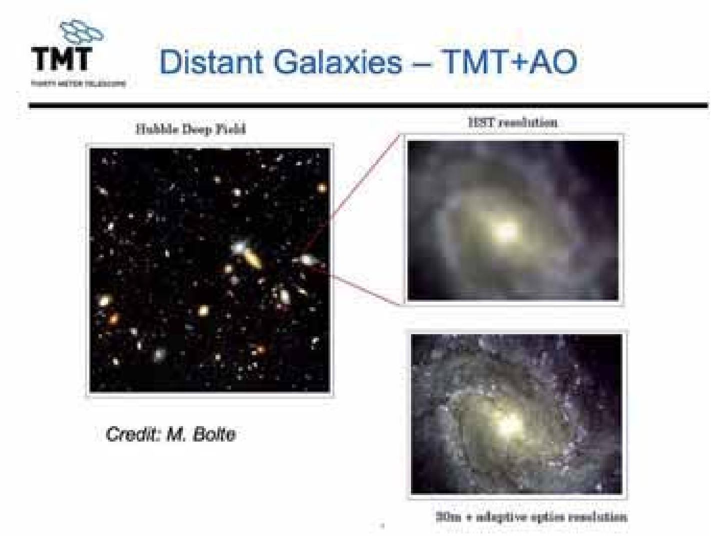

***Figure 7** To show the power of the improved angular resolution that AO brings, we have taken the Hubble Deep Field and picked a typical galaxy from it, and shown it at the resolution of Hubble and at the resolution of TMT with AO.*

NFIRAOS resides on one of the Nasmyth platforms. It can send corrected light to any of three science instruments that can mounted on NFIRAOS itself. The general layout is shown in Figure 8. NFIRAOS feeds any of the three instruments by rotating a fold flat inside of NFIRAOS. The main enclosure is cooled to -30°C to reduce thermal emission from NFIRAOS. This is important for the wavelength region 2.0-2.6µm.

A better view of the actual optical system inside of NFIRAOS can be seen in Figure 9. There are two off–axis paraboloids that image the atmospheric layers onto the deformable mirrors. The DM at 0km is mounted on a fast tip-tilt stage that will remove rapid image motion as sensed by the three natural tip tilt stars. More details of the optics are available in a number of published papers.

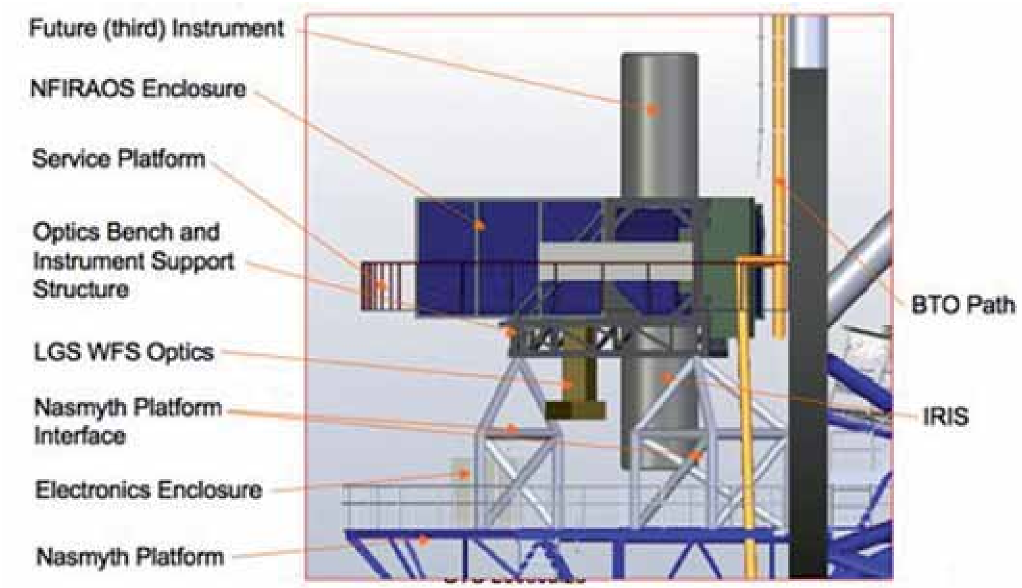

Figure 8 NFIRAOS is shown on the Nasmyth platform. Three science instruments can be fed by NFIRAOS. Two are shown (grey cylinders) and the third instrument is on the far side. Any of these instruments are fed by rotating a fold flat mirror that is inside of NFIRAOS.

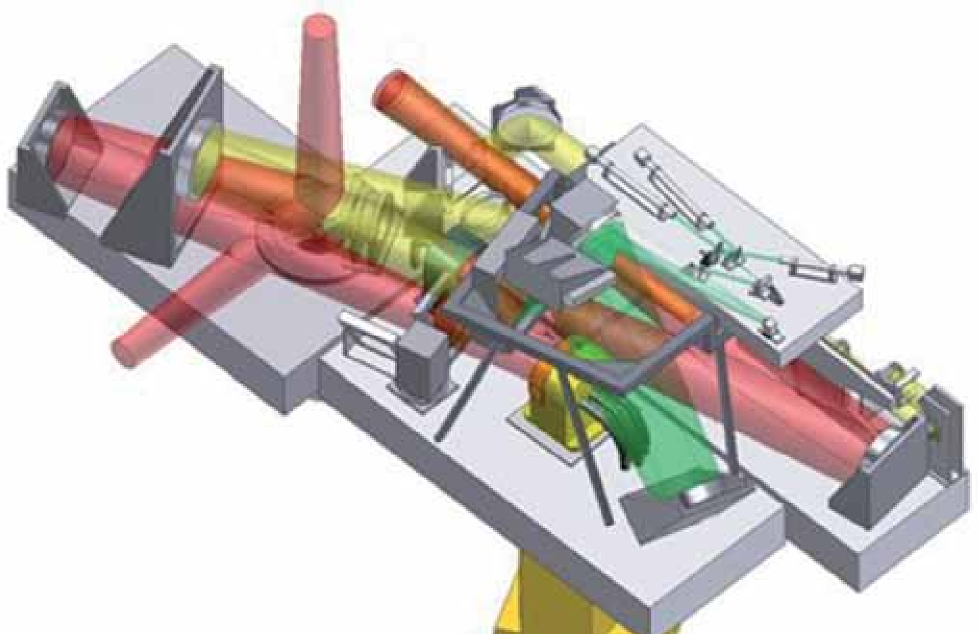

Figure 9 The optical bench of NFIRAOS shows the science beam (in red) and the laser light (in yellow). The three possible feeds to science instruments are shown. The yellow box directed downwards contains the wavefront sensing system for the laser light.

5.2. The first decade Suite of Science Instruments

The TMT Science Advisory Committee (SAC) has selected 8 instruments for the first decade of observations. These were selected after conceptual studies for a variety of instruments were carried out. These studies generated conceptual designs, performance estimates, and cost and feasibility estimates.

We recognize that its impractical and perhaps inappropriate to have all these instruments available for first light. We may not have sufficient funds, and it may be that only after some experience with TMT and the science discoveries it makes can we properly design additional instruments.

As a result of this, the SAC has selected three of the eight science instruments to be available at the beginning of observing with TMT. These are broadly capable instruments that should have the highest possible initial science impact. The Table lists the names, spectral resolution, and some key science goals of each instrument. The instruments in red are seeing limited, visible light instruments. The others are infrared instruments that will use adaptive optics to produce diffraction-limited images. The first three instruments will be the initial suite.

TMT First Decade Instrument/Capability Suite

4Instrument	Spectral Resolution	Science Case
Near-IR DL Spectrometer & Imager (IRIS)	~4000	• Assembly of galaxies at large redshift • Black holes/AGN/Galactic Center • Resolved stellar populations in crowded fields • Astrometry
Wide-field Optical Spectrometer (WFOS)	1000-5000	• IGM structure and composition 2<z<6 • High-quality spectra of z>1.5 galaxies suitable for measuring stellar pops, chemistry, energetics • Near-field cosmology
Multi-slit near-DL near-IR Spectrometer (IRMS)	2000 - 5000	• Near-IR spectroscopic diagnostics of the faintest objects • JWST follow-up
Mid-IR Echelle Spectrometer & Imager (MIRES)	5000 - 100000	• Physical structure and kinematics of protostellar envelopes • Physical diagnostics of circumstellar/protoplanetary disks: where and when planets form during the accretion phase
ExAO I (PFI)	50 - 300	• Direct detection and spectroscopic characterization of extra-solar planets
High Resolution Optical Spectrograph (HROS)	30000 - 50000	• Stellar abundance studies throughout the Local Group • ISM abundances/kinematics, IGM characterization to z~6 • Extra-solar planets!
MCAO imager (WIRC)	5 - 100	• Precision astrometry • Stellar populations to 10Mpc
Near-IR, DL Echelle (NIRES)	5000 - 30000	• Precision radial velocities of M-stars and detection of low-mass planets • IGM characterizations for z>5.5

Figure 10 The suite of science instruments planned for the first decade of TMT. The first three will be available for initial science. WFOS is a seeing-limited instrument and IRIS and IRMS are AO-fed diffraction limited instruments.

6. Conclusions

TMT is nearing the end of its preliminary design and the Observatory, the AO system, and the first three science instruments are far along in their designs, performance and cost estimates. We expect to begin construction on Mauna Kea in 2011, and begin science observations with the completed Observatory in 2018.

Foundation documents for TMT can be found at: www.tmt.org/foundation-docs/index.html. There one can find:

Detailed Science Case 2007

Observatory Requirements Document

Observatory Architecture Document

Operations Concept Document

TMT Construction Proposal

There are many reports about the TMT design that can be found in recent SPIE proceedings (Marseille, 2008).

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Taft Armandroff

W. M. Keck Observatory

Instrumentation, Adaptive Optics, and Scientific Productivity

Abstract

For the past fifteen years, the W. M. Keck Observatory has played a leading role in astronomy and astrophysics. This paper discusses the instrumentation and adaptive optics systems at Keck Observatory with an emphasis on recent developments and future plans. It also discusses the high scientific productivity of Keck Observatory using various metrics. Keck Observatory's strategy to remain highly scientifically productive is outlined, with an emphasis on how the strategy is influenced by the design and construction of new facilities, particularly extremely large telescopes.

1. Overview of W. M. Keck Observatory

The W. M. Keck Observatory (WMKO) operates twin 10 meter optical/infrared telescopes on the excellent site of Mauna Kea. Keck I achieved first light in 1992 and Keck II in 1996. The two telescopes feature a highly capable suite of advanced instrumentation for both optical and near-infrared wavelengths, including imagers, multi-object spectrographs, high-resolution spectrographs, and integral-field spectroscopy. WMKO has developed and operates a sophisticated natural and laser guide star adaptive optics system and related instrumentation. The Observatory also operates the only large-aperture infrared interferometer in the U.S., and one of only two such interferometers in the world.

The partners in the operation of Keck Observatory are Caltech, the University of California and NASA. The University of Hawaii participates in Keck observing by providing access to Mauna Kea. The allocation of observing time is divided among these institutions as follows: Caltech (36.5%), University of California (36.5%), NASA (14.5%), and University of Hawaii (12.5%). Yale University and the Swinburne Institute of Technology participate in Keck observing via a partnership with Caltech. The broad U.S. community gains peer-reviewed access to the Keck telescopes via the NASA partnership and through the NSF/NOAO Telescope System Instrumentation Program (approximately 24 nights per year).

2. Current Keck Instrumentation

Keck Observatory offers a wide range of highly capable instrumentation. Table 1 lists all of the observing capabilities offered at Keck Observatory. Instrumentation that works in conjunction with the Keck adaptive optics is covered in Section 3. WMKO's suite of efficient, state-of-the-art instruments has been a key factor in its success.

Optical spectroscopy at low to moderate spectral resolution is provided by LRIS, DEIMOS and ESI. LRIS is a dual-beam multi-object spectrograph and imager first commissioned in 1994. It later received CCDs with high sensitivity for its blue channel, and LRIS's excellent blue sensitivity is one of its strengths. DEIMOS provides $R = 6{,}000$ multi-object spectroscopy over a field of 16.3 arcmin × 5 arcmin. DEIMOS became fully operational in 2002. ESI is a high-throughput, echellette spectrograph that was commissioned in 1999.

High-resolution optical spectroscopy is provided by HIRES, a large echelle spectrograph with a resolving power of 30,000 to 80,000. It includes an optional iodine cell for precision radial velocity calibrations and is housed in a thermally stable environment. HIRES has been very productive in exoplanet detection and characterization using the Doppler wobble technique. Originally commissioned in 1994, HIRES's CCD camera and electronics were upgraded in 2004 for greater sensitivity and wavelength coverage.

NIRSPEC is a cross-dispersed cryogenic echelle spectrograph with wavelength coverage from 0.95 to 5.5 microns. NIRSPEC has two modes: low-resolution spectroscopy with R = 2,000; and high-resolution, cross-dispersed spectroscopy with R = 25,000. NIRSPEC is relatively unique in providing high-resolution, cross-dispersed infrared spectroscopy on a large telescope.

Telescope	*Instrument*	*Initials*	*Bandpass*	*Field of View*	*Resolving Power*
Keck I				82 sq. arcmin	
	High Resolution Echelle Spectrometer (blue cross disperser)	HIRESb	0.31-0.65 microns	(0.4", 0.574", 0.861", 1.148", 1.722") X (3.5", 7", 14", 28") slits	24,000-84,000
	High Resolution Echelle Spectrometer (red cross disperser)	HIRESr	0.42-1.0 microns	(0.4", 0.574", 0.861", 1.148", 1.722") X (3.5", 7", 14", 28") slits	25,000-87,000
	Low-Resolution Imaging Spectrometer	LRIS	0.3-1.1 microns	6×7.8 arcmin	400-3600
	LRIS polarimeter	LRISp	0.3-1.1 microns	20x20 arcsec	400-3600
	MOSFIRE (arriving in 2010)	MOSFIRE	1.0-2.4 microns	6.1x6.1 arcmin	3270
Keck II					
	Deep Imaging Multi-Object Spectrometer	DEIMOS	0.4-1.1 microns	94 sq arcmin	1,000-6,000
	Echellette Spectrometer and Imager	ESI	0.39-1.1 microns	16 sq arcmin	1,000-13,000
	Near-IR Spectrometer (low dispersion)	NIRSPEC-L	0.95-5.4 microns	0.7 x 42 arcsec	2000
	Near-IR Spectrometer (high dispersion)	NIRSPEC-H	0.95-5.4 microns	0.7 x 12 arcsec	25,000
	Near-IR Spectrometer (behind AO)	NIRSPAO	0.95-2.6 microns	0.04 x 2.24 arcsec	25,000
	Near-IR Camera 2 (imaging)	NIRC2	1.0-5.0 microns	10 x 10, 20 x 20, and 40 x 40 arcsec	
	Near-IR Camera 2 (spectroscopy)	NIRC2	1.0-5.0 microns	(0.010-0.160 arcsec) x (10-40 arcsec)	1000-5000
	OH Suppressing IR Integral-field Spectrometer	OSIRIS	1.0-2.4 microns	4.8 x 6.4 arcsec	3800
Keck Interferometer (Keck I + II)	Keck Interferometer				
	Nulling mode	Nuller	N	251 milliarcsec	
	Standard visibility-squared (V2) mode	V2-H	H	41 milliarcsec	
	Standard visibility-squared (V2) mode	V2-K	K	55 milliarcsec	
	Standard visibility-squared (V2) mode	V2-L	L	91 milliarcsec	
	High dispersion V2 mode	V2-SPR	K	55 milliarcsec	1800
	High sensitivity V2 mode	V2-DFPR	K	55 milliarcsec	
	Astrometry mode	Astrometry	K	30 arcsec	

Table 1: Keck Observing Capabilities

During 2009, the red arm of LRIS was upgraded. A new red camera for LRIS replaces the existing CCD in the red side of LRIS with a 2 × 1 mosaic of 2048 × 4096 high-resistivity thick substrate LBNL CCDs. These CCDs were acquired and deployed in order to substantially enhance the red sensitivity compared to the former CCD. In addition, due to their thick substrate, these CCDs exhibit no fringing. Observers are also benefitting from a modest increase in spatial and spectral coverage, more uniform image quality due to a flatter detector, and increased reliability from the new CCD control electronics.

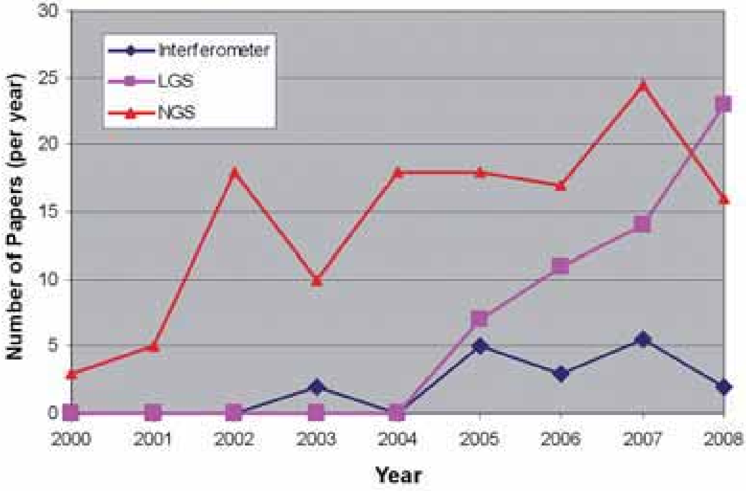
3. Keck Adaptive Optics

With primary mirror diameters of 10 meters, the Keck telescopes are among the largest ground-based telescopes and therefore have the potential to obtain the highest spatial resolution of any telescope once the effects of atmospheric turbulence are mitigated. Thus, Keck Observatory has a long-standing and ambitious adaptive optics program. The existing adaptive optics systems on Keck II and Keck I were commissioned in 1999 and 2000 respectively. Initially, both systems carried out natural guide star adaptive optics observations, and Keck was the first of the large telescopes with a natural guide star system. The Keck II system was designed to accomplish laser guide star observations as well, and a laser was added and the system commissioned in 2003-2004 (Wizinowich et al. 2006). Keck was the first large telescope to deploy laser guide star adaptive optics. Laser guide star adaptive optics overcomes the restriction of requiring a bright natural guide star close to the object being studied, and thus enables adaptive optics observations over most regions of sky. Under typical atmospheric conditions, the laser guide star system yields K-band Strehl ratios between 30% and 40% (using bright tip-tilt stars).

The two primary instruments used with the Keck II adaptive optics system are NIRC2 and OSIRIS. NIRC2 is a near-infrared instrument optimized to exploit the images provided by Keck II's adaptive optics system. NIRC2's camera has three pixel scales and provides coverage from 1 to 5 microns. NIRC2 also provides grism spectroscopy at low and moderate spectral resolution. NIRC2 achieved first light in 2001. OSIRIS is an OH-suppression infrared integral field spectrograph that achieved first light in 2005. OSIRIS employs a focal plane lenslet array to enable diffraction-limited R=3,900 integral field spectroscopy with the adaptive optics system. OSIRIS provides four pixel scales from 0.02 arcsec to 0.1 arcsec.

The Keck adaptive optics systems have been a great success and have been applied to a wide variety of astronomical targets and investigations. As shown in Figure 1, the scientific productivity of adaptive optics at Keck has been high. Papers based on natural guide star and laser guide star adaptive optics are shown separately in Figure 1. The production of papers from the more recent laser guide star system has increased significantly since installation, and in 2008 papers from the laser guide star system surpassed for the first time those resulting from natural guide star observations.

Figure 1: The number of refereed Keck papers published each year based on adaptive optics is plotted against year of publication. Papers based on natural guide star observations (NGS), laser guide star observations (LGS), and Keck-Keck interferometry are shown separately. Note the rapid rise in the number of LGS papers in recent years.



An upgrade to the wavefront sensors and wavefront controllers of the Keck I and II adaptive optics systems was successfully carried out and commissioned in 2007 (Johansson et al. 2008). By replacing aging components in these systems with new technology, significant gains were achieved in limiting guide star magnitude and Strehl ratio for both natural guide star and laser guide star modes. Reliability and maintainability were also enhanced.

4. Future Enhancements to Instrumentation and Adaptive Optics

MOSFIRE is a near-infrared multi-object imaging spectrograph for the Cassegrain focus of Keck I. This instrument will provide a field of view of 6.8 arcmin in diameter for imaging, and it will enable spectroscopy at R = 3,000 for 46 slits over a field of view of 6.1 arcmin × 3 arcmin. MOSFIRE will deliver almost full band spectral coverage in Y, J, H, or K. The multi-slit capability is delivered by an innovative cryogenic configurable slit unit that operates under computer control. Unlike most other near-infrared multi-object spectrographs, thermal cycling of the instrument is not required to reconfigure the multi-slits. MOSFIRE is being developed and fabricated for Keck Observatory by a consortium consisting of Caltech, UCLA, and the University of California Observatories. As of July 2009, MOSFIRE is in the integration and test phase, undergoing cold cycles. Delivery and commissioning is expected in 2010.

An upgrade of the Keck I adaptive optics system to a laser guide star system is currently underway. This project, which will deploy a new solid-state laser from Lockheed Martin Coherent Technologies and a center-laser-launch telescope, will deliver improved performance relative to the Keck II system. In addition, it will provide redundancy against failure of the Keck II adaptive optics system and will enable using laser-guide-star adaptive optics to extend the performance of the Keck Interferometer. Once the Keck I laser guide star adaptive optics system is complete and commissioned, expected for 2010, the OSIRIS integral field spectrograph will be moved from Keck II to Keck I to take advantage of the system.

In order to further exploit the benefits of adaptive optics observations and to respond to enthusiasm from our observer community for even greater adaptive optics performance than delivered by existing systems, Keck Observatory has embarked on the design and development of a Next Generation Adaptive Optics System (NGAO; Wizinowich et al. 2008; Max et al. 2008). NGAO has five goals: 1) provide diffraction-limited performance in near-infrared (K-band Strehl ratio > 80%); 2) provide good AO correction at red wavelengths (0.7-1.0 microns); 3) deliver increased sky coverage; 4) enable improved angular resolution, sensitivity and contrast relative to the current Keck II adaptive optics system; 5) provide improved photometric and astrometric accuracy. New optimized instrumentation for imaging and integral field spectroscopy will be developed with NGAO. In order to achieve the above goals, the system features multiple sodium laser guide star tomographic wavefront sensing to overcome the cone effect. A cooled AO system would be implemented to meet the infrared background requirements.

NGAO successfully passed its system design review in April 2008 and is currently in the preliminary design phase. NGAO should enable a wide variety of new and impactful science through improved sensitivity, higher Strehls, improved PSF knowledge and stability, increased sky coverage, and performance at shorter wavelength.

NGAO will offer a set of observing capabilities that are not available at any other observatory. Almost all other second-generation adaptive-optics development projects are targeting either wider-field seeing improvement (e.g., ground layer adaptive optics) or very high contrast adaptive optics with the goal of detecting extrasolar planets. The one exception is the Gemini South MCAO system, which is a multiple laser system that employs tomography like NGAO. However, MCAO's objective is more modest Strehl ratios over a wider field compared to NGAO. NGAO is unique among current large telescope adaptive optics development projects in seeking to deliver diffraction-limited images in the infrared and significant high-order correction at red wavelengths.

5. Keck Observatory Scientific Productivity

Although there are now a significant number of 6-10 meter optical/infrared ground-based telescopes, by almost all measures, Keck Observatory has maintained the lead in research productivity. Figure 2 shows the number of refereed publications per year based on data obtained using the WMKO from 1996 to present. The number of refereed publications per year has increased with time. This increase in productivity can be attributed to the frontier instruments and adaptive optics systems that have been installed on the Keck telescopes over the period between first light and today. The modest drop of papers in 2008 compared to 2007 is likely attributable to the publication of many papers from the DEEP2 survey in 2007 and the fact that several weeks of observing time were lost in late 2006 due to a major earthquake and the need for repairs afterward (there is, of course, a lag between the acquisition of astronomical data and its publication).

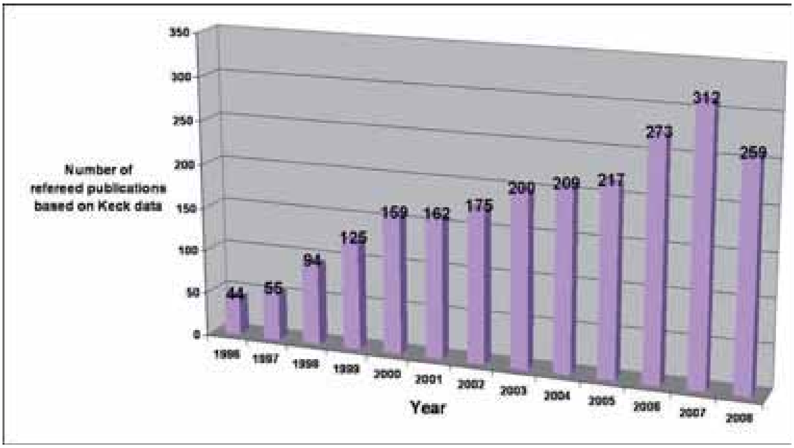


Figure 2: Number of refereed publications per year based on data from W. M. Keck Observatory.

Keck currently produces approximately 150 papers per telescope per year, which as shown in Figure 3, exceeds the scientific output of any other ground-based observatory in the world.

The impact of papers based on Keck Observatory data also significantly exceeds that of peer observatories. Crabtree (2008) showed that Keck Observatory has the most highly and extremely cited papers and the fewest weakly cited papers compared to all other major optical/infrared telescopes (both ground and space-based). The comparator group in this study includes the ESO VLT, Gemini, Subaru and Hubble Space Telescope. A study conducted by ESO staff (Grothkopf et al. 2007) compares the scientific impact of four major observatories with 8-10 meter telescopes based on the h-index, where the counted publication number equals the number of citations, in order to not overly weight the most heavily cited papers nor lowly cited papers (Hirsch 2005). They concluded that the aggregate scientific impact of Keck Observatory exceeds that of the VLT, Gemini, or Subaru. Grothkopf et al. also show that WMKO has been significantly more productive than the other three observatories even when the different start-of-science-operations dates are taken into account.

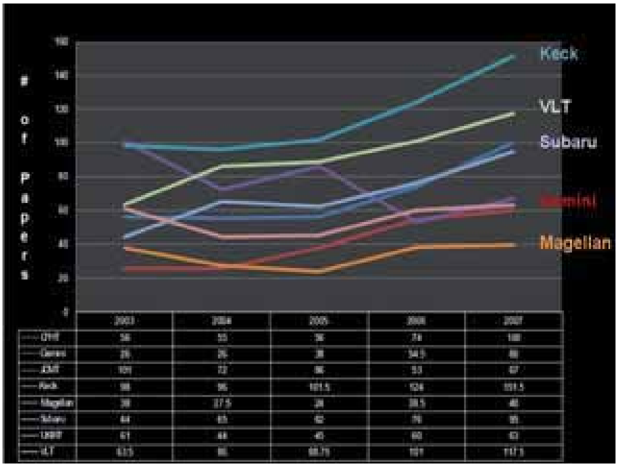


Figure 3: The number of refereed publications per telescope per year for various observatories (courtesy of Dennis Crabtree, Gemini Observatory).

6. Future Strategy

The next generation of extremely large telescopes (ELTs) is likely to complete construction and be commissioned circa 2020. Given the time required to conceive, design, build, and commission new instruments and adaptive optics systems, observatories operating today must consider the likely arrival of extremely large telescopes in their strategic planning. Keck Observatory has recently carried out an extensive scientific strategic planning activity with our user community. The two senior partners in Keck Observatory, Caltech and the University of California, are also founding partners of the Thirty Meter Telescope Project. Thus, the eventual arrival of ELTs is clearly in the minds of Keck Observatory management and users.

Keck Observatory and its user community are committed to maximizing the Observatory's scientific productivity up to and after the advent of ELTs. In general, the observing time on ELTs is expected to be in much shorter supply than on Keck. Therefore, both in the near term and after the advent of ELTs, Keck will remain a very valuable resource for our community to accomplish their scientific aspirations.

A number of strategies have been discussed in our strategic planning process to maximize the value of Keck to our scientific community in the ELT era. First, the Observatory must remain nimble to avail itself of scientific and technical opportunities. Because the ELTs will be much larger projects with many tasks required to achieve success and many partners, we aspire to preserve the nimbleness of a smaller, more focused organization. Keck Observatory also seeks to retain its strong, close relationship with our user community.

Another element of strategy concerns the types of observing programs that will be executed using Keck. Keck Observatory has carried out a number of large long-term observing programs, for example radial velocity surveys for planets (e.g., Wright et al. 2009), the Galactic Center proper motion program that has characterized the supermassive black hole (e.g., Ghez et al. 2008), and the DEEP2 galaxy redshift survey (e.g., Davis et al. 2003). We expect that the high demand for time on ELTs will render most programs relatively short in duration. Keck Observatory will likely support more large programs in the future in order to create unique datasets that result in high-impact scientific publications.

A new generation of wide-field imaging surveys is on the horizon (e.g., Pan-STARRS and LSST). In addition to producing well-defined surveys for objects over wide areas of the sky, these surveys will open up the time domain. Keck users were very quick to leverage the Sloan Digital Sky Survey to yield important new scientific results. Similarly, we envision Keck playing an important role in following up unique data sets revealed in these wide-field surveys. There will likely be a significant time-domain component to this follow-up. Modest investments in observing flexibility at Keck Observatory will be needed to support the growing profile and potential science impact of time domain astrophysics.

Keck Observatory's future scientific strategy recognizes that time on ELTs will be highly oversubscribed. Given the value of ELT time, we anticipate that a subset of future investigations carried out with Keck will study fairly large samples of objects. Only the most interesting of these objects would then be investigated in greater depth using an ELT. Thus, we expect that a many investigators will use an 8-10 meter telescope and an ELT as an observing system.

Our future strategy recognizes that continued investment in science-driven instrumentation and adaptive optics systems is a necessity for maintaining Keck Observatory's scientific productivity and leadership. The 6.5 to 10 meter optical/infrared telescopes of today are the workhorses that will enable the scientific productivity of the optical/infrared community until the next generation of large telescopes are fully commissioned for science operations toward the end of the coming decade or perhaps in the subsequent decade. Even after the commissioning of GSMT, the 8-10 meter telescopes will play an important role for many years. Therefore, keeping the large telescopes in the U.S. observing system properly instrumented and taking advantage of advances in adaptive optics, detector, coating and other instrumentation technologies are crucial to the community's scientific productivity over the coming decade. The resources to build new, innovative instruments and adaptive optics systems need to be found in an era when there is strong demand for resources to construct the next generation of telescopes. One compelling reason for investing in instrumentation for the existing 8-10 meter telescopes is that such instruments can be brought into operation more rapidly than the next generation of telescopes. Thus, the scientific productivity of the optical/infrared astronomy community in the period 2010 to 2020 will be much more dependent on the operation of existing telescopes and the strength of their suite of instruments and adaptive optics systems than it will be on the next generation of ground-based optical/infrared telescopes. Because of limited resources and the modest time span before the next generation of telescopes is expected to come on line, Keck and the other large telescopes of today must make very thoughtful choices about the instruments and adaptive optics systems to be deployed in the near future and which science problems these systems will address.

Our scientific strategic planning process identified opportunities for new and enhanced instrumentation at Keck to contribute to our high scientific productivity and strategic positioning. The following types of instrumentation enhancement were identified for study and consideration for implementation in the future (beyond the initiatives already in progress described earlier in this article): high-efficiency optical integral-field spectroscopy; upgrading our wide-field optical spectroscopic capabilities; upgrading our infrared cross-dispersed spectroscopic capability with new detectors and possibly higher resolution; enhancing our precision radial velocity capabilities; and improving our ability to respond rapidly to time-sensitive phenomena, including rapid change of instrumentation.

Instrumentation for large telescopes has become more complex and ambitious due to the community-based scientific demand for sophisticated adaptive optics systems, enhanced multiplexing for wider-field multi-object spectroscopy at both infrared and optical wavelengths, and integral field unit spectroscopy with ambitious combinations of resolution and field of view. Instruments for large telescopes are costly and only likely to become more so as they increase in capability and complexity. Examples of ambitious instruments being designed and considered for implementation on large telescopes include the wide-field spectroscopic instrument WFMOS for Subaru and NGAO for Keck. NGAO has an estimated cost of $60 million, and HETDEX for the HET is estimated to cost $40 million. The typical cost of a significant, but not as ambitious instrument for an 8-10 meter telescope is of order $10 million.

Despite the relatively high cost of instrumentation for 8 to 10 meter telescopes, the costs are significantly lower than those for ELTs. Because of the high aggregate cost of ELTs and the cost of ELT instruments, in the reality of limited funding, ELTs are likely to have a rather limited number of instruments. Given the limited number of instruments an ELT will have and given the strong desire to manage overall risk in an ELT project, ELTs are likely to have a small appetite for assuming substantial risk in the design and construction of their instruments. All this is likely to encourage the ELT instruments to be general purpose and to use concepts that have already been demonstrated successfully on other telescopes. Therefore, truly innovative instrumentation is unlikely to deployed first on ELTs. Similarly, instrumentation that is fairly to highly specialized for a particular scientific goal is also unlikely to be selected for ELTs. This creates two opportunities for the current generation of 8-10 meter telescopes in the ELT era: 1) developing and testing truly innovative instrumentation and adaptive optics concepts that are sufficiently unproven to be impractical for ELTs; 2) developing and deploying instrumentation that is more optimized for a particular scientific area than is likely to be attractive to an ELT project. In both cases, this promises to create scientific productivity in certain niches for an 8-10 meter telescope where the ELTs are unlikely to dominate.

The capabilities of large-aperture interferometers will not be eclipsed by ELTs. Therefore, with their unique ability for extremely high spatial resolution, we imagine that the Keck Interferometer in the north and the VLT Interferometer in the south will remain scientifically productive and unique in the next decade and into the ELT era.

Acknowledgments

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Jean-René Roy
Gemini Observatory

Gemini as Pathfinder for 21st Century Astronomy

"We have been going round a workshop in the basement of the building of science. The light is dim, and we stumble sometimes. About us is confusion and mess which there has not been time to sweep away. The workers and their machines are enveloped in murkiness. But I think that something is being shaped here – perhaps something rather big. I do not quite know what it will be when it is completed and polished for the showroom. But we can look at the present designs and the novel tools that are being used in its manufacture; we can contemplate too the little successes which make us hopeful."
(A. Eddington 1933)

Abstract

Synergies between new ground- and space-based observatories are promises for the role of 8- to 10 meter telescopes, with a generous discovery space that still lies ahead in the coming decade. I explore examples of science areas where our largest ground-based telescopes can build up a precious inventory of targets and fields to be probed deeper with the coming Extremely Large Telescopes (ELTs). The operational model of the Gemini telescopes is dominated by queue/service observing. A visiting and interaction model that helps to re-engage astronomers with their "machines" is presented and discussed. I surmise that ELTs may not be the last generation of single aperture ground-based optical-infrared telescopes. The recent history of radio astronomy–going in the direction of un-filled reconfigurable arrays of antennae–points to the increasing importance of interferometry in optical/infrared astronomy. Finally, I share some candid lessons learned from the Gemini partnership that deal with operational issues and governance.

1. Introduction

In late November and early December 1609, Galileo Galilei observed the sky with a small telescope of his own design and fabrication. Its aperture (30-50 millimeters) was tiny. To minimize aberrations, he had sized down the aperture with a diaphragm. Compared to the giant telescopes of today, his apparatus was extremely modest. Still, the discoveries that it enabled were staggering and rocked the 17th century scholarly world. The invention (a rather complex and debated topic) and early use of the telescope had a dramatic effect on the course of astronomy. The subsequent application of the telescope to the whole electromagnetic spectrum is proof of the success and power of this versatile observing tool. Today's telescopes have become giant hi-tech machines run by sophisticated organizations. It is significant that the Gran Telescopio Canarias (GTC) is being dedicated almost exactly four centuries after Galileo stupendous achievement.

In the middle of the coming decade, the infrared James Webb Space Telescope (JWST) will start operating. The Hubble Space Telescope (HST) will likely have been decommissioned. As HST did, JWST will have a huge scientific impact and also influence the way ground-based observatories operate and follow up on their discoveries. Synergies with the radio millimeter Atacama Large Millimeter Array (ALMA) expected to be in full operations in 2012 will be enormous. Large dedicated survey telescopes (Pan-STARRS (Panoramic Survey Telescope & Rapid Response System) 1&2, VISTA (Visible and Infrared Survey Telescope for Astronomy), VST (VLT Survey Telescope) or Subaru Telescope/HyperSuprimeCam) now coming on-line will be very powerful for finding new objects and transients that will require spectroscopic follow up on 8 to 10 meter telescopes.

The Large Synoptic Survey Telescope (LSST, still not funded, and unlikely to be so within a few years) may start operations on Cerro Pachón, Chile around 2018. Because of its mission and capabilities, this powerful survey facility will put huge demands in terms of spectroscopic follow-up. Robust "Point-and-shoot" capabilities will become essential for the next generation of ground-based telescopes. Interestingly, the GTC is located at a meridian that will increase coverage of the diurnal time domain from both hemispheres.

Large gains made by the current 8 to 10 meter aperture telescopes will not be attributable to aperture size but successful active and adaptive optics systems that have demonstrated that the turbulent structure of the atmosphere is amenable to analysis and correction (Mountain 2000; Smith 2009). Also, new developments in spectrograph design (single slit, multi-object, integral field unit, immersed gratings, cryogenic system, detector technology etc.) for all wavelengths have equipped astronomers with enhanced tools that would have been dreams a few decades ago (see, for example, the review of European Southern Observatory (ESO) optical spectrographs by Dekker 2009).

Any Extremely Large Telescope (ELT) with fully-operational instruments will come into full science operation only during the first half of the 2020s. Hence, the current generation of 8 to 10 meter telescopes have a ten-year window of scientific "freeway" ahead with a generous discovery space.

2. Gemini science niches for the ELTs

The Gemini telescopes (Figure 1 and 2) built and commissioned during the 1990s, started science operations in late 2000 (Gemini North) and 2001 (Gemini South). The two 8 meter optical/infrared telescopes are separated by 11,000 kilometers and present some interesting technical, and logistical challenges. They have been under steady operation for about eight years (as of mid-2009) and their lifetimes are likely to overlap with the next generation of 20 to 42 meter behemoth telescopes. What can the role be for telescopes such as Gemini in the preparatory and transitional era for these new machines? Among several possible areas Gemini, and others, can lay the groundwork for ELT exoplanets research, fine-scale spectroscopic mapping of galaxy cores and gamma-ray bursts study as sites of first light objects.

3. Imaging of exoplanetary systems, a pathfinder for exploring outer worlds

Everyday the field of exoplanet imaging research is progressing in ways and with jumps that appeared impossible yesterday. The current trends in discovery will continue to be driven by the massive efforts from space and ground facilities (now including several amateur programs that monitor planetary transits). The techniques of reflex motion and primary/secondary eclipsing by planetary companions will continue to reveal hundreds of planets, from a few Earth masses to that of several Jupiter, from the rocky/watery smaller bodies to giant gaseous, brown-dwarf-like objects and perhaps even stranger objects. However, we now have the means to go beyond these baby-steps with direct imaging of exoplanetary systems.

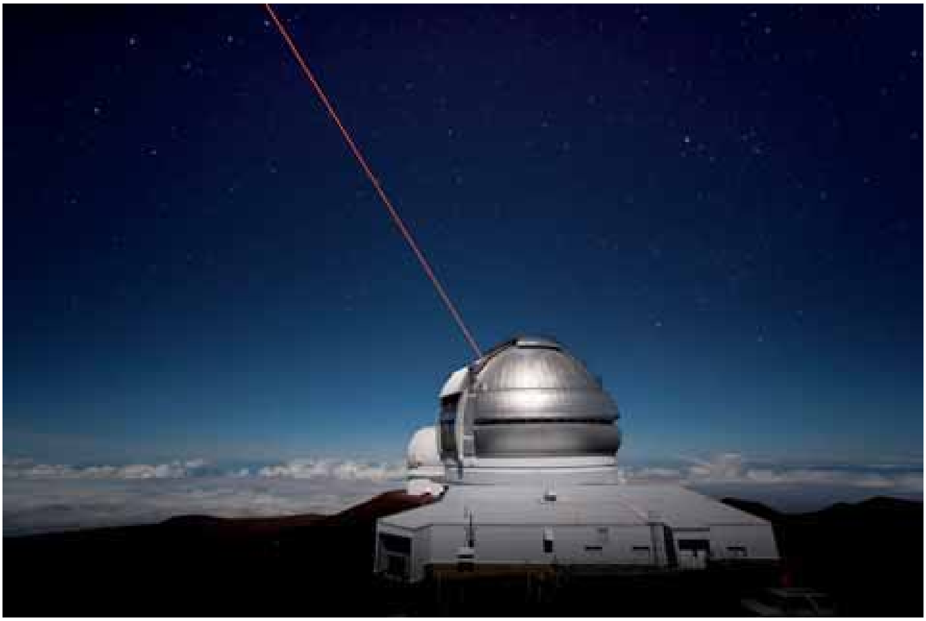

Figure 1. View of the Gemini North telescope with its 12 watt solid-state laser beam propagating for laser guide star adaptive optics observations.

Figure 2. View of the Gemini South dome (from inside) and telescope. The Near-Infrared Coronagraphic Imager (NICI) is the instrument visible attached to the Cassegrain instrument support structure. Three other instruments (not visible) are mounted on the remaining ports.

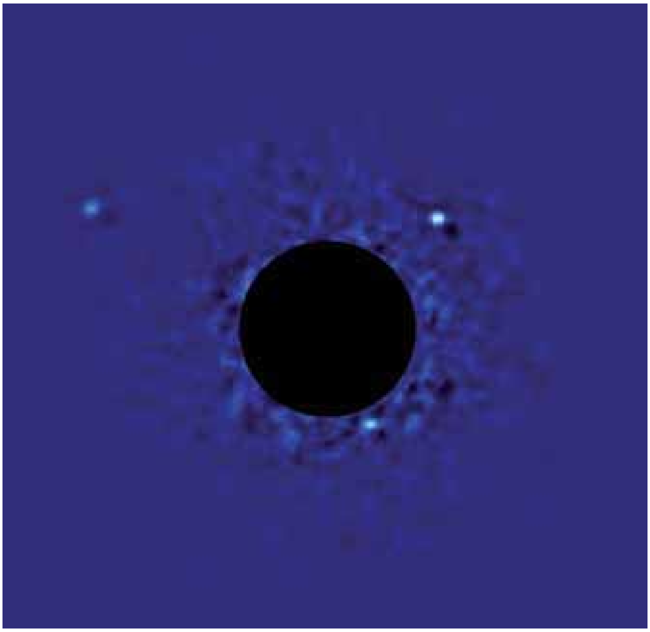

Figure 3. The exoplanetary system of nearby star HR8799 as viewed in K-band by Gemini North NIRI infrared imager. The system was discovered using the adaptive optics system on the Gemini North and W.M. Keck telescopes. (Credit: Marois et al. 2008)

It is up to the current generation of large 8 to 10 meter telescopes equipped with very high contrast adaptive optics imagers and spectrographs to build an "atlas" or inventory of exoplanet systems. These will be probed by imaging to further depths by the ELTs a decade from now. Indeed, systems now on-line at Gemini (NICI), Subaru (CIAO), Keck and VLT (NACO) are capable of building a large inventory of known exoplanetary systems and and leading to a grasp on the nature of extra-solar planets (Figure 3). The Gemini Planet Imager (Macintosh et al. 2006) and ESO/SPHERE (Beuzit et al. 2006, 2008) will take this to the next step by boosting our ability to perform spectroscopy on these systems.

A new era of characterizing the physical, chemical and biological states of exoplanets has already begun. While many parameters will require JWST, ALMA and ELT capabilities, the current 8 to 10 meter-class telescopes, equipped with adequate instrumentation are capable of searching for key but simple bio-signatures or biomarkers (such as H_2O, O_2 or O_3 and the "spectral edge" of vegetation that indicates plant cover) in well-identified exoplanetary bodies. Both direct spectroscopy of the planetary objects, or their transit observations, allow planetary structures and atmospheric studies, e.g. from high precision light curves and transit spectroscopy (e.g. Redfield et al. 2008).

In summary, the current generation of large 8- to 10-meter telescopes can play a key role in building an inventory of exoplanet systems to be probed deeper with the ELTs.

4. Mapping the cores of galaxies and meshing IFU datacubes

The study of the centers of galaxies has become an important step in understanding their merger histories and the growth of massive objects in their cores. Measurement of reliable stellar kinematics of the center of galaxies is important in generating maps of mean stellar velocity, velocity dispersion and higher order moments of the line-of-sight velocity distributions. It is important to make these maps at different scales and mesh them together. It is also essential that the highest spatial resolution be obtained in regions where the velocity fields change rapidly on a small scale, i.e. at the core of the galaxies. For example, Figure 4 shows the kinematics at the center of the galaxy NGC 7332 as extracted from datacubes produced by the SAURON (Spectrographic Areal Unit for Research on Optical Nebulae) integral field unit (IFU) spectrograph on the 4-meter William Herschel Telescope and by the 8 meter Gemini Multi-object Spectrograph (GMOS) IFU. The top left image was taken from the SAURON velocity map from Emsellem et al. (2004). The top right image is the GMOS 5"x7" 0.2"/spaxel close-up of the inner part of that galaxy showing a level of detail in the velocity map that SAURON's 0.9" spaxels could not see (Maier et al. 2009). The bottom right is a close-up of the SAURON map scaled up to the size of the GMOS field (Falcon-Barroso et al. 2004) which shows how much more detail can be seen with smaller pixels or finer resolution provided by the GMOS-IFU. Still larger scale and lower resolution mapping remain essential to fit the different scales properly.

The point of this comparison (Figure 4) is to show that very unexpected things can be seen at different resolutions. For instance, in this case, the SAURON team was relatively sure that there would be a kinematically decoupled core (KDC), as the "S" in the zero velocity line is usually a good indicator that in higher spatial resolution the subcomponent can be

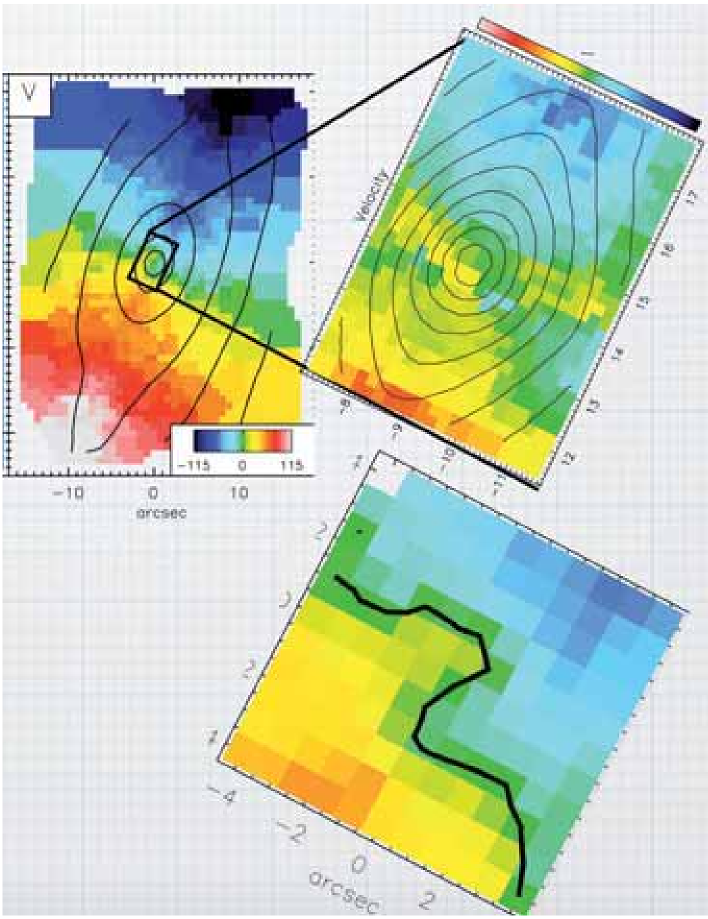

Figure 4. Comparison of the line-of-sight velocity fields of the central regions of the S0 galaxy NGC 7332 as measured by integral field unit spectrographs on the William Herschel Telescope (WHT, left) and Gemini North (right) from Maier (2008).

resolved. In this case, this galaxy had undergone a minor merger so recently that the subcomponent has not had enough time to settle into a regularly rotating KDC. This is backed up by the age of the stellar populations and by calculating the dynamical time in the center. Probably what we are seeing here is a KDC in the making. This very centralized tri-axial structure is most likely temporary (as this is a very fast rotating S0 galaxy with very low velocity dispersion) and after one dynamical time will look more like a more smoothly rotating subcomponent.

5. GRBs at z > 7: signposts for proto-galaxies

Locations of distant Gamma Ray Bursts (GRBs) are fields to be blind-imaged in the near-future with JWST and ELTs. Very high redshift GRBs are the smokestacks of intense massive star factories. With the observation of the first GRB at z = 8.3 (Tanvir et al. 2009), we are now probing the re-ionization era (Figure 5). Before the ELT era opens, another way to apply "gain" to the problem of detecting objects at the extreme margins of sensitivity for 8 to 10 meter class telescopes will be to use gravitational lensing to amplify the light from catastrophic events occurring all the way back to z~20. Once detected, we will need to perform low-resolution spectroscopy to characterize the physics of these enigmatic objects. Gemini's near infrared multi-object spectrograph FLAMINGOS-2 will be equipped with a special tunable Fabry-Perot system (F2T2). Combined with Multi-Conjugate Adaptive Optics (MCAO) it will be a totally unique capability well into the next decade and could be the only system capable of detecting/characterizing these objects from the ground. Basic measurements may be only redshift, element abundances of oxygen and elementary dynamical/kinematical properties of proto-galaxies. Still, this will be a crucial step to break effectively through the z = 7 "wall" while waiting for ELTs.

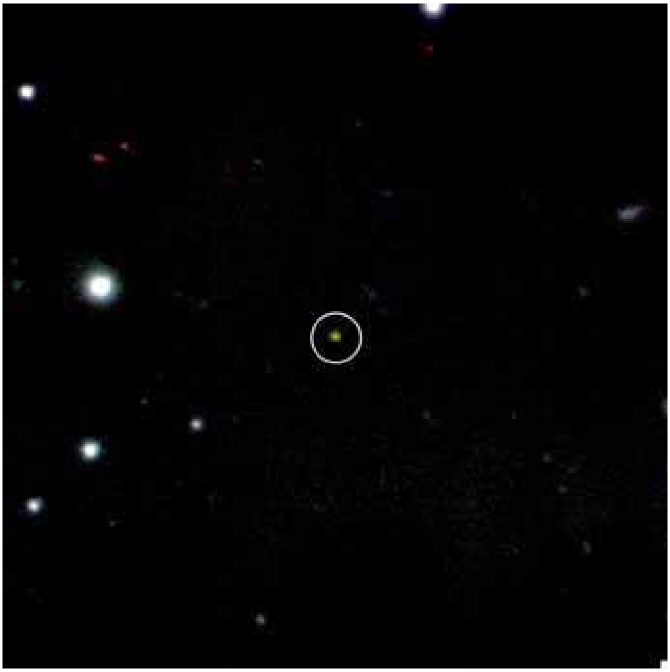

Figure 5. Near infrared image of GRB 090423 from NIRI on Gemini North. The host object is at z = 8.3 based on photo/spectro determination from Gemini, UKRIT and VLT measurements (Tanvir et al. 2009).

6. “Queue” observing and re-engaging astronomers with their science machines

The original Gemini operating model was 50% “queue” (or service observing) and 50% “classical” (i.e. observer scheduled for a fixed block of time and dates), because the Gemini Board assumed that 50% queue would not actually be used. However, the demand for queue proved to be overwhelming. Gemini’s current operational model of 90% queue 10% classical (determined by demand) is rather unique, but not exclusive, amongst 8 to 10 meter telescopes. The transition to 90/10 was therefore dramatic.

Gemini has conclusively shown that the multi-instrument queue model delivers completed science programs in the conditions required, for the highest ranked science programs. Nevertheless, queue or service observing on this scale is still rather new to the ground-based community and it is just now being learned. Hobby-Eberly Telescope (HET), South African Large Telescope (SALT) and VLT also have an observing model dominated by queue and new telescopes like the GTC are adopting a similar model.

Gemini’s queue model enables science to be performed that simply could not be accomplished with a classically scheduled model. One example is the follow up spectroscopy of supernova candidates of the now completed Supernova Legacy Survey (SNLS) (Astier et al. 2006). The goal of SNLS was to produce a definitive sample of distant type-Ia supernovae to distinguish between the different theories of dark energy. Gemini provided spectra for 230 objects (500 hours over five years) of the 400 spectroscopically confirmed supernovae. This program utilized approximately nine hours of Gemini telescope time per month over five years. If this program were classically scheduled on one night per month, it would have had a 25% chance of obtaining the required conditions. Our regular and continuous monitoring of the large-scale cloud system on Saturn’s moon, Titan, is another good example of the benefits of a queue observing model (Schaller et al. 2009).

Rapid Targets of Opportunity (ToO) programs do routinely take advantage of the Gemini queue and quick data access from the Gemini Science Archive (GSA). PIs have been known to submit follow-up triggers based on preliminary data analysis within the same night and to issue an IAU circular within hours of the observation. The quality of Gemini’s networking and videoconference infrastructure, and the 15-minute average access to data in the GSA, make fast, remote data fetching a capability within the queue that is unique to Gemini.

The NICI exoplanet search campaign at Gemini South is conducted in a block-scheduling mode within the queue. The NICI campaign, which requires clear sky and very good image quality, is the top priority in the queue when these conditions are met during the “NICI blocks.” Campaign target selection is a complicated real-time process. From their offices at the University of Hawaii, team members access their data within minutes from the GSA in Victoria, Canada, and provide feedback to the observers on Cerro Pachón (and/or La Serena) in Chile via a live video link.

For the period 2011-2015, Gemini will take the queue model to the next level of efficiency and effectiveness, while simultaneously addressing many of the concerns raised by the science user community. Gemini has the following main goals for science operations that could provide clues to more efficient science operations and data delivery for the future ELTs. We will try to (1); deliver all requested data for all scheduled queue programs, (2); deliver optimal signal-to-noise (or maximum exposure time) on all science targets, and (3); complete a quality assessment pipeline that runs at each telescope and which facilitates the previous goal.

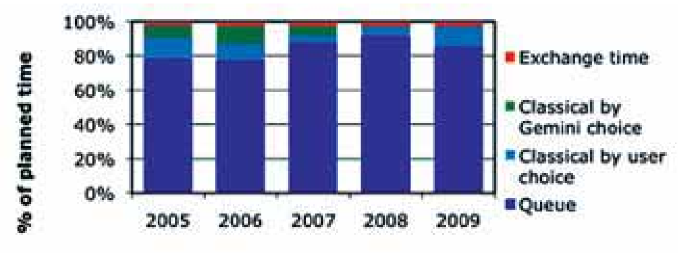

Figure 6. Statistics of queue and classical time on both Gemini telescopes over the last semesters 2005 to 2009.

In the past several Gemini proposal rounds, less than 10% of the total time requested was for classical time (Figure 6). From Gemini's perspective, the market demand is clear. However, our operational model which is dominated by service/queue observing has the disadvantage of isolating the users from the facility. This is not a good thing because of the desire to keep a synergy of innovation between the users and the observatory, and the need to train the future generation of observational astronomers. A close relationship and interaction between users and the observatory's staff needs to be developed in a different and more imaginative way.

First, the queue/service system at Gemini is very versatile and allows for last minute changes (e.g. targets or filters to be approved by Gemini management, normally with a very quick response time). Exchanges between Gemini staff and PIs can be simply triggered by "notes" in the Observing Tool requesting that we call or notify the PI (or co-I) at the time of the observations or when data are ready by an e-mail message. We also are implementing a system of fast notification of data availability. Unfortunately, not all our users are aware of this flexibility of the queue and responsiveness of the observatory. For example, we have discovered that several PIs are unaware of our "repeat" observing guarantee, if they realize that the data they have received were not obtained under the requirements they put in their proposal. While we had foreseen about 7% "repeat" of observations, we repeat only between 2-3%.

A survey of Gemini users from 2006 and 2007 showed overwhelming support for Gemini's queue operations model. Of 246 respondents, 81% expressed a preference to dedicate 75% or more of the available telescope time to queue observing, over traditional visiting observer, or "classical" observing.

Only 2% of the respondents indicated a preference for 100% classical observing, compared to 17% in favor of 100% queue-scheduled observing.

Nevertheless, many users are interested in visiting the observatory and participating in the observing process. The Gemini operations model affords this possibility in two ways: through the traditional "classical" observing mode and by welcoming queue PIs to visit the observatory while their programs are in the queue.

One of the most productive ways for Gemini users to participate in data collection is as a visiting queue observer. Gemini makes every effort, within the constraints of priority and weather conditions, to schedule the visitors program while they are at the telescope. There is no guarantee that the PI will see their program executed, but this system has been very popular and successful. This approach is particularly useful for students who come for two-three weeks and participate fully in observatory life. This offers the student much more training than they would receive by accompanying their supervisor for a two-night run on the telescope (that may be clouded out!).

"The days leading up to my time at the summit were ominous. Just a few days before, a large snowstorm hit the top of Mauna Kea. In addition, cirrus clouds had been plaguing observations the whole week prior. However, as the night of my visit approached, the weather changed and there were four photometric nights out of five. Time at the telescope was the most exciting of the visit. On a given night we would take up to six different types of observations: Coronagraphic imaging of exoplanets, Near Infrared (NIR) Integral Field Unit (IFU) observations of compact galaxies, multi-object spectroscopy. Being exposed to such a diversity of observations, I gained a deep appreciation for the difficulty of running such a wide array of instruments. However, the high point of my visit was being present when the last of my 2008B data, NIR observations of four gravitational lenses, were observed."

Ross Fadely (Rutgers University)

The user will often participate in the observations for their program, working side by side with Gemini staff, and learns more about Gemini operations in the process. The observatory benefits from the interaction as it would with a classical visitor, but retains the flexibility to make the most efficient use of the telescope time.

In semester 2008B the massive star Eta Carinae underwent a unique eruption event. This program required several epochs of observations over the semester, a program that could only have been done in queue mode. One of the Co-Investigators visited Gemini South over a 2+ week period, and participated closely in several observations, both from the summit and the base facility in La Serena, Chile.

Therefore, Gemini has developed a system in consultation with its users that allows the observational astronomers to remain fully "attached" to the telescopes and participate in different ways in the observing process and the use of the battery of complex instruments. The observatory and the staff have to remain "reachable" which is very important to ensure cross-fertilization in developing new approaches and ideas for observing strategies and future instruments.

7. Will E-ELTs be the last machines?

No!

Credible concepts of single aperture 50 meter telescopes and an array of 16 x 8 meter fully adaptive telescopes have been explored for several years now (e.g. Mountain 1997). ESO's plan to build a 100 meter optical/infrared telescope, OWL, the OverWhelmingly Large telescope indicates that ELTs are just one more step toward even larger single, full-aperture, telescopes in the foreseeable future. The November 2005 OWL review judged the project feasible, but it identified some technical risks. The review panel "recommended that the project proceed to Phase B, but that a smaller size be considered to mitigate the risks and to contain the budget" (Gilmozzi 2009). Hence the question is whether OWL will be the last machine. The currently planned Giant Magellan Telescope (GMT), Thirty Meter Telescope (TMT) or E-ELT are not the final machines on the drawing board.

Quantum efficiencies of detectors are close to one, and therefore increases in sensitivity on the ground can only be obtained by larger aperture with good adaptive optics capability at this point (Spectroscopy is still waiting for a huge gain with efficient energy detectors that not only detect photons but measure their energy).

Could more information be acquired through means other than telescope size? Clearly if one is after spatial resolution, interferometry (especially with aperture synthesis) is the way to go. Optical interferometers for astronomy have generally been considered marginal players but this situation is changing rapidly. Several optical/infrared interferometers are operational and are providing forefront astrophysical results, such as direct measurements of the size and shape of nearby stars (see review by ten Brummelaar et al. 2009). The current success of the ESO VLT Interferometer (VLTI) that currently emulates a ~100 meter telescope as a new facility on Paranal is bringing aperture synthesis into the toolbox of the "main street" astronomer (Figure 7 and 8).

An even larger Very Large Inteferometer Array (VLIA) of steerable 8 meter telescopes would have the ability to probe structure at infrared wavelengths down to the milli-arcsecond scale. However, the real performance of VLIA will depend on the ability to concentrate a significant fraction of the flux collected by the equivalent

Figure 7. Virtual full aperture ~100 meter telescope as emulated by the VLTI currently in science operation at Cerro Paranal, Chile. (ESO)

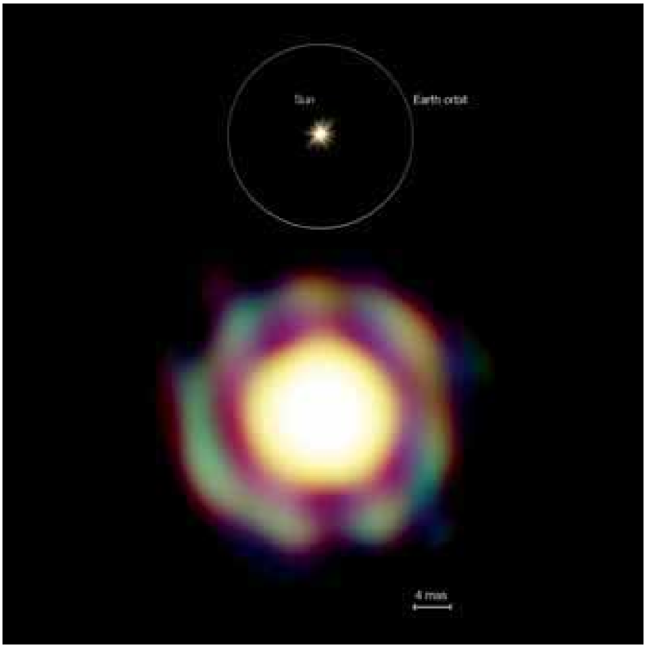

Figure 8. ESO VLTI image of the Mira-like star T Leporis with a comparison of the size of the orbit of the Earth around the Sun. Note the 4 milli-arcsecond scale. (ESO/ J-B. Le Bouquin et al.)

of a 32 meter telescope into milli-arcsec apertures while maintaining a scientifically interesting imaging field of view (Mountain 1997). Let us remember the issue is not only to increase collecting power with aperture but also decrease sky background. On this last front, a smaller telescope in space (e.g. at L2) with 10^3 -10^5 reduction in background is a very efficient approach, although still costly and risky. For the same cost of around $1B (US), a smaller size facility in space may be a serious competitor.

A quick look at the recent history of radio telescopes provides some perspective. The Office of Naval Research 600-foot radio dish at Sugar Grove initiated and canceled in the 1962 may have been the last attempt to build an enormous large single-aperture fully steerable antenna. Today the 100 meter Robert C. Byrd Green Bank Telescope is the largest fully steerable radio telescope. After the 305 meter Arecibo reflecting fixed dish and the Chinese Five-hundred-meter Aperture Spherical Telescope (FAST), radio astronomers have the ambition of the Square Kilometer Array (SKA). Large unfilled apertures is definitely the future direction. ALMA is an interesting reference point: considering the scale and complexity of the project, the size of the partnership needed to make it happen, one may ask: "Is ALMA the last mm/sub-mm facility?" Certainly this is true for some time. However, there is no indication that optical/infrared astronomers show less appetite or imagination than their radio colleagues for aperture growth or creative designs.

Non-scientific or technological considerations will drive the move, or not, to bigger apertures: cost effectiveness of ground versus space and societal threshold, institutional and national economic barriers. Indeed, we see the current ability of national funding organizations challenged by on-going projects. They may balk at providing sufficient money to built a facility for fundamental research where knowledge acquisition and prestige are the key drivers, and spin-offs are relatively minor. One important limiting factor is the cost not only to build but to also operate these extreme systems.

As pointed out by many (e.g. Roy and Mountain 2006), the globalization of astronomy is also strongly driven by external forces. Funding agencies are looking for strong national and international partnerships and prefer collaboration to competition. They also favor a strategic approach that avoids duplication of efforts, encourages the merging of the best ideas and technologies, rewards the mitigation of risks, and optimizes investments in esoteric research areas that are out of the mainstream. The European agencies, leveraging off their collective and coordinated investment through ESO, are managing to fund their current operations at a highly competitive level. This unified approach has yet to be endorsed by the US and Asian communities.

It will be extraordinary to see a significant fraction of the proposed facilities built, outside of very well coordinated international partnerships (Roy and Mountain 2006). As a project's size grows, so does its visibility. Hence the growing importance of accountability to funding agencies for programs that utilize space telescopes and billion-dollar-scale ground-based facilities has changed the dynamics of doing astronomy on a large scale.

8. Reflections on partnership and lessons learned from Gemini

The latter remarks raise the issue and challenges of partnerships. Exemplary, and most successful, the unification of all European ground-based astronomy under ESO has brought with it a highly focused investment in key technical talent and technology.

In the New World, the development of our national institutions sometimes has had difficulty keeping pace with new funding directions and international opportunities that push astronomy toward even more ambitious partnerships. An unfavorable economic environment and emphasis of stimulus packages toward non-traditional scientific areas may be taking their toll. The current funding context in the light of global financial crisis looks challenging. However, it should encourage the re-deployment of existing partnerships and the creation of new partnerships. Since most European and American countries have saturated the market, many look at Asia as the potential for new consortium initiatives.

Many of the technologies required for new facilities (adaptive optics, large optics manufacturing, large detectors, high speed computers) will require substantial and coordinated investments to bear fruit. Contrary to previous decades, many of these technology investments (particularly those required for adaptive optics and large format infrared detectors) will not be provided "for free" by the U.S. Department of Energy, the Department of Defense or NASA. Ground-based astronomy is very much on its own this time around, and hence needs to pool resources.

As existing partnerships evolve and new partnerships and consortia develop, the lessons from Gemini, which operates under a different model from ESO, may be useful to consider. Examples of this new approach are the current exchange of observing time between Subaru, Keck and Gemini or Keck and Gemini joining forces to get two solid-state lasers through a single contract. The exchange of nights represents, at the moment, only a few nights per semester, but this trade will likely increase in the near future as it fulfills the demand of our users for multi-telescope access. This also addresses the issue of unnecessary instrument duplication by providing a path for a more coordinated and integrated environment for future instrument development.

Asymmetric partnerships. The Gemini Observatory has six contributing partners, a host institution in Hawaii (University of Hawaii Institute for Astronomy) and the host country Chile (CONICYT). The hosts have 10% of the telescope observing time. Currently Gemini Staff obtain 10% of the Gemini telescope time. Once these allocations are removed from the top, the members have the following observing time allocations: United States 50.1%, UK 23.8%, Canada 15%, Australia 6.2%, Brazil 2.5% and Argentina 2.4% in proportion to their contributions to the annual operating budget. The decimal numbers of these percentages have interesting histories in themselves. The partnership is highly asymmetric and this is reflected in the representation on the Board of Directors, the participation in instrument building, and the overall influence of each 'shareholder' in the decision making process. Asymmetry is not an issue, but having partners with too small a share is questionable. Or if a large partner runs into financial difficulty, the impact is huge.

Distributed model of support. Gemini partner agencies introduced right at the beginning of the observatory's history a system of distributed support where National Gemini Offices (NGOs) handle the telescope observing time proposal process, provide first-line support to the users and act as the intermediary between the various national communities and the observatory. After some early challenges the model has evolved enough to fulfill its core mission. ALMA has adopted a similar approach with its "arclets" system. The distributed model is drastically different from the centralized model of ESO and HST support. The advantage for a multi-time zone consortium like Gemini is a closer and faster interaction between users and observatory support staff. The inconvenience is the risk of the users getting different levels and qualities of service; quality and depth of support depend on the strength of their NGO, its funding level and quality of its staff. Thus, the observatory cannot guarantee an equal, or uniform level of quality of support to its users.

Multi-TACs. Gemini has a single centralized archive center, the Gemini Science Archive (GSA) at the Canadian Astronomical Data Center (CADC) at Herzberg Institute of Astrophysics (HIA), Victoria, Canada. However, it has nine time allocation committees (NTACs): six for the contributing partners, two for the hosts and one for the Gemini staff time. Each partner or institution manages its Time Allocation Committee (TAC) that selects and ranks its proposals. The proposals are then merged through an algorithm that ensures a fair treatment between partners. The merged list is then submitted to the International TAC or ITAC, made up of representatives of each NTAC. ITAC does the final ranked list after reviewing duplication and conflicts of proposals (science or targets) and makes a recommendation to the Gemini Director, who has full authority on the scheduling of recommended programs. The advantage of this system is that each Gemini partner owns and controls its TAC process and each country/institution has their own strategic approach, depending on their access to other 8 to 10 meter-class telescopes or instruments or science priorities. The largest inconvenience is that a multi-TAC is an impediment to large programs that require significant allocation of time in a given, or over several, semesters. Although astronomers can put in a joint proposal requesting time from more than one partner, this is very demanding in terms of multiple reviews and increases "multiple jeopardy".

Governance issues. The Gemini Observatory is under a 20 year International Agreement coming to an end on 31st December 2012. Despite a very heavy penalty for early withdrawal, the partnership has had to face the on-going threat of defaults (i.e. if a partner does not pay its annual dues) or early withdrawal (e.g. the UK announcement (and subsequent reversal) of its plan to pull out in November 2007, and now again in July 2009). This has transformed a strong partnership predicated on mutual trust into a confederation of loosely aligned interests. This has pulled future development programs in odd directions, as some partners may only provide funding for instruments deemed interesting by their specific community, with the risk of sub-critical funding overall.

This text is my sole responsibility. However several colleagues have contributed to many of the ideas presented in this paper. I am grateful to several members of the Gemini Observatory staff, members of the Gemini user community and other colleagues. I am particularly indebted to Doug Simons, Wayne van Citters, William S. Smith, Nancy Levenson, Dennis Crabtree, Inger Jørgensen, Peter Michaud, Bernadette Rodgers, Millicent Maier, Julian Christou, Joe Jensen, Matt Mountain, Phil Puxley, Thijs de Graauw, and Gustavo Arriagada.

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M. Iye

National Astronomical Observatory

Subaru Instruments, Science Achievements, and Future Plans

Abstract

The outline, history, specific features and operational status of the 8.2 m Subaru Telescope are reviewed. The currently available instrument package consists of SuprimeCam, FOCAS, HDS, IRCS, COMICS and MOIRCS, covering a wide range of wavelength-spectral resolution space for the instruments. AO188 is also available with natural guide stars for operation. Among the many science achievements of the Subaru Telescope, studies of high redshift Lyman alpha emitters using SuprimeCam to elucidate the cosmic re-ionization history and studies of the GRB-SNe connection using FOCAS spectropolarimetry are mentioned as successful examples that have exploited the full capability of these unique instruments. Further instruments under construction or at the final test stage are FMOS, LGSAO188, HiCIAO and HSC.

Subaru will strengthen its observational capabilities at its unique prime focus. In addition to HSC, which produces an image covering 1.5 degrees, a possible new instrument could be a wide field multi-object spectrograph for cosmology and galactic archaeology if funds become available. These unique instruments would also serve for isolating key targets to be observed by ELTs.

Keywords: Subaru Telescope, instruments, performance, future plan

1. Introduction

The 8.2 m Subaru Telescope atop Mauna Kea (Figure 1), Hawaii, received its engineering first light in December 1998. It has been available to the astronomy community since December 2000. Details of the telescope system and its performance can be found in review papers[1,2]. The best image size ever confirmed is 0.”2, both in the optical and near infrared, and the median seeing size is about 0.”6, as shown in Figure 2.

Figure 1. Subaru Telescope at the summit of Mauna Kea.

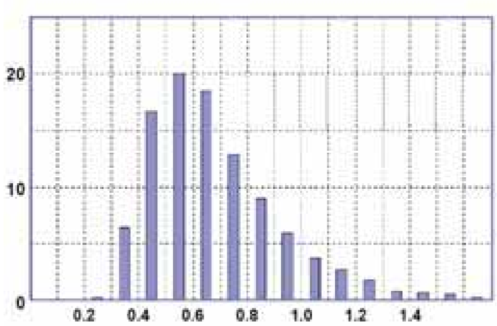


Figure 2. Subaru seeing size statistics.

The first generation scientific instruments consisted of :

1) the SUbaru PRIME-focus CAMera (Suprime-Cam)[3],
2) the InfraRed Camera and Spectrograph (IRCS)[4,5],
3) the Faint Object Camera And Spectrograph (FOCAS)[6],
4) the OH airglow Suppression spectrograph (OHS)[7] and its camera module (CISCO)[8],
5) the High Dispersion Spectrograph (HDS)[9],
6) the Cassegrain 36-element Adaptive Optics (AO36)[10],
7) the COoled Mid Infrared Camera and Spectrograph (COMICS)[11],
8) the Coronagraphic Imager with Adaptive Optics (CIAO)[12].

All these instruments received their first light by the end of 2000. Four Cassegrain instruments - FOCAS, IRCS, CIAO, and COMICS - were stored at four standby ports on the observing floor and they can be tested there, if necessary, with connection to the network system. The Cassegrain instruments, weighing 2 tons each, can be exchanged by using the semi-automatic instrument exchanging system CIAX[13] in about an hour during the daytime (Figure 3). The Suprime-Cam and other secondary mirrors are stored on the top unit floor and can also be exchanged by using the top unit exchange system (Figure 4) in 6 hours during the daytime[1]. During the first 28 months between 2000 May and 2002 August, the telescope was operational for 26 months. The top unit was exchanged 56 times and the instruments were changed

Figure 3 Cassegrain Instrument Automatic eXchanger.

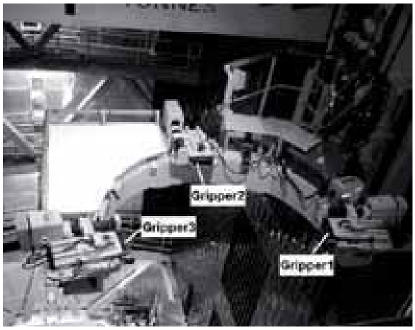


Figure 4 Top Unit Exchanger system

89 times, corresponding to roughly 2.2 top unit exchange operations and 3.4 instrument exchange operations per month. Note that more than an average of 70% of telescope time is used for science observations.

Suprime-Cam, covering a 34' x 27' field of view with an unvignetted area of 30' diameter, with ten 4k x 2k CCDs, has been the most heavily used of the Subaru instruments. In good seeing, the wide field prime focus corrector provides a superb image quality of 0."3 even near the edge of the field. Standard sets of broad band filters B, V, R, Ic, g', r', i', and z' and a number of narrow band filters are available with some restriction on usage. Suprime-Cam has an automatic filter exchanger that can hold up to ten filters. The images taken during the first light campaign of Suprime-Cam were shown to be as deep as those taken by WFPC2 on the HST.

Table 1. List of the current and near future Subaru instrument suite

	Acronym	Full Name	Focus	FL	Status
1	Suprime-Cam	Subaru Prime Focus Camera -.	Pr	07/00	Av
2	IRCS	Infrared Camera and Spectrograph	IR Ns	06/00	Av
3	FOCAS	Faint Object Camera And Spectrograph	Cs	03/00	Av
4	HDS	High Dispersion Spectrograph	Opt Ns	08/00	Av
5	COMICS	Cooled Mid-Infrared Camera and Spectrograph	Cs	01/00	Av
6	MOIRCS	Multi-Object Infrared Camera and Spectrograph	Cs	09/04	Av
7	LGSAO188	Laser Guide Adaptive Optics system	IRNs	02/09*	Av/Con
8	FMOS	Fiber Multi-Object Spectrograph	Pr	-	Con
9	Hyper Suprime	Hyper Suprime-Cam	Pr	-	Con-
10	HiCIAO	High-Contrast Coronagraphic Imager for Adaptive Optics	IRNs	-	Con

*Av: Available, Con: under Construction, * NGSAO available*

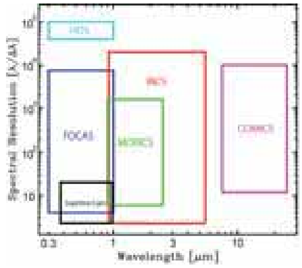


Figure 5. Wavelength – spectral resolution domain coverage of Subaru instruments.

OHS, CISCO, and AO36 were decommissioned by 2009 and CIAO was removed from an open use package. Figure 5 shows the region in the wavelength—spectral resolution plane covered by the current suite of instruments. All the instruments employ closed-cycle refrigerators to cool the detector. No liquid nitrogen is used.

Five second generation new instruments:

9) the Multi-Object InfraRed Camera and Spectrograph (MOIRCS)[14,15],

10) the Laser Guide Star Adaptive Optics (LGSAO188)[16],

11) the Fiber Multi-Object Spectrograph (FMOS)[17-19],

12) HiCIAO[20,21],

13) Hyper Suprime Cam (HSC)[22,23]

will join the Subaru instrument suite. MOIRCS is a fully cryogenic double beam multi-object infrared camera and spectrograph constructed as a joint project between the NAOJ and Tohoku University. The imaging mode has been in service since S05B, and the MOS mode became available from S06B, operated with a natural guide star, has been available for open use since S09A. Table 1 gives an updated list of the current and near future Subaru instrument suite.

2. Science Achievements

By November 2008 536 refereed papers based on observations made with the Subaru Telescope had been published, for which a total of 13,637 citations had made by 27 July 2009. In addition 630 proceeding papers were published for the same period. These include many original studies of scientific significance. Let me introduce here just two cases, in which I think the unique properties of Subaru instruments led to successful findings.

The first example is the search for high redshift Lyman alpha emitters (LAEs). The Subaru Deep Field survey[24] was designed to probe galaxy populations at high redshifts by making deep imagings at B, V, R, I', z' to derive photometric redshift estimates and luminosity functions for galaxies at various redshifts. In addition to these broad band images, several narrow band filter images were designed to isolate emission line galaxies. For example, the NB711, NB816 and NB921 filters can pick up galaxies with LAEs at redshift 4.8, 5.7, and 6.6, respectively. The spectra of these candidate galaxies were obtained by FOCAS and Keck DEIMOS and a large fraction of the photometric candidates was confirmed to be the real LAEs. The Subaru Deep Field survey used these narrow band images to derive the LAE luminosity functions[25,26] at these redshifts and found a significant decline in the population at their bright end from redshift 5.7 to 6.6[26].

A further survey using NB973 to probe LAEs at redshift 7.0 yielded only one object (Figure 6,7,8), leading to the discovery of the most distant galaxy with redshift confirmation[27]. Table 2 shows the top ten list of most distant galaxies with published redshift measurements. Note here that the lack of LAEs at redshifts between 6.7 and 6.9 doesn't imply the absence of galaxies. This list reflects the result of surveys made only at redshift 6.6 and 7.0. One feature to be noted in this table, however, is

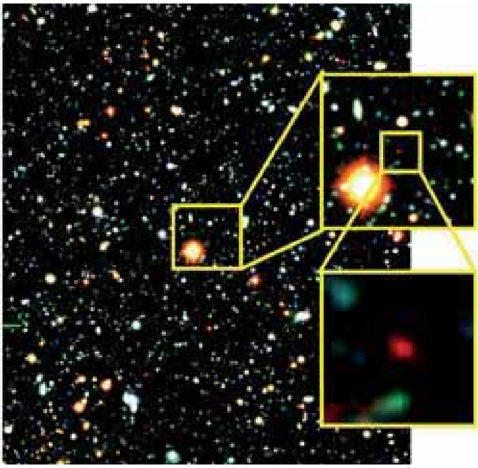


Figure 6. The most distant galaxy IOK-1 with redshift z=6.964, discovered among 41,533 objects detected in a 15 hour exposure.

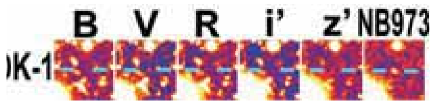


Figure 7. IOK-1 was isolated as a candidate object visible only in the image taken with a narrow band filter with central wavelength 973 nm and band width 22 nm but not in other images taken at shorter wavelengths.

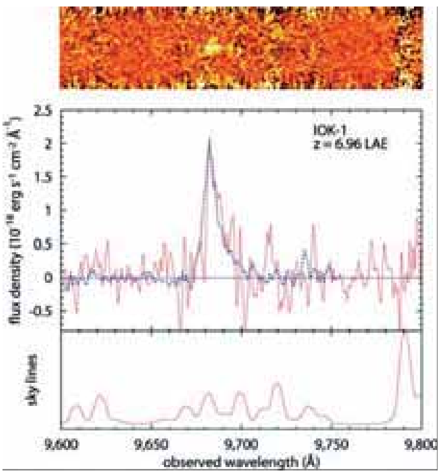
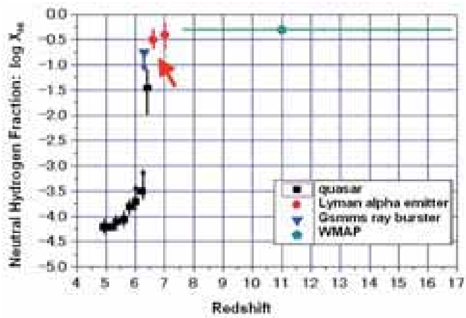


Figure 8. Spectroscopic follow-up observations clearly showed Lyman alpha emission line at 968 nm with an asymmetric line profile that matches the average line profile of Lyman alpha emitters observed at redshift 6.6.

Rank	ID	Coordinates	Redshift	0.1Gyr	Paper	Date
1	IOK-1	J132359.8+272456	6.964	128.8	Iye et al.	Sep. 14, 2006
2	SDF ID1004	J132522.3+273520	6.597	128.2	Taniguchi et al.	Feb. 25, 2005
3	SDF ID1018	J132520.4+273459	6.596	128.2	Kashikawa et al.	Apr. 25, 2006
4	SXDF Himiko	in SXDS field	6.595	128.2	Ouchi et al.	Jul. 25, 2008
5	SDF ID1030	J132357.1+272448	6.589	128.2	Kashikawa et al.	Apr. 25, 2006
6	SDF ID91163	J132343.4+272954.5	6.587	128.2	Kashikawa et al.	Feb. 2009
7	SDF ID91988	J132342.2+272644.5	6.587	128.2	Kashikawa et al.	Feb. 2009
8	SDF ID71101	J132450.7+272159.7	6.587	128.2	Kashikawa et al.	Feb. 2009
9	SDF ID1007	J132432.5+271647	6.580	128.2	Taniguchi et al.	Feb. 25, 2005
10	SDF ID1008	J132518.8+273043	6.578	128.2	Taniguchi et al.	Feb. 25, 2005

Table 2. Top ten highest redshift galaxies with published redshift measurement. Note that the surveys are made at redshifts 6.6 and 7.0.

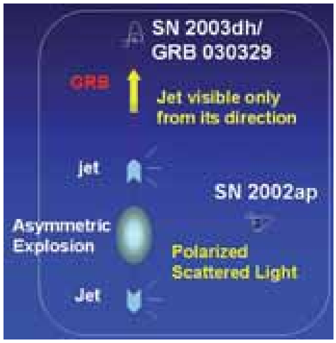
Figure 9. Logarithmic fraction of neutral hydrogen. Gunn-Petersonn tests of quasars at z<6.4 indicate the completion of cosmic re-ionization by z~6. Recent assessments comparing the luminosity functions of LAEs at z=5.7, 6.6 and 7.0 indicate the presence of residual neutral hydrogen at z=6.6 and 7.0. Measurement of the electron scattering of microwave background radiation indicates cosmic re-ionization at around z~11. These disparate facts seem to be piece together to reveal the cosmic dawn.



that the SDF survey confirmed only one LAE at redshift of 7.0 while tens of LAEs were detected at redshift 6.6. Although the limiting magnitude for the survey at redshift 7.0 is slightly shallower than that at redshift 6.6, this decrease in the LAE population from redshift 6.6 to 7.0 strengthens the previous finding of a declining observable LAE population at higher redshifts.

Since such a decrease in the LAE population from redshift 5.7 through 6.6 to 7.0 is seen only at Lyman alpha emission but not in the UV continuum close to the Lyman alpha emission, this is unlikely to reflect the evolution of primordial galaxies during this period. Instead, this decrease towards higher redshifts can be explained by the increasing fraction of neutral hydrogen towards higher redshift. The SDF team interprets this as evidence for late cosmic re-ionization. The WAMP result implies that cosmic re-ionization could have taken place at redshift 10.9+-1.428, if this event was an instantaneous one. Subaru's possible witnessing of the final phase of cosmic re-ionization implies that the cosmic re-ionization process was a slow and inhomogeneous process. Figure 10 shows the implied fraction of the cosmic neutral hydrogen as a function of redshift.

Figure 10. Conceptual drawing showing the geometry of core-collapse type supernovae (hypernovae) having an asymmetric explosion with relativistic jets. When such an explosion is observed from the directions where the jets point, one can see a long-burst GRB and its afterglow showing no polarization. On the other hand if such an explosion is observed sideways, one does not see the GRB although one may be able to detect the polarized and scattered light from the jets.



A second example of Subaru science achievements is the study of GRBs and hypernovae by using the spectro-polarimetric observations. Spectropolarimetric observations of SN2002ap[29,30] elucidated the presence of a polarized component whose spectrum resembles that of the supernova but Doppler shifted by about 11% of the speed of light. SN2002ap is ascribed to a core-collapse type Ic supernova for which no GRB counterpart was identified. On the other hand observations of SN2003dh confirmed that not just the position but also the date of explosion, as estimated from the evolving spectral features, of this SN coincide with those of GRB030329[31]. The spectra suggested a core-collapse type supernovae and no evidence for the presence of the scattered light component was confirmed. These findings, together with theoretical model predictions, led to the picture that core collapse type Ic supernovae generally have energetic asymmetric explosions with a pair of relativistic jets at their pole directions. When such an explosion is observed from the directions of jets, one can first see them as gamma ray bursts (GRBs) while the later optical observations of afterglows do not show a polarized component because of their axisymmetric view. On the other hand, when these objects are observed sideways, GRBs are not visible due to large angle between the relativistic beaming and the lines of sight. Although the beamed jets are not directly seen, one can see the scattered light from these jets as polarized light redshifted with respect to the star due to the jet motion. Further spectroscopic studies also show the asymmetric explosion in the emission line profiles[32,33].

3. New Instruments and Future Plans

In this section, let me touch on new instruments that are under construction or in the test phase.

3.1 Laser Guide Star Adaptive Optics (LGSAO) [16]

Construction of a new AO system with 188 sensing and control elements, five times in number more than the former 36 element Cassegrain system, has been available at the IR Nasmyth focus since 2009. The final tests for a laser guide star system is under way to increase the sky coverage. An all solid-state sodium laser produced by mixing two YAG lasers was successfully developed in collaboration with RIKEN.

Figure 11. (a) Left: Layout of the laser, relay optical fibre, laser launching telescope, 188-element adaptive optics and instruments of LGSAO. (b).Right: Images of the Orion Trapezium, with (centre) and without (right) AO.

A photonic crystal optical fibre to avoid non-linear scattering of the high power laser is developed to relay the laser beam to the launching telescope (Figure 11a). Figure 11b shows the first light image taken with AO188 without a laser guide star in 2006 and the image 8 the same object taken in 1999 without AO. It is clearly seen that the AO improved the point spread function from 0.6 arcsec to 0.06 arcsec. Upgraded IRCS and HiCIAO are the instruments to be used in conjunction with the 188 element LGSAO.

Figure 12 shows one night when Subaru, Keck and Gemini launched their laser beams simultaneously. Although it reminds us of a “star wars” scenario, astronomers on Mauna Kea are collaborating to establish a system to control laser guide star observations so that the laser beams do not interfere other observations. The lasers are shut down when there is a risk of the laser beam being intercepted by aeroplanes or satellites flying above the mountain. An automatic control system using an IR camera to detect aeroplanes is being tested but for the moment we employ plane spotters while operating LGSAO.

Figure 12. Three laser beams shot from Subaru, Keck and Gemini.

3.2 High-Contrast Coronagraphic Imager for Adaptive Optics (HiCIAO)[20,21]

HiCIAO is a coronagraphic simultaneous differential imager to be placed at the Nasmyth platform under construction in collaboration with IfA, UH. HiCIAO consists of the cryogenic camera part and the non-cryogenic pre-optics part and designed as a flexible, experimental instrument to develop new technologies. A big project, SEEDS project, to search for extrasolar planets using this instrument started from S09A.

3.3 Fiber Multi-Object Spectrograph (FMOS) [14-16]

FMOS is a fibre multi-object spectrograph for the J and H bands to be mounted at the prime focus for spectroscopic observation of up to 400 objects in a 30’ field (Figure 13). The prime focus unit with an infrared corrector was fabricated and tested on the telescope. Two sets of Echidna under fabrication at the Anglo-Australian Observatory (AAO), each having 200 fibre head positioners (Figure 14), are installed in the focal plane unit. The Echidna picks up target objects and relays the sampled light to the infrared spectrographs. Two of the infrared spectrographs were built at Kyoto University and in the UK. The commissioning of FMOS began in

Fig. 13. Prime focus corrector for FMOS

Fig.14 Fibre spine heads of Echidna. Fibre positioner.

2007. The engineering test has shown rather high scattered light within the instrument and work is being carried out to overcome of problem.

3.4 Hyper SuprimeCam [22,23]

Hyper SuprimeCam (HSC) is a third generation instrument now under construction (Figure 15). It will cover a 1.5 degree field of view. For installing this massive instrument, significant modification of the telescope structure, including the top-end unit, is necessary. The HSC, expected to have its first light in 2013, will be a unique survey instrument for studying the dark energy through the baryonic acoustic oscillation in the distribution of galaxies, and a large scale consortium to enable such a survey is planned in collaboration with Princeton University.

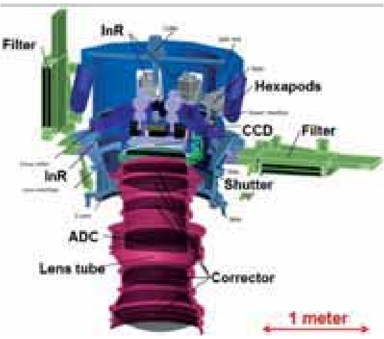


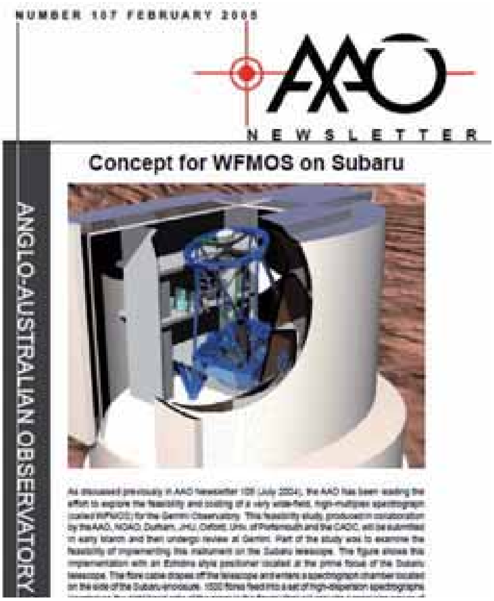
Figure 15 . Hyper SuprimeCam under construction. First light is expected at 2013.

HSC will also be a powerful instrument to extend current frontiers to survey high redshift LAEs and Lyman break galaxies. As a unique wide field and deep imaging camera for the ELT era, HSC will serve to isolate faint and rare objects to be closely studied by ELTs.

3.5 Hyper FMOS

Assuming the availability of a new prime focus that can accommodate massive instruments, the Gemini group made a study for Wide-field Fiber-fed optical Multi-Object Spectrograph (WFMOS) under the ASPEN initiative (Figure 16). Such an instrument, together with HSC, will make the Subaru prime focus capability an

Figure 16. WFMOS conceptual study by the Gemini AURA initiative.



extremely unique feature among 8-10 m class telescopes. By establishing a large sample of galaxies with spectroscopic redshift measurements, one can draw the 3-dimensional distribution of galaxies to study the evolution of galaxy assembly. It took about 2 years for the Japanese community to nurse this concept for acceptance as a potential strong plan for the future. Although the Gemini board decided to abandon this plan in May 2009, NAOJ is, instead, starting to seek finance to revive this instrument concept.

3.6 Subaru in the ELT era

The TMT board announced its decision to choose the 13 North site of Mauna Kea as the first choice to construct the TMT (Figure 17). This is good news for the NAOJ, which has longed to join the TMT on Mauna Kea. A new instrument package plan for the decade 2010 clearly foresees the importance of the wide field capability of

Figure 17. The TMT on Mauna Kea

the Subaru telescope with a synergy to serve as a pathfinder telescope for the TMT. Japan's community regards the international coordination and collaboration to share the instruments for 8-10 m class telescopes as a mandatory policy for the ELT era to keep the observatories in the forefront

Acknowledgement

First of all, I would like to extend my sincere and respectful congratulations to the GTC consortium for inaugurating a superb telescope. This visit is actually my fourth visit to this island. I first came to La Palma back in 1990 looking for a site for Japanese 8 m telescope, later named the Subaru Telescope. My second visit was in 1995, when the Spanish community invited several foreign astronomers involved with large telescopes to review the Spanish large telescope project. I recall Jerry Nelson, the father of the GTC, making a persuasive argument at that time to convert the Spanish community from an 8 m meniscus mirror to a segmented primary. The brave decision of the Spanish community to adopt a segmented mirror concept led to today's great success. My third visit was in 1997 to carry out half a night of observation on the WHT of a high redshift galaxy candidate at z~3.2, which ended up without a result due to adverse weather. This time, twelve years since my last visit, I am deeply impressed not only by the GTC but also by the growth of the entire observatory.

I would like to thank the LOC and SOC for inviting me to give a talk at this unforgettable conference and wish the GTC community all the best for the future.

Regarding the present paper describing the Subaru Telescope, readers are encouraged to obtain the most recent information from http://www.naoj.org. The author is grateful to all the Subaru staff members and the group members of individual instrument development. All the credit should go to those people who actually made the sophisticated telescope and its instruments a working reality and any blame for errors or biased statements in the present paper should be ascribed to the author.

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From Disks to Planets – The Large Facilities

1. Introduction

The large diversity of detected exoplanetary systems, ranging from close-in hot Jupiters to planets in resonances and on eccentric orbits to the recently detected super Earths and directly imaged planets on wide orbits, has revived interest in the formation history of planetary systems. Population synthesis studies are now trying to build the bridge between the properties of protoplanetary disks, the early formation process of planets and the subsequent planet-disk and planet-planet interactions (Mordasini et al. 2009). Disk metallicity, mass, lifetime, and surface density profiles are among the various disk parameters setting the stage for the planet formation process.

Since the first detection of circumstellar disks around solar-type pre-main sequence stars through the measurement of their infrared excess emission (Strom et al. 1989) and the determination of their dust masses through submillimetre and millimetre observations (Beckwith et al. 1990), an enormous amount of data on these objects has been collected. These studies demonstrated that the analysis of their spectral energy distributions alone is not sufficient to reveal the structure of disks (e.g. Thamm et al. 1994); spatially resolved information and spectroscopy data have to be added. The variety of disk studies has led to a picture where stellar irradiation, inner disk structure, and dust evolution – such as grain growth and sedimentation – determine the global disk morphology and the observational appearance of disks. An example is the frequent observation of silicate emission features, which requires an optically thin surface layer or disk atmosphere on top of an optically thick dust disk. Another disk feature is the flaring angle which may have a direct connection to dust sedimentation.

There are a number of questions we want to answer with our studies of protoplanetary disks. What is the lifetime of disks? What is the influence of stellar parameters on disk properties? How is the dust and gas evolution coupled? What is the influence of environment on disk evolution? Is there a difference in disk evolution between single stars and close binaries? How important are the initial conditions of the molecular cores for the subsequent disk structure? What is the chemical evolution of disks and their content of water and complex organic molecules? We are just starting to answer these questions with comprehensive studies of larger samples of young stars and their protoplanetary disks.

The availability of large facilities played a major role in understanding disk structure. The data ranged from superb images coming from the Hubble Space Telescope to images from ground-based facilities for larger disks such as β Pictoris (see Figure 1). AO-assisted disk imaging from the ground with 8m-class telescopes had some success, but often needed the addition of a variety of contrast-enhancing techniques

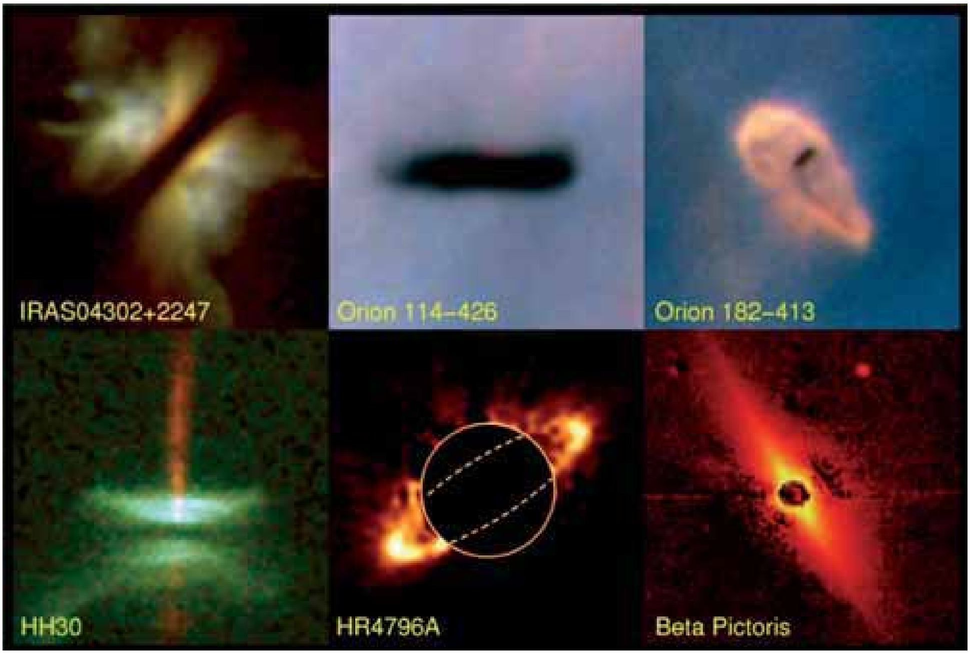

Figure 1 Hubble Space Telescope Images of protoplanetary disks (Padgett et al. 1999: IRAS04302+2247; McCaughrean & O'Dell (1996): Orion disks; Burrows et al. 1996: HH30; Schneider et al. 1999: HR 4796A) and the early ground-based image of β Pictoris (Kalas & Jewitt 1995).

such as polarimetry. The various submillimetre and millimetre interferometry facilities, including the IRAM-PdBI, SMA, and CARMA, provided images of the cold dust distribution and allowed us to find evidence for Keplerian rotation in disks. VLA observations at millimetre and centimetre wavelengths were essential to prove the presence of larger particles in disks. Recent advancements in long-baseline infrared interferometry with the Keck telescopes and with ESO's Very Large Telescope Interferometer allowed us to resolve the inner few AU of protoplanetary disks and provided evidence for a radial variation in dust properties.

Starting with the Infrared Space Observatory and followed by the Spitzer Infrared Space Telescope, the mineralogy of protoplanetary dust could be analysed. The main dust components are amorphous silicates and crystalline Mg-rich silicates. In addition, Spitzer's much increased sensitivity led to the detection and spectroscopic characterization of disks around brown dwarfs and to a statistical investigation of disk properties in quite a number of star-forming regions and nearby moving groups. Herschel will soon extend these studies to longer wavelengths; JWST will provide unprecedented sensitivity for disk imaging and spectroscopy.

Most of the previous studies dealt with the characterization of the dust in protoplanetary disks, an easier measurement due to the higher dust opacities compared with the gas. Dust evolution is certainly very important if one wants to understand the formation of planetesimals, Earth-like planets, and the cores of gas giants. On the other hand, dust is only a minor contributor to the total mass budget of disks, and the dynamics and angular momentum transport is regulated through the gas, which also provides the material reservoir for the formation of giant planets. Recently, we have seen enormous progress in the search for gas in inner disks, thanks to the sensitivity of Spitzer and a number of high-resolution spectrographs on 8 m-class telescopes such as CRIRES at ESO's Very Large Telescope and NIRSPEC at Keck. This will be an interesting avenue for both sensitive spectroscopy with JWST and high-resolution mid-infrared instruments on the new class of extremely large telescopes. Millimetre interferometry provides information on the vertical and radial structure of disks and allows us to measure molecular tracers of disk ionization. With the ALMA facility we will soon get much increased sensitivity and spatial resolution for disk studies.

Multi-object spectroscopy at optical and near-infrared wavelengths is being used to characterize the stellar properties and the accretion rates of statistically relevant samples of young stars and to relate these quantities to disk properties.

In this paper, I will summarize some of the major results coming from the various large ground-based and space-based facilities. For more extended reviews, I refer to the papers by Natta et al. (2007) and Henning (2008). I will also specifically discuss the Large Binocular Telescope and its potential for the investigation of protoplanetary disks and the planet formation process.

2. Disk lifetimes and global disk properties

Disk lifetimes have been studied using the disk frequency as an indicator for this important parameter. In determining disk frequencies, one has to make sure that the sensitivity of the infrared surveys is high enough to measure both the infrared excess emission and the emission from the stellar photospheres of the cluster members. In addition, disk emission may set in at different infrared wavelengths. Therefore, these studies require sufficient wavelength coverage. In addition, age estimates of young stars are notoriously difficult and often associated with large uncertainties.

Ground-based infrared surveys and sensitive studies with Spitzer have led to estimates of disk lifetimes with the latest values close to $10^{6.4\pm0.4}$ yr (Hernandez et al. 2008 and references therein). In general, 90% of the systems have lifetimes less than 5 Myr and only a very small percentage survive for 10 Myr. Here we should stress that there is considerable scatter in disk lifetimes for individual clusters. Some stars loose their disks very early or were never associated with extended disks.

Disk lifetimes can be different in different environments. In a recent study of the NGC 2244 cluster, Balog et al. (2007) found a reduction in disk frequency by a factor of 2 in the inner cluster region, but concluded that the effect of high-mass stars on disk evolution is significant only in their immediate environment. In a study of young clusters in Orion, a difference in disk lifetime between objects in L 1630N and L 1641C (clustered populations) vs L 1641D (distributed population) has been found (Fang et al. 2009), with a reduced disk frequency in the clusters for the 2-3 Myr age bin. Finally, close binarity seems to be a very important factor for inner disk evolution. In a study of the η Chamaeleontis cluster, Bouwman et al. (2006) found that the presence of inner disks was anticorrelated with close binarity. The mean disk dissipation timescales were estimated to be 5 and 9 Myr for the binary and single-star systems, respectively. All these studies illustrate that there are other "hidden" parameters beyond time which influence disk evolution.

All "disk lifetimes" discussed so far refer to the disappearance of thermal emission from small dust grains. This does not necessarily imply that gas evolution occurs on the same timescale. Pascucci et al. (2006) searched for gas in disks around Sun-like stars with ages between 3-100 Myr and did not detect any gas-rich disks (i.e. gas mass greater than 0.1 Jupiter mass). This suggests that gas disks dissipate on a similar timescale to the dust disks. Recently comprehensive studies using multi-object spectroscopy showed that the accretion behaviour has a temporal dependence similar to the dust evolution, suggesting that dust and gas evolution are well coupled (see Figure 2).

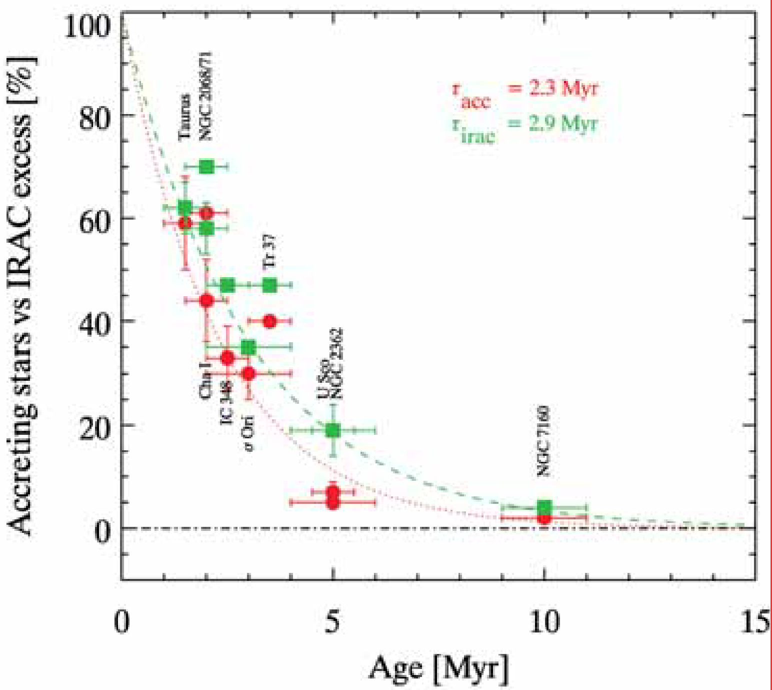

Figure 2 Fraction of accreting stars (dots) vs near-infrared excess emission (squares). After Fedele et al. (2009).

Global disk parameters, such as disk mass, inner and outer radii, and radial temperature and density profile, are of utmost importance for planet formation in disks. Large submillimeter surveys of disks in the Taurus and Ophiuchus star-forming regions lead to typical disk masses between 0.001

and 0.01 solar masses and a disk-to-stellar mass ratio of 1% (Andrews & Williams 2005, 2007a). Here, one has to keep in mind that the derivation of total disk masses from dust continuum observations includes assumptions on dust opacities and gas-to-dust ratios which remain uncertain. There is some evidence that the actual disk masses are somewhat higher than inferred from these observations. Submillimetre interferometry observations are starting to provide constraints on disk radii and surface density profiles. In a recent SMA study of 24 circumstellar disks, Andrews & Williams (2007b) found radial surface density profiles with a median exponent of -0.5 for a power law distribution, although values around -1.0 may be more reasonable taking systematic effects into account. The distribution of the outer radii has a distinct peak at 200 AU and only a very few disks remained completely unresolved. Observations with the Very Large Array provided convincing evidence for the presence of large centimeter-sized "boulders" in protoplanetary disks, thereby demonstrating rapid grain growth from small submicron-sized grains to larger planetesimals (e.g. Rodmann et al. 2006).

3. Dust and Gas Properties

Infrared dust spectroscopy, both from the ground and space, resulted in a comprehensive overview about the various dust components in disks (Henning & Meeus 2009). Despite the power of this technique, one also needs to be aware of its limitations: infrared spectroscopy only traces the composition of the optically thin surface layer, is only sensitive to certain radial regions of the disk, reflecting their temperatures, and is not able to provide sensitive information on featureless grain components, such as iron particles or pure carbon grains. The investigation of high-quality disk spectra showed that the main dust components are amorphous silicates with olivine and pyroxene stoichiometry, crystalline forsterite and enstatite and in some cases silica (e.g. Juhasz et al. 2009).

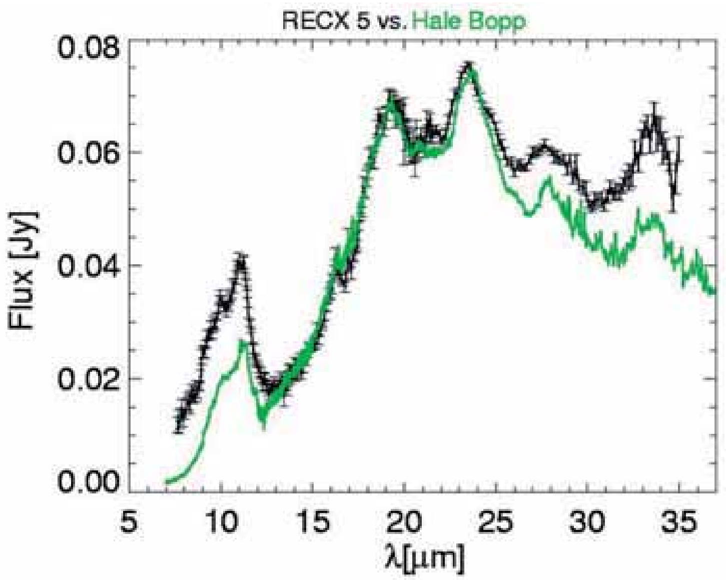

***Figure 3** Comparison of the Spitzer infrared spectrum of the M4 star RECX 5 (Bouwman et al. 2009) with the ISO spectrum of comet Hale Bopp (Crovisier et al. 1997). Flux values of comet Hale Bopp scaled to fluxes of RECX 5.*

The forsterite-to-enstatite ratio shows a radial dependence with more enstatite in the inner disk. The appearance of crystalline silicates in a large variety of protoplanetary disks (see Figure 3) indicates the importance of thermal annealing and mixing processes, because such grains are not abundant in the general diffuse interstellar medium or star-forming regions. In addition, spectra of the disks around predominantly intermediate-mass stars frequently display emission from Polyaromatic Hydrocarburbons (e.g. Geers et al. 2007, Boersma et al. 2008). A variety of molecular ices has also been detected in an edge-on disk by Pontoppidan et al. (2005).

Submillimetre and millimetre line observations are providing important information on chemistry, ionization degree, turbulent mixing, and surface density profiles in the colder outer regions of protoplanetary disks (e.g. Semenov et al. 2005, Bergin et al. 2007, Dutrey et al. 2007). More recently, infrared spectroscopy with both high-resolution instruments on the ground and the Spitzer telescope started to reveal the gas composition in inner disks. CO fundamental ro-vibrational lines, observed in the M band around 4.7 µm, can provide important kinematic information on inner disks and deliver lower bounds to the total inner gas mass (Brittain et al. 2003, Najita et al. 2003, Blake & Boogert 2004, Goto et al. 2006; see Figure 4). A recent study of transition disks demonstrates a large diversity of gas content and gas-to-dust mass ratios in the inner disk regions, revealing a variety of planet-forming conditions (Salyk et al. 2009). In addition to the CO molecule, molecu-

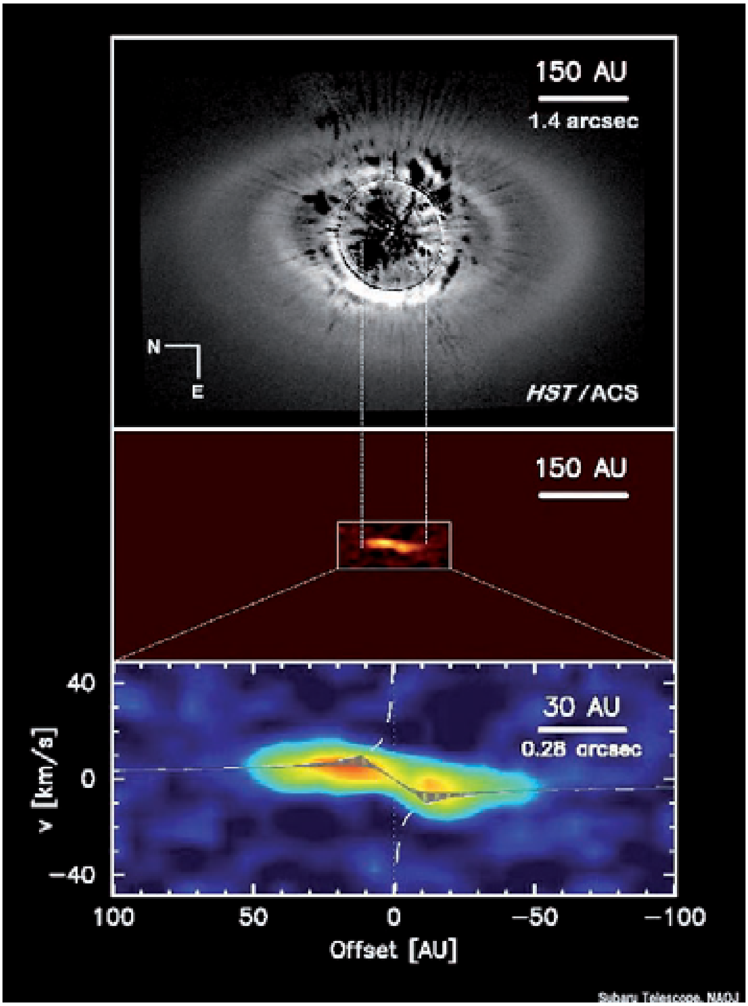

***Figure 4** The upper part of the figure shows the HST/ACS image of the disk around HD 141569A (Clampin et al. 2003). The lower part shows the CO emission and reveals an inner cavity with 11 AU radius and a Keplerian velocity curve (Goto et al. 2006).*

lar hydrogen emission (Bitner et al. 2008) and water (Carr et al. 2004) have been detected with high-resolution spectroscopy.

Despite the relatively low spectral resolution, the sensitivity of the Spitzer telescope allowed the observation of the rich molecular emission spectrum of inner regions of protoplanetary disks and revealed a high abundance of simple organic molecules (HCN, C_2H_2, CO_2) (Carr & Najita 2008, Lahuis et al. 2008, Salyk et al. 2008, Pascucci et al. 2009). In the inner disk of AA Tauri, Carr & Najita (2008) found the first evidence not only for organic molecules, but also for water vapour and OH molecules. In a comprehensive study of protoplanetary disks, Pascucci et al. (2009) revealed differences in the abundance of organic molecules between disks around solar-type stars (K1-M5) and disks around low-mass objects and brown dwarfs (M5-M9). These authors found a significant underabundance of HCN relative to C_2H_2 in the disk surface of cool stars, probably pointing to the importance of UV radiation for defining the chemical composition of these regions (see Figure 5).

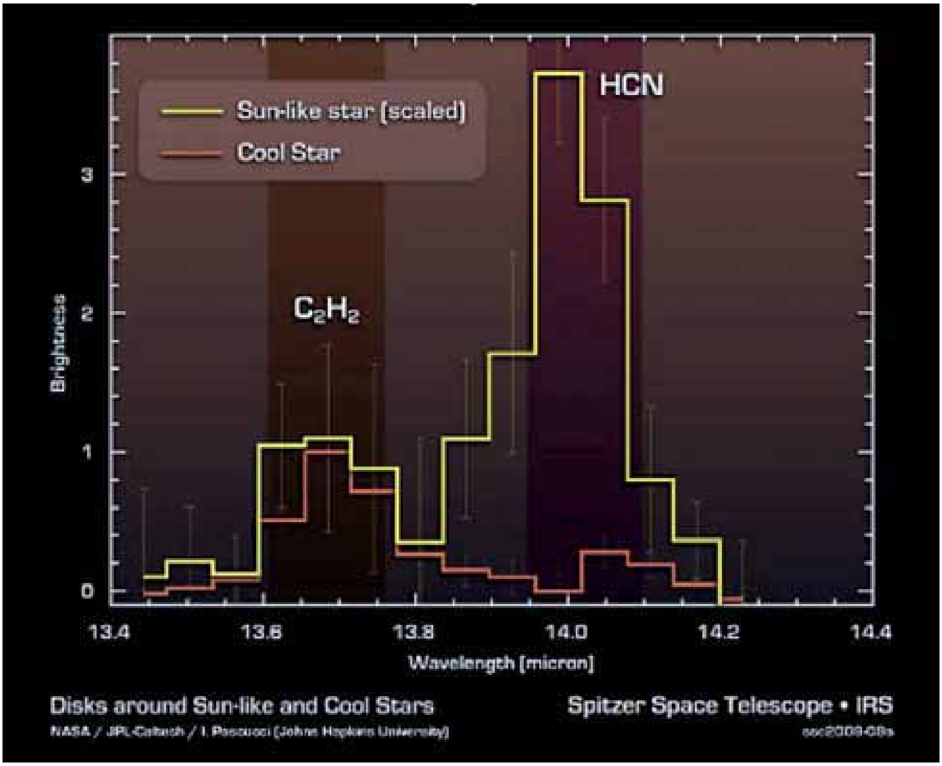

Figure 5 Spitzer infrared spectroscopy of disks around sun-like stars and cool stars. After Pascucci et al. (2009).

4. The Large Binocular Telescope

The Large Binocular Telescope (LBT), with its two 8.4 m mirrors, adaptive secondaries, large-array optical cameras and multi-object optical and infrared spectrographs, will provide unique opportunities for studying young stars and their protoplanetary disks. When operated together, the two mirrors will have the light gathering power equivalent to a single 11.8 meter telescope. A new spin casting technique, developed by the University of Arizona, resulted in very lightweight, stiff mirrors. Their steep curvature (f/1.14) permitted the construction of a compact, solid telescope structure, and hence a smaller, less expensive enclosure. The open telescope structure represents a significant departure from traditional designs. The J-shaped vertical braces are each about 19 m long. On their outer faces a variety of swing arms are mounted. These hold the various mirrors and instruments. This modularity provides great flexibility and allows the observing configuration to be changed in approximately 15 minutes.

Figure 6 The Large Binocular Telescope (LBT). The LBT is a joint American-German-Italian project with the University of Arizona, Ohio State University, the US Research Corporation, the Italian INAF and the German LBTB (led by the MPI for Astronomy, Heidelberg) as partners.

The entire telescope is 24 meters wide by 15 meters deep and 21 meters high. Despite carrying two 8.4 meter mirrors, the innovative design leads to a total moving telescope weight of only 900 tons, not much larger than that of a conventional telescope with a single 3.5 meter mirror. The LBT is mounted 30 meters above the ground on a large, cement pier. This height is necessary to get into clear air above the surrounding trees. A large rectangular enclosure protects the telescope. Occasional storms on the 3200 meter peak can be severe, so the telescope and enclosure are designed to withstand sustained winds of 225 km/hr.

An especially interesting feature is the possibility to combine the light of the two telescopes interferometrically, thereby providing the resolution of a 23 m telescope. Two instruments will make use of this possibility: The thermal infrared imager and nulling instrument LBTI provided by the Steward Observatory and the near-infrared instrument LINC-NIRVANA (see Figure 7) being built at the Max Planck Institute for Astronomy together with other partners in Germany and Italy. Both instruments will provide superb resolution imaging capabilities in the infrared and will start regular operation in the 2011-2012 timeframe. LINC-NIRVANA will provide 10 times higher resolution in the near infrared than the Hubble Space Telescope. In contrast to the Very Large Telescope Interferometer, this instrument will allow true Fizeau imaging of complex regions. It will provide rich information on AU-scales

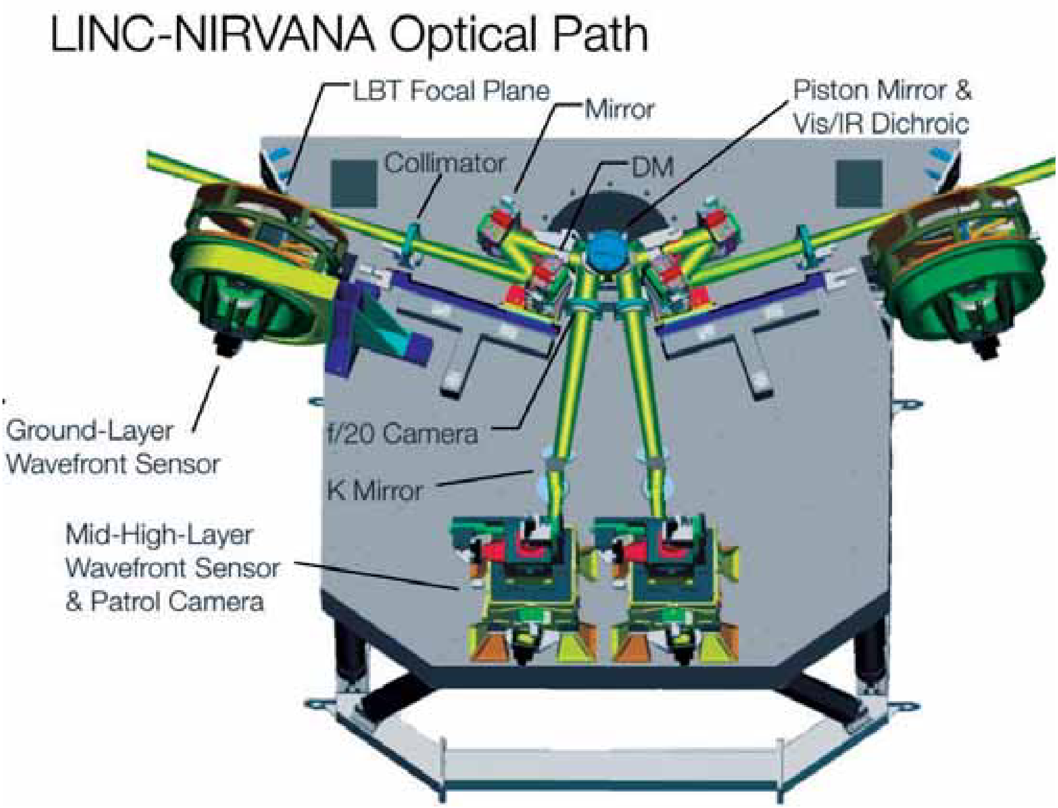

Figure 7 Optical path in the LINC-NIRVANA instrument

of complicated structures in nearby star-forming regions and their protoplanetary disks. It will cover the 1.0-2.45 µm range and will provide a FoV of 10.5”x10.5”. The LBTI instrument is especially designed for high spatial resolution, high dynamic range imaging in the thermal infrared. Key science programs include a survey of nearby stars for debris disks down to levels which may obscure detection of Earth-like planets by space missions (nulling in the N band) and the direct imaging search for giant planets (M band).

5. Lessons Learned from Building a Large Telescope

The design, construction, and commissioning of a large facility such as the LBT remains a considerable challenge and adventure. In return, it provides the tools to advance observational astronomy to the next level of sophistication. The unique interferometry capabilities of the LBT will enable a better understanding of the evolution from protoplanetary disks to debris disks. In addition, such large-scale projects always result in "lessons learned" which should be transferred to the next projects in order to increase their efficiency. This is especially true for the LBT, which can be seen as our first step towards the new class of 20 - 40 m telescopes.

What have we learned? From an observatory perspective, it turned out to be very important to work together with all the stakeholders to secure the site for development under the least restrictive terms. Upfront investment in system engineering, subsystem design, and software development is likely to be balanced by a shorter period required for integration and commissioning of the telescope. Realization of state-of-the-art concepts requires assignment of a substantial contingency in both schedule and budget. Building a complex machine sometimes leads to an underestimate of the importance of basic and "simple" features. In a multi-partner international project it is important that the partners define clear technical and science goals and set priorities. Finally, one always has to be prepared for the unexpected.

Acknowledgements

I would like to thank all partners of the Large Binocular Telescope, the observatory staff and the director Richard Green for building a wonderful and innovative telescope. I thank Phil Hinz (Steward Observatory, PI of LBTI) and Tom Herbst (Max Planck Institute for Astronomy, PI of LINC-NIRVANA) for interesting discussions.

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Phil Charles[1]

Southern African Large Telescope (SALT)

Science with SALT in the ELT era: a “low-cost” option

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Abstract

The 10m-class Southern African Large Telescope (SALT) is now in the final stages of commissioning. This new paradigm in low-cost, large-telescope construction is based on the HET prototype but with significant improvements to its optical design. Amongst current large telescope designs SALT has special capabilities in terms of UV throughput, temporal resolution and polarimetry. The key technical constraint is the fixed elevation, which significantly restricts sky access, making 100% queue-scheduled operation a necessity. However, this can be turned into a number of scientific advantages which are much harder to implement in classical schedules, examples of which include long-term monitoring and ToO programs. Furthermore, the in-house staff control of data acquisition has benefits for quality control and the definition of data archiving and reduction standards and procedures. SALT also needs support from SAAO's small telescopes (which include a variety of classically and robotically operated facilities), not just in the provision of photometric calibration observations, but in a wide variety of ways which will be reviewed and discussed.

1. Introduction

SALT, the Southern African Large Telescope, is at the forefront of a major bid by South Africa to establish a suite of multi-wavelength, ground-based observing facilities. HESS, the High Energy Stereoscopic System, began operating in Namibia in 2004, and the radio astronomy technology demonstrator, KAT, the Karoo Array Telescope means that Africa will soon offer front-rank astronomical observing from ultra-high energy γ-rays, through optical to radio wavelengths. That this is possible is a result of this region's clear, dark skies and quiet radio environment, both of which are due to low population density. These sites are now protected by the Astronomy Geographic Advantage Act, making South Africa only the third country to promulgate such a Bill.

SALT was constructed by a partnership of South Africa and 11 other international institutions (located in USA, Poland, Germany, India, UK and New Zealand). Constructed in just 5 years, the subsequent commissioning and testing of SALT over the last 3 years has revealed a number of areas that require redesign, upgrade or repair. This should not be surprising given the significant number of changes that were made to the HET design paradigm on which SALT was based. HET is the Hobby Eberly Telescope, at McDonald Observatory in Texas (one of the SALT partners). Even with the additional costs incurred by the extended commissioning period, the approximate construction cost of \$22M (plus a further \$9M for the suite of first-generation instruments) is extremely low compared to conventional (both single mirror and segmented mirror design) 8-10m telescopes around the world. This is principally due to the small and simple, spherical mirror segments, the fixed elevation angle and that the primary is stationary during actual observing. For more details

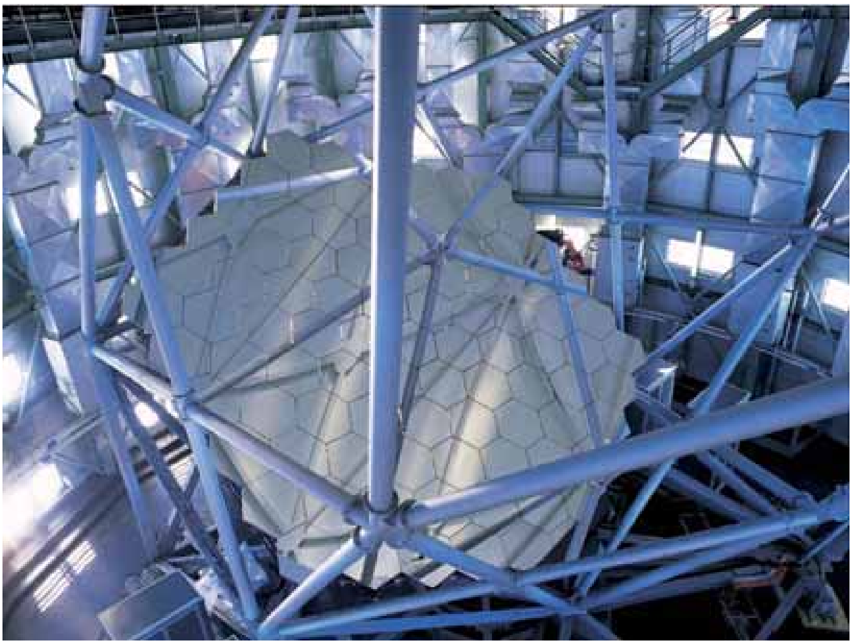


Figure 1: Photo of SALT's primary mirror array. There are 91 hexagonal, 1 m segments.

see Buckley et al (2008) and references therein. It should be noted that this design ought to be capable of straightforward scaling to larger mirror areas at comparable cost-saving factors.

2. Basic SALT Design, and Enhancements over HET

Formed in 1999, the SALT Foundation aimed to produce a southern hemisphere equivalent of HET. While the last decade has seen a remarkable number of 8-10m class facilities come to fruition, HET's design was radically different as it endeavoured to produce a large collecting area at very low cost. The design is based on the principle of operation of the Arecibo radio telescope, except that the radio dish is replaced by a segmented, spherical primary mirror. Furthermore, the SALT primary is held at a fixed elevation of 53° (slightly different from HET, in order to fully access both Magellanic Clouds), but the primary can be rotated to any azimuth. A unique feature of this design is that the primary is stationary during observing, requiring the target field to be observed with instrumentation on a Tracker unit that moves across the primary's wide focal surface (Figure 2).

Figure 2: Cutaway schematic of SALT and its environs, showing the key elements of the segmented primary mirror, which can rotate in azimuth, but is at a fixed elevation of 53°, and the Tracker (which carries the instrument payload). Image courtesy SALT Foundation.

However, even before construction of SALT began, testing of HET had revealed that a number of design enhancements were essential. The most challenging of these was the need to improve the performance of the spherical aberration corrector (SAC), that is critical for this optical design. The SAC design of O'Donoghue (2000) was dramatically better than that of HET, demonstrating much improved image quality, a much wider field of view, a larger effective collecting area (because of the increased pupil size) and a larger back-focal distance. Indeed, an extended version of the SALT SAC design is now at the heart of a new instrument (HETDEX) currently under development for HET.

Combined with the use of carbon composites in the Tracker's moving mass, the new SAC design permitted an increased mass budget and easier servicing access. In order to achieve high throughput in the UV (down to 320nm), the presence of the SAC's 4 mirrors in the optical path made it necessary to use advanced multi-layer coatings.

The building design also differs substantially from HET, with careful attention to heat control (a cooled glycol system operates throughout) and louvres (for natural ventilation at night) to deliver a target image quality of 0.7 arcsecs (FWHM).

3. Instrumentation Suite

3.1 Imaging Camera, SALTICAM

The first light (and principle telescope commissioning) instrument has been SALT's imaging camera, SALTICAM (O'Donoghue et al 2003, Buckley et al 2006). Based on a pair of mosaiced E2V 4096x2048x15μ frame-transfer CCDs, SALTICAM acts as both an efficient acquisition camera (it covers SALT's 10 arcmin diameter field of view, consisting of the central 8 arcmin science field and surrounding 1 arcmin annulus for autoguiding) and science instrument. Equipped with a range of broad and narrow band filters, SALTICAM's CCDs have high throughput down to ~320nm. When operated in frame-transfer mode SALTICAM can provide 2.5s time-resolved images, or even faster (approx 60ms) when used with a special 20 arcsec wide occulting mask ("slot" mode). To date, this has been applied to observations of relatively bright (V<20) targets, as SALTICAM's autoguider has not yet been installed (and hence precludes deep imaging exposures).

3.2 Imaging Spectrograph, RSS

Intended as its "workhorse" instrument, the principal spectrograph on SALT is RSS (the Robert Stobie Spectrograph), named after the former SAAO Director, one of SALT's original driving forces. Formerly known as PFIS (the Prime Focus and Imaging Spectrograph), RSS is a low to intermediate dispersion spectrograph that was designed and constructed by the University of Wisconsin (UW, see Nordsieck et al 2003), together with Rutgers University (mechanical structure and Fabry-Perot optical subsystem) and SAAO (CCD detectors). RSS offers a wide range of modes to exploit SALT's very good UV performance and wide wavelength capability. These include long and multi-slit capabilities, plus tunable Fabry-Perot imaging and spectropolarimetry (Table 1).

RSS was installed on SALT in late 2005, and most of its observing modes have been exercised. The poor image quality of the telescope precluded comprehensive testing of its wide field capabilities, but the major problem exhibited by RSS was in its poor UV/blue throughput. Eventually traced to an optical flaw (degraded lens coupling fluid in the multiplets), RSS was removed from SALT in late 2006 and its optics were repaired by its manufacturers (see Buckley et al (2008) for more details). At the time of writing, the repaired optics have been re-integrated into RSS and re-aligned, and a full program of ground tests are underway prior to its being re-installed on SALT later this year. For an example of RSS science that was accomplished during its initial commissioning see Väisänen et al (2008).

	Mode	λ Range (Å)	Resolving power
RSS	long-slit/multi-slit	3200-9000 (-1.7μ with NIR*)	800-6000
	spectropolarimetry	"	"
	Fabry-Perot	4300-9000 (-1.7μ with NIR*)	320-770; 1250-1650; 9000
HRS*	Single target (fibre-fed)	3700-8700	16,000-65,000

Table 1: SALT Spectroscopic Capabilities
**** under construction***

The original mechanical and optical design of RSS included room for its extension into the near-IR band. This was to be accomplished with a dichroic which allows light beyond 900nm to enter a separate NIR arm. At present a folding flat is in place, as the NIR arm was not part of SALT's suite of first generation instruments. However, the RSS/NIR arm has now been funded and designed at UW, with the aim of extending the wavelength coverage to close to 1.7μ. The NIR arm will have a similar range of operating modes as in the optical, and should be completed by 2011.

3.3 Fibre-fed High Resolution Spectrograph, HRS

The first-generation suite is completed by a high resolution spectrograph, HRS. In order to reach resolving powers of up to 65,000 (as is needed for precision radial velocity work), the spectrograph is housed in a vacuum tank to provide extreme stability against temperature and pressure variations. Such a scale dictates that HRS be located in the spectrograph room underneath the main telescope observing floor, where fibres from the Tracker feed light from the single target plus sky region. The dual-beam design which is now under construction (at Durham University's Centre for Astronomical Instrumentation) uses an R4 echelle, after which a dichroic splits the spectrum into blue and red arms, each of which has its own VPH cross-disperser and camera giving a range of resolving powers (from 16,000 to 65,000, depending on the use of image slicers; see table1). HRS is expected to enter commissioning in early 2010.

4. SALT Commissioning and Performance Verification

Simultaneous imaging over the full SALT 8 arcmin field of view was first obtained in late 2005, and demonstrated that there was a field-dependent image quality (IQ) problem, appearing as a focus gradient. There were additional time-dependent effects associated with the instrument rotator angle and temperature. A detailed study of this problem was able to rule out the instruments (SALTICAM, RSS) and the primary mirror array as the source, implying that it must reside in the opto-mechanics of the SAC. A full report on this can be found in O'Donoghue et al (2008), who established that (i) the last pair of mirrors in the SAC are mis-aligned with respect to the optical axis of the telescope, and (ii) there are significant mechanical stresses transmitted into the SAC via the Tracker interface due to thermal effects (at the SAC/non-rotating structure interface) and instrument rotation. Since high quality (0.85 arcsec) images have been obtained within SALT images, there is no reason to doubt the overall SAC optical design and quality of the individual SAC mirrors. A complete mechanical redesign of the SAC-Tracker interface has been performed and new components recently installed on the SAC, which was removed from SALT in mid-April 2009. At the time of writing, the SAC mirrors are being fully tested and re-aligned, with the aim of remounting the SAC within a matter of weeks. All this work is being performed in the SALT building at Sutherland by Observatory staff, exploiting recent developments in testing such advanced optical components by using a specially designed computer generated hologram.

Despite the extended commissioning period of SALT, the total project timescale actually compares favourably with other large-telescope projects. Also, the recent recruitment of additional partners (AMNH, the American Museum of Natural History in New York, and IUCAA, the Inter-University Centre for Astronomy and Astrophysics in Pune, India) has brought new investment into the SALT Foundation, demonstrating confidence in the direction of the project. Furthermore, all the partners recognise the enormous importance of promoting and stimulating science education in South Africa (see Whitelock 2008), for which SALT acts as an iconic stimulus.

5. SALT Key Science Areas

With its limited resources and constrained sky-access, the instrumentation suite on SALT has necessarily focussed in ways that are of particular interest to the partnership, yet are intended to be internationally competitive. The key science areas are:

- *Time Domain Astrophysics*: already an important component of SAAO's existing facilities, the detectors on both SALTICAM and RSS allow for fast operation (up to 60ms), thereby allowing time-resolved photometry, spectroscopy, polarimetry up to a few hours, and synoptic monitoring on much longer timescales. The Q-scheduled mode of operation is particularly powerful for ToO programs, such as rapid follow-up of GRBs.
- *Multi-wavelength Studies*: the flexible scheduling of SALT is ideal for contemporaneous observing with other ground-based facilities (e.g. South Africa's SKA demonstrator, KAT) and space observatories (e.g. RXTE, XMM, JWST...)
- *Survey Science*: where objects are uniformly distributed with densities of a few per square degree or are clustered on a scale of a few arcmins (e.g. follow-up of XMM, CXO, Vista, KAT surveys), which exploit either the Tracker's 12^ox12^o or SALT 8 arcmin fields.
- *SALT's rare capabilities*: spectroscopy and polarimetry from 320-900nm (eventually extending to 1.7μ). The prime focus instruments cover a wide region in parameter space in terms of wavelength coverage, resolving power (R~370-13,000) and multiplex advantage (MOS of ~100 objects, F-P imaging spectroscopy).

All of the above have the ability to provide excellent support and drive new science initiatives for ELT programs.

6. Constraints and Benefits of Queue-mode Scheduling

SALT's queue-scheduled mode of operation is obviously an unavoidable restriction to sky access (imposed by the fixed elevation angle) and the duration/timing of observing any given target. Indeed, scheduling SALT, which has therefore been planned to be 100% queue-mode from the beginning, is much more akin to a space than a ground-based telescope. However, whilst imposing clear scientific limitations on SALT observations, it also opens up an enormous range of new scientific possibilities as well as technical and operational advantages:

- ToO (Target of Opportunity) programs for fast follow-up of transient phenomena. The observing schedule can be very flexible, as the majority of programs in the queue will not depend on being executed at particular times, thereby allowing

ToOs to be implemented on the basis of established trigger criteria. This could be the state of a target variable star or AGN, or the notification of occurrence of unpredictable events such as supernovae or GRBs (Gamma-Ray Bursters).

- Synoptic monitoring, especially on timescales of weeks to months. Many galactic and extragalactic systems display long-term variations which require widely-spaced observations (particularly spectra) in order to investigate fully. Such observations are very difficult to accommodate through classical mode scheduling.
- Survey follow-up. Many surveys cover a large fraction of the sky and hence generate targets for follow-up which are similarly widely spread. Obtaining systematic sampling of such targets is much more straightforward through queue-scheduling than classical mode.
- Multi-wavelength observing campaigns. Both on the ground (particularly in SA with the soon-to-be-operational KAT radio telescope, and the already functioning HESS) and in space (with X-ray, UV and IR facilities), SALT's instruments can provide a powerful component in simultaneous observing campaigns. Most spacecraft generate short intervals of potential simultaneity, but they can repeat over many weeks, again making queue-scheduling far more effective than classical mode.
- Instrumentation quality control. With only in-house staff observers executing the queue, their familiarity and experience with the instrumentation can translate into much better levels of performance quality control.
- Data quality and consistency control. The establishment of standard setups and archiving procedures is also much easier to implement with staff observers, thus ensuring data uniformity in the final archive. This has the added benefit of making it easier to define data reduction pipeline procedures for the most commonly used instrument/detector configurations. The ability to offer essentially science-ready reduced data to PIs is particularly important for a small, low-resourced community such as in SA.

Whilst SALT has not yet completed its commissioning and acceptance phase, for the reasons described earlier, the software group have developed proposal preparation tools which will be part of the scheduling and execution of SALT observations. The benefits for SALT of the queue-schedule are considered to be:

- maximise the efficiency of use of the telescope (minimise overheads, maximise shutter-open time, check remaining track time, etc.)
- match the selected program to the current observing conditions
- quality control of instrument/detector performance and uniformity/consistency of data

- maximise program completion rates
- ensure distribution of time is proportional to partner shareholding

However, the software to generate this is still at an elementary stage, as our limited software resources have been focussed on the proposal preparation tools, the observation control software (which links the program setups into the instrument and telescope control systems) and the data reduction pipeline.

The observing programs will be selected by individual partner TACs and then combined in SA by the Astronomy Operations Team, in the process resolving any conflicts that arise. Programs will be rated under a simple, 4-level scheme: 0 (the highest, for ToO programs), 1 (for top-rated normal programs), 2 (mid-rating) and 3 (to be used as "fillers" for poor observing conditions). All proposals enter the SALT database, which acts as a repository for the program proposal, observing implementation details and data that is obtained. The actual observations are undertaken by one of the 6-strong group of SALT Astronomers, all of whom are fully trained in the performance and capabilities of the SALT instrumentation.

While "Service" mode (an earlier term, which has now largely been superceded by Queue mode) has been offered on a variety of telescopes for almost 3 decades, it was mostly used as a minor adjunct to classical (or "visitor" mode) telescope schedules. The aim under Service was mostly to use it for "trial" observations in order to test the feasibility of a potential program, or, occasionally, to obtain a small number of additional observations in order to complete a program (e.g. one that had been adversely affected by weather). It is only in the last decade that optical telescopes have appeared where queue mode was planned to be a significant component from the beginning. The best example of this is Gemini, and it is instructive to consider their experiences of Queue (hereafter, "Q") mode operations.

6.1 Gemini Queue-scheduling

Both Gemini telescopes and their instrumentation suites were designed from the start to be capable of exploiting the finest conditions available at the Mauna Kea and Cerro Pachon sites. In order to do this, it was essential to use flexible scheduling in order to optimise program selection to the extant conditions. Hence their initial target of 50:50 between Q and Classical mode observing. But, as reported by Puxley & Jørgensen (2006), demand for Classical mode was much lower (only ~10%) and this consequently had a serious impact on their staffing capacity. They also found that the average time request per Q-proposal was ~12hr, significantly less than the typical 2-4 night request under Classical. This was attributed to absence of any weather factor, or "padding" in order to justify the number of nights.

With 7 partners (and national TACs), Gemini found that multi-partner programs quickly developed, reaching ~50% of the total. They also found that multiple TACs have a large overhead and duplication of effort, something that might appear worse for the 12-partner SALT consortium. However, the "closed" nature of (most of) the SALT partnership means that the individual TAC operation is much simpler, and multi-partner programs have been strongly encouraged.

Gemini proposals are assigned into 3 Bands, essentially analogous to the ratings 1-3 described above, and in the proportions of 20:30:50% of the total. While beginning operations in 2001 with the aim of maximising the number of programs that actually receive some data (which can be beneficial in demonstrating the capabilities of the facility to a wide audience), it not surprisingly led to low completion rates. Gemini now aim to complete all of Band 1, most of Band 2 and most of those in Band 3 that are actually started, and are very close (mostly ~90%) to achieving this.

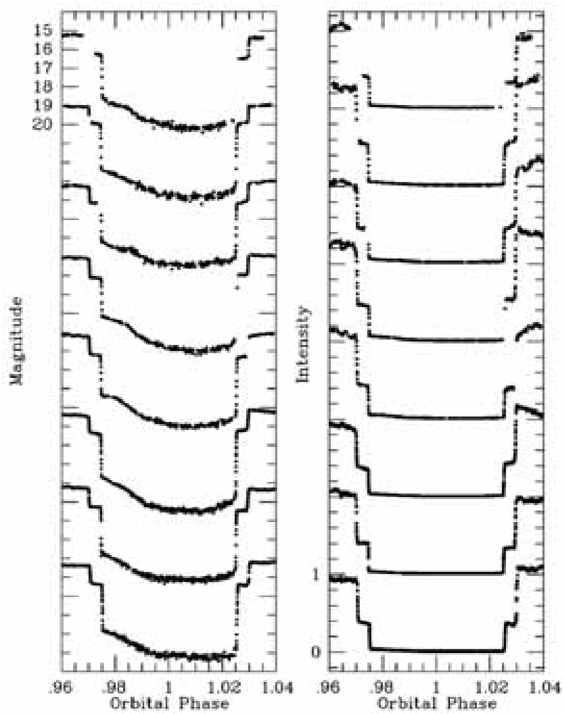
The Gemini Q has aims very similar to those listed above for SALT, but their much larger and more diverse instrumentation suite leads to an additional constraint on any given night that is linked to the staff astronomer's capability to actually use the instrument that would be dictated by the conditions. They also found that they were unable to achieve a distribution of telescope time according to the partners' shares as they had hoped to do within 2-3 semesters of beginning operations. There were a number of reasons for this, but the unpredictable creation of multi-partner collaborations is a component. With SALT's larger partnership (12, many with small, <4%, holdings) this is likely to be a similar problem. However, if large collaborations dominate the time allocations and these include all the partners, then holding strictly to the shareholdings is unlikely to be as serious an issue.

7. SALT Science Examples Exploiting Flexible Scheduling

7.1 Resolving the Magnetic Caps on Polars

Accreting white dwarfs in interacting binaries with short orbital periods (few hours), are common in the galaxy (several hundred are known within a few hundred parsecs, see Warner 1995). A subgroup of this class (the AM Her systems, or polars) contains white dwarfs with very powerful magnetic fields (10-200 MGauss) along which the mass transfer stream flows directly onto the white dwarf's polar caps. Although relatively nearby (~100pc), direct spatial resolution of the mass transfer process is impossible. Instead, spatial information is encoded within the structure of the eclipse light-curve in high inclination polars. However, this requires short exposure times, as the fine scale of the accretion geometry (such as the polar caps) produces structure in the light curves lasting only a few seconds. The combination of the intrinsic faintness of even the nearest polars, and the need for short (sub-second) exposures, requires the use of very large telescopes.

Initially discovered through their X-ray emission, the polar SDSS J015543.40+002807.2 (hereafter J015543) was identified through the Sloan Digital Sky Survey (Szkody et al 2002) and subsequently found to be eclipsing. It was subsequently confirmed



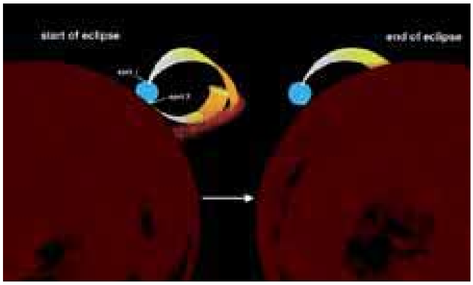


Figure 3: SALTICAM high time resolution light-curves of the magnetic polar SDSS J015543+002807 (left) showing the two "steps"' into and out of eclipse, that are only clearly resolved at sub-second time resolution. The 8 observations were made between 2005 Aug 5 and Sep 7, and are shown in both magnitudes and linearly, so as to emphasise detail during eclipse and the ingress/egress respectively. The schematic of this interacting binary (right) shows the two polar caps (the accreting hot spots) that dominate the optical output and that are sequentially eclipsed and revealed by the passage of the donor. From O'Donoghue et al (2006).

as a polar through follow-up optical spectroscopy and X-ray observations (Schmidt et al 2005). SALTICAM observed J015543 on several nights in 2005 Aug/Sep, producing high time resolution (down to 112ms) light curves of the white dwarf eclipse which revealed intricate detail of the accretion process through both the ingress and egress (see Figure 3 (left)). These results were the highest temporal resolution and highest S/N yet obtained on such a system. For a full description and analysis see O'Donoghue et al (2006). The light curves clearly show that the optical emission of J015543 is dominated by two small, approximately equally bright regions (the polar caps) as depicted in Figure 3 (right). These regions are fully resolved in the SALTICAM data, with eclipse ingress/egress durations of 1.2s and 1.5s, which correspond to spot radii of a few hundred km. There is no detection of the white dwarf eclipse itself in these data, as the spots dominate the output in the high accretion state. Observations in the low state will reveal the extent of the white dwarf directly, and can then be combined with these data to constrain the physical size, and hence mass of the white dwarf.

A particularly interesting future prospect is to use RSS to undertake time-resolved spectropolarimetry through the eclipses. The strong and broad H, He emission-line spectra of polars are known to show complex variations as a function of orbital phase, but the eclipse detail observed by SALTICAM, particularly with polarimetry as well, has never been attempted as it is essentially beyond the capability of instrumentation on 4m-class telescopes.

7.2 ToO Programs: Fast Follow-up to GRBs

Observations over the last two decades indicate at least two classes of GRB, one of which is associated with the supernova explosions of massive stars, the other is suspected of arising when a pair of orbiting neutron stars (or possibly neutron star - black hole binary) eventually merge (see Mèszàros (2006) for a recent review). Both appear to require special orientation with respect to our line of sight, as the rapid rotation of the collapsing star produces an extended disc of material around the forming black hole, which then leads to a super-Eddington accretion rate of matter, and a consequent ultra-relativistic jet being ejected along the spin axis. Alignment of our line of sight with, or close to, that axis produces the extreme brightness seen in a number of GRBs (such as GRB990123 which famously peaked in the visible at almost 8th magnitude for a few minutes, Akerlof et al 1999). Nevertheless, the ejected material is only (apparently) bright while it is relativistic, and so it decays rapidly, making prompt (at least within hours, preferably minutes) follow-up crucial in order to observe the interval during which the physical processes occurring are at their most extreme.

During RSS' initial commissioning year, it was therefore gratifying that GRB060605, which was detected by SWIFT could be observed by SALT just 8 hours after the burst, when it was still at R ~ 19. The resulting 40 min RSS low-resolution spectrum is shown in Figure 4 and was reported by Still et al (2006). The featureless afterglow from the burst is viewed through a forest of Lyman α absorption due to intervening clouds. While the broad, damped Lyman α seen at 575 nm indicates a dense system at (the large redshift of) z=3.7, this may not in fact be the host galaxy. Assuming that the Lyman edge is unambiguously detected at 440 nm, then the redshift of

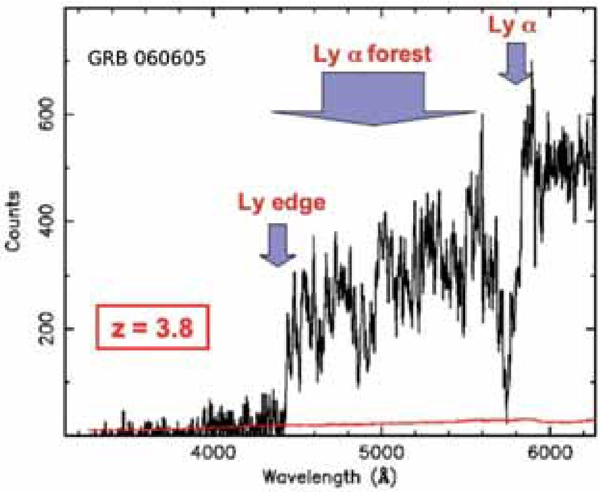


Figure 4: RSS spectrum of GRB060605 obtained just 8 hours after the initial alert, by which time the afterglow had faded to V~20.

the GRB is actually z=3.8. The Lyman α line from the host galaxy is blended with the red wing of the damped system at 483 nm.

The observation of GRB 060605 represented a significant scientific milestone for SALT and demonstrates how important it is to have queue-scheduled telescopes such as SALT involved in programs to study these enigmatic objects.

A key feature of all GRB models is that the radiation produced is highly directional and hence should be strongly polarised. Consequently some of the most important contributions to GRB physics will come from spectropolarimetry, and these must be done rapidly in order to have sufficient flux to be feasible, even with very large telescopes. SALT should be ideal for this given RSS' capabilities, and a demonstration of this was provided in Figure 5 when spectropolarimetry was performed on SN2006mq. While the systematic calibration of these data is still at a very early stage, and the results are not unusual, these spectra are a clear demonstration of SALT's great potential in this field.

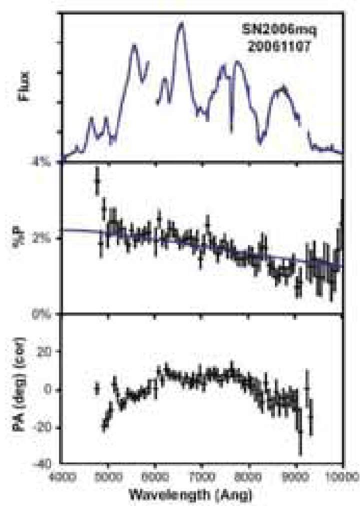


Figure 5: Demonstration of RSS's spectropolarimetric capability with the spectrum of SN2006mq (top), its linear polarisation (middle) and position angle (bottom) as a function of wavelength.

8. Role of Small Telescopes in Supporting Large Telescope Science

Whilst many small telescopes around the world have been closed or mothballed as a result of financial constraints brought on by the need to support the largest (and newest) facilities, it is interesting to note the simultaneous growth in development of new small telescopes! Examples of the latter include the Liverpool and Faulkes Telescopes, Las Cumbres Observatory Global Telescope Network, SuperWASP and PanSTARRS projects, all of which use telescopes with apertures in the range 0.1-2m. However, these are all either robotic in operation or designed with very specific science goals in mind, making them very different facilities from the small telescopes of old.

However, with appropriate maintenance and regular instrumentation/detector refurbishment, even some of the older small telescopes can have a role to play in parallel with these new robotic facilities in support of very large telescopes, such as SALT.

Key points to note here include:

- the SAAO 1.9m and 1m telescopes will provide calibration data to complement SALT imaging and spectroscopy (SALT's time-varying pupil means it cannot provide absolute photometry)
- the SAAO 1.9m's Newtonian focus and the IRSF 1.9m IR telescopes both have fields of view that are identical to that of SALT, and can thus be used to free up SALT time in providing images for preparing MOS masks, and obtain JHK images to broaden the wavelength coverage of SALT images
- provision of survey or monitoring capacity in feeding targets into the SALT Q, e.g.
    - searching for targets with particular properties (e.g. locating AGB stars in nearby galaxies, Whitelock et al 2009)
    - checking states of time-variable targets (e.g. CVs in particular activity states can be easily monitored by Monet)
- by participating in global campaigns (e.g. the Whole Earth Telescope, Nather et al 1990) programs can be undertaken that are impossible at single sites (e.g. Sullivan et al 2007), and yet require very large telescopes for detailed follow-up spectroscopy
- provision of student training opportunities, from undergraduate through to graduate student programs. The (relatively) easy availability of time and the lack of staff telescope operators, means that students gain hands-on practical experience that is simply not possible with the large and very large telescope facilities. This is particularly important at SAAO where many graduate students come from backgrounds that provided no practical astronomy opportunities whatsoever. Hence we run regular summer and winter school programs which make extensive use of our smallest (0.5m, 0.75m) telescopes. A recent PhD student (just completing) succeeded in making the 0.75m telescope remotely operable. A current MSc student is participating fully in the installation and commissioning of KELT-S.

It is thus becoming clear that small telescopes in future will be operating in a variety of different ways, all of which can contribute to "feeding" the SALT Q. These can be summarised as operating in one of the following ways:

- General-purpose, multi-instrumented, taking part in both multi-site (global) and long-term campaigns e.g. WET. Operate in Classical mode.
- General-purpose, single-instrument, available for many programs which can extend over long periods e.g. SMARTS. Operate in Q mode.
- General-purpose, single-instrument, available for long (multi-week) runs e.g. IRSF. Operate in Classical mode.

- General-purpose, survey mode capable of producing fundamental catalogs e.g. WFCAM, Vista, PanSTARRS. Operated by observatory staff.
- Dedicated science projects, survey mode which generates huge databases with spin-off potential e.g. SuperWASP, KELT. Robotic operation.
- General-purpose, single-instrument, available for many programs which can extend over long periods e.g. Monet. Robotic operation.

9. Final Thoughts

Gemini was driven to Q-scheduled mode by the obvious desire to always exploit the best observing conditions with the optimal science programs, but was then surprised by the alacrity with which this was taken up by the astronomy community. Given the huge investment contemplated for the current ELT designs, the need to exploit the extant conditions at all times will be even stronger, making 100% Q-mode operation inevitable.

Does this mean that the current 8-10m suite of telescopes will undergo a dramatic change in their modus operandi once the ELTs are functional, in the same way as has happened for 2-4m class telescopes? It is interesting to note that there are as many 8-10m class telescopes (nine) as there are 4m-class, a situation that was not anticipated 20 years ago. However, the cost of the ELTs and their associated technologies is vastly greater than that of the 8-10m telescopes, and so we consider it unlikely that there will be a comparable growth in the number of ELTs. Consequently, and bearing in mind that the first of the ELTs (TMT) is still a decade away from commencing operations (http://www.tmt.org/timeline/index.html), we believe that the 8-10m telescopes will be at the forefront of ground-based optical/IR astronomy for a substantial period of time.

Nevertheless, the ELTs will need supporting research and survey material from which to optimise their observing programs, and the 8-10m telescopes will play a large role in this, in much the way that the small telescopes described in section 8 are doing right now. There will be a need, for example, for narrow-field surveys and faint object monitoring, both of which SALT would be well suited to.

Hence, in 2020 and beyond, we expect the ground-based telescope population to have evolved into 4 basic classes:

- ELTs (probably just 3, TMT, GMT and E-ELT), operating in Q-mode
- 8-10m (~10-15), mostly Q, some classical
- 2-4m (~30), mostly classical, some Q
- <2m small/robotic (hundreds, possibly thousands).

As we have attempted to describe here, the modes of operation, and hence the scientific areas addressed, will be very different. But we fully expect them to function in a highly complementary way, and all to be doing world-class science.

Acknowledgements

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Gran Telescopio Milimétrico (GTM)

The "Gran Telescopio Milimétrico" (GTM), built in México, will be the largest and most powerful telescope of its kind in the world. Operating at wavelengths as short as 1mm, it will probe the early universe to study the processes which ultimately formed the galaxies, stars, and planets that we observe today. GTM has been constructed by The University of Massachusetts Amherst (UMass Amherst) in the United States and by the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) in México.

The GTM includes a single, extremely high precision alt-azimuth antenna 50 meters in diameter. It is located at an altitude of 4580 m above sea level on an extinct volcano, the Tliltépetl, within the National Park Pico de Orizaba, about 100 km east of the city of Puebla and to the west of the Gulf of México.

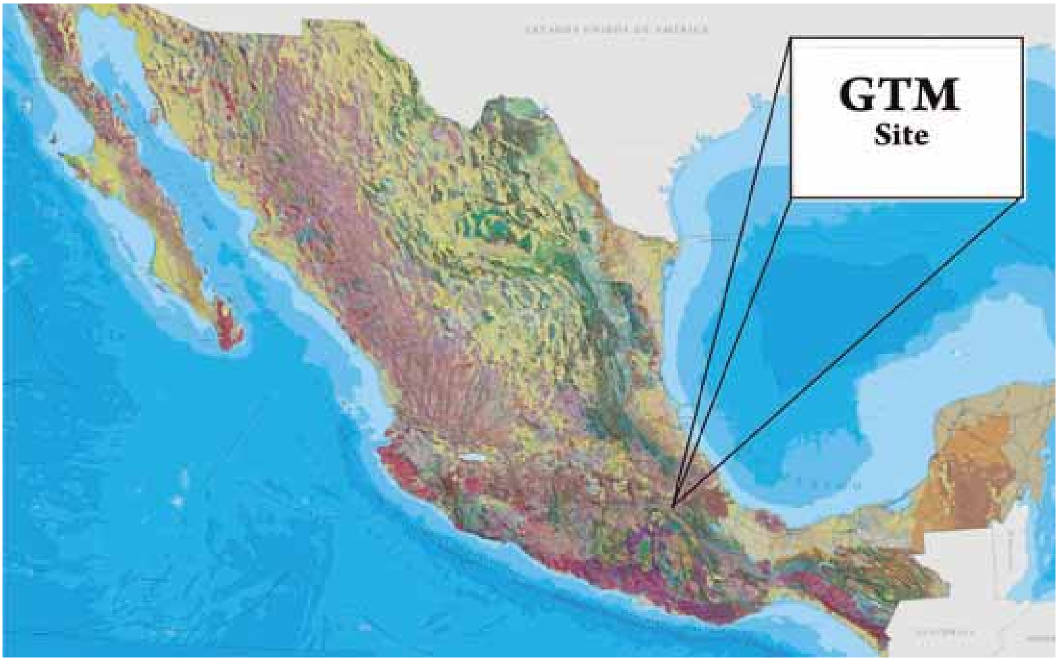


Figure 1. Location of GTM

The GTM is the largest scientific project ever undertaken in México in any field. The national development of novel technologies was set as a requirement for approving the project, a test in itself of the capabilities of México to construct large and sophisticated scientific instruments.

Figure 2. The GTM

Why are observations at mm wavelengths important? Much of the material in the universe is in "dust" or "grains", too cold to radiate at wavelengths shorter than the mm/submm range, and so only observable in emission at these longer wavelengths.

Moreover, the dust in the Milky Way and other spiral galaxies is concentrated in the clouds where new stars form, and it obscures the most interesting interior regions of these clouds at optical, ultraviolet, and even infrared wavelengths. However, it is transparent at mm wavelengths, since the dust grain dimensions are smaller than this. The dust is concentrated in the plane of a typical spiral galaxy. Much of the ultraviolet and visible radiation emitted by young stars is absorbed by dust and re-radiated in the infrared.

Galaxies that are forming massive stars or that contain active galactic nuclei (AGN), presumably powered by super massive black holes, emit the bulk of their energy in the mid and far infrared. But the expansion of the universe shifts this emission for very distant galaxies into the millimeter and submillimeter range. Consequently, one of the major research areas for the GTM will be the study of the early universe and the origin of the structures that became galaxies, stars, and planets.

GTM will be an open-air telescope with no radome enclosure. Much of the improvement over existing telescopes can be obtained with an open loop active surface that includes 180 moveable surface segments. In each segment eight sandwiches of electroformed nickel are supported by a very stiff reaction structure, which is attached to the reflector back structure by a space frame: a 1440 ensemble of such panels.

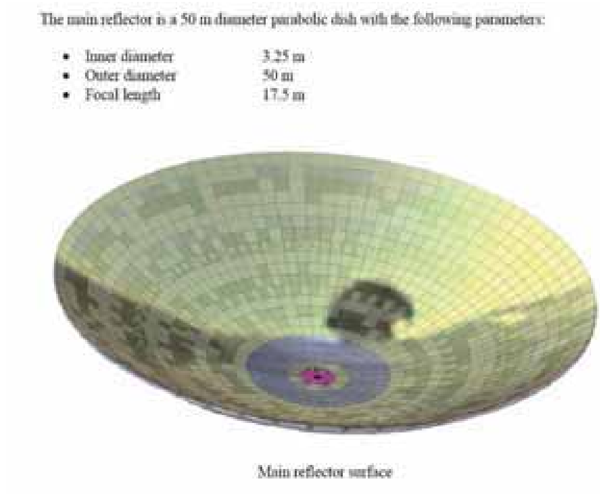


Figure 3. The primary surface of GTM, formed by 1440 panels of electroformed Ni.

Four actuators can adjust each space frame in relation to the back structure to correct for deformations due to gravity, thermal gradients and wind. Temperature sensors on all relevant parts of the structure will report to the control system, and the surface will be periodically measured by holographic techniques. Simulations indicate that the GTM should be able to maintain surface accuracy in the presence of winds up to 10 m/s.

Under good conditions, with low wind and stable nighttime temperatures, the structure is capable of satisfying the basic pointing requirements. However, wind and thermal loads introduce significant pointing errors that must be sensed and compensated for. The initial system will rely on standard techniques, such as the use of an antenna pointing model, thermal stabilization of the structure, and careful attention to the design of the antenna motion controllers. These basic principles will be supplemented by measurements to characterize the behavior of the structure, including inclinometers mounted near the telescope elevation axis and temperature sensors on the structure, which may be used with finite element models to determine structural deformations and predict pointing behavior.

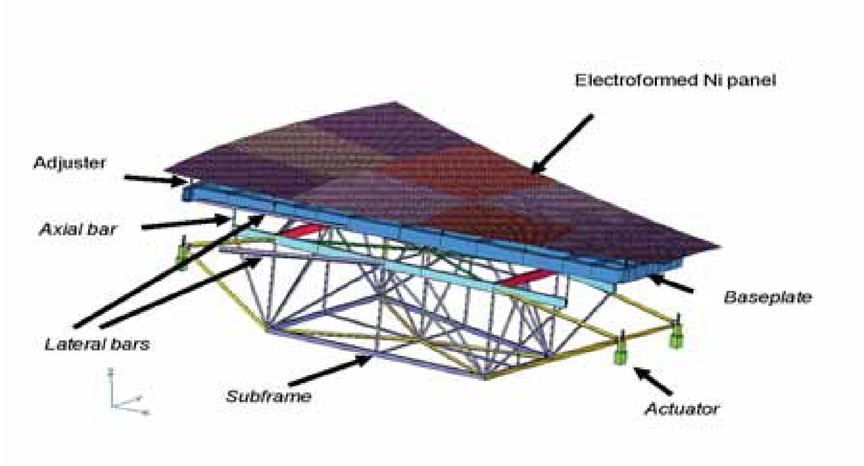


Figure 4. One of 180 segments formed by a subframe, a stiff baseplate, 40 adjusters and 8 panels of electroformed Ni.

SPECIFICATIONS OF GTM				
Property	**Specification**		**Goal**	
	1.2 mm	3 mm		
Effective Surface Accuracy	75 μm rms	75 μm rms	70 μm rms	
Pointing Accuracy	1 arcsec		0.6 arcsec	
Aperture efficiency	0.4	0.65	0.45	0.70
Sensitivity	3.5 Jy/K	2.2 Jy/K	3.1 Jy/K	2.0 Jy/K
FWHM beam size	5 arc sec	16 arcsec		

Ultimately, metrology systems to actually measure structural deformations, such as the shape of the primary mirror and the location of the sub reflector with respect to the best fit parabola, will be used to bring the pointing properties of the antenna to the final performance goal.

The GTM is sited at an altitude of 4585 m (about 15,000 feet) atop Tliltepetl (Volcan Sierra Negra), an extinct volcano in the state of Puebla that is adjacent to Citlaltepetl (Pico de Orizaba), the highest mountain in México. The atmospheric opacity is low, with a median value of 2 mm of precipitable water vapor during approximately nine months of the year.

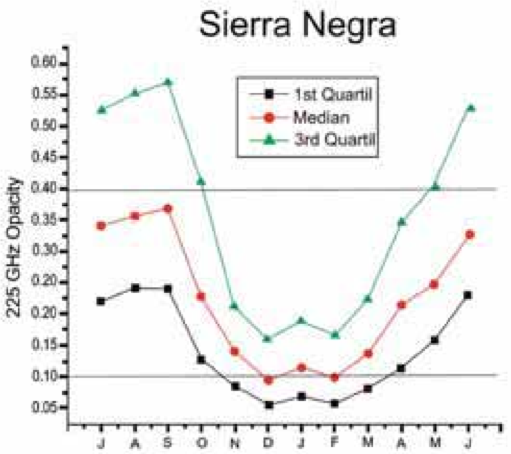


Figure 5. Opacity of GTM site at 4600 m altitude.

In spectroscopy the detected radiation is analyzed to measure the signal strength as a function of frequency, utilizing heterodyne techniques to obtain extremely high frequency resolution. Continuum systems, in contrast, measure the entire amount of energy received within a broad frequency range.

Figure 6. Tliltepetl, a 4600 m mountain site of GTM.

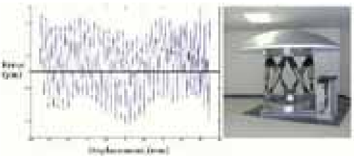


Figure 7. Secondary mirror and hexapod

In spectroscopy the detected radiation is analyzed to measure the signal strength as a function of frequency, utilizing heterodyne techniques to obtain extremely high frequency resolution. Continuum systems, in contrast, measure the entire amount of energy received within a broad frequency range. With nearly 2000 m of collecting area and excellent surface accuracy, the GTM's sensitivity will exceed that of existing mm wavelength telescopes by a wide margin. This basic sensitivity is enhanced for continuum observations by the single dish's ability to make use of very wide bandwidth incoherent bolometers. The GTM will consequently take an important place in the world's complement of mm wave facilities.

Already operating is a 32 pixel, dual polarization heterodyne focal plane array for spectroscopy in the 80 to 115.6 GHz frequency band, SEQUOIA, with an associated digital autocorrelation spectrometer. It represents a real breakthrough in mm wave radio astronomy receivers, utilizing the lowest noise amplifiers ever built in this frequency range (InP MMICs), with narrow band noise as low as 30K at 103 GHz.

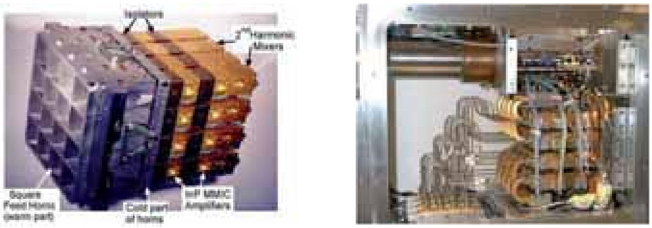


Figure 8. SEQUOIA heterodyne array.

SEQUOIA has already produced, for example, by far the largest scale images of the gas distribution in the Milky Way ever obtained. It plays a major role in studies of the physics and chemistry of interstellar material in the Milky Way and other galaxies.

The other system in the 3 mm band is an ultra wideband receiver/spectrometer which switches rapidly between two positions on the sky with dual polarization feeds which simultaneously cover the range from 75-111 GHz with a spectral resolution of 30 MHz, Called the Redshift Search Receiver, its principal purpose is to measure the redshift of spectral lines from galaxies in the early universe, thus determining their distance and properties. The associated spectrometer is an analog autocorrelator with a large dynamic range. The 1.3 mm wavelength atmospheric window will be its primary frequency band.

AzTEC (Astronomical Thermal Emission Camera), which is a sensitive bolometer array for the GTM, has been built by the GTM project team with an international group. It is a second realization of the Bolocam I instrument, which is being used successfully at the CSO. It provides 144 pixels and is designed to operate in the 2.1 and 1.1 mm bands. It will be a principal tool in the search for newly forming galaxies in the young universe, for astrochemical studies of dust in galaxies, for identifying protostellar cores in molecular clouds, and for the study of asteroids and comets in the solar system.

A second continuum instrument known as the SPEctral Energy Distribution (SPEED) camera will be used for simultaneous multiband photometry. SPEED uses a recently developed bolometer technology known as Frequency Selective Bolometers (FSBs) to simultaneously measure power in four frequency bands ranging from 2.1 mm to 0.85 mm wavelength. Measurements of the spectral energy distribution with SPEED will, for example, locate and study distant galaxy clusters by the distortions that they imprint on the Cosmic Microwave Background, and determine the temperature of dust emission in cometary atmospheres or interstellar molecular clouds in the Milky Way and other galaxies.

Figure 9. AzTEC cryostat and readout electronics.

Very Long Baseline Interferometry (VLBI) delivers submilliarc second angular resolutions, and provides a singularly powerful method of studying energetic astrophysical phenomena on the smallest size scales. The commissioning and planning of new mm and submm wavelength telescopes will significantly increase the collecting area of VLBI arrays in the 86 GHz to 230 GHz frequency ranges. Chief among these new facilities is the GTM. At 86 GHz, an array comprising the Very Long Baseline Array (VLBA) and the GTM would be over twice as sensitive as the VLBA alone. At 230 GHz, the difference is even more striking, with the addition of the GTM increasing current sensitivities of 1 mm wavelength VLBI arrays by more than a factor of 3.

The 50 m GTM is a unique facility, equipped with an array of state-of-the-art instruments that are complemented by the high angular resolution and sensitivity provided by the large collecting area. These properties give the capability to carry out critical new scientific research. For example, the resolution of the GTM, 4.2 to 14.8 arcsec between 850 μm and 3 mm, is higher by a factor 3 to 5 than that provided at the same wavelengths by current single dish telescopes such as the CSO 10 m, the JCMT 15 m, and the IRAM 30 m, and is hence sufficient to resolve the extragalactic background into discrete sources. In contrast, the deepest imaging surveys conducted by the existing submm/mm telescopes are confusion limited at a sensitivity level that can resolve only 20-50% of the individual sources that contribute to the integrated emission of

	GBT	CARMA	ALMA	LMT
Flux sensitivity				
Line (3 mm)	0.6	2.5	0.3	1
Continuum (1mm)		19	0.7	1
Surface Brightnes sensitivity				
Line (3 mm)	2.3	3.3	2.5	1
Continuum (1mm)		25	6.6	1
Mapping Speed				
(Point Sources)				
Line (3 mm)	15	4.5	0.1	1
Continuum (1mm)		1100	2.2	1
Mapping Speeded				
(Extended emission)				
Line (3 mm)	350	7.7	5.8	1
Continuum (1mm)		1900	180	1

Table 2. Performance values of different mm facilities normalized to the GTM. For values in red GTM is better, for those in blue, GTM is worse.

the extragalactic background. Less than 0.01% of the sky has been mapped and resolved at mm wavelengths. Hence, the GTM can survey large regions of the sky to characterize the typical properties of the extragalactic millimeter population.

The GTM offers a natural complement to the next generation of mm interferometers such as ALMA and the Combined Array for Research in Millimeter wave Astronomy (CARMA). The GTM's extended imaging will place the high resolution interferometer maps into an environmental context and will provide the emission that will be resolved out in the interferometric maps, even when they operate in their most compact configurations. The large primary aperture of the GTM, coupled with its sensitive imaging cameras, results in a mapping speed 100 times faster than other facilities.

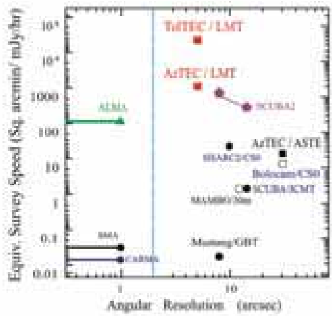


Figure 10. A comparison of survey speed on GTM with respect to other present and future instruments. High angular resolution is needed to probe deeper into the fainter population through reduced confusion and better identification of the counterpart detected at other wavelengths.

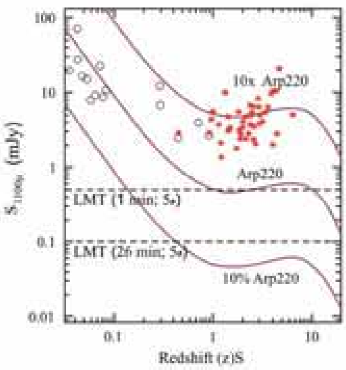
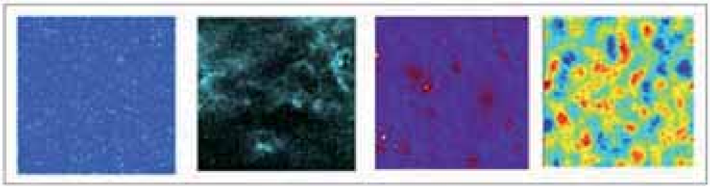


Figure 11. The 5s detection sensitivity of AzTEC on GTM at 1.1mm. Expected 1.1mm continuum flux for an Arp220-like (SFR=200 Msun/yr) object is shown.

Much of the ongoing star formation in the universe takes place in the dusty, heavily obscured interstellar medium (ISM) in galaxies. Hence, the star formation activity cannot be observed by ultraviolet, optical, or infrared surveys. A more transparent view of the universe can be provided by sub-millimeter and millimeter wavelength observations, which are insensitive to the obscuring effects of dust.

When the universe was less than 10% of its current age, the first galaxies had already formed from the first generations of stars, which then proceeded to enrich the primeval ISM with heavy elements and the other by products of star formation. The physical environment of the high-redshift universe (and therefore presumably in high-redshift galaxies) is potentially different from the presently observed, with different processes and efficiencies of star formation. Thus, in order to understand the formation and evolution of galaxies, we must also understand the formation and evolutionary history of stars, and then place the galaxies and clusters in the context of the larger-scale distributions of matter that have evolved from the initial structures observed in the cosmic microwave background anisotropies.

Figure 12. From left to right: Mm wavelength simulations of a strongly evolving and clustered starburst galaxy population, Galactic cirrus, Sunyaev Zel'dovich clusters, and fluctuations in the Cosmic Microwave Background. These simulations are merged to provide realistic maps of the extragalactic sky, which can be combined with an instrument and telescope simulator to estimate the feasibility of possible GTM surveys.



The history of High Redshift violent star formation in dusty, optically obscured galaxies manifests itself in far infrared (FIR) to mm wavelength observations. Because the strong FIR emission peak is increasingly shifted into the submm and millimeter range as the distance and hence redshift (z) increases, millimeter wavelength observations are able to trace the evolution of star formation in dusty galaxies throughout a large volume of the high redshift universe (as easily at redshift z ~ 8 as at z ~ 1), and therefore back to extremely early epochs. With a large accessible volume from mm surveys, it is possible to test whether galaxies observed at these wavelengths represent the rapid formation of massive (elliptical) systems in a single violent collapse of the highest density peaks of the underlying large-scale matter distribution, or whether they are built over a longer period from the continuous merging of lower mass systems with much more modest rates of star formation.

A major scientific goal for the GTM is therefore to exploit its higher angular resolution, sensitivity and mapping speed, in the effort to understand the evolutionary history of the galaxy populations that dominate the integrated FIR mm extragalactic background emission. More specifically, the GTM will conduct a range of narrow, confusion limited surveys and larger area, shallower surveys of the high redshift universe at mm wavelengths.

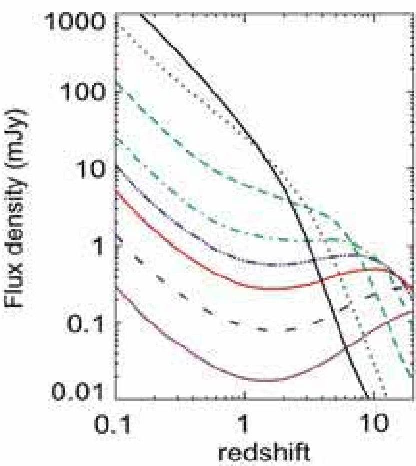


Figure 13. The effect of redshift on flux density at far infrared to mm wavelengths for an object similar to the ultraluminous galaxy Arp220. From top to bottom (at a redshift of z=0.1) the colored curves show this effect at 160, 250, 500, 850, 1100, 1400, 2100, 3300 microns, respectively.

Together with complementary multiwavelength observations, these data will (a) identify the individual galaxies that supply that part of the FIR mm background (~ 50% of the integrated energy budget of the universe emitted by discrete sources) and determine their redshifts; (b) measure their individual bolometric luminosities, star formation rates and the evolution of their integrated luminosity functions; (c) determine the fraction of active galactic nuclei (AGN) in the various FIR mm galaxy populations; (d) measure the spatial clustering properties of these galaxies; and (e) characterize the multiwavelength spectroscopic and continuum properties of these dusty galaxy populations. These various mm surveys, which covered areas ranging from a few square arc minutes to 0.5 square degrees, have contributed significantly to the first efforts to understand the history of obscured star formation in the early universe.

Figure 14. The predicted redshift distribution of dusty starburst galaxies for different GTM surveys. The deep, small area surveys (solid line) will be dominated by a high redshift (z > 2), while the shallower and wider area GTM surveys (dashed line) will contain a bimodal population that also includes bright galaxies in the local universe (z < 0.05).

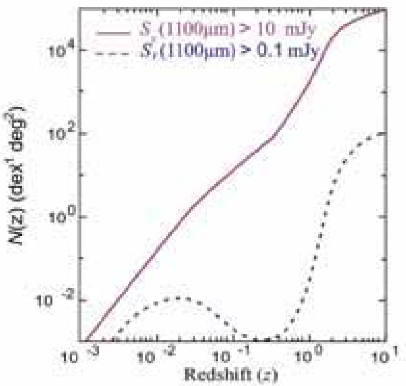
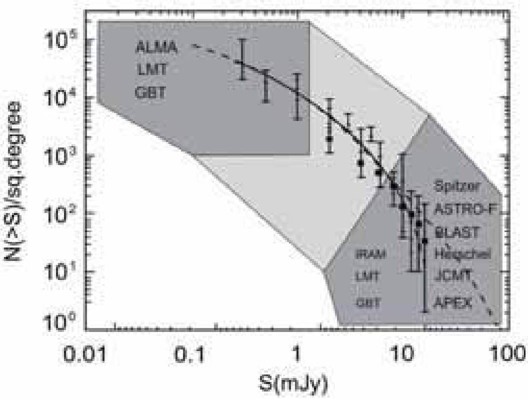


Figure 13 illustrates: first, the measured submm source counts from the extragalactic surveys cover only a narrow range of source brightness; second, the uncertainty in source count is substantial, because the total number of sources detected with a signal to noise of at least four is less than 100.

Thus, it is difficult to determine the flux density at which the faint end source counts converge, and therefore determine the contribution of this mm population to the extragalactic background emission. Galaxy clustering and the small areas covered by the surveys also make the count of faint sources uncertain, and it is difficult to know whether there is a cutoff in the evolving luminosity function because of the scarcity of bright sources.

Figure 15. Extragalactic 850 μm source counts as a function of flux. The solid line represents one of many possible strongly evolving models that fit the 850 μm data. The measured source counts cover a narrow range of flux densities (~ 0.5 – 12 mJy) and therefore leave two unexplored regions (shown as dark grey shaded polygons) populated by the numerous, faint galaxies below the existing observational confusion limits, and the brightest, but rarer galaxies that can only be detected in the widest area surveys.



Restricted wavelength coverage; low spatial resolution; restricted field of view with the current mm bolometer arrays (typically 5 square arcmin); and low system sensitivity are factors that restrict even the widest and shallowest mm surveys to areas smaller than half a square degree. Hence, the existing mm observations are necessarily only sensitive to the most luminous and massive star forming galaxies corresponding to a star formation rate (SFR) greater than 300 solar masses per year.

Cosmological surveys with the GTM will improve upon all of the above limitations. The GTM will use its very high mapping speed, sensitivity, and angular resolution to measure the surface density and clustering properties of dusty starburst galaxies detected between 850 µm and 3 mm over a wide dynamic range of flux densities, making it one of the most powerful of all the future FIR mm experiments.

The capabilities of the GTM allow it to simultaneously search for and detect the optically obscured galaxies with low FIR luminosities and star formation rates (~10-50 solar masses per year), as well as discover the brightest mm sources in the high redshift universe. For example, a search for the most extreme star forming galaxies (SFR >> 5000 solar masses per year), associated perhaps with the rapid formation of a massive elliptical in less than a few billion years, would require a submm survey covering > 100 square degrees.

The integrated FIR mm emission from all the galaxies in the universe peaks at ~ 250 µm and contributes approximately 50% of the total radio to X-ray extragalactic background light, and it is a component that needs to be spatially resolved and understood. It is also important to note that << 1 square degree of the extragalactic sky has been mapped at mm wavelengths with sufficient resolution and sensitivity to resolve a major fraction of this background emission. For example, it is only in the deepest surveys (rms > 0.5 mJy at 850 µm) that a significant fraction (= 30%) of the 850 µm background has been resolved into discrete galaxies, yet these same surveys have only observed = 100 square arcmin in total. Furthermore, an extrapolation of the source counts to shorter submm wavelengths indicates that the same populations of galaxies detected in these deepest surveys contribute less than 15% of the FIR (250 µm) background emission, while the combined shallower (rms ~ 2.5 mJy at 850 µm) and

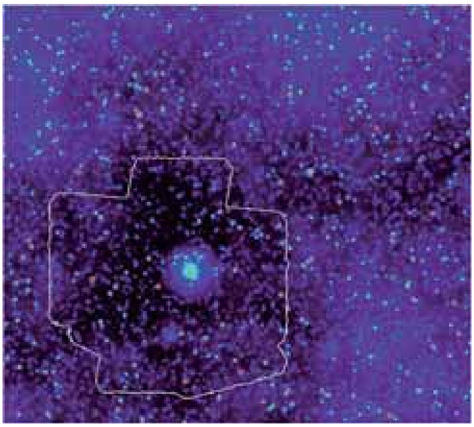


Figure 16. Simulated emission from extragalactic point sources at 1.1 mm for an area 0.5 x 0.5 square degrees, including contributions from the spectral Sunyaev-Zel'dovich increment caused by the thermal effect in the cluster near the map center (the extended source) and foreground Galactic dust ("cirrus"). More than 100 starburst galaxies would be detected in a 2 hour integration with AzTEC in the outlined region.

wider area (~ 2000 square arcmin) mm surveys provide only a few percent of the FIR background.

The GTM will have an extremely low confusion limit due to extragalactic sources. The opportunity to resolve the entire millimeter wavelength background into individual galaxies is thus well within the capabilities of the GTM and the first light continuum camera, AzTEC.

Dusty mm galaxies at high redshift contain enormous reservoirs of molecular gas (mass of H ~ 102 10 solar masses) that fuel the high rates of star formation. Given these expected gas masses, the GTM has sufficient sensitivity to conduct a blind search for molecular line emission from the rotational transitions of CO in the galaxies identified in the GTM blank field surveys.

Taken together with the two-dimensional GTM surveys describing their angular distribution, it will be possible to measure the spatial clustering of these luminous starburst galaxies over a wide range of redshifts and cosmological epochs. Once a spectroscopic redshift is measured for a mm galaxy, the GTM can carry out higher spectral resolution observations to resolve the line profile, and hence estimate the rotational velocity of the gas and infer a dynamical gas mass.

A measure of the distribution of high redshift massive (elliptical) galaxies, which are thought to trace the underlying dark matter distribution, offers one way to map out over densities. It is needed to search the high redshift universe for clear signatures of the short, yet powerful bursts of obscured star formation (>> 100 solar masses per year) associated with the building of elliptical galaxies or their progenitors. GTM can efficiently target fields in which we expect to sample high density peaks in the underlying mass distribution. Observations towards high redshift AGN are examples of these special environments, where, e.g., over densities of Lyman break galaxies and mm sources have been found. The most massive galaxies in the local universe are giant ellipticals which are also found in the centers of rich clusters. The most luminous radio quiet quasars (RQQs) at high redshift are also expected to be found inside massive ellipticals.

The Cosmic Microwave Background (CMB) is both a perfect 2.73K blackbody (with fluctuations over the entire sky smaller than ~ 80 μK) and is isotropic. This background is the primordial light from the surface of last scattering, the epoch at which the universe first cooled below the ionization temperature of hydrogen some 380,000 years after the Big Bang. As neutral atoms recombined from the hot plasma, radiation decoupled from matter, leaving the photons free to travel relatively unhindered until detected by CMB experiments some 13 billion years later.

Small deviations from a perfectly smooth cosmic background have been observed at a level of one part in 100,000 ($dT/T = 10^{-5}$). Primary fluctuations contain information about the conditions of the universe at the earliest moment that can be directly observed, the time of decoupling. Secondary fluctuations arise from the scattering of photons as they interact with gravitational potentials and sources of local ionization along the line of sight to the present-day observer.

Measurements of the CMB power spectrum on the small angular scales probed by the GTM can be used to constrain the shape and Gaussian nature of the primordial spectrum of density fluctuations, which provide a test of the inflation theories, and also provide an estimate of the epoch of hydrogen reionization in the early universe due to the formation of the first stars and powerful AGN.

The dominant source of secondary CMB fluctuations, caused by local ionization in clusters, will be detectable by the GTM. Plasma in the intergalactic medium within clusters interacts with CMB photons through inverse Compton scattering, whereby hot electrons preferentially scatter lower energy photons to higher energies. This thermal Sunyaev Zel'dovich (SZ) effect distorts the mm wavelength spectrum of the CMB in the vicinity of clusters to produce a maximum decrement at 2.3 mm, a maximum increment at 0.85 mm, and a null at 1.4 mm. This distinctive spectral feature, combined with the sensitivity and resolution of the GTM, makes it possible to identify distant clusters from the confused foreground and background mm wavelength radiation due to point like galaxies and Galactic cirrus. The combination of GTM observations of the SZ effect (independent of redshift) at mm wavelengths with X-ray observations can constrain the mass of an individual cluster. Follow-up optical and IR imaging and spectroscopy of the galaxies associated with the identified clusters will provide measurements of their redshifts and velocity dispersions. This collective information will provide strong constraints on the growth of structure.

The GTM will accurately image complexes of molecular gas and dust that are current or future sites of star formation within the disks of galaxies, and, rapidly conduct unbiased surveys of the properties of these disks. For example, the angular resolution of the GTM corresponds to about 20 parsec at the distances of the Andromeda Galaxy (M31) and the Triangulum Galaxy; sufficient to resolve individual giant

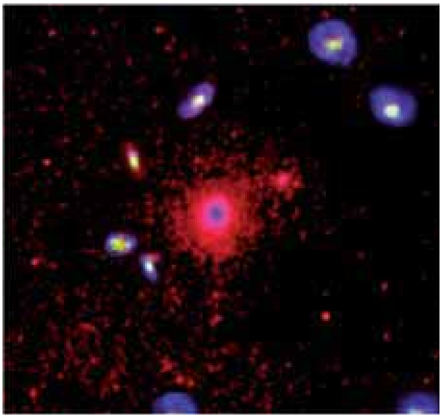


Figure 17. Color composite images of nine Virgo cluster galaxies (CO in green, HI in blue, and optical, inside individual galaxy images, in red). The CO emission has been imaged using the SEQUOIA array. The X-ray emission in the cluster is shown in red and magenta.

molecular gas clouds. The GTM will be able to map the location and kinematics of dense molecular clouds in several hundred nearby spiral galaxies, and to study cloud formation and dissipation as they pass through the shock fronts within galactic spiral arms.

GTM can define the spatial and kinematic relationships between the population of giant molecular clouds and the overlying atomic gas component most readily traced by the HI 21 cm transition. Such relationships can distinguish the most relevant factors responsible for the development of giant molecular clouds and the subsequent formation of stars in galaxies.

GTM can conduct observations to investigate the variation of molecular gas conditions as a function of radial position within a galaxy. These conditions can be directly compared to local star formation rates and efficiencies to assess the regulatory processes within galaxies.

Hundreds of galaxies in clusters like this can be imaged and studied simultaneously using the GTM. The high sensitivity of the GTM increases the number of available target sources to several thousands, and the frequency agility of the GTM instruments is extremely well suited for absorption system searches and detailed follow-up investigations. When a large number of molecular transitions are detected in several systems spanning a wide range of redshifts (distances), interesting insights on variations in physical properties of the ISM, such as gas density, temperature, and chemical abundances, can be obtained.

GTM can perform imaging surveys of molecular gas tracers such as CO for a large sample of nearby galaxies representing different galactic environments, as in the Coma cluster. Comparisons of CO emission with the HI and infrared images should reveal the relationship between the large scale cold gas and stellar structures, the gas distribution, and star formation activity. During the first few years of operation the GTM will image CO emission in hundreds of galaxies with sub kiloparsec spatial resolution out to a distance of 100 megaparsecs.

The GTM can investigate the many scales and processes related to star formation in molecular clouds. The capability of the GTM to rapidly image both molecular line and thermal dust continuum emission provides powerful tools to study the global cloud dynamics, the development of massive cores and pre protostellar condensations from the low density substrate, the gravitational collapse of material onto the central object and circumstellar disk, and the protostellar wind phenomenon.

Accurate descriptions of the dynamics of molecular clouds are essential to our understanding of the star formation process. The dynamics of a cloud plays a pivotal role in setting the time interval over which the cloud can produce stars and the mode (clustered or distributed) in which stars are generated. A high-resolution view of a nearby molecular cloud reveals a web of filaments, shells, and high density cores that attest to a complex dynamical state. The observed complexity is produced by expanding motions from HII regions and stellar winds, and the interplay between magneto turbulent pressures and the self gravity of the cloud. Determining the relative roles of the magnetic field, turbulence, and wind driven shocks is a central goal of molecular cloud studies.

The Taurus molecular cloud is the prototypical example, and much of the observational and theoretical efforts to understand star formation have been focused on this basic mode. The dense regions from which newborn stellar clusters emerge are larger (0.51pc), more massive (1,000 to 10,000 times the solar mass), denser (1 million molecules per cm^3), and more inhomogeneous than the core counterparts

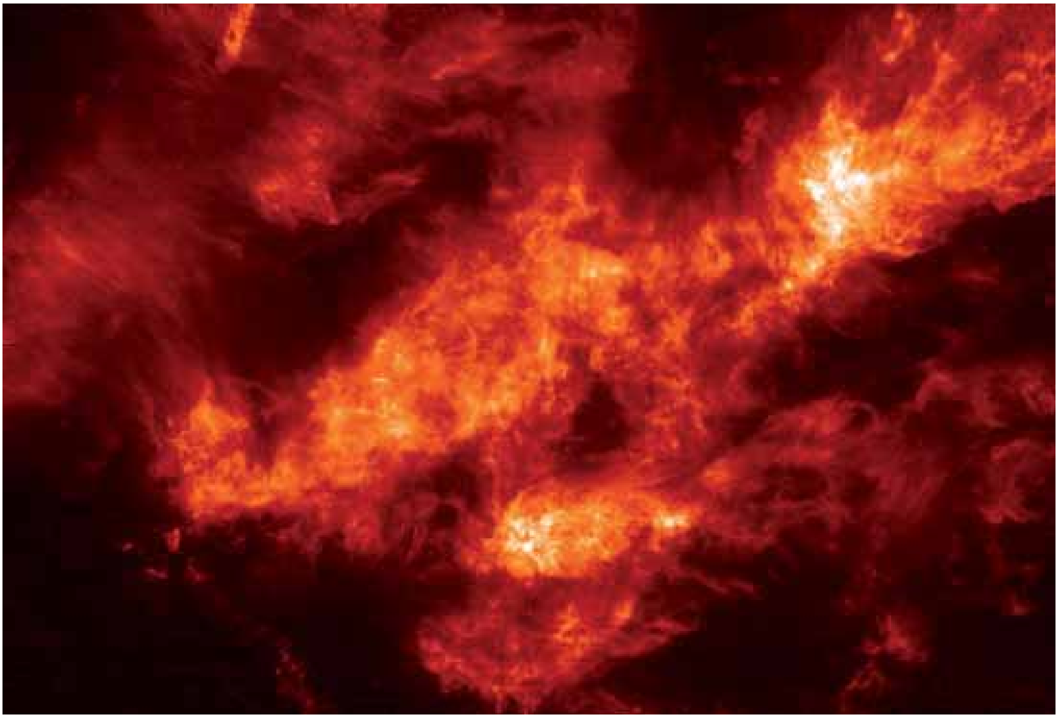


Figure 18. An image of the ^{13}CO J = 10 - 0 emission from the Taurus Molecular Cloud, a nearby star forming region observed with the FCRAO telescope and SEQUOIA receptor. GTM can image similar but more distant star forming systems to sample a broader range of interstellar environments.

associated with distributed star forming regions. Such regions have the capacity to produce 100 to 1,000 stars and are almost the only sites of massive star formation.

The GTM will produce definitive descriptions of massive cores in the interstellar medium of the Milky Way. Mapping of the thermal dust continuum emission with the AzTEC and SPEED bolometer arrays will reveal the column density distribution of material and identify protostellar objects within the massive cores. The local dynamics and chemistry of the massive core will be determined by imaging of spectral line emission that directly traces the dense gas. Such measurements will define the coupling of the dynamics to the protostellar condensation.

The high sensitivity, angular resolution, and mapping speed of the GTM will enable detailed investigations of the chemistry of interstellar molecular clouds, protoplanetary disks, and comets. The mapping speed of the GTM will allow detailed comparisons of the chemical content of a variety of molecular clouds in differing stages of evolution and with differing physical conditions and environments. Likewise, the high spectral resolution and sensitivity available with the GTM will produce data on isotopic fractionation and its dependence on cloud physical parameters and evolution. Such results will address the relative importance of purely gas phase versus grain surface synthesis of complex molecules in the ISM, and the relation between interstellar molecules, the chemistry of primitive solar system bodies such as comets, the delivery of organic molecules to the early Earth from space, and the role of such molecules in the origin of life.

The GTM is an important station in the millimeter VLBI network as it provides a large collecting area at 1 and 3mm bands and a valuable north-south baseline connecting with ALMA. Its participation in the millimeter VLBI campaigns is critical to efforts to resolve the event horizon of the SgrA* SMBH, to reveal shadowing generated by orbiting or infalling plasma, and to measure the spin of the SMBH from flaring events.

The terrestrial planets, planetary satellites, asteroids, and comets have all proved to be fruitful objects for study by radar astronomy. In addition, radar measurements of Near Earth Objects would provide distance and velocity data vastly more accurate than that available from optical images, a critical consideration for the protection of Earth from potentially impacting asteroids and comets.

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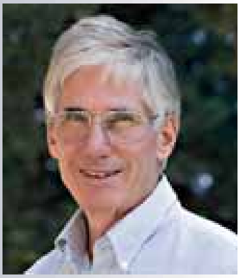

New frontiers with LSST: leveraging world facilities

Abstract
Comprehensive understanding of new astrophysical phenomena requires multi-wavelength and/or temporal investigations using a variety of instruments on multiple facilities. Because of cost these large facilities or instruments tend to be unique. Astronomy thus must evolve to a coordinated collaboration of world facilities. GTC is perfect for co-observing with LSST to leverage discovery. The shared sky overlap and the joint science discovery space is more than sufficient. Such world collaborations, while effective scientifically, need to be planned in advance.

1. Introduction

Driven by the availability of new instrumentation, there has been an evolution in astronomical science towards comprehensive investigations of new phenomena, encompassing complementary observations using a range of special facilities. Science and specialized instrumentation know no borders. Thus, our field is driven towards coordinated use of world facilities - world collaboration. This is particularly true of discoveries emerging from a new generation of sky surveys. Imaging data from a large ground-based active optics telescope with sufficient étendue ($\geq 300 m^2 deg^2$) can address many scientific missions simultaneously. By providing unprecedented sky coverage, cadence, and depth, the Large Synoptic Survey Telescope (LSST) will make it possible to attack high-priority scientific questions that are far beyond the reach of any existing or planned facility. LSST will produce a 6-band (0.3-1.1 micron) wide-field deep astronomical survey of over 30,000 square degrees of the sky to 34 deg north latitude using an 8.4 m (6.7 m effective) telescope and 3.2 Gpixel camera. Each patch of sky will be visited 1000 times (2 x 15 sec exposures each time) in ten years. With 20 trillion photometric and temporal measurements covering 20 billion detected objects, this will produce the world's largest database.

The 30 terabytes of pipeline processed data obtained each night will open the time domain window on the deep optical universe for variability and motion. Rarely observed events will become commonplace, new and unanticipated phenomena will be discovered. The combination of LSST with contemporary facilities such as Gran Telescopio Canarias (GTC), E-ELT, TMT, and JWST will provide powerful synergies. The deep coverage of ten billion galaxies provides unique capabilities for cosmology. Astrometry, 6-band photometry, and time domain data on 10 billion stars will enable studies of galactic structure. This chapter describes the evolving astronomy survey frontier, the LSST survey, and the science synergies with the full range of complementary facilities.

2. Evolving Research Frontiers

Over the past decade, large scale sky surveys, such as SDSS, 2MASS, GALEX and many others have proven the power of large data sets for answering fundamental astrophysical questions. This observational progress, based on a synergy of advances in telescope construction, detectors, and information technology, has had a dramatic impact on nearly all fields of astronomy, and areas of fundamental physics. The LSST builds on the experience of these surveys and addresses the broad scientific goals of the coming decade.

Survey science tends to fall into several broad categories: (1) Statistical astronomy, where large datasets of uniformly selected objects are used to determine distributions of various physical or observational characteristics; (2) Searches for rare and unanticipated objects - every major survey that has broken new ground in sensitivity, sky coverage or wavelength has made important serendipitous discoveries, and surveys should be designed to optimize the chances of finding the unexpected; and (3) Surveys of the sky become a legacy archive for future generations, allowing astronomers interested in a given area of sky to ask what is already known about the objects there, to photometrically or astrometrically calibrate a field, or to select a sample of objects with some specific properties. All three of these survey science modalities reach their full scientific potential often through use of complementary facilities.

3. Astro Sociology

The exponential increase in survey data and the resulting science opportunities has resulted in the development of a new breed of scientist, the "survey astronomer". These include both the people who develop the infrastructure of these surveys and those who analyze these data. The hardware and computational technical challenges and the exciting science opportunities are attracting scientists from high-energy physics, statistics, and computer science.

The way astronomers pursue their science is also evolving. Breakthroughs in observational astronomy in the last fifty years have been driven by two types of facilities (often working in synergy):

- Survey facilities are often dedicated telescopes with a wide field of view, which gather data on large numbers of objects, for use in a wide variety of scientific investigations.
- Observatories are designed to allow detailed studies of individual objects or relatively small fields in a given waveband. Much of the push towards telescopes of ever larger aperture is motivated by studies of individual objects.

The history of astronomy has taught us repeatedly that there are unanticipated surprises whenever we view the sky in a new way. Complete, unbiased surveys are the best technique we have both for discovering new and unexpected phenomena, and for deriving the intrinsic properties of source classes so that their underlying physics can be deduced. Both types of facilities, wide-field and narrow-field, are driven by new technological developments.

Although astronomers often make use of multiple specialized facilities, the cost of these instruments has been rising. One can question whether the traditional model of a suite of the same type of instruments duplicated on many telescopes is an optimal in the future. In the E-ELT era observing time on 8-10 m telescopes will likely evolve in complementary roles, either in instrumentation or observing strategy. For example, it will be possible for collaborations to pursue highly effective joint observations with other facilities (survey and/or different wavelength). Telescopes in the 8-10m class will be able to serve a unique enabling scientific role which would be difficult if observing time was assigned in traditional small blocks of nights reserved for the largest facilities. Telescope allocation committees and observatory directors have recognized that taking such strategic planning risks has scientific payoffs (the HDF is an example.)

Another kind of risk-taking which is crucial to preserve in all areas of science is access to experimental observing modes and novel instrumentation experiments. While some of this can take place on small telescopes, much of it must happen on 8 10m class telescopes simply because of the usual photon-starved nature of the experiment. This is the engine for technical innovation and resulting discovery. Astronomers must be empowered to take these risks. It also makes possible the needed career paths for instrumentalists, already an endangered species.

For these reasons, in an ELT era the 8 10m telescopes will play a critical new enabling role for scientific discovery. The sociology (web collaborations of scientists self organized around problems, or multi facility co-observing) may be novel, but so too will the scientific discoveries.

4. Planning for Science Leverage

Many of the most important astronomical problems we face require multiple probes via interlocking surveys. Cross-correlation between surveys allows science that would be impossible with any one survey alone. This comparison can be temporal (comparing the proper motion of an object between the POSS and the SDSS, for example) or across wavelength regimes (looking for long-term optical counterparts to gamma-ray bursts).

The discoveries made in surveys are often exploited by detailed study with other telescopes. Unusual objects from an imaging survey will require follow-up spectroscopy to determine their physical nature; one can imagine, for example, a great deal of synergy of this sort between the LSST and the E-ELT and between LSST and GTC. Similarly, transient objects such as the gamma-ray bursts which synoptic surveys will find, require multi-wavelength follow-up over an extended period of time, to allow these discoveries to be placed in astrophysical context. We cannot guess what currently unknown types of objects or phenomena will be discovered. But we can rest assured that collaborations of world facilities will be required for the full exploration of the resulting science.

5. Surveys, Moore's Law, and World Facilities

Surveys have been an engine for discoveries throughout the modern history of astronomy, and have been among the most highly cited and scientifically productive observing facilities in recent years. This observational progress has been based on advances in telescope construction, detectors, and above all, information technology.

Aided by rapid progress in microelectronics, current sky surveys are again changing the way we view and study the Universe. The next-generation instruments, and the surveys that will be made with them, will maintain this revolutionary progress. Figure 1 charts the trend in optical sky surveys over 50 years. The effect of technology is clear. While the available collecting area of telescopes has remained roughly constant, the information content of sky surveys (using the number of galaxies measured per year to a given signal-to-noise ratio as a proxy) has risen exponentially. This is in large part due to high efficiency imaging arrays growing to fill the available focal plane, and to the increase in processing power to handle the data flood. The corresponding increase in science output is a result of the development of software to analyze these digital data in new ways.

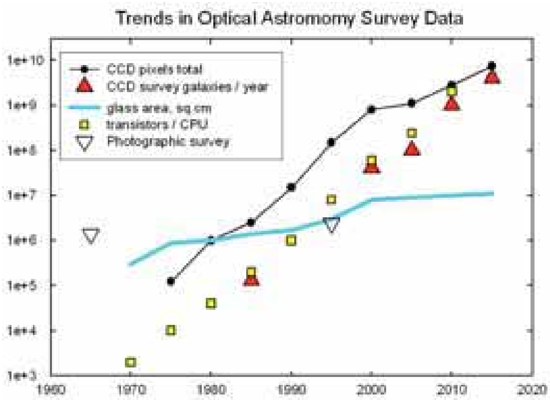

Figure 1. Data trends in optical surveys of the sky. While photographic surveys covered large area, the data were not as usable as digital data and did not go as faint. Information content (in galaxies surveyed per unit time to a given S/N ratio) in CCD digital surveys roughly follows Moore's law. Processing capability has kept up with pixel count. Next generation wide-fast-deep surveys will open the time window on the universe.

Shown in Figure 1, photographic surveys had the large focal plane area advantage early on, but have been eclipsed by CCD surveys, driven by the exponential rise in pixel count and computer processing capability – both enabled by the microelectronics "Moore's Law". Plotted vs time is the sum of all CCD pixels on the sky, as well as the number of transistors on a typical CPU. Processing capability keeps up with the data rate. Also plotted is the result of CCD surveys – the number of galaxies photometered per unit time – ranging from a survey using a single 0.16 Mpixel CCD on a 4 m telescope to the 3.2 Gpixel 8.4 m LSST.

From the start, CCD detectors had more than an order of magnitude higher sensitivity than photographic plates (and far better dynamic range). The population of faint blue galaxies was discovered immediately in the first small CCD survey in the early 1980s. This high efficiency coupled now with many square degree focal plane arrays on large aperture wide-field telescopes means that for the first time we can tile the sky quickly with deep exposures - opening up a new window on the universe.

6. Time Domain: A New dimension

Exploration of the variable optical sky is one of the new observational frontiers in astrophysics. No optical telescope to date has had the capability to search for transient phenomena at faint levels over enough of the sky to fully characterize phenomena. Variable and transient phenomena have historically led to fundamental insights into subjects ranging from the structure of stars to the most energetic explosions in the universe to cosmology. Existing surveys leave large volumes of discovery parameter space (in wavelength, depth, and cadence) unexplored.

Because of its wide coverage and broad time sampling, some of the transient object science will be accomplished largely from the LSST database, combined where appropriate with multi-wavelength databases from other facilities, space and ground. For fast or repeating transients, the LSST Deep Drilling sub-survey of ~50 selected ten square degree fields will yield the highest quality data with excellent sampling. However, much of the transient science enabled by LSST will rely on additional observations of selected transient objects based on their classification using the LSST data. The LSST science collaborations and the world astrophysics community are developing a roadmap for multi-observatory collaboration. Some of the additional observations will be in the follow-up mode and some will (optimally) be in a "co-observing" mode where complementary facilities monitor the same sky during LSST operations. For example, it is known that there are non-repeating bursts on tens of seconds timescales over a wide spectral range; progress in opening this new window can be made in a co-observing mode with both space and ground facilities. Both GTC and E-ELT spectroscopy co-observing in the optical and near IR would capitalize on the new discoveries.

Spectroscopic follow-up will be a world effort. Some observatories are already beginning the process of evaluating optimal modes and spectroscopic instruments for maximal use of LSST transient data. A well-designed follow-up strategy must include end-to-end planning and must be in place before first light. In terms of the required photometric and spectroscopic follow-up, generally there are two distinct cases of transients.

7. Rare bright transients detected by LSST on their way up:

In this case the transients will be sparse on square degree scales. Efficient follow-up would then focus on one transient at a time. Requirements include multi-band simultaneous photometry and IFU spectroscopy on rapidly deployed telescopes around the world that can continuously follow transients brighter than ~22 nd mag. An example is the Las Cumbres Observatory Global Telescope Network of 2 m telescopes and photometric + IFU instruments dedicated to follow-up. It will be important that 1-4m class facilities be capable of following the brief transient to its peak brightness, which could be 10th mag or even brighter.

8. Many faint (22-24th mag) transients:

Every night LSST is expected to deliver data on variability for ~100,000 objects and information on tens of thousands of astrophysical transients. The majority of these will be moving objects or variable stars. Accurate event classification can be achieved by real-time access to the required context information: multi-color time-resolved photometry and host galaxy information from the survey itself, combined with broad-band spectral properties from external catalogs and alert feeds from other instruments.

For photometry, LSST itself provides sparsely time-sampled follow-up on hours-days timescales. Because we expect many transients per LSST field of view, efficient spectroscopic follow-up would best be carried out with multi-slit or multi-IFU systems. Wide field follow-up would be possible with AAT/AAOmega and Magellan/IMACS. If built, BigBOSS may eventually be at the Blanco at CTIO. Some northern facilities will partially overlap with the LSST survey: GTC (with first and second generation instruments), BigBOSS at the Mayall, Keck MOSFIRE and DEIMOS, MMT/Hectospec, and LAMOST. Smaller field of view spectroscopic follow-up in the south can be done with Gemini/GMOS, the VLTs, and SALT/RSS. It is possible that new instruments will be built for these and other spectroscopic facilities by 2015. As described below, there will be considerable overlap with GTC, and therefore this a science opportunity for GTC IFU spectroscopy and AO imaging and near IR spectroscopy. Multi-object spectroscopy in the optical and near IR and multi-dIFU over 8 arcminute or larger fields of view will be particularly effective in leveraging LSST data.

Efficient follow-up will depend on focusing limited resources on the interesting transients. After the first year of operation LSST will be able to produce enough archival and current transient information to enable useful event classification. Combining the optical transient data with survey or archival data at other wavelengths will be routine through the VO. We expect that the community will make significant progress on classification of transients before LSST operations begin, given lessons learned from Palomar Transient Factory and PS1 in the optical and MAXI in the X-ray. There is 11,000 – 18,000 deg^2 overlap in the GTC-LSST shared sky, so that the most important factor in joint science is the accuracy of classifications in order to minimize errors in sample spectroscopic selection. Classification accuracy is driven by the precision deep LSST photometry and many repeat measurements.

About 90% of the observing time will be devoted to a uniform deep-wide-fast (main) survey mode. All scientific investigations will utilize a common database constructed from an optimized observing program. The system is designed to yield high image quality as well as superb astrometric and photometric accuracy. The survey area (shown in Figure 3) will cover 30,000 deg^2 with $\delta < +34.5$ deg, and will be imaged many times in six bands, ugrizy, spanning the wavelength range 320 -1050 nm. The main deep-wide-fast survey mode will observe a 20,000 deg^2 region to +15 deg dec about 1000 times (summed over all six bands) with pairs of 15 second exposures during the anticipated 10 years of operations, resulting in a co-added map with 5σ point source limiting magnitude of 27.7. This map will enable photometric and other measurements of 10 billion stars and a similar number of galaxies.

Figure 2. Two views of the sky to the same signal-to-noise level. On the left is shown a 7.5x7.5 arcminute part of an SDSS field. On the right, to LSST one-year depth and a factor of two worse angular resolution than LSST, 2800 galaxies are seen in this same 0.016 deg^2 field which covers the field of view in a single pointing of the GTC.

The remaining 10% of the observing time will be allocated to special programs such as a Very Deep + Fast time domain survey (so-called “Deep Drilling” fields). The north ecliptic survey from dec 15-34 deg is planned in griz bands, at higher airmass. For transient and variable phenomena LSST extends time-volume discovery space a thousand times over current surveys.

9. LSST Science Drivers and Surveying Strategy

A wide-fast-deep survey of a large fraction of the sky in multiple optical bands is required in order to explore many of the exciting science opportunities of the next decade. The most important characteristic that determines the speed at which a system can survey the sky to a given depth is its étendue (or grasp): the product of its primary mirror area and the field-of-view area. The effective étendue for LSST will be more than an order of magnitude larger than that of any existing facility. As was the case with SDSS, we expect the scientific community will produce a rich harvest of discoveries.

The LSST surveys will overlap 11,500 deg^2 with the GTC AO observable sky, and up to 18,000 deg^2 in non-AO modes. In that 11,500 deg^2 overlap area there are 2.3 billion galaxies brighter than 25th *i* AB mag which will have photometric redshifts in the LSST data, and an estimated 5000 to 50,000 variable or transient alerts per night from LSST. In other words, the overlap area is not a constraint on GTC-LSST science.

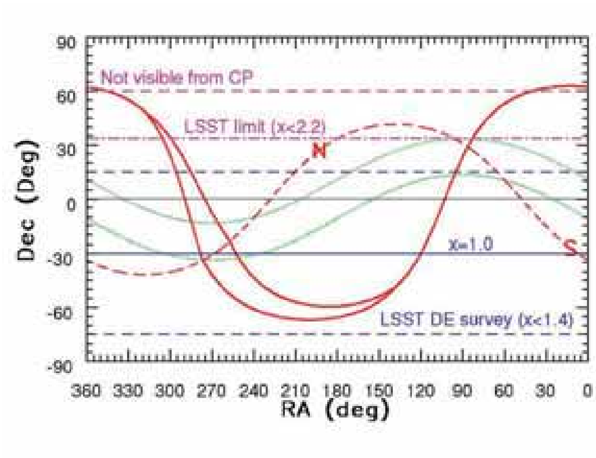

Figure 3. A plot of LSST survey sky coverage in equatorial coordinates. The sky above 60° dec is not observable. The Galactic poles are marked by N and S, and connected with the galactic center by a great circle, shown by the red dashed line. The horizontal solid blue line (dec = −30°) passes through the LSST zenith and the two dashed blue lines (dec = −75° and dec = 15°) outline the region for which the minimum airmass reaches values below 1.4. The area bounded by −75° < dec < 15° is 24,000 deg^2. The galactic plane regions with the highest stellar density are enclosed by solid red lines. The ecliptic band is shown in green. The overlap between the planned LSST main survey of 20 billion objects and the GTC AO sky coverage is 11,500 deg^2. LSST will also survey the north ecliptic region to +34° dec at higher airmass, and the south pole region.

Below we briefly describe four science themes. LSST will meet the requirements for these plus a very broad range of other scientific programs [Ivezic, et al. 2008arXiv0805.2366I]

10. Dark Energy and Dark Matter

LSST is unique in that its deep, very wide-field, multi-color imaging survey can undertake four cosmic probes of dark matter and dark energy physics with a single data set and with much greater precision than previously: (1) Weak lensing cosmic shear of galaxies as a function of redshift, (2) Baryon acoustic oscillations (BAO), (3) Redshift distribution of shear peaks (i.e. clusters), and (4) Type Ia supernovae. Dark energy affects the cosmic history of the Hubble expansion H(z) as well as the cosmic history of mass clustering (which is suppressed at epochs when dark energy dominates). If combined, different types of probes of the expansion history (via distance measures) and structure history can lead to percent level precision in dark energy parameters. Using the cosmic microwave background as normalization, the combination of these LSST deep probes over wide area will yield the needed precision to distinguish between models of dark energy, with cross checks to control systematic error.

11. Inventory of the Solar System

The small bodies of the Solar System offer a unique insight into its early stages. LSST, with its unprecedented power for discovering moving objects, will make a giant leap forward in the Solar System studies. The baseline LSST cadence will result in orbital parameters for several million moving objects; these will be dominated by

System

Étendue	319 m² deg²
Sky coverage	20,000 deg² (Main Survey)
Field of view (diameter, area)	3.5 deg (9.6 deg²)
Effective clear aperture (on-axis)	6.7 m (accounting for obscuration)
Wavelength coverage (full response)	350-1080 nm
Number of concurrent filters in camera	5
Filter set	u, g, r, i, z, y

Telescope

Configuration	3-mirror, Alt-azimuth
Final f/ratio; plate scale	f/1.23; 50 microns/arcsec
Diameter of optics (physical)	M1: 8.4 m; M2: 3.4 m; M3: 5.02 m
First camera lens; focal plane diameter	Lens: 1.55 m; field of view: 63 cm
Residual Aberrations (arcsec) 80% encircled energy	u: 0.26 g: 0.26 r: 0.18 i: 0.18 z: 0.19 y: 0.2

Camera

Pixel size; pixel count	10 microns (0.2 arcsec); 3.2 Gpixels
Readout time	2 sec
Dynamic ranage	16 bits
Camera rotation range	$\pm$ 90 deg
Focal plane device configuration	4-side buttable, >90% fill factor
Filter change time	120 seconds

Data Management

Real-time alert latency	60 seconds
Raw pixel data/night	15 TB
Yearly archive rate (compressed)	Images; 5.6 PB; Catalogs: 0.6 PB
Computational requirements	Telescope: < 1 Tflop; LaSerena: 30 Tflop; Archive Center: 250 Tflop by year 10
Bandwidth	Telescope to LaSerena: 40 Gbits/sec; LaSerena to archive: 2.5 Gbits/sec avg.

System Capability

Single-visit depths (point source; 5σ)	u: >24 g:25.0 r:24.7 i:24.0 z:23.3 y:22.1 AB mag
Baseline number of visits over 10 yr	70, 100, 230, 230, 200, 200
Main survey depths (point source; 5σ) zenith	u: >26.3 g:27.5 r:27.7 i:27.0 z: 26.2 y:24.9 AB mag
Photometry accuracy (rms mag)	repeatability: 0.005; zeropoints: 0.01
Astrometric accuracy at r=24 (rms)	parallax: 3mas; proper motion: 1mas/yr

Table 1. LSST System Parameters.

main-belt asteroids, with light curves and colorimetry for a substantial fraction of detected objects. This represents an increase of factors of 10 to 100 over the numbers of objects with documented orbits, colors, and variability information.

12. The Transient Optical Universe

Characterization of the variable optical sky is one of the true observational frontiers in astrophysics. To date, no optical telescope has had the capability to search for transient phenomena at faint levels over enough of the sky to fully characterize the phenomena. LSST will survey the sky on a variety of time scales from years down to 15 seconds. Because LSST extends time-volume space a thousand times over current surveys, the most interesting science may well be the discovery of new phenomena.

The LSST, with its repeated, wide-area coverage to deep limiting magnitudes, will enable the discovery and analysis of rare and exotic objects, such as neutron star and black hole binaries, and high-energy transients, such as optical counterparts to gamma-ray bursts and X-ray flashes (at least some of which apparently mark the deaths of massive stars). LSST will also characterize in detail AGN variability and new classes of transients, such as binary mergers and stellar disruptions by black holes. LSST will also monitor an unprecedented number of periodic variables, such as RR Lyrae stars (pulsating stars used as standard candles), which will be used to map the Galactic halo and intergalactic space to distances exceeding 400 kpc. GTC optical and near-IR spectroscopy would be a powerful probe of new transient phenomena.

13. Mapping the Milky Way

The LSST is ideally suited to answering two basic questions about the Milky Way Galaxy: What is the structure and accretion history of the Milky Way? What are the fundamental properties of all the stars within 300 pc of the Sun? LSST will enable studies of the distribution of numerous main-sequence stars beyond the presumed edge of the Galaxy's halo, their metallicity distribution throughout most of the halo, and their kinematics beyond the thick disk/halo boundary, and will obtain direct distance measurements below the hydrogen-burning limit for a representative thin-disk sample.

LSST will produce a massive and exquisitely accurate photometric and astrometric data set. LSST will detect of the order 10^{10} stars, with sufficient signal-to-noise ratio to enable accurate light curves, geometric parallax and proper motion measurements for about a billion stars. Accurate multi-color photometry can be used for source classification and measurement of detailed stellar properties such as effective temperature and metallicity with an impressive accuracy (rms of about 100 K for temperature and 0.3 dex for metallicity).

14. LSST System

LSST has been designed to accomplish the science outlined above and much more with a single coherent dataset over a ten-year survey. An international site selection committee evaluated many sites in both hemispheres worldwide. The telescope will be located on Cerro Pachón in northern Chile and will survey the sky to +34 deg declination. Near real-time alerts for transients will be provided. The project scope accordingly includes construction of the facilities, acquisition of data, calibration of the observations, archiving both the raw and processed data, and serving data products and analysis tools to the user community.

The realization of the LSST involves engineering and technological challenges: the fabrication of large, high-precision optics; construction of a huge, highly-integrated array of sensitive, wide-band imaging sensors; and the operation of a data management facility handling tens of terabytes of data each day. A significant part of the cost of the facility and its operation is in data management: pipeline processing the data, serving the data and processing CPU intensive user queries and uploaded specialized data analysis scripts. The design and development effort, has been underway since 2000. Over 100 technical personnel at a range of institutions are currently engaged in this program. A selection of the high-level system specifications is presented in Table 1.

We have run full simulations of the LSST survey and system design, for a matrix of depth, data flow, and observing cadence so that we can optimize the system hardware design, develop the appropriate algorithms, and understand the limitations and trade offs for LSST science operations.

The LSST operations simulator (http://opsimcvs.tuc.noao.edu/) has established the étendue required to meet survey specifications in terms of the number of visits/per filter in 10 years, time sampling, and image quality. The simulator includes models for the weather and local seeing based on actual site measurements, the lunar cycle, telescope dynamics, etc. The LSST exposure-time calculator (http://lsst.org/etc) enabled derivation of requirements for system sensitivity parameters including effective aperture, mirror and lens coatings, sensor quantum efficiency, observing conditions, and usable sky brightness. The LSST image simulator (http://lsst.org/imsim) produces 'end-to-end" image simulations to verify the scientific performance of the complete LSST system design.

The LSST facilities include: (1) the telescope and associated support buildings on Cerro Pachón, Chile, (2) a Data Access and operations center in La Serena, Chile, (3) the Archive Center located at the National Center for Supercomputing Applications, Univ. of Illinois, Urbana-Champaign. All the sites are interconnected via dedicated high-bandwidth fiber optic links.

15. Telescope

An international committee evaluated potential sites and selected Cerro Pachón, Chile as the most advantageous for LSST. The LSST optical system consists of three reflective optical surfaces (primary, secondary, and tertiary) and three refractive lenses to flatten the focal plane and correct chromatic aberrations introduced by the filters. The annular primary mirror has an outer diameter of 8.4 m and an inner diameter of 5.0 m for an effective diameter of 6.7 m. Combined with the 3.5-degree field of view, the étendue of the LSST is 319 m^2 deg^2. Wavefront quality is maintained across the field of view for all bands via an active optics system so that intrinsic design aberrations are insignificant compared to atmospheric effects.

The LSST optical design combined with unique fabrication facilities at the University of Arizona allowed the co-planar 8.4 m diameter primary surface with the nested 5-m diameter tertiary surface to be cast into a monolithic mirror blank. The compound mirror provides a stiff primary mirror and simplifies control of the mirror system during operations. The casting has been completed successfully, and the mirror is now being prepared for polishing.

The 3.4 m diameter secondary mirror is a thin meniscus made of low expansion glass. The fusing of the glass boules has been completed at Corning. The 300 ton telescope structure is an alt-az configuration with an 8.2 Hz first frequency. Specifications require 5 second average step-and-settle times to subsequent pointings.

16. Camera

LSST's single scientific instrument is the large optical camera with 3.2 gigapixels covering the flat 64 cm diameter focal plane. The camera system includes the readout electronics, shutter, 75 cm filters, and three refractive optical elements, the largest being 1.5 meters in diameter. The camera is 1.6 m diameter by 3.5 m long and weighs 3,000 kilograms.

The camera focal plane is tiled with 189 4k x 4k innovative CCDs with 10 micron pixels. Each CCD has 16 readout channels to support the 2 second readout of the entire sensor and focal plane. The devices are back illuminated, 100 micron thick, fully depleted silicon sensors that offer excellent quantum efficiency in the challenging red end of the 0.3 to 1.1 micron wavelength range. Delivery of the commercial prototype sensors is scheduled for mid-2010.

17. Data Management

The LSST software and hardware system must automatically ingest ~15 terabytes (TB) of raw 16-bit/pixel images taken each night, apply proper system corrections, verify data quality, process the data to identify and publicly broadcast categorized alerts, archive the data, create catalog products, and serve the data to the community.

The alerts of discovered transient, moving, and variable objects are to be issued within one minute. The system is sized to keep up with data generation on a daily pace and for catalog releases and full re-computation on yearly intervals.

The LSST data products are organized into two groups distinguished by cadence (see Figure 4). Nightly data products are generated by pipeline-processing the image data stream during observing and issuing alerts. A highly automated process generates and archives raw science images, creates a catalog of variable sources, and issues transient alerts within 60 seconds of detection. Archive center data products include calibration images, co-added images, and the resulting catalogs. Archive center data products also classify objects based on both their static and time-dependent features. These data products are generated on a slower cadence at the Archive Center at NCSA; their release will be validated with data quality assessments.

Over the 10-year survey, the LSST project will accumulate 250 TFLOPS of dedicated computational power and 165 petabytes of digital storage. In order to ensure that both the LSST data products and the data reduction algorithms are completely open and usable by the community, the LSST Data Management System is being developed as an open source system. All software used in the DMS will be available in source form to anyone in the community under an open source license. This ensures that the data quality and data provenance for all data products are completely transparent, provides a means for rapid development of analytical codes, and enables researchers to document the complete derivation of all scientific results.

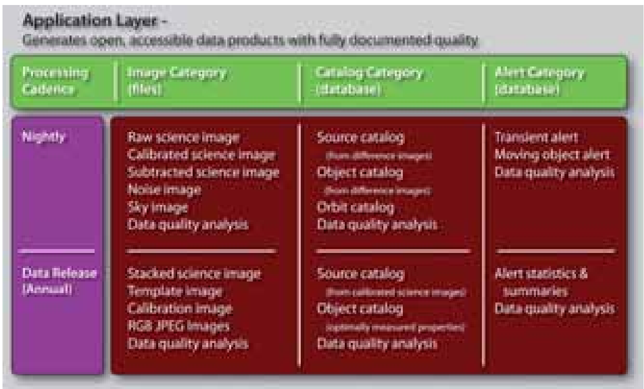

Figure 4. A summary of LSST data products. Transient alerts will be issued to the world within 60 seconds (likely less than 30 seconds after detection). JPG color images will also be world public. All other data and meta-data products will be available to collaborating observatories. With 20 trillion photometric and temporal measurements covering 20 billion detected objects, this will produce the world's largest non-commercial database.

18. Partnerships and Current Status

The LSST project is being managed by LSSTC, which is a non-profit organization. As of July 2009, 28 institutions (universities, DOE laboratories, corporations) have joined LSSTC. This is described at http://www.lsst.org/lsst/about/team.

Over 250 scientists have joined the ten autonomous LSST science collaborations. These scientists are actively refining the science cases, defining the required data products, developing optimal algorithms and calibration strategies for photometry, astrometry, photometric redshifts, and image analysis, etc. Membership in the science collaborations is open to staff at the member institutions, and through periodic open calls for applications for membership to the US and Chilean communities (information is available at http://www.noao.edu/lsst/collab_prop/Scicollab.htm). Foreign organizations joining LSST will also be able to join the science collaborations.

Our goal is to make as many of the LSST data products as possible world-public. We have an open collaboration and funding model for LSST, based on contributions from organizations around the world, US funding agencies, and private grants. In this model, there is no proprietary time and the data is as open as world-wide contributions permit. LSST is committed to providing open access to the data with no proprietary period. However, access is not without cost. Rather than duplicate the data processing and reduction facility, the most cost effective approach for foreign organizations would be to build a data access center and then support their share of the US data processing.

The current budget covers US and Chilean access only. For US and Chilean scientists there is no proprietary period for any of the data products. The policy governing access by non-US scientists will be determined by the US funding agencies and the LSST Board of Directors. There are a number of ways a foreign partner can become involved in the LSST project and likely a number of routes to operations support. From a science perspective any organization wishing to explore new and difficult frontiers with LSST (and thus have the in-depth understanding of the properties of the data that is required) should join the LSST collaboration now during the final design stage rather than later when the survey parameters have been fixed. For example, an agreement is already in place with the French high energy physics lab IN2P3, which is contributing to the camera development. Membership in the collaboration, on planning committees, and on steering committees for science and operations will be limited to those who are partners at this stage of the project.

With start of telescope (Figure 5) construction in 2011, engineering first light will occur in 2014. One year of integration and test follows engineering first light. The 3.2 Gpixel LSST camera will be installed and operational no later than 2015. Full survey operations will begin no later than 2016. At that time, calibrated images, pipeline results, nightly catalogs, and real-time alerts of transients will be available on a nightly basis. The archive and data access centers will be fully operational. The first LSST Data Release will occur after six months. Data Releases involve periodic major reprocessing of all data accumulated to date with full data quality validation and provenance metadata. After one year, the second Data Release will follow. Data Releases will follow on an annual basis until the end of the survey.

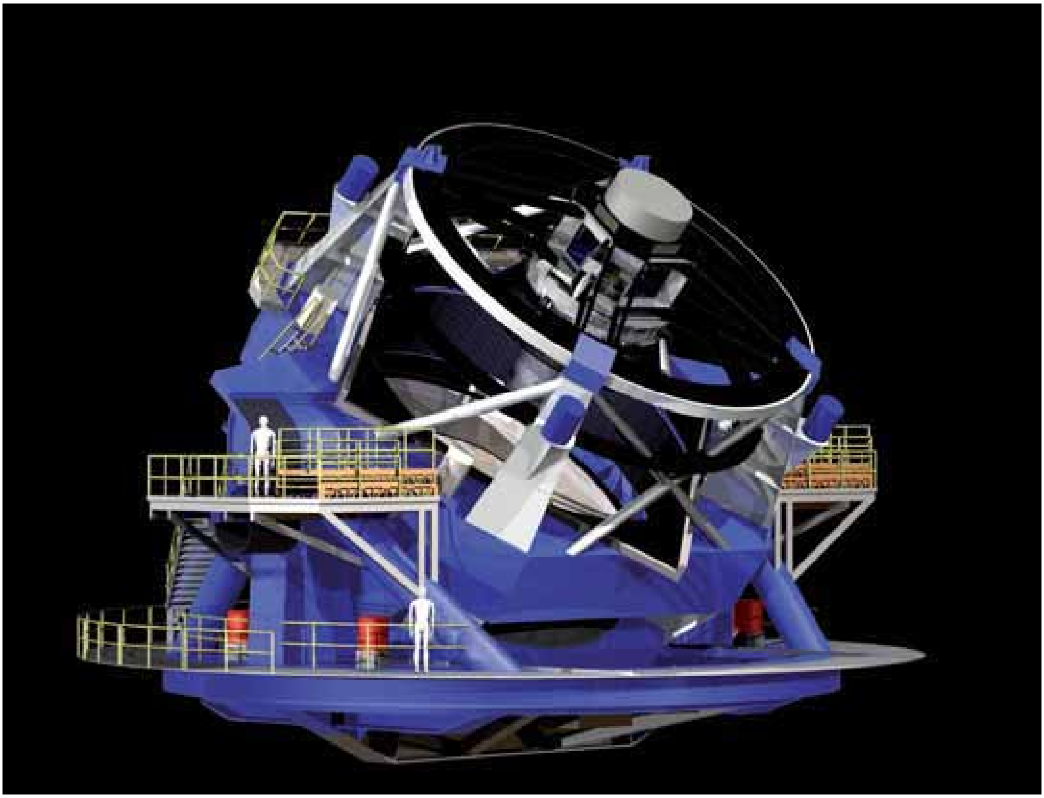

Figure 5. The 8.4 m LSST telescope.

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Science with the Synoptic All-Sky Infrared Survey Telescope (SASIR)

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Summary

The Synoptic All-Sky IR Survey Telescope project, SASIR, is aimed at obtaining a simultaneous multicolor (Y, J, H, K) synoptic infrared (IR) imaging survey of the entire sky (above declination δ = -30°) with a new, dedicated 6.5-meter telescope at San Pedro Mártir (SPM) Observatory in México. This initiative is being developed as a partnership between the Instituto de Astronomía at UNAM and INAOE, in México, and the University of California and the University of Arizona, in the USA. The 4-year, dedicated survey with a field of view of about one degree, planned to begin in 2017, will reach more than 100 times deeper than 2MASS [31], increasing the effective detection volume by more than one million. The Synoptic All-Sky Infrared Survey will reveal the missing sample of faint red dwarf stars in the local solar neighborhood, and the unprecedented sensitivity over such a wide field will result in the discovery of thousands of z ~7 quasars (and reaching to z > 10), allowing detailed study (in concert with JWST and Giant Segmented Mirror Telescopes) of the timing and the origin(s) of reionization in the early universe. As a time-domain survey, SASIR will reveal the dynamic infrared universe as never seen before, opening new phase space for discovery. Moreover, synoptic observations of over 106 supernovae and variable stars will provide better distance measures than optical studies alone.

SASIR also provides significant synergy with all present and future major facilities, improving the overall scientific return of community investments. Compared to optical-only measurements, IR colors vastly improve photometric redshifts to z ≈ 4, enhancing dark energy and dark matter surveys based on weak lensing and baryon oscillations. The wide field and target of opportunity capabilities will enable a connection of the gravitational wave (e.g., Advanced LIGO and LISA) and neutrino universe – with events otherwise poorly localized on the sky – to transient electromagnetic phenomena. SASIR will enable the distribution of dust to be mapped more precisely and with higher dynamic range than currently possible, removing systematic bias in extragalactic distance and galaxy studies.

Technical Overview: The 6.5 m primary mirror is already funded and casting begins in Summer of 2009. The SASIR telescope and dome structure will be based on the Magellan or MMT design - with demonstrated capability to deliver excellent image quality in an f/5 beam over 1+ degree diameter. This will mitigate risk and speed development. The camera consists of reimaging optics, 3 dichroics and 4 separate focal planes each seeing ~1° diameter of the sky (f/2.5 net focal ratio). In total, there will be 124 2k x 2k arrays, constituting the largest IR imager ever constructed. Thermal emission control and weight/space constraints will present significant engineering challenges, but no new technical development is required. The étendue-couleur is more than 3 orders of magnitude larger than 2MASS and >10x that of VISTA. Still, data rates (~TB per/night) are roughly 100× smaller than those expected from LSST and can be accommodated with ongoing upgrades at SPM. We expect to release survey data in incremental stages throughout the science operations, and to release transients daily.

1. SASIR Key Science Goals

The following discussion highlights the expected impact of SASIR in just some of the fields of interest in the next decade. Many of these areas are covered in a number of science white papers (WP) that were submitted to The Astronomy and Astrophysics Decadal Survey (Astro2010) generated by the SASIR collaboration. All these WP are already publicly available at http://www8.nationalacademies.org/astro2010/publicview.aspx.

2. Unveiling the Lowest-Temperature Neighbors

Our understanding of stellar populations stems from our sampling of the immediate Solar Neighborhood. This sample is woefully incomplete for brown dwarfs (BDs), objects which are incapable of sustaining core Hydrogen fusion. With masses extending from ~ 0.075MSun to below ~ 0.013MSun (the hydrogen and deuterium-burning minimum masses) BDs probe the low-mass limits of star formation processes and serve as a bridge between stellar astrophysics and planetary science. Lacking nuclear energy generation, they evolve steadily to low luminosities and low effective temperatures and are thus useful chronometers for a variety of Galactic studies (see following Astro2010 Whitepaper [WP]: Burgasser). They ultimately achieve photospheric conditions similar to those of gas giant planets ($T_{eff} \approx 100$ - 1000K). Overall, studies of BD populations and their atmospheres support a wide range of scientific endeavors: providing discriminating constraints on star- and planet-formation theories; driving advances in the properties of cool atmospheres; and guiding direct detection strategies for exoplanets. Testing models of BD atmospheres, and identifying true analogues to directly detected exoplanets (e.g., Formalhaut b, $T_{eff} \approx 500$K; [16]) will require detailed studies of BDs cooler than those currently known ($T_{eff} \approx 600$K).

UKIDSS [19] and the pending WISE [8] experiments should detect the first $T_{eff} \approx 500$K brown dwarfs within 10 pc (Fig. 1), but deeper optical/NIR surveys are required to extend samples to lower T_{eff} and beyond the local neighborhood. SASIR will provide a 100-fold increase in sensitivity over current NIR surveys, facilitating the detection of 1000K brown dwarfs out to 1 kpc (sampling the Galactic scale height of BDs), 500K brown dwarfs out to 100 pc (a 1000-fold increase in sampled volume over UKIDSS) and 300K "water-cloud" brown dwarfs out to 10 pc. This will help complete the census of stars and BDs down to the lowest masses in the

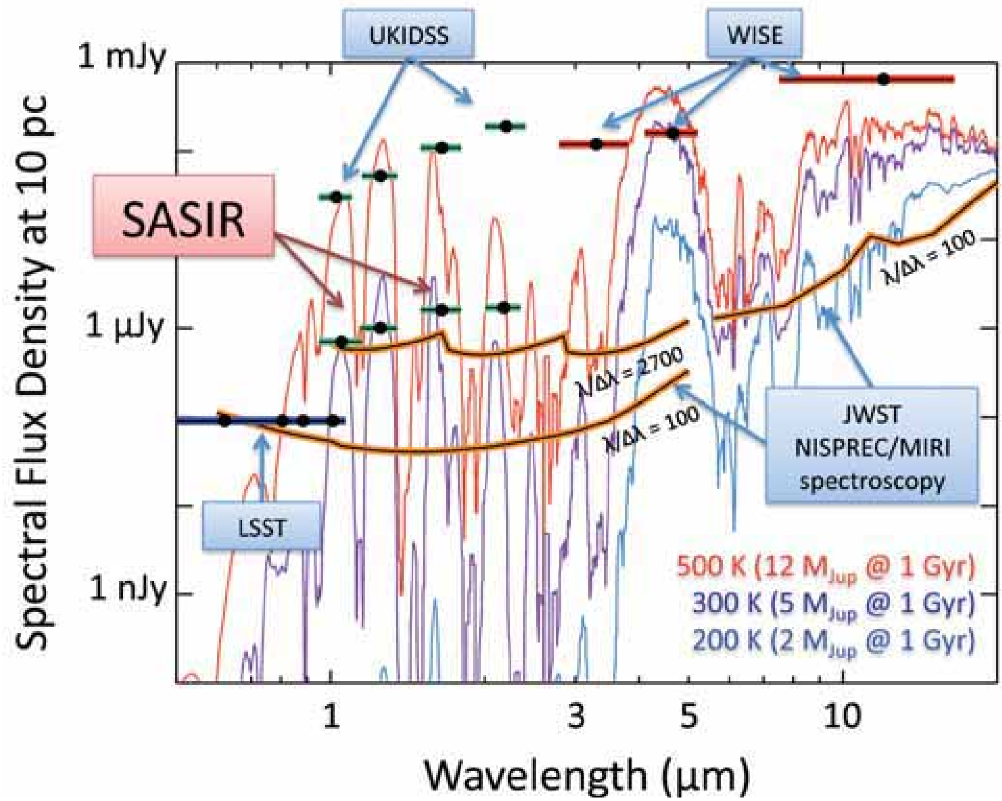

Figure 1. Model spectra [5] for 500 K, 300 K and 200 K brown dwarfs (top to bottom), scaled to a distance of 10 pc. These models correspond to masses of 12, 5 and 2 Jupiter masses at an age of 1 Gyr, respectively. Sensitivity limits for current and proposed imaging surveys (including SASIR) and spectroscopic facilities (5σ in 1 hour) are indicated.

immediate Solar Neighborhood, while sampling the density structure of brown dwarfs far from the Galactic plane. The multi-band and multi-epoch detections with SASIR, optimized in cadence for parallax discovery and proper motion studies, in conjunction with single-band detections and upper limits from WISE in the mid-IR and LSST in the optical, will enable robust color- and motion-selection of sources for efficient spectroscopic follow-up with GSMTs and JWST. Expansion of the local census will also enable direct imaging searches for Earth-mass exoplanets and other companions with next-generation high-angular resolution facilities.

3. Probing the Epoch of Reionization with Quasars

With no in situ observations, the objects responsible for the reionization of Hydrogen beyond $z \approx 7$ span a wide range of theoretical possibilities [21, 26] (WP: Prochaska, McQuinn, Bouwens, Stiavelli). The consensus is that bright quasars (QSOs) have insufficient number density at $z > 5$ to drive reionization [e.g., 11], but AGN remain the only extragalactic source known to have high escape fractions of ionizing radiation. Surveys for $z > 5$ QSOs have observed the brightest sources, leaving the faint end of the luminosity function mostly unconstrained. If the faint end steepens (as for high z galaxies in the UV) or if entirely different classes of AGN [e.g. mini-quasars; 20] exist at early times, these would contribute to the extragalactic ultraviolet background at $z > 5$. Independent of reionization studies, surveys for $z > 6$ QSOs are also valuable as tracers of the growth of supermassive black holes (BHs) that populate modern galaxies or as signposts for follow-up studies of early galaxy formation [1, 6]. In the next decade, it will be possible to determine the nature and role of QSOs during reionization with SASIR as a major contributor.

QSO searches in the reionization epoch are challenged by three effects: (i) cosmological dimming; (ii) low number density; and (iii) their extremely red color. Thus, high z QSO surveys require deep near-IR and optical imaging over a large area of sky. While SDSS and 2DF (and the upcoming Pan-STARRS project) provide large areas of optical imaging, no project has achieved comparable depth and area in the near-IR. The nearly completed UKIDSS and the upcoming VISTA surveys (a joint UK/ESO venture) should increase the current samples, but these programs also lack sufficient depth and/or area to meaningfully constrain the QSO population, especially at $z > 7$ (Fig. 2). A systematic study of AGN during the reionization era requires the survey characteristics of SASIR. At $z \sim 6$, such surveys would establish the QSO luminosity function (surpassing even LSST for reddened AGN) and are necessary for sampling even the brightest sources at higher z. These measurements would be compared against estimates of the black-hole merger rate at $z \approx z_{reion}$ from gravitational-wave experiments (e.g. LISA).

Our estimations for the number of quasars predicted to be detected by SASIR, UKIDSS, and VISTA hinges on one's assumptions for the quasar luminosity function at each redshift. Following work on surveys for quasars at $z < 5$, we model the luminosity function as a double power-law:

$$\Phi(L) = \Phi(L^*)(L/L^*)^b, \text{ with } \beta = \beta l \text{ for } L < L^* \text{ and } \beta = \beta h \text{ for } L \geq L^*.$$

At z ~ 6, Fan and collaborators [9] have estimated the bright-end exponent to be βh = -3.2 ± 0.7 and this group's recent publication reports βh values ranging from -2.6 to -3.3 [17]. These values are consistent with the null results for gravitational lensing of z ≈ 5 quasars (e.g. [27]). We adopted βh = -3.2 as the fiducial value and varied it from βh = -4 to -2.8. Presently, there are no empirical constraints on the shape of the faint-end of the quasar luminosity function at z > 5. We adopted $M^*_{1450} = -24.5$ and βl = -1.64. These values do not alter the predictions for a (relatively) shallow survey like UKIDSS but would alter the predictions for SASIR at z < 8.

Regarding Φ*, [9] reported $6 \pm 2 \times 10^{-10}$ Mpc^{-3} quasars with M1450 < -26.7 at z ~ 6 assuming a cosmology (H_0 = 65 km s^{-1} Mpc^{-1}, Ω = 0.35 and Λ = 0.65). We adopted values as low as 3×10^{-10} and as large a 1×10^{-9} in Figure 2, coupling the lower Φ* values with the shallower power-law slope. Lastly, we accounted for redshift evolution only in the estimation of Φ* and adopted the same functional form proposed [9]: Φ* (z) αexp(Czz) where Cz = -0.43 is the fiducial value. We also considered Cz = -0.2 and Cz = -1.0, again coupling the faster evolution with the steeper slope (i.e. combining pessimistic assumptions).

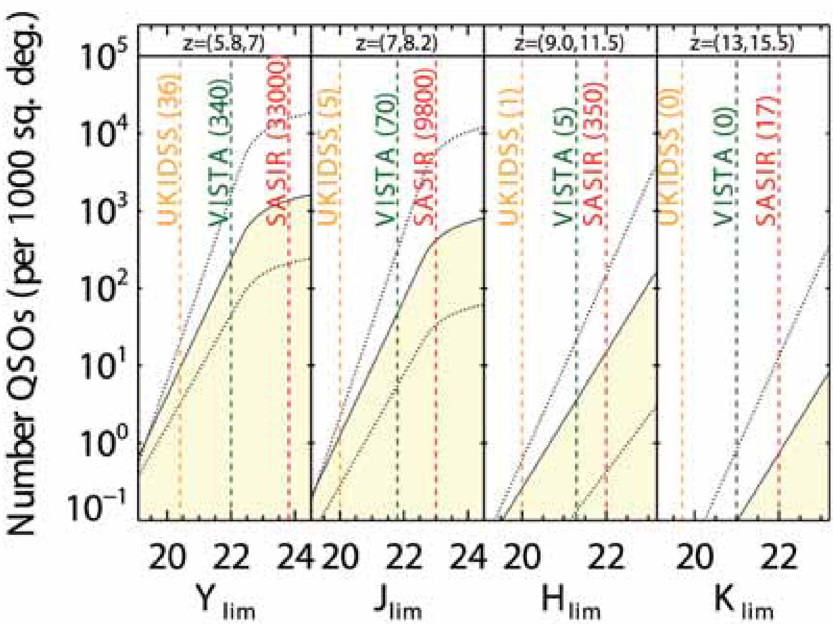

*Figure 2. Predicted surface density of quasars (solid black line) per 1000 sq. deg as a function of limiting magnitude assuming a double-power law luminosity function with βl = -1.64, βh = -3.2, with M*1450 = -245 and 6 x 10-10Mpc-3 quasars brighter than M = -26.7 [9]. The solid curves assume a number density evolution α exp(-0.43z). The doted lines indicate more optimistic and pessimistic assumptions on the number density and redshift evolution (see table 1). Vertical lines indicate the magnitude limits of UKIDSS, VISTA and SASIR with the number of detections given the proposed survey area in parenthesis. Only SASIR survey will have the depth and sky coverage to provide a meaningful sample of z > 7 quasars with a realistic chance of detecting sources at z > 10.*

For each redshift interval corresponding to the rough wavelength range of a given filter, we then computed the total volume probed (with the same cosmology as [9]) and therefore the total number of quasars per 1000 sq. deg observed. The numbers listed for the UKIDSS, SASIR, and VISTA surveys correspond to the nominal depths and area for their primary high z quasar survey assuming our fiducial values for the quasar luminosity function. These correspond to the predicted number of quasars that will be detected by the various surveys not the number of sources that will necessarily be discovered.

In Table 1, we present the set of values assumed for the evolving luminosity functions and the predicted number of quasars for each survey. One notes that even for the most pessimistic assumptions (which are inconsistent with the UKIDSS results to date), SASIR is expected to detect hundreds of quasars at z ~ 8 and ≈ 10 at z ~10.

Table 1: Luminosity Function and Surveys

Descr.	M^*_{1450}	β_l	β_h	Φ^* (10^{-10})	C_z	z = [5.8, 7] U	B	S	z = [7, 8.2] U	B	S	z = [9, 11.5] U	B	S	z = [13, 15.5] U	B	S
Fiducial	- 24.5	-1.64	-3.2	6	-0.43	36	340	33000	5	70	9800	1	5	350	0	0	17
Optimistic	- 24.5	-1.64	-4.0	10	-0.2	79	2500	370000	9	470	140000	2	32	3600	0	1	320
Pessimistic	- 24.5	-1.64	-2.8	3	-1.0	13	69	5100	1	8	800	0	0	10	0	0	0

To actually discover quasars, one must (i) distinguish quasar candidates from other sources and (ii) obtain confirmation spectra. Regarding the former, the principal contaminant is cool, Galactic stars (presuming that one can pre-select point sources from the imaging data). To efficiently discriminate quasars from stars, it is necessary to measure photometry of these sources to higher precision than the simple detection limit of the survey. One then attempts to separate quasars from the stellar locus. For sources at z ~ 6, recent efforts to follow-up UKIDSS candidates have emphasized the value in deep optical imaging (i, z; [13]; [23]). In this regard, SASIR would surely benefit from the ongoing Pan-STARRS survey and (eventually) the proposed LSST project. For higher z candidates, color selection could be made with the near-IR photometry alone. We have not yet folded in all of these considerations for SASIR, in part because our own near-IR magnitude limits are still under consideration. The final step is to acquire near- IR spectra of the sources to classify the target and measure the redshift. For SASIR, the faintest sources detected would require new facilities, e.g. JWST, GSMT. Indeed, this science case is one of the many that highlight the synergy between SASIR and other planned/proposed near-IR projects.

It is important to consider in greater detail whether our assumptions were consistent with the search for high z quasars using the UKIDSS survey. The latest UKIDSS publication on high z quasars reports the discovery of 4 objects with z = 5.72 to 6.13 [23], two of which were previously discovered by SDSS. These four were drawn from 870 sq. deg. of the UKIDSS Large Area Survey (LAS). Our estimation of 36 quasars assumes the full 4000 sq. deg. planned for the UKIDSS-LAS. Extrapolating their success thus far, one estimates UKIDSS will discover 4 - 40 quasars (95% c.l.) in the full LAS. It is possible, therefore, that our fiducial model is somewhat optimistic but the UKIDSS team has yet to make any rigorous estimates of completeness corrections for their follow-up efforts. In either case, we are confident the range of assumptions listed in Table 1 conservatively brackets the plausible range of quasar luminosity functions.

4. The Cosmic Distance Scale, Dark Matter and Dark Energy

An IR View of Periodic Variables in the Local Universe: Pulsating variable stars (WP: Walkow-icz) are preeminent distance indicators in the local universe. When RR Lyrae and Cepheids are used, however, unmodeled dust and metallicity effects manifest directly as uncertainties in cosmological parameters [3, 33]. SASIR would allow for precise calibration of the period–luminosity (P-L) relation of these two classes in the IR, largely skirting the problems with dust (and potentially metallicity [32]) which complicate similar efforts at optical wavebands. Multiple observations at random phases would build an unprecedented calibration of the P-L relations and enable GSMTs to measure precise distances well beyond the Local Group and fix the rungs of the cosmic distance ladder out to ~ 25 Mpc. Mira variables, promising new distance indicators, would also be observable with SASIR to ~ 4 Mpc with what appears to be a metallicity independent P-L relation [12].

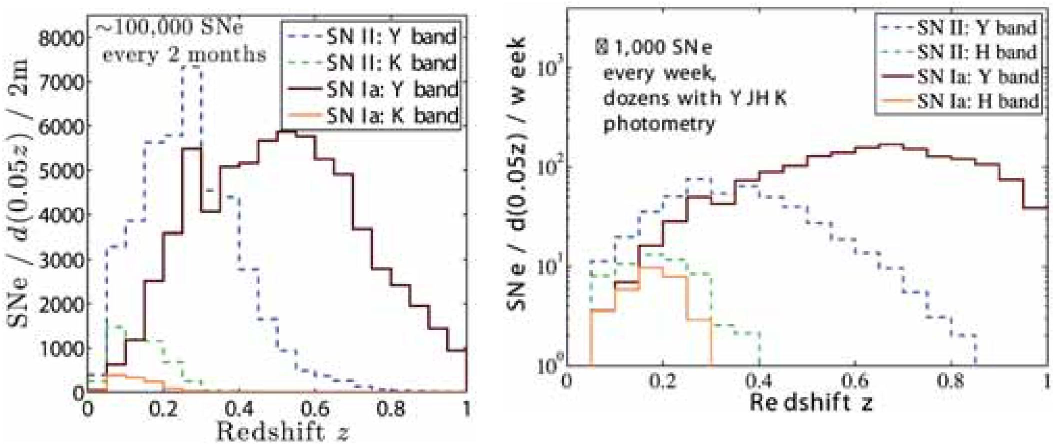

Figure 3. Expected SN counts for two types of surveys with SASIR: a rolling search with weekly cadence (left), and "all-sky" monitoring every two months (right). The number of SNe in the different surveys is inversely proportional to the light-curve information we will have for each SN. The samples are complementary and both have cosmological use.

Infrared Supernovae: Type Ia supernovae (SNe Ia) (WP: Howell) are better standard candles in the IR than at optical wavebands [36] and minimize systematic effects that plague Ia optical cosmography. Type II-P SNe are an emerging distance indicator (e.g., [28]) recently shown to be almost comparable in precision to SNe Ia ([25]; WP:

Poznanski), and could be even better standard events in the IR. In addition to cosmography, searching for SNe in the IR will improve our understanding of their rates (largely circumventing dust effects) and hence constrain their diverse progenitors. Using optically determined rates alone, SASIR will detect more than 106 SNe during the four-year survey (Fig. 3).

Photometric Redshifts for Weak Lensing and Baryonic Oscillations: Wide-field IR photometry provides a compelling improvement in the photo-z measurements of galaxies, especially beyond z ~ 1.5 (Fig. 4, left). The enhanced accuracy for galaxies across the Northern sky will greatly improve the returns on weak lensing and baryonic oscillation experiments with wide-field optical facilities (WP: Riess, Eisenstein, Heap, Zhan).

Galaxy Evolution and High-redshift Clusters: A frontier endeavor for the next decade will be to determine the progress of nascent galaxies as a function of local environment as the proceed from the the "blue swarm" of small star-forming objects at 2 < z < 3 to the well-defined red sequence of massive galaxies seen in both galaxy clusters and the field at z < 1 (WP: Holden, Labbe, Stanford). The appearance of the red sequence will probably spread from the high- to low-density environments, such as groups, before becoming established in the field. Such a study requires identifying the full range of environments at z > 2, through wide-area imaging, since halos of mass M > 1014 MSun are exceedingly rare at z > 2 (Fig. 4, right).

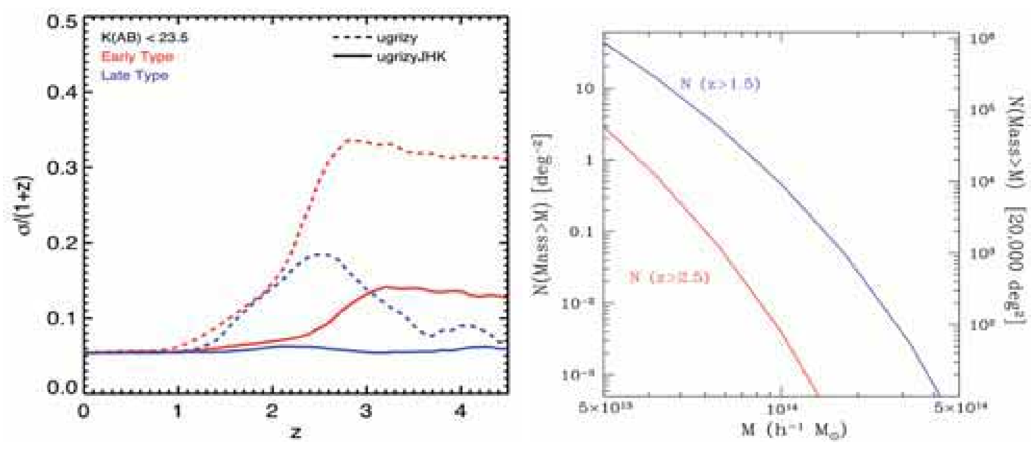

Figure 4. (Left) Simulated photometric redshift accuracy for early (red) and late-type (blue) galaxies. Dashed lines show the expected performance of LSST/Pan-STARRS4 alone. Solid lines include NIR data from SASIR, which vastly improve accuracies at z > 1. Simulations assume a 4% floor to these accuracies [4]. (Right) Expected cluster demographics by mass in two redshift regimes. Finding the rarest massive clusters requires a wide-field near-IR imaging survey so that galaxy populations at z > 2 are selected at rest frame wavelengths.

5. A New Phase Space for Transient Discovery

Deep multicolor synoptic monitoring on hundreds to thousands of square degrees on minutes to months timescales would break new ground in the infrared, opening up the potential for totally new classes of objects found by IR variability. There are indications that exploration in this space phase will be fruitful (e.g., WP: Kulkarni Wozniak, York), particularly relevant to "multi-messenger" astrophysics. Indeed the explosive events which dominate the high-energy sky - involving compact objects such as neutron stars (NSs) and BHs (BHs) (of both the stellar and supermassive varieties) - should produce long-wavelength signatures (Figure 5).

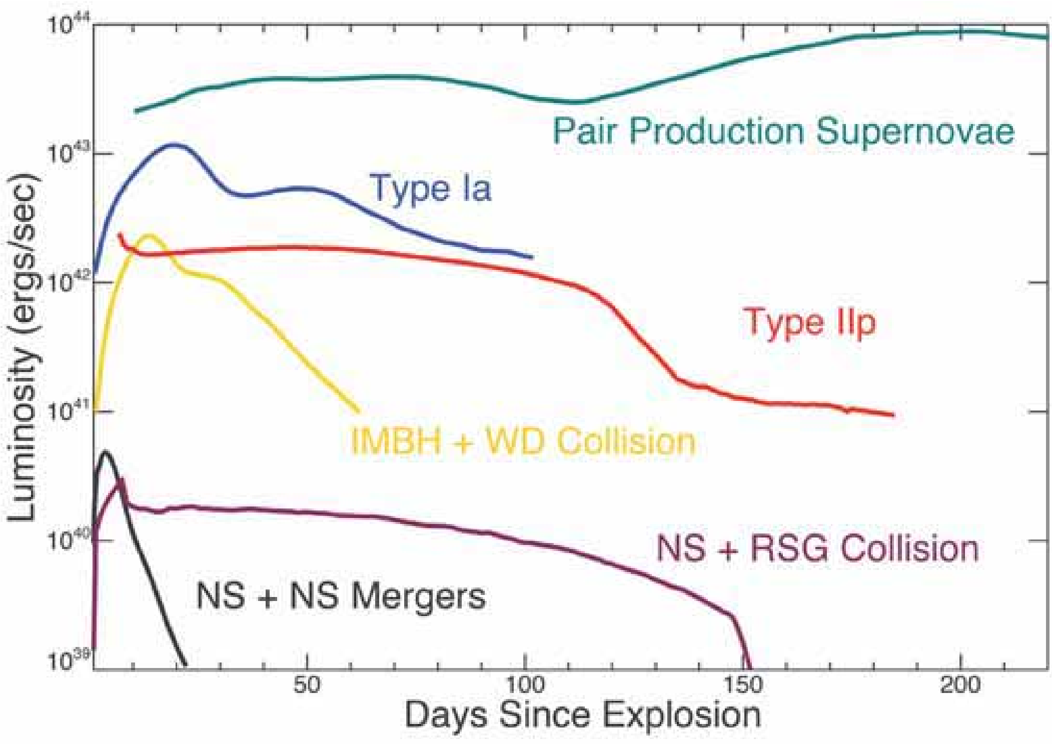

Figure 5. Characterizing the transient universe at IR wavelengths. Aside from the "known" Type Ia (blue) and core-collapse (red) SNe, new types of extragalactic transients are expected to arise from cataclysmic events. Shown are our estimated restframe infrared light curves resulting from the collision between a NS and red supergiant (RSG; purple), the disruption and ignition of a white dwarf by an intermediate mass BH (yellow), and the merging of a NS binary (powered by r-process nucleosynthesis; (black). SASIR will readily see NS-NS mergers to the Advanced LIGO volume (see §2.4). These preliminary model calculations suggest that an assortment of peculiar transients should be uncovered by SASIR, providing a complementary view (less obscured by dust) of the transient universe than that offered by optical synoptic surveys.

Motivating the need for wide-field monitoring, TeV gamma-ray Čerenkov telescopes and neutrino detectors will localize events only to degree-scale accuracy. Likewise, Advanced LIGO and LISA are expected to localize degenerate object merger events through gravitational waves (GW) with, typically, one-degree scale uncertainties. Much of the science extracted from these new windows on the universe will require the identification of electromagnetic counterparts, which would yield the redshift of the host galaxy and enable their use as standard sirens for cosmography [18, 30] (WP: Bloom). Little is known of these signatures but indications are that the IR is a valuable window [Fig. 5; 16, 29] (WP: Hawley, Phinney, Bloom). As such, SASIR, with its rapid access to deep wide-field imaging is a promising tool.

6. Broad Scientific Reach and Synergies with Other Major Facilities

Beyond the above SASIR highlighted projects, the following lists additional examples of science white books (WP) submitted by us and other groups to Astro2010 (one can reach all papers directly at http://www8.nationalacademies.org/astro2010/publicview.aspx):

- Discover new satellites of the Galaxy minimizing dust biases (WP: Bullock, Johnston),
- Produce large new samples of strong lenses (WP: Coe, Koopmans, Marshall),
- Survey the oldest (i.e. coldest) white dwarfs in the Milky Way (WP: Kalirai),
- Produce a Galactic dust-extinction map of unparalleled spatial resolution (WP: Gordon),
- Probe the bright end of the galactic luminosity function at $z > 5$ (WP: Bouwens),
- Stellar population analysis of nearby galaxies (WP: Kalirai, Kirby, Lu, Meixner, Worthey, Wyse),
- Discover star cluster systems (WP: Rhode),
- Study stellar morphology (bulge/disk) in nearby galaxies (WP: Clarkson),
- Map the distribution of low-mass stars well beyond the solar neighborhood (WP: Cruz),
- The search for light bosons (WP: Chelouche),
- Finding Type IIn SNe at $z > 5$ (WP: Cooke),
- Probing quasar variability (WP: Elvis, Murray),
- Long-wavelength signatures of tidal disruption events (WP: Gezari),
- Exploring the nature of X-ray and explosive transients (WP: Soderberg, Wozniak),
- Studies of variable stars from near to far (WP: Walkowicz)

It is worth emphasizing that many of the science WPs submitted to Astro2010 have called for wide-field, near-IR surveys of the sky. While some science goals demand the high spatial-resolution afforded by space missions, most could be done for far less expense by a ground-based observatory like SASIR.

7. Technical Overview

The enormous scientific promise of SASIR is based on a dedicated wide-field (1 degree diameter) large aperture telescope (6.5 m in diameter), located in a dark site with a large fraction of clear nights (~75%), enabling deep and synoptic imaging of the whole Northern sky simultaneously in NIR bands (Y , J , H and K) with four independent focal planes.

This uniquely powerful survey and facility does not require new technology exploration or a totally new kind of telescope. Indeed, as described in §3.1, the SASIR telescope design will use already proven and operational concepts (such as from the Magellan and MMT telescopes) as the point of departure. Nevertheless, given the confluence of a moderately wide field with multiple and large focal planes, its actual design and technical feasibility, with present day technology and IR materials, needs to be carefully studied in the preliminary design phase

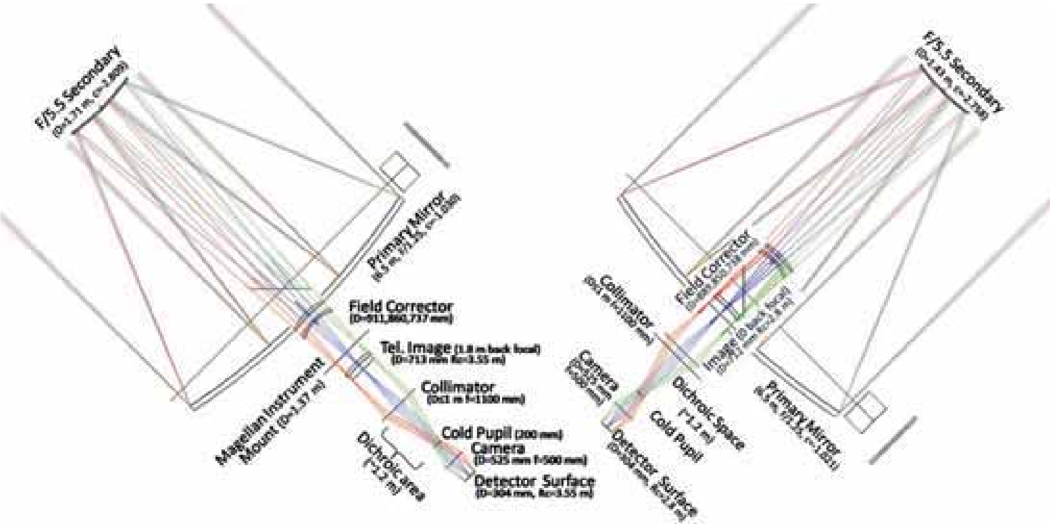

Figure 6. SASIR telescope designs (Magellan nominal back focus at right, null back focal at left). A single arm is shown with indicative camera and collimator parameters (dichroics not drawn). The telescope and corrector deliver and effective f/5.5 focal, the whole system is ~f/2.5. Relevant characteristics of the main components are shown. These two baselines are to be studied (optics, mechanics, costing) in more detail.

8. The 6.5 meter SASIR Telescope

The telescope structure and primary mirror are to be based on the highly successful and efficient Magellan Telescopes in operation at Las Campanas Observatory in Chile and the MMT telescope at Mt. Hopkins. The Magellan and MMT optics and structures are each well suited to wide-field imaging. In particular, a successful one-degree f/5 corrector has been in operation at the MMT [10] while a second system is being commissioned at Las Campanas. Furthermore, we have demonstrated [14] that this design is quite capable of delivering fields of view beyond 1.5° in diameter. The three main challenges facing the design of the SASIR telescope are therefore of a different nature:

- Simultaneous feeding of up to four focal planes, with collimator/camera NIR optics of reasonable size;

- Controlling spurious thermal emission in the H and K bands (under a proper baffling system, coupled with space for a cold pupil);

- Maintaining the instrument within the weight and envelope limits of the Magellan or MMT structure.

The first challenge not only drives the survey speed but makes SASIR different and quite powerful with respect to its closest relatives, the 4 m-class VISTA and UKIDSS systems and the 8 m LSST. The SASIR collaboration will be developing its telescope concept by fully investigating and resolving among potential telescope solutions that optimize the science returns and minimize the risks of the camera design: a conventional telescope plus image reducer(s), as here presented, a 3-mirror telescope with an intermediate collimated beam, or a conventional telescope with dichroic(s) in non-parallel beams.

A range of variants on the base Magellan design are currently under consideration for a solution that will permit up to four individual-band cameras, each with about 1° field of view (FoV), with NIR refractive optics under about 500 mm in diameter. The current reference concept consists of a f/5.5 Ritchey-Chretien design with a 3-lens field corrector (all spherical, Silica-like glass). In order to allow for a cold pupil as well as the placement of dichroics, the telescope is coupled to a focal reducer, with a collimated beam of 200 mm and a camera with focal length of 500 mm. Figure 6 shows two examples of the telescope concept, the first one maintaining the back focal distance of Magellan, while the second telescope focuses at the primary vertex, exploring the range in which the diameter of the secondary and the height of the pupil can be controlled.

The present studies include cases for telescope f-ratios from f/3.5 up to f/11, at both Cassegrain and Nasmyth stations, and a range of pupil diameters. The designs shown deliver an image quality close to the diffraction limit across the whole FoV, between 0.03" and 0.1" FWHM. These idealized (pre-construction) telescope performances indicate that most of the optical error budget can be left for the more difficult collimator and camera designs, as well as for the construction and operation of the entire system. These telescope concepts let us explore the main parameter space and general dimensions for the SASIR collimator and camera systems. A full range of parameter exploration is expected for the conceptual and preliminary design phases of the project.

9.The SASIR Camera

Foreoptics: SASIR plans a split-beam design for the camera optics, like 2MASS, to simultaneously image in 4 filters. The full optical design of SASIR will be driven by the following guide-lines and constraints: the aperture and curvature of the primary mirror (f/1.25), a FOV of 1.06°, a plate scale of 0.228" per 18 μm pixel (f/2.5 net system), an after-construction-under-operation image quality that does not deteriorate by more than a few percent the median NIR seeing, a high-throughput design (e.g. efficiency > 30%) at least within the $\lambda = 0.8–2.4$ μm range, and a system with low thermal emission from its optical components that also permits the proper buffering of scattered thermal emission. The conceptual designs of the collimator and camera, based essentially on a scaled version of already known systems (e.g. FourStar NIR Camera for the Magellan Telescope; [24]), will be developed in parallel and share optimization constraints with the telescope concept.

Detectors: Given the expense for science-grade IR detectors, our design is driven by a desire to cover a large field of view with the fewest pixels while still adequately sampling the good seeing at SPM. The nominal detectors are 2048 x 2048 arrays with 18 or 20 μm pixels, now commercially available.1 This translates to 0.228 - 0.25 "/pixel. We are baselining 124 science-grade arrays (Figure 7). SASIR will not be sensitive to the read-noise of the detectors, as even short exposures are expected to be background limited. We will thus allow for as flexible and dynamic imaging as the science requires.

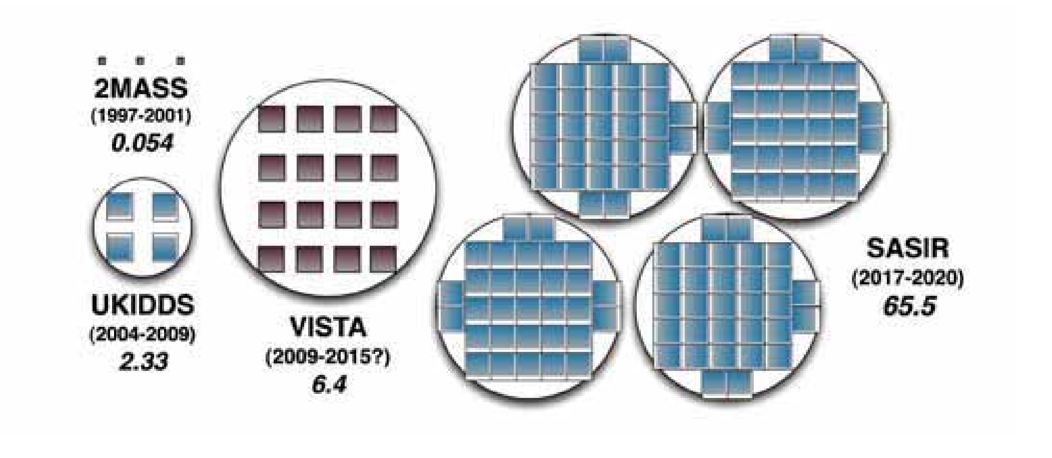

Figure 7. To scale physical comparison of the focal planes of 2MASS, UKIDDS, VISTA and SASIR. The éntendue-couleur (m^2 deg^2 x number of simultaneous bands), the instantaneous light grasp, is shown for each facility.

A Pathfinder Instrumentation Project: Our collaboration has begun construction of a new camera, the Reionization & Transients Infrared (RATIR) Camera, to be housed on the 1.5 m telescope at SPM. The 2-year experiment has its own transients science drivers, but will serve as an important pathfinder for SASIR development: RATIR will be used for collaboration building, to engage 3rd party vendors and to help the collaboration gain first hand experience with the detector operations in advance of SASIR. RATIR will obtain nightly transmission and sky brightness statistics in Y, J, H for the duration of that experiment; this will directly feed into the SASIR survey simulations. As of now, we have only limited information about the SPM IR sky background as a function of lunar phase and almost no information about the Y-band site metrics.

10. Survey Strategy and Cadence Optimization

The Survey optimization will be revised in detail during the preliminary design, accounting for articulated priorities of the diverse science cases. The baseline plan calls for 20 second double-correlated exposures – this optimizes on-sky exposures without saturating fainter 2MASS stars (which will be crucial for establishing the photometric baseline). For a total on-source dwell of 80 seconds (2 visits per night consisting of 2 integrations each) and nominal slew time to next field of 6 seconds, we expect to cover about 140 sq. deg per 8-hour night, implying that the entire visible sky from a single site could be imaged every 2-3 months. Table 2 shows the expected point source and extended source sensitivities (see also Figure 8).

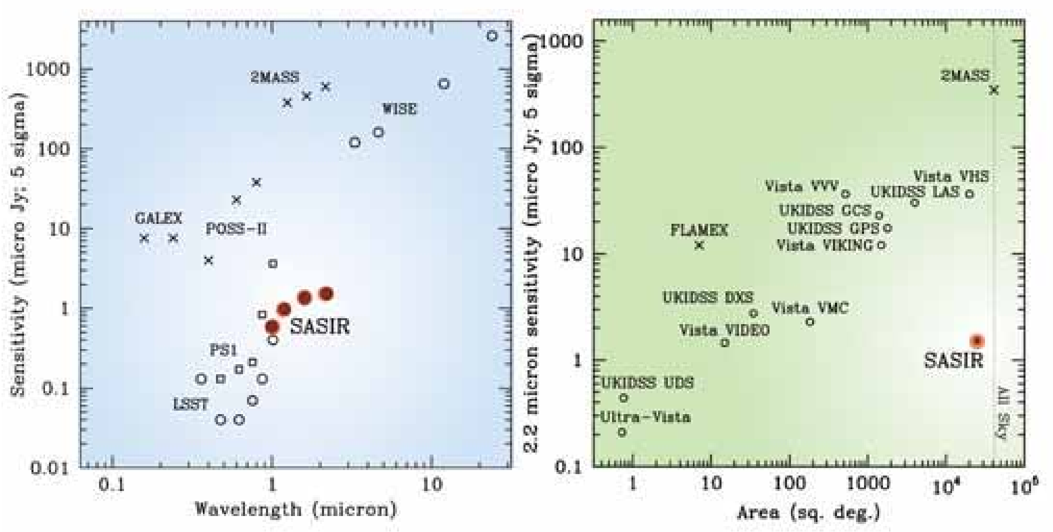

Figure 8. Comparison of the nominal SASIR survey with other significant surveys already completed (x symbol) or planned (circle or square open symbols). Left: The point source sensitivity versus wavelength for wide- area surveys where we have assumed 6 total visits (480 s) for SASIR. Right: The point source K -band sensitivity versus sky coverage. The other survey data for these figures were compiled by D. Stern (JPL).

The simplest survey strategy would be to cover the sky repeatedly with roughly equal time between visits. Over a 4-year survey each position could be observed ~ 6 times. To determine the parallax and proper motions of objects in the solar neighborhood (§2.1), we require at least three visits per field. In practice, there will be several different cadence strategies, with both competing and complementary goals. For instance, a fast transients search would yield very deep imaging in several hundreds of degrees squared. The SN search (§2.3) would benefit from repeated scans of the same part of the sky every few nights, while a search for high proper motion objects would only require repeat observations on a months to years timescale.

Table 2. Nominal Sensitivities from SASIR Concept Design

Filter	Point Source Sensitivity Single Epoch (5-σ) [AB mag]	 [μJy]	 Survey (5-σ) [AB mag]	 [μJy]	Extended Source Sensitivity Survey (5-σ per pixel) [AB arcsec^{-2}]	 [μJy arcsec^{-2}]
Y	23.49	1.45	24.47	0.59	23.32	1.71
J	22.95	2.40	23.93	0.97	22.78	2.82
H	22.60	3.30	23.57	1.35	22.42	3.89
K_S	22.47	3.74	23.44	1.52	22.29	4.40

Note. - Based on a preliminary simulation of a four band survey (Y and 2MASS filters J, H, KS) with 75% clear weather fraction and average seeing of 0.6 arcsec and 18 μm pixels. Each epoch assumes 80 sec total integration with 6 epochs per field over the entire survey (24,000 sq. deg.). As a consistency check to the simulation, note that the 5σ limiting magnitude of 2MASS (1.3m diameter, 7.8 s integration, seeing ~ 2.5”) was 17.55 AB (346 μJy). For sky-limiting imaging, the limiting magnitude increases as 2.5 Log10 (diameter time 0.5/seeing), with diameter, time, and seeing expressed as ratios. For the nominal six visit all-sky survey, this implies a nominal depth of 5.4 mag fainter than 2MASS.

11. Data Taking and Data Management Strategies

SASIR Data Management will benefit from direct experience with the Peters Automated Infrared Imaging Telescope (PAIRITEL) Project [2], the largest time-domain robotic telescope operating at infrared wavelengths. In particular its low-level telescope and camera interfaces, pipeline and archive system, and autonomous scheduling system are a reference for determining a baseline data taking strategy commensurate with instrument limitation and SASIR science goals. We envision that the Data Management architecture developed fully in the conceptual design phase will most resemble that of Pan-STARRS, UKIDSS and VISTA.

12. Project Site and Infrastructure

The site, located in the northern part of Mexico in the Sierra San Pedro Mártir in the state of Baja California at an altitude of 2890 m, has been developed over the last forty years and has three telescopes with main optics diameters of 2.1-, 1.5-, and 0.84 m, with a number of photometric, spectroscopic and imaging capabilities in the optical, near-, and mid-infrared regimes. SPM excels in the transparency and darkness of the night sky as well as in the seeing quality and stability [7, 34, 35]. Comparison with other sites suggests that SPM has the largest percentage of clear nights of any site in the Northern Hemisphere. The median seeing reported by Michel et al. 20 is 0.6" in the in the V band. It is yet to host competitive next-generation telescope facilities that fully exploit its unique virtues. The site had been considered by the LSST consortium prior to the decision to locate it in Cerro Pachón (Chile), as well as by next-generation extremely large telescope projects, such as the Thirty Meter Telescope (TMT).

The road that climbs the Sierra is paved up to the entrance to the National Park, while the last 16 km (within the park) is being completed now. Ample lodge and workshops at the Observatory are located 2 km from the telescopes and the selected SASIR site. The Observatorio Astronómico Nacional (OAN) has five electric generators with capacities of 280, 230, 200, 150, and 90 kW, respectively, but plans to soon connect SPM to the public electric network. This new line will also carry a fiber-optic network for a very high speed network, upgrading the current microwave link. IA-UNAM has a research branch in nearby Ensenada with a staff of 25 astronomers and a similar number of technical staff and students. IA-UNAM headquarters at Ensenada also serves as the logistic and administrative station for the observatory at SPM.

13. Design Considerations for the 2nd-Phase Operations

The SASIR Telescope is expected to be operational for 30+ years, well after the SASIR Survey is completed. The consortium envisions the telescope to continue mostly as a dedicated surveying facility. The current plan is to perform a wide-field optical/NIR spectroscopic survey, making use of the large detector investment. The SASIR telescope will be designed so as not to preclude or undermine the feasibility of such a multiobject spectroscopic survey.

14. Project History, Partnerships, and Current Status

The SASIR initiative started in 2007 and the design is still at a preliminary conceptual level. The preliminary conceptual design was created in tandem with the development of the SASIR science case over 2008, culminating in the production of a preliminary whitepaper. Two principals meetings were conducted in the first half of 2008 (in Santa Cruz and in México City). A two-week collaboration workshop, with >40 people in attendance, was held in Puebla, México in August 2008. The most significant engagement (face-to-face meetings, regular telecons) with third party vendors to-date has been with detector manufacturers (Raytheon and Teledyne).

SASIR is an international partnership between the Instituto de Astronomía at Universidad Nacional Autónoma de México (IA-UNAM), the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), the University of California, and the University of Arizona. The SPM site (OAN) is operated by UNAM. The University of Arizona is in charge of the casting and figuring of the primary mirror. Extending partnerships, particularly universities and national laboratories, is a priority for the collaboration.

The SASIR telescope and camera are to be developed over an eight year span, starting in 2009. The facility will be operated to carry out and complete the SASIR Survey in four to five years, starting in 2017. The SASIR collaboration expects to release SASIR survey data to the astronomy community incrementally during the science operations (following the models of 2MASS, SDSS, UKIDSS), with no more than a 18-20 month delay. Following the LSST model, transients will be released to the community at least as quickly as everyday, and possibly in near real-time.

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Matthew Greenhouse and the JWST Science Working Group[1]

The James Webb Space Telescope: Mission Overview and Status

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Abstract
The James Webb Space Telescope (JWST) is the infrared successor to the Hubble Space Telescope. It is a cryogenic infrared space observatory with a 25 m² aperture (6 m class) telescope yielding diffraction limited angular resolution at a wavelength of 2 μm. The science instrument payload includes three passively cooled near-infrared instruments providing broad- and narrow-band imagery, coronagraphy, as well as multi-object and integral-field spectroscopy over the 0.6 μm < λ < 5.0 μm spectrum. An actively cooled mid-infrared instrument provides broad-band imagery, coronagraphy, and integral-field spectroscopy over the 5.0 μm < λ < 29 μm spectrum. The JWST is being developed by NASA, in partnership with the European and Canadian Space Agencies, as a general user facility with science observations to be proposed by the international astronomical community in a manner similar to the Hubble Space Telescope. Technology development and mission design are complete, and construction is underway in all areas of the program. The JWST is on schedule to reach launch readiness during 2014.

1. Designing for Discovery

The science motivation for the JWST mission was developed by a succession of international science working groups and is described by Gardner et al. 2006, with updates maintained by the JWST flight science working group[1] at: http://www.stsci.edu/jwst/science/whitepapers/ . This science case forms the basis from which detailed science and mission requirements were derived to guide engineering design and development of the JWST as a research tool. The science observations that are actually implemented by the JWST will be proposed by the international astronomical community in response to annual peer reviewed proposal opportunities. The discovery potential of the JWST relative to other concurrent facilities is discussed in Thronson, Stiavelli, and Tielens 2009.

The emergence of the first sources of light in the universe (after decoupling) marks the end of the "Dark Ages" in cosmic history (Rees 1997). The ultraviolet radiation field produced by these sources created the ionization that is observed in the local intergalactic medium (IGM). The JWST design provides unique capability to address key questions about this era in cosmic evolution including: what is the nature of the first galaxies; how and when did ionization of the space between them occur; and what sources caused the ionization?

The JWST architecture is primarily shaped by requirements associated with answering the above questions. In contrast to the Hubble Space Telescope (HST), the JWST is designed as an infrared optimized telescope to observe the redshifted ultraviolet radiation from the first galaxies and supernovae of the first stars. To achieve the nJy sensitivity needed to observe this era (z ~ 6-20), the observatory must have a telescope aperture that is larger in diameter than the largest rocket faring, and the entire optical system must be cooled to ~40-50K. Finally, the resulting large deployable cryogenic telescope must achieve HST-like angular resolution across the SWIR spectrum. The major observatory design features seen in Figure 1 trace directly from these requirements and differ markedly from those of the HST (Table 1).

Performance Parameter	HST	JWST
OTE Diameter (meters)	2.4	6.1 by 6.6
Mass (kg)	11600	6330
Output Power at Load Input (watts)	2400	2079
Unobscured Aperture (Sq meters)	4.5	25
Overall Optical Transmission	45 to 25%	62% to 43%
Telescope Field of View (Arcmin)	14.6 (Radius)	18 by 9
Wavelength of Diffraction Limited Performance (Microns)	0.5	2
Rayliegh Radius (Arcsec)	0.043	0.069
Telescope Strehl Ratio	80%	80%
Pointing Accuracywithout Fine Guidance (Arcsec)	22	7
Pointing Stability with Fine Guidance (Arcsec)	0.007	0.007
Total Pixels (Megapixels)	25	60
Data Throughput (Gbits/day)	27	471
Observing Efficiency	50%	70%

Table 1. Key design parameters of the JWST and HST

Figure 1. Full scale display model of the JWST space vehicle

The JWST science instrument payload is designed to probe the first galaxies with high angular resolution near-infrared image surveys in broad-band filters. This capability enables identification of primeval galaxies by searching their Lyman continuum break with multi-filter photometry. This prominent feature occurs in the near-infrared (1.3 – 2.6 μm) for galaxies with redshifts in the range of 10 – 20. This broad-band technique exploits the maximum sensitivity of the observatory, such that the space density of galaxies can be probed to z~20. JWST high angular resolution imagery across the 0.6 – 29 μm spectrum will probe the assembly and evolution of galaxy morphologies to enable observation of when and how the Hubble sequence formed.

The JWST is designed to enable near-infrared multi-object spectroscopy of thousands of galaxies at several spectral resolutions ($\sim 10^2$, $\sim 10^3$). This capability will probe the chemical evolution and metallicity of galaxies, and the ionization state of the IGM across cosmic time. Low resolution multi-object spectroscopy will enable calibration of photometric redshifts for primeval galaxy studies. The JWST spectrometers include integral field capability over the 0.6 – 29 μm spectrum that will enable detailed spectral, morphological, and kinematic studies of high redshift galaxies and local galaxy nuclei. JWST spectroscopy includes wide field scanning Fabry-Perot and narrow-band filter imagery at low (~1%) spectral resolution and high angular resolution to enable both wide field emission line imagery and high redshift surveys of emission line galaxies.

The JWST observatory design enables wide discovery potential beyond cosmology and galaxy studies. The JWST high angular resolution imagery and imaging spectroscopy across the 0.6 – 29 μm spectrum will open a new window on observation of star formation in our own galaxy to reveal: how molecular clouds collapse; how environment effects star formation and vice-versa; the mass distribution of low mass stars; and the relationship between stellar debris disks and the formation of terrestrial planets.

The JWST instruments include coronagraphic imagery and spectroscopy capability that will enable a wide range of stellar debris disk studies and extra-solar planet observations at high angular resolution. High dynamic range modes of the JWST instruments will enable extra-solar planet transit photometry and spectroscopy across the above wavelength range. The JWST observatory enables non-sidereal tracking so that the full observatory capability can be used to observe the outer solar system to enable comparative studies between stellar debris disks and our own solar system.

2. Architecting for success

The large primary mirror area and cryogenic operating temperature are key drivers on the JWST mission architecture. The telescope is the largest space telescope ever constructed. Liquid cryogen cooling techniques used by prior infrared space observatories (IRAS, ISO, Spitzer) cannot be practically scaled to meet JWST requirements, and existing cryo-cooler technology could not meet the heat lift requirements of this large system. As a consequence, a passively cooled architecture was adopted for the majority of the system. A libration point orbit about the Sun-Earth L2 point (Figure 2) was selected to meet this requirement. In this orbit, the observatory follows the earth around the sun such that the sun and earth always appear in the same direction. Hence, it is possible to continuously shield portions of the observatory from the sun and earth to enable passive cryogenic cooling. The orbit about the L2 point itself is sized to avoid eclipse; thus enabling continuous generation of power with solar arrays. This orbit has a period of approximately 6 months and is unstable, requiring use of station-keeping thrusters. Propellant for orbit maintenance and momentum management ultimately limits the lifetime of the observatory to approximately twice the duration of its required 5 year science mission.

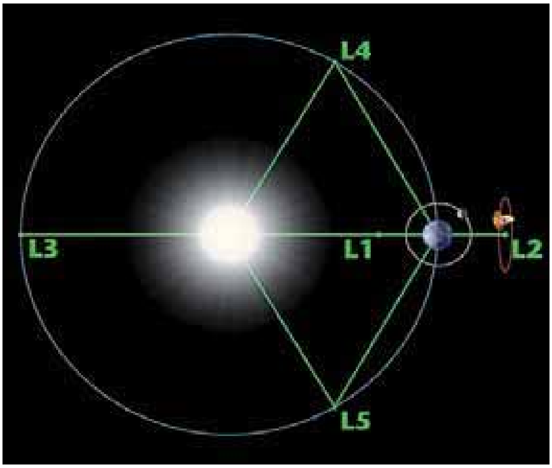

Figure 2. The JWST will orbit the Sun-Earth L2 point.

The JWST can observe the whole sky while remaining continuously in the shadow of its sun shield. As shown in Figure 3, the space vehicle can pitch through an angle of 50 degrees and rotate completely about the earth-sun line to observe sources within an annulus that covers approximately 39% of the sky. As the observatory orbits the sun, this annulus sweeps over the whole sky each year with small continuous viewing zones at the ecliptic poles.

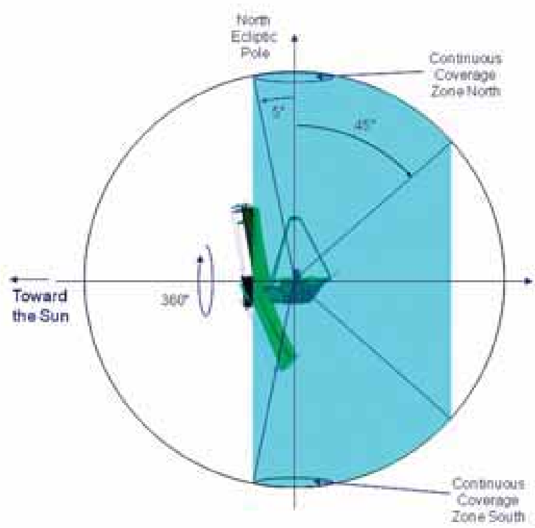

Figure 3. The JWST can observe the whole sky while re-maining in the shadow of its sunshield.

The JWST can reach this orbit in approximately 100 days after launch from Kourou Launch Center in French Guiana using an Arian 5 ECA launch vehicle via a direct transfer trajectory. This class of launch vehicle provides adequate fairing volume and mass capability to enable an observatory design that meets the above science requirements.

The 6.5 m diameter telescope and its tennis-court sized sunshield, are designed to be stowed within the Ariane 5 m diameter fairing along with the science instrument payload and spacecraft (Figures 4, 5) such that the observatory can deploy into the operational configuration shown in Figure 1 (see animation at: www.jwst.nasa.gov/videos_deploy.html). The observatory is launched warm and cooling begins after sunshield deployment en route to the L2 point.

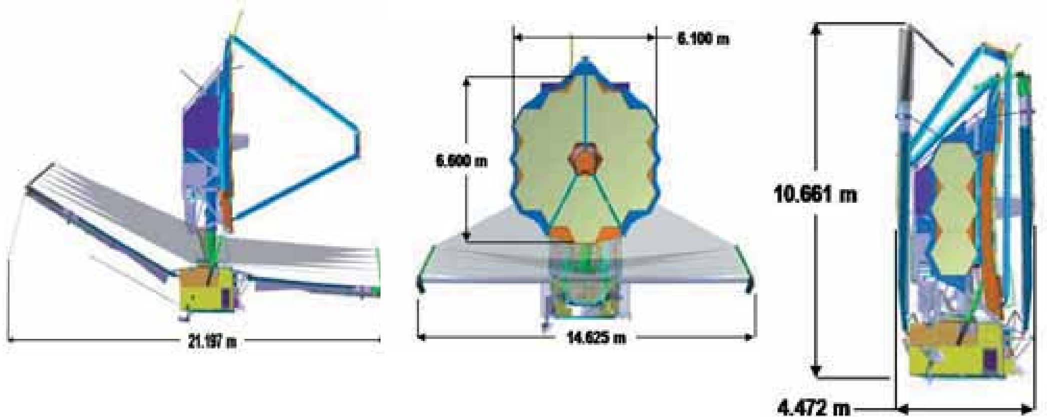

Figure 4. The JWST is the largest cryogenic optical system ever constructed.

Figure 5. The JWST is designed to integrate with an Ariane 5m diameter fairing.

The resulting mission architecture is shown in Figure 6. During operations, the NASA Deep Space Network is used to support two 4 hr communications contacts each day during which approximately 470 Gbits of science and engineering data are downloaded. Both mission and science operations are supported by the Space Telescope Science Institute. Overall mission management, as well as guidance, navigation, and control, are provided by Goddard Space Flight Center.

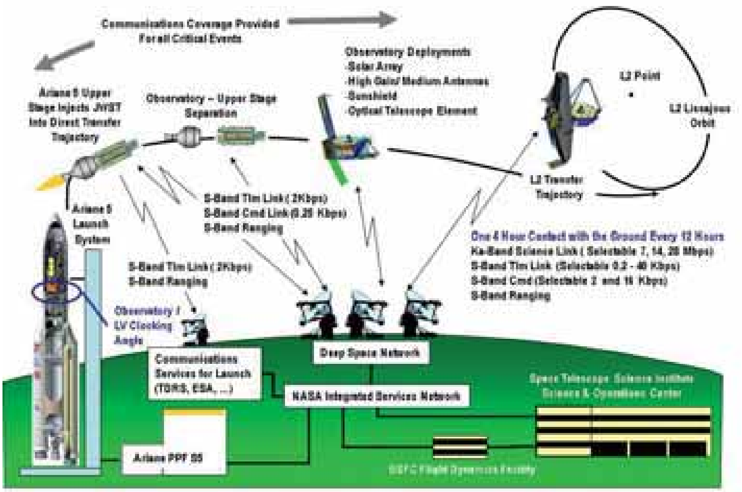

Figure 6. The JWST mission architecture.

3. Collecting the first light

A three mirror anastigmat (TMA) telescope design was selected to enable high image quality over a wide field of view. In contrast to ground-based telescopes, minimizing mass is a key design driver on the JWST telescope. Beryllium was selected as a material for the three TMA mirrors due to its high thermal conductivity, high stiffness to mass ratio, and low expansion coefficient at the ~50K operating temperature. A segmented primary mirror design was chosen to enable fold-up stowage as shown in Figure 7. The deployed aperture is tricontagon in shape with a collecting area of 25 m^2. The primary mirror is composed of 18 hexagonal segments (1.32 m flat-to-flat) of three optical prescriptions. Each primary mirror segment and the secondary mirror are mechanized to provide in-flight position adjustment in 6 degrees of freedom (Figure 8). The primary mirror segments also have in-flight radius of curvature adjustment. A fine steering mirror is located near a pupil position (Figure 7). This mirror is servo controlled using an image-based fine guidance sensor located in the science instrument focal plane to enable 7 mas rms pointing stability. The mirrors are polished to a cryogenic figure error of approximately 20 nm rms via an iterative cryopolishing process. Gold was selected as a mirror coating to provide high throughput over the 0.6 - 29 micron spectrum. This coating choice limits the JWST to wavelengths >0.6 μm. The 29 μm long wavelength limit results from detector technology and cooling constraints. The telescope structure consists of a M55J-954-6 cynate ester composite material that affords a high stiffness to mass ratio and a low cryogenic expansion coefficient to yield high optical alignment stability.

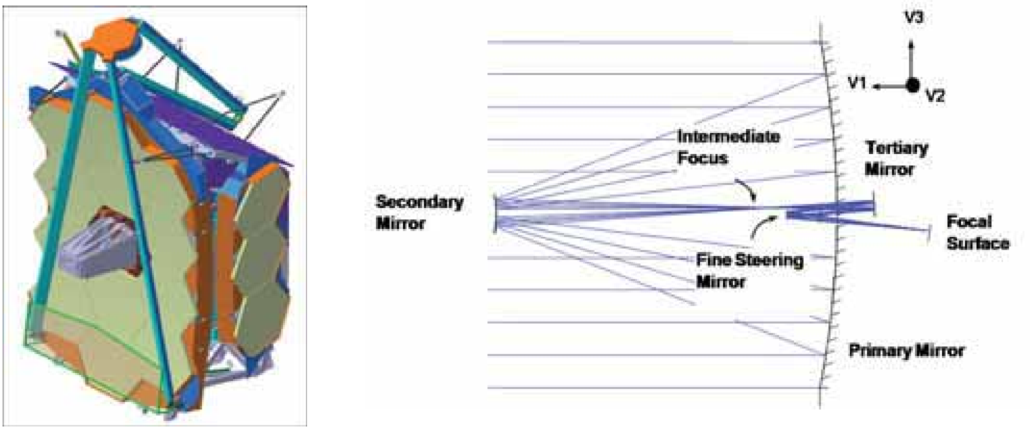

Figure 7. Left - The telescope in its stowed configuration; Right - The telescope deploys into a three mirror anastigmat configuration.

Figure 8. A primary mirror segment entering cryogenic testing (left), mechanized segment mount assembly provides 6 DOF and radius of curvature adjustment (right).

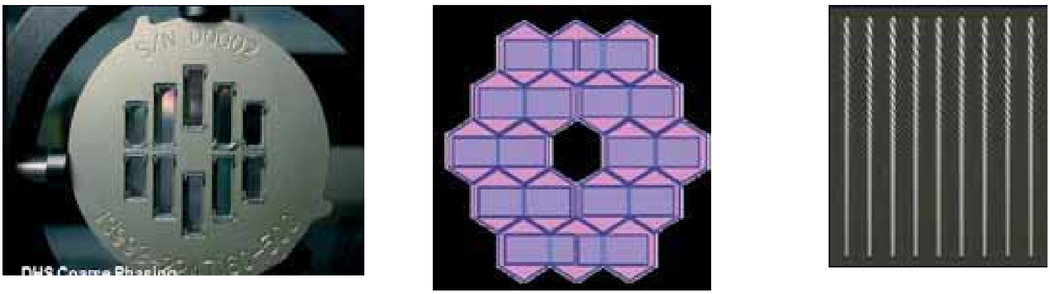

Figure 9. Dispersed Hartman sensing is used to perform coarse phasing of the mirror segments.

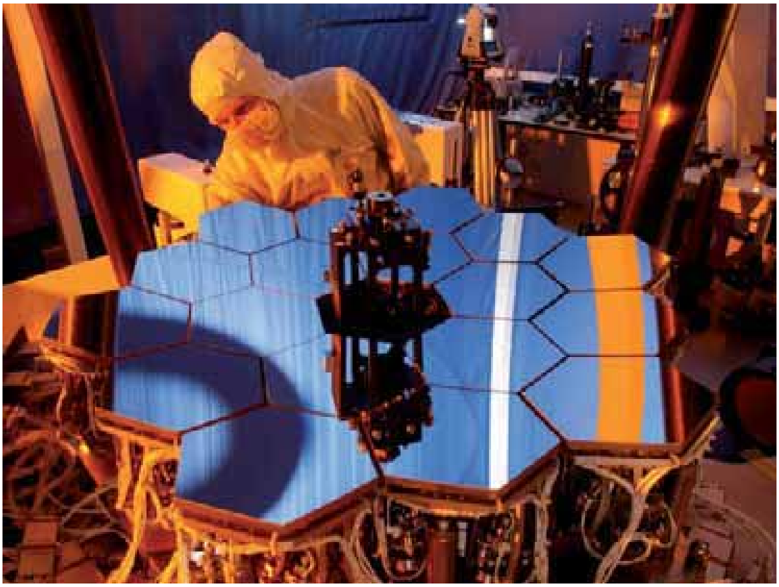

Figure 10. A 1/6 scale fully functional model of the JWST telescope was used to develop the overall wavefront sensing and control process.

The mirror segment actuators are periodically adjusted in flight to ensure diffraction limited image quality throughout the mission. The observatory's main near-infrared science camera (Section 4) is used as the wavefront error sensor for this process. Initial coarse phasing of the segments is accomplished using dispersed Hartman sensing optics in this camera (Figure 9). The subsequent fine phasing is performed on defocused images using a modified Gerchberg-Saxton algorithm (Acton 2004). This process is designed to achieve a telescope Strehl ratio of 0.8 at a wavelength of 2 μm. The dispersed Hartman coarse phasing process was demonstrated on the Keck telescope (Albanese 2006). The overall flight wavefront sensing and control process has been demonstrated on a 1/6 scale fully functional model (Figure 10) of the JWST telescope (Feinberg 2007, Contos 2008).

4. Extracting information from starlight

The JWST science instrument payload contains four science instruments, a fine guidance sensor, and supporting systems for instrument control, command and data handling, cryogenic thermal control, and other functions (Greenhouse 2006). Near-infrared imagery is provided by the NIRCam instrument (Rieke 2005, 2008) shown in Figure 11. This camera provides high angular resolution wide-field imagery over the 0.6 – 5 μm spectrum. The detector pixel scale is chosen to optimally sample the telescope point spread function across this wavelength range by use of a dichroic beam splitter (Table 2). Two identical optical modules image adjacent fields of approximately 4 square arcminutes to provide full redundancy for telescope wavefront sensing. Occulting coronagraphy, yielding a rejection ratio of $\sim 10^4$, is provided in both long and short wavelength channels. All focal plane arrays support high cadence sub-array exposures to provide a high dynamic range capability for exoplanet transit observations.

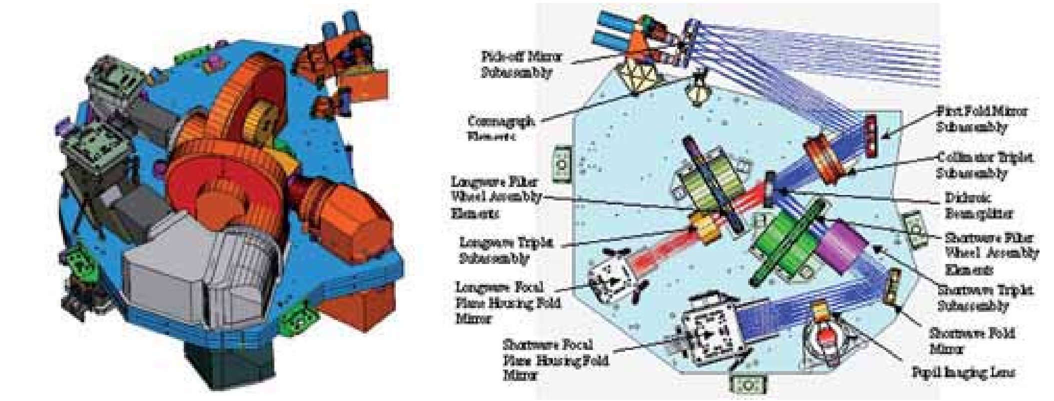

Figure 11. The NIRCam provides high angular resolution imagery.

Key Instrument Characteristics (as of Mar 08)									
Instrument	Channel/Mode	Wavelength (microns)	Typical Spectral Resolution (λ/Δλ)	FOV	Angular Resolution (arc sec)	Number of Sensor Chip Arrays	Mega Pixels	Detector Type / Format NIR=18 um pixels MIR=25 um pixels	Detector Temp (K)
NIRCam	Shortwave	0.6 - 2.3	4,10,100	2.2' x 2.2' each of 2 modules	0.032 / pixel	8	34	HgCdTe / 2048 x 2048	40
	Longwave	2.4 - 5.0	4,10,100	2.2' x 2.2' each of 2 modules	0.065 / pixel	2	8	HgCdTe / 2048 x 2048	40
NIRSpec	Multi-Object Spec	1.0 - 5.0	1000	203 x 463 mas clear shutter aperture; 267 x 528 mas pitch, 4 x 171 x 365 shutter array format; 3.7 sq arcmin multi-object targetable solid angle	see FOV	2	8	HgCdTe / 2048 x 2048	37
		0.6 - 5.0	100						
	Long Slits (5)	1.0 - 5.0	100, 1000, 2700	200 x 3500 mas x 3, 400 x 4000 mas 100 x 2000 mas					
	IFU	0.7 - 5.0	2700	3 x 3 arc-sec	0.10 slice width				
MIRI	Imager	5 - 27	4-6	1.9' x 1.4'	0.11 / pixel	1	1	Si:As / 1024 x 1024	7
	Low Res Slit	5 - 11	100	5" x 0.6"	see FOV	1	1	Si:As / 1024 x 1024	7
	Med Res IFU	4.87 - 7.76 7.45 - 11.87 11.47 - 18.24 17.54 - 28.82	3000 3000 3000 2250	3.7" x 3.7" 4.7" x 4.5" 6.2" x 6.1" 7.1" x 7.7"	0.18 slice width 0.28 slice width 0.39 slice width 0.65 slice width	1	1	Si:As / 1024 x 1024	7
FGS-TF		1.6 - 2.5, 3.2 - 4.9	100	2.2' x 2.2'	0.065 / pixel	1	4	HgCdTe / 2048 x 2048	40
FGS-Guider		0.8 - 5.0	0.7	2.3' x 2.3' each of 2 modules	0.068 / pixel	2	8	HgCdTe / 2048 x 2048	40

Table 2. JWST science instrument characteristics (coronagraphic modes not shown).

Figure 12. The FGS-TF instrument layout (left), test unit in space simulation chamber (center), and prototype Fabry-Perot etalon (right).

Near-infrared scanning Fabry-Perot imagery is provided by the FGS-TF instrument (Doyon 2008). This instrument (Figure 12) provides a narrow-band imaging capability with the same size field of view as the NIRCam and over a similar wavelength range (Table 1). Its applications include deep surveys for emission line objects over a flexible range of redshifts. The instrument includes occulting coronagraphy that can achieve a contrast ratio of $\sim 10^4$ using a speckle suppression technique that is enabled by the scanning capability of the etalon.

The FGS-TF shares an optical bench with the FGS-Guider. The latter is a fully redundant very broad-band camera (Table 2) that functions as the fine guidance sensor for the telescope fine steering mirror system (Figure 7). It delivers guide star centroid measurements with a noise equivalent angle of 4 mas at a rate of 16 Hz. Its wide field of view enables 95% probability of guide star acquisition over the whole sky and autonomous pattern recognition for guide star identification.

Spectroscopy over the 0.6 – 5 µm spectrum is provided by the NIRSpec instrument (Bagnasco 2007). The NIRSpec affords a range of spectral resolutions shown in Table 2 that can be used with long slit, multi-object, and integral field aperture control modes. This instrument (Figure 13) is the first multi-object spectrometer developed for space flight. It is designed to target 100 compact sources simulta-neously within a 9 square arcminute field.

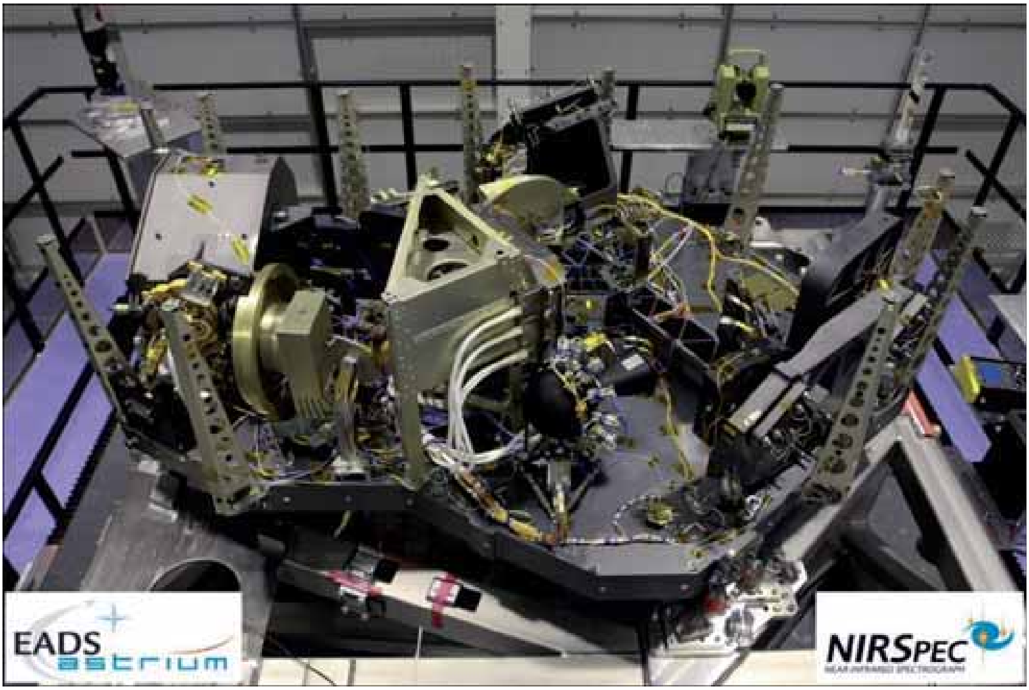

Figure 13.The NIRSpec instrument engineering test unit.

Aperture control for multiobject spectroscopy is provided by a 0.25 Mpixel array of micro-shutters (of dimensions shown in Table 2) that are configured for the desired target field based on prior NIR-Cam imagery (Figure 14). A variety of fixed long slits are provided to enable high contrast and exoplanet transit spectroscopy. Integral field spectroscopy is provided over a 9 square arcsecond field via a conventional image slicer.

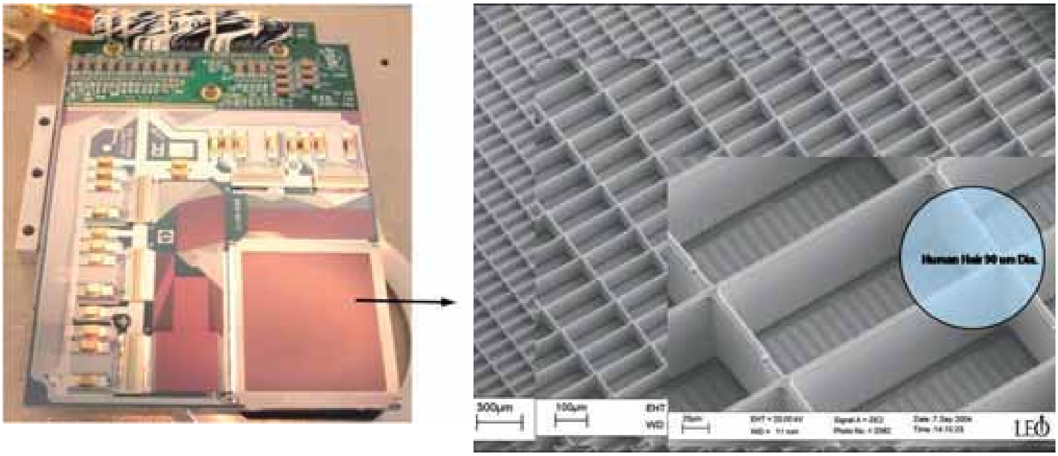

Figure 14. A quadrant of the NIRSpec micro-shutter array for multi-object spectroscopy is shown (left) along with a micrograph of its optical area (right).

Imagery and spectroscopy over the 5-29 µm spectrum is provided by the MIRI instrument (Wright 2008). This instrument (Figure 15) provides broad-band imagery, low spectral resolution (1%) long slit spectroscopy, and medium spectral resolution (~10^3) integral field spectroscopy (Table 2). The imaging mode includes both occulting and quadrant phase mask coronagraphy. The latter type enables very small inner working angle observations of stellar debris disks and exoplanet systems. When used in combination with the NIRSpec instrument, an optimally sampled integral field spectrum covering the whole 0.6 – 29 µm JWST wavelength range can be obtained at medium spectral resolution.

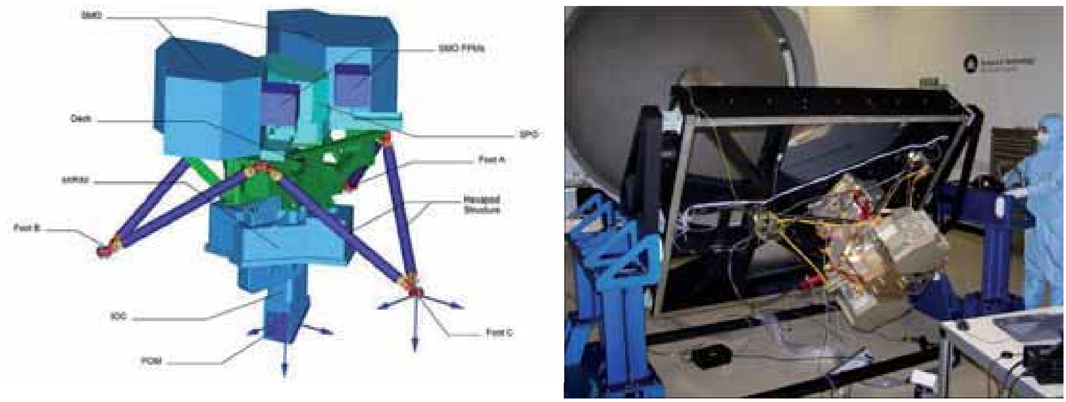

Figure 15. The MIRI instrument configuration (left) and verification model (right).

The detectors for the JWST instruments define the state of art for high performance space flight infrared imaging arrays. The near-infrared instruments utilize HgCdTe

JWST Sensitivity							
Wavelength (microns)	Instrument/Mode	Bandwidth (λ/Δλ)	SNR	Wall Clock Time (s)	Continuum Flux Density (nJy)	Continuum Flux Density (10^{-33} W m^{-2} Hz^{-1})	Unresolved Line Flux (10^{-21} W m^{-2})
2	NIRCam	4	10	10,000	11.40	0.11	NA
3.5	FGS-TF	100	10	10,000	126.00	1.26	NA
3	NIRSpec/Low Res	100	10	10,000	132.00	1.32	NA
2	NIRSpec/ Med Res	NA	10	100,000	NA	NA	0.57
10	MIRI/ Broadband	5	10	10,000	700.00	7.00	NA
21	MIRI/Broadband	4.2	10	10,000	8700.00	87.00	NA
9.2	MIRI/Spectrometer	2400	10	10,000	NA	NA	10
22.5	MIRI/Spectrometer	1200	10	10,000	NA	NA	56.00

Table 3. JWST sensitivity benchmarks.

4 Mpixel sensor chip arrays (SCA) operated at ~40 K. Zodiacal background limited sensitivity is achieved in all broad-band instrument modes (Table 3). The MIRI instrument utilizes Si:As 1 Mpixel SCAs operated at ~7 K. Significant gains in noise performance and SCA format were achieved during the JWST technology development phase to enable the above mission science goals (Figures 16, 17). The

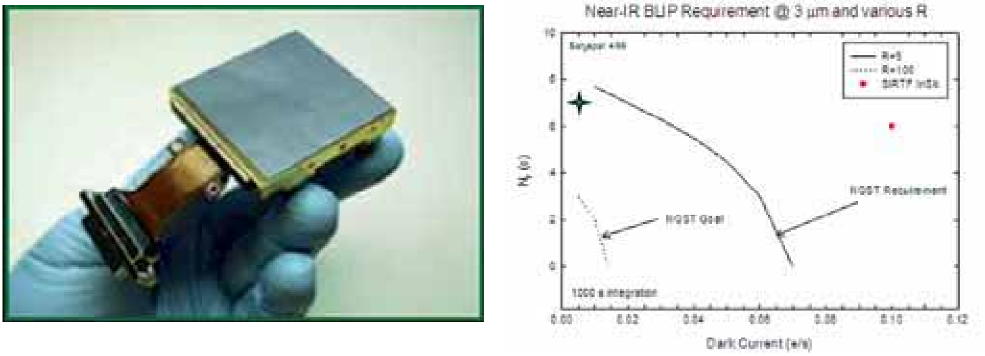

Figure 16. Left -- A Teledyne H2RG 4 Mpixel sensor chip array; Right -- noise performance of this technology (green cross) compared to that of 0.07 Mpixel InSb sensors used on the Spitzer space telescope (red dot). The lines shown are the original (circa 1999) requirement and goal for background limited performance (BLIP) for the JWST (then called NGST).

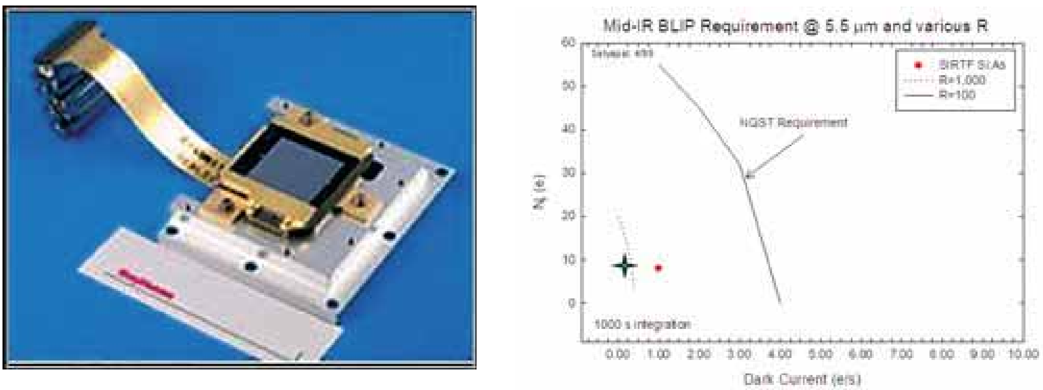

Figure 17. Left -- A Raytheon Si:As 1 Mpixel sensor chip array; Right -- noise performance of this technology (green cross) compared to that of 0.07 Mpixel Si:As sensors used on the Spitzer space telescope (red dot). The lines shown are the original (circa 1999) requirement and goal for background limited performance (BLIP) for the JWST (then called NGST).

near-infrared SCAs are designed to be edge-butted on three sides to from larger format focal plane array (FPA) assemblies. For example, the NIRCam short wavelength channel utilizes a 16 Mpixel FPA consisting of 4 of these SCAs, and the NIRSpec utilizes an 8 Mpixel FPA consisting of 2 SCAs. The mid-infrared SCAs are used individually in 1 Mpixel FPA assemblies.

5. Making sure it all works

Testing at the scale and operating temperature of the JWST requires the largest deep cryogenic (~30K) space simulation facilities in the world. The system is built up and tested in incremental steps in which each subunit is tested before it is integrated into the next higher level of assembly. As integration proceeds, larger and larger facilities are needed. The fully integrated instrument payload will be tested at Goddard Space Flight Center using a telescope simulator (Hagopian 2007, Ohl 2009). After integration with the actual telescope, the whole system is tested in a larger facility at Johnson Space Center (Figure 18) (Atkinson 2008). Unlike the Hubble Space telescope, which resides in low earth orbit, the JWST cannot be serviced by astronauts due to its more distant L2 point orbit. However, in contrast to prior space observatories, the JWST telescope and instrument optical systems employ a high degree of freedom for in-flight adjustment (Barto 2008), and lessons learned from prior observatory test programs are carefully taken into account in design of the JWST test program (Feinberg 2008).

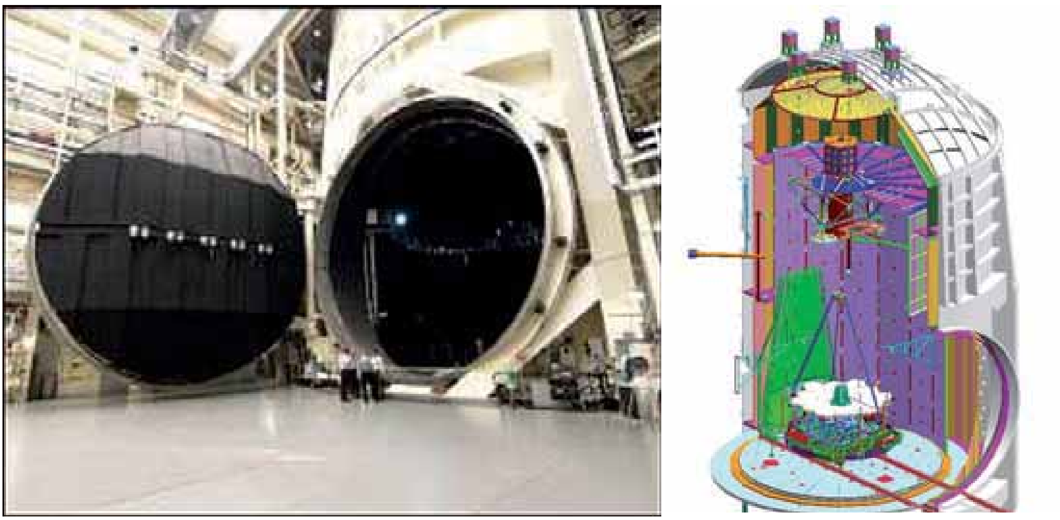

Figure 18. The JWST will be tested in JSC chamber A (120 feet tall, 60 feet diameter).

6. Synergism with ground-based observatories

The GTC and future ground-based ELTs will provide unique discovery potential and synergism with the JWST throughout its flight mission and beyond. Ongoing advances in adaptive optics performance toward wide field diffraction limited near-infrared imagery, the inherent ability of ground-based observatories to continuously upgrade science instrumentation, and their overall versatility ensure the power of these facilities at wavelengths where telluric absorption and telescope emission are low.

Ground-based and orbital facilities will be powerful partners throughout the JWST era and for the foreseeable future with the former leading in medium and high resolution spectroscopic applications shortward of the thermal infrared (Figure 19).

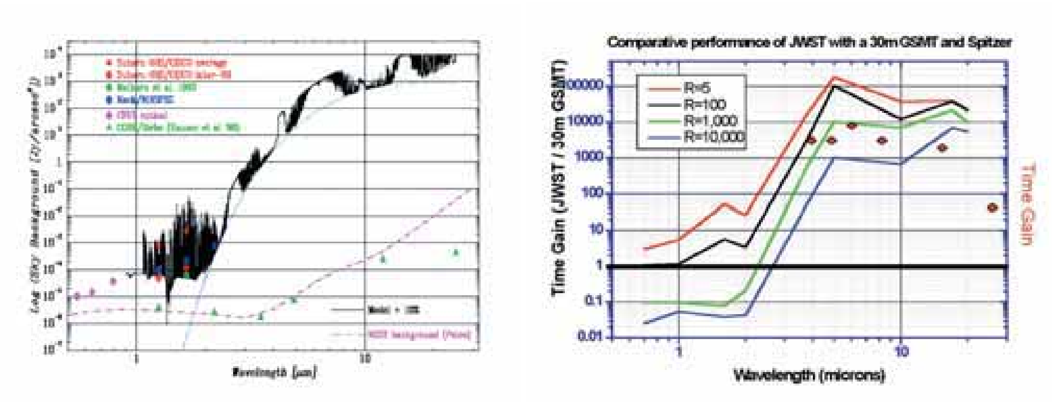

Figure 19. Left – The relative background emission of ground-based and orbital observatories depart markedly at wavelengths > 1.7 μm; Right – The relative time gain of JWST compared to a GSMT (lines) or Spitzer (diamonds). The vertical axis is in relative units, where 1.0 means an observation with JWST or GSMT or Spitzer will take the same time to reach equivalent S/N on a point source; a number <1 means GSMT is faster.

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Astronomy from Space: Achievements and Future Plans of ESA Activities

1. Introduction

Space offers to astronomers a new perspective to explore our Universe. Global access to the sky and the possibility to obtain high-quality observations without the nuisance of the Earth atmosphere or the day/night cycle, are among the advantages of space Astronomy. Operational constraints, and specially budget limitations, require very careful planning of the facilities to be put in space. Coordination with ground-based facilities is essential. Observatories on Earth or in space have to be designed to complement the wavelength ranges covered with the appropriate resolution and sensitivity as well as with the possibility to observe targets from both hemispheres. This contribution is focused on the advances in Europe in space Astronomy along the last decades paying special attention to the connection with very large ground-based telescopes.

In October 1957, the launch by the old Soviet Union of Sputnik-1 opened the space era. The United States reacted immediately by launching their first spacecraft in January 1958 and formed the National Aeronautics and Space Administration (NASA) to develop the necessary technologies and programmes. By July 1969, in less than 12 years, man landed on the Moon and the Americans took over the initial Soviet leadership in space.

In the mean time, Europeans started to participate in the space adventure. The idea of an independent space agency dates back to the early sixties. Different European countries formed two organizations at that time: the European Launcher Development Organization (ELDO) and the European Space Research Organization (ESRO). The first one to provide access to space and the second to develop programmes for the scientific exploitation of space missions, very much in the spirit of the other large European joint scientific effort, the Centre for Nuclear Research (CERN) established near Geneva. Scientific and technical resources coming from different countries are necessary since isolated European countries on their own can hardly make the effort required to be competitive in space astronomy. Space is indeed an example of the great challenges that Europeans can only afford together, thus strengthening our common identity as well as making our investments more efficient.

By 1975, the two organizations, ELDO and ESRO, were merged into the European Space Agency (ESA), which now has 18 Member States. Activities of ESA go from launcher development for access to space, to Earth observation programmes, Telecommunication satellites, Navigation, Human spaceflight (including the European contribution to the International Space Station), future technology programmes, the exploration of the Solar System, space Physics and space Astronomy. The annual budget of ESA is close to 3.2 billion €, out of which 435 millions are in the mandatory Science programme. Nevertheless, taking into account the scientific activities carried out in other programmes, essentially optional, the ESA effort reaches around one third of the total budget.

The general goals of the Science programme of ESA are: a) to understand our Universe; its structure, content and evolution, b) to understand the physics underpinning the observed processes, and c) to explore the Solar System; understanding its origin and evolution, as well as Life. With these aims, ESA provides astronomers with the necessary space tools to carry out their scientific research.

In order to achieve its goals, the Science programme of ESA is structured as Mandatory, i.e. Member States contribute to the budget according to their Gross National Product and not their specific interests in proposed missions. Moreover, the programme has a long-term planning allowing for the balanced development of the scientific areas that the community needs. The current long-term plan is called “Cosmic Vision” and succeeds the previous Horizons 2000 whose implementation is now being finished. Projects are developed in cooperation with scientific institutes in Member States that essentially contribute with the in-kind delivery of the scientific instrumentation. Missions and instruments are selected in a competitive process with the involvement of the scientific community.

2. The first missions: exploring the advantages of space

During the first decade of scientific research in and from space, under the structure of ESRO, ideas were centred in acquiring the necessary technological capabilities or to explore the advantages of space for science by having instruments above the Earth atmosphere. This implied mainly the use of satellites to study the sky in high-energy wavelength ranges for which the Earth atmosphere is opaque. Global surveys to identify sources and their luminosities emitting from the ultraviolet to gamma rays were thus planned.

Within a series of small missions with technology and space physics goals, the first astronomical satellite was ESRO-2B, also called IRIS, and launched with a Scout in May 1968. The ESRO-2b satellite was designed to measure the X-ray and energetic particle flux of the Sun but could also detect other sources. After 6.5 months of normal operations it showed problems with the data recording system and by the end of the year it was no longer scientifically operational. A more ambitious satellite was TD-1, launched from California on a Thor-Delta rocket (hence the name of the mission) in March 1972. The 470 kg spacecraft, with a scientific payload of 120 kg, was put in a Sun-synchronous orbit. The main objective of the mission was to survey the ultraviolet sky, though several instrument for higher energies were also onboard. A problem with the data recording system soon after launch was mitigated by means of a rapidly developed ground-system rescue for real-time telemetry. Most of the sky was scanned and more than 30,000 ultraviolet sources were catalogued. Interstellar dust could also be studied and its distribution throughout the Galaxy initially plotted. The mission was operational until May 1974.

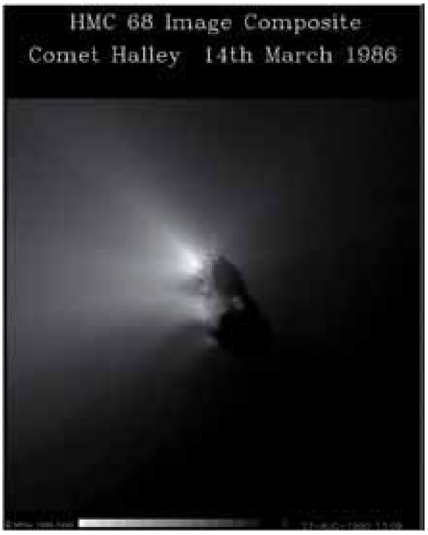
In August 1975, another satellite was launched called COS B, this time with a Delta rocket, just after ESA had been formed. The mission was designed to perform an extensive, pioneering survey of the Galaxy at energies of 50 MeV to 5 GeV. Major achievements included observations of the Crab and Vela pulsars, the discovery of numerous point sources in the galactic disc and the first observation of gamma rays from an extragalactic source (3C273). Operations were terminated in April 1982 and the database was formally released to the scientific community in September 1985.

The International Ultraviolet Explorer (IUE) was the first real observatory mission, in cooperation with NASA and the UK, to observe individual sources in the ultraviolet domain between 1150 and 3200 Å. It was launched with a Delta rocket in January 1978 and was operated successfully until September 1996, well beyond its design lifetime and becoming the longest-serving astronomical satellite. It returned more than 104,000 high and low resolution spectra providing astronomers with a unique tool for the study of many astrophysical problems. IUE was also the first scientific satellite that allowed astronomers to make real-time observations in the UV and provided an unprecedented flexibility in scheduling targets of opportunity. The satellite could be operated continuously, and for one third of the time the operational responsibility was taken by the newly created centre by ESA in Villafranca del Castillo, near Madrid, which later became the European Space Astronomy Centre (ESAC). The impact of IUE in the training and scientific achievements of Spanish space astronomers in the eighties was very important and they kept the responsibility of the data archive of the mission for the future. Users around the world are still actively using this data despite the time passed, and the collected information has been incorporated to the Virtual Observatory developments.

The IUE satellite

Initially selected to be COS-A, a highly performing X-ray mission had been delayed to incorporate the latest developments in building X-ray imaging systems at the time. Exosat was finally launched in May 1983 with a Delta rocket and was operated until May 1986. ESA´s X-ray Observatory Satellite (Exosat) studied the X-ray emission from most classes of astrophysical objects, including active galactic nuclei, white dwarfs, stars, supernova remnants, clusters of galaxies, cataclysmic variables, and X-ray binaries. Exosat obtained 1780 observations locating the sources and analyzing their spectral features and time variations. Though it was designed to analyze previously detected X-ray sources, it could also discover many new ones serendipitously. Exosat was operated as a real-time observatory and the spacecraft was in a highly eccentric orbit. European astronomers learnt about the possibilities of the X-ray domain for the understanding of the physics underpinning high-energy sources, and started to work in the definition of a much more performing mission that later became XMM.

Despite all these activities in space astronomy, European scientists did not forget the possibilities of space technology to explore some astronomical objects in situ within the Solar System. The initial mission in this new field was Giotto, the first close flyby of a comet. Giotto was launched on July 1985 with an Ariane-1 rocket from French Guyana, and passed by comet Halley on March 1986. The mission was later extended for a flyby of comet Grigg-Skjellerup on July 1992. Halley had been selected because its uniqueness in being young, active and with a well-defined path, essential for an intercept mission. Giotto was the first spacecraft to take a payload close in to a comet (600 km) and obtained the first image of Halley's comet nucleus showing a lumpy body of 15 by 7-10 km, the full width being obscured by two large jets of dust and gas in the active sunward side. The dark side, with an unexpected low albedo, was quiescent but circular structures, valleys and hills, could be identified. The jets broke through the dark crust that insulated the underlying gas from solar radiation.



Close view of comet Halley

The following mission was a breakthrough for fundamental astronomy. Hipparcos (High Precision Parallax Collecting Satellite) was launched in August 1989 with an Ariane 4. The spacecraft, with 1140 kg, contained a science payload of 215 kg and was expected to be in geostationary orbit but a boost motor failure forced the mission to be put in a highly elliptical orbit and a completely revised operations scenario was needed. Operations were nevertheless finished by March 1993 with a very successful scientific outcome fulfilling all expectations. The most accurate positional survey of more than 100,000 stars had been performed leading to the determination of their distances on the basis of trigonometric parallaxes, their proper motions and other characteristics such as their variability and binary nature. Improving on ground-based accuracies by a factor of 10 to 100, Hipparcos is fundamentally affecting every branch of Astronomy, and specially theories of stars, their structure and evolution. 1000 Gbit of data were returned during the 4 years of operations, making the production of the catalogues the largest data analysis problem ever undertaken to achieve precisions within about 0.001

The Hipparcos spacecraft

arcsec. The final processed data set was published in 1997. Hipparcos not only put Europe in a leading role in stellar astronomy but also demonstrated that space could provide excellent opportunities even in optical wavelengths when global measurements or precision photometry is required.

3. The observatory missions: exploiting the advantages of space

The times of the survey missions exploring the sky in different regions of the electromagnetic spectrum were to finish by the nineties and a new phase in the development of large observatories had to start. This new era was to be devoted to detailed analyses of the physical processes taking place in a variety of objects, from the solar system to the largest structures of the Universe.

The first of these large observatories, still in operation, was the Hubble Space Telescope (HST), a NASA-led mission with a European contribution to its development, as well as to the operations. In return, European astronomers from ESA Member States are guaranteed a minimum of 15% of HST observing time. HST is a 2.4 m astronomical telescope operated as an international observatory with the advantage over a ground-based facility of adding to diffraction-limited angular resolution, access to the UV and near-IR ranges. It was launched with the Space Shuttle in April 1990 carrying onboard the European Faint Object Camera (FOC), which was returned to Earth in March 2002. Despite some problems at the very beginning of the mission with the optical focus of the mirror, the Space Telescope has become the greatest observatory available in space for astronomy. The possibility to service the observatory with manned missions by the Shuttle has allowed upgrading instruments at the focal plane, using more efficient detector technologies at each opportunity, and moving from the original optical-ultraviolet domain to the current near-infrared main objective.

Scientific results go from the study of stellar formation regions and proto-planetary disks, through the characterization of extra-solar planets, using high-resolution measurements during transits, to the original scope for which it was designed, the large structure of the Universe; for example, measuring the Hubble constant to 74.2 + 3.6 km/s/Mpc using Cepheids in other galaxies. Disturbed-looking galaxies of the early Universe have been imaged by means of the Ultra Deep Field exposure and type Ia supernovae have allowed to demonstrate that the universe is not slowly decelerating its expansion, as previously expected, but actually accelerating, what requires the introduction of dark energy. Dark matter has also been studied through weak-lensing effects in distant galaxies, leading us to a vision of our universe where the normal matter content is not more than 4%; dark matter contributing with some 23% and the rest being dark energy. Not only are we not located near the centre of the Universe; we are not even made of what 96% of the Universe is made of!

The spectacular success of the Infrared Space Observatory (ISO) provided a fresh perspective on the cold component of the universe, boosting most areas of Astrophysics. It was launched with Ariane 4 in November 1995 and remained operational until May 1998. With a launch mass of 2,500 kg, ISO was cryogenically cooled to study the universe in the 2.5 to 240 microns IR domain, as a follow-up to the all-sky survey of IRAS in 1983, with sensitivity about 1000 times greater and spatial resolution 100 times higher. ISO was operated from Villafranca in Spain as an observatory and measured from planets to quasars, studying in detail the early evolution of galaxies and the history of star formation. Clouds of gas and dust leading to collapses where stars are formed could be analyzed with particular attention to disks of matter to understand planetary formation. Complex molecules, including organic compounds, were identified in the interstellar medium boosting the development of Astro-chemistry. Spectrographs found abundant water in many different places, like

The ISO spacecraft

planets and comets, young and evolved stars and even in external galaxies. Thanks to ISO, the cosmic history of water was traced for the first time. Moreover, ISO could find the characteristic chemical signatures of bursts of star formation in ultra luminous IR galaxies. The scientific community is still actively using the database and obtaining great results.

Our star, the Sun, could of course not be left forgotten by the astronomical community as a key reference for stellar astrophysics. A mission devoted to the study of the Sun, the Solar and Heliospheric Observatory (SOHO), developed as a cooperative project between ESA and NASA, was launched in December 1995. SOHO is providing solar physicists with the first long-term uninterrupted view of our star, allowing us to understand its interactions with the Earth environment. SOHO has revolutionized our knowledge of the Sun by answering questions of the internal structure and dynamics, how is the corona heated and how is solar wind accelerated. It is of particular importance for astronomers the results obtained by means of helioseismology about the internal density distribution and differential rotation of the Sun, leading to an accurate comparison with theoretical models and clarifying long unsolved issues like stellar convection or the expected flux of solar neutrinos. SOHO is still in operation and the coordination of data with the ESA Earth magnetosphere mission Cluster is giving new clues about the physical processes underpinning space weather in our neighbourhood.

At the end of 2006, the COROT mission, a French-led project in cooperation with ESA, was launched to study the structure of stars and search for relatively small planets. For the first objective, the same technique developed by SOHO for the study of the Sun, is being applied to stars bringing astro-seismology to the front line of stellar astrophysics. In the domain of extra-solar planets, the search for super-Earth candidates continues and cooperation with ground-based facilities has proven to be essential. New candidate planets need follow up observations to secure radial velocity measurements to obtain orbital parameters and high-resolution imaging and photometry to identify and characterize the host star.

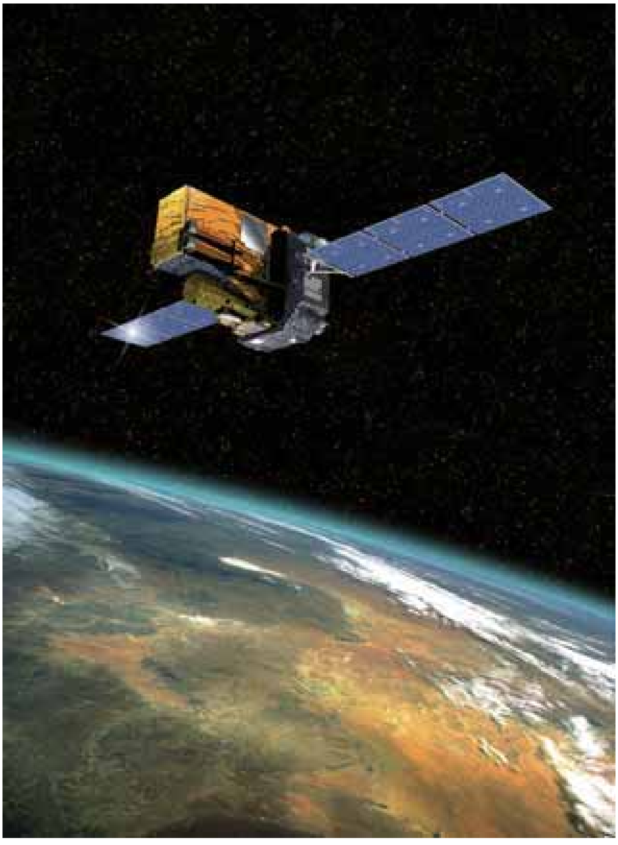
Continuing with large observatories, Europeans decided to build on the previous experience of Exosat and developed the large X-ray Multi-Mirror (XMM) observatory. Named Newton after launch, XMM-Newton provides high-throughput, broad-band (100 eV to 10 keV), medium resolution (20 to 30 arcsec) X-ray spectrophotometry and imaging of sources, ranging from nearby stars to quasars. The launch took place with an Ariane 5 from Kourou in December 1999 and operations continue providing excellent scientific results. Achievements cover a large number of topics thanks to its large collecting area provided by three mirror modules each carrying 58 nested gold-coated nickel mirrors using shallow incidence angles to guide the incoming X-rays to a common focus for imaging by the scientific instruments. Examples are isolated neutron stars, interacting X-ray binaries, distant galaxy clusters, the study of the galactic centre black hole as revealed by X-ray flares, dark matter maps based on the combination of hot matter pictures with HST weak-lensing studies, bursts of star formation, etc.

An interesting new area of Astronomy connected to the launch and operation of large observatories is the development of Virtual Observatories using databases from space missions as well as ground-based facilities. ESA projects have been all made VO compatible and included in the access protocols for their exploitation as part of these new technologies. In particular, the developments at ESAC in Villafranca, Madrid, joining efforts between Spanish and European groups have shown to be a successful approach. Within this context, the data archive of the large Canary Islands telescope, Grantecan, has been designed to be part of the Spanish virtual observatory programme.

Integral was launched on October 2002 with a Proton rocket from Baikonur to provide a detailed spectroscopy and imaging of celestial gamma-ray sources. It is a large spacecraft, weighting 4 tons at launch, that carries sophisticated instruments providing an unprecedented combination of celestial imaging and spectroscopy over a wide range of hard X-ray and gamma-ray energies, including optical monitoring. Gamma-ray astronomy explores nature's most energetic phenomena and addresses some of the most fundamental problems in physics and astrophysics. Phenomena like nucleosynthesis, nova and supernova explosions, the interstellar medium, cosmic ray interactions and sources, neutron stars, black holes, gamma-ray bursts, and active galactic nuclei, are among those studies by the Integral mission. First investigations to be carried out showed the point sources responsible for the apparent diffuse radiation of the galactic disk or the distribution of the annihilation emission line at 511 keV recently interpreted as due to positrons formed as decayed products of the explosion of massive stars. The 26Al emission line at 1.8 MeV allowed an independent estimate of the galactic core collapse SN rate of 2 per century. Gamma-ray Bursts (GRB) of course attracted much attention of Integral and recent results showed polarized prompt emission of GRB 041219A and a new population of low-luminosity GRBs. The combination of Integral data with ground observatories follow-up measurements has shown excellent results with spectroscopic studies or a photometric redshift estimation of the farthest GRB (z = 6.3).

During the first 5 years of the new century an impressive effort was done by ESA to position itself in the international effort to explore our Solar System. In order to study the atmosphere of Titan, the giant satellite of Saturn showing a dense pre-biotic atmosphere, ESA cooperated with NASA in the Cassini mission to the planet (launched in October 1997). Europeans provided the Huygens probe that landed on Titan in January 2005 with a 150 min parachute descent and presented an extraordinary view of a world dominated by methane in different physical states.

After the cooperative development of Cassini-Huygens, Europeans concentrated in a number of missions to study the inner rocky planets of our Solar System, starting with Mars Express to the red planet. This mission was launched in June 2003 and is still in a healthy state of operations. Short after, in September 2003, a technology mission to test navigation by means of electric propulsion was launched with the name of Smart-1. It was decided to use it to go to the Moon and orbit around it resulting in a successful study of our satellite during almost two years which finished with an impact with the lunar surface in September 2006 after all the fuel had been exhausted. As a continuation of the early experience of Giotto that flied by comet Halley, the mission Rosetta was designed and developed. This ambitious project is a probe to comet Churyumov-Gerasimenko that carries a lander to do in situ measurements while the main probe is monitoring the evolution of the comet until perihelion. Rosetta is now on its way to the comet, after performing a flyby of asteroid Stein, and preparing for next flyby in July 2010 of asteroid Lutetia. Arrival to the comet will take place in 2014. Finally, within this ambitious solar system exploration programme, Venus Express was launched in November 2005 and is now studying the dense atmosphere of the planet with great detail in order to understand why Venus is so different from Earth while having similar mass and radius.

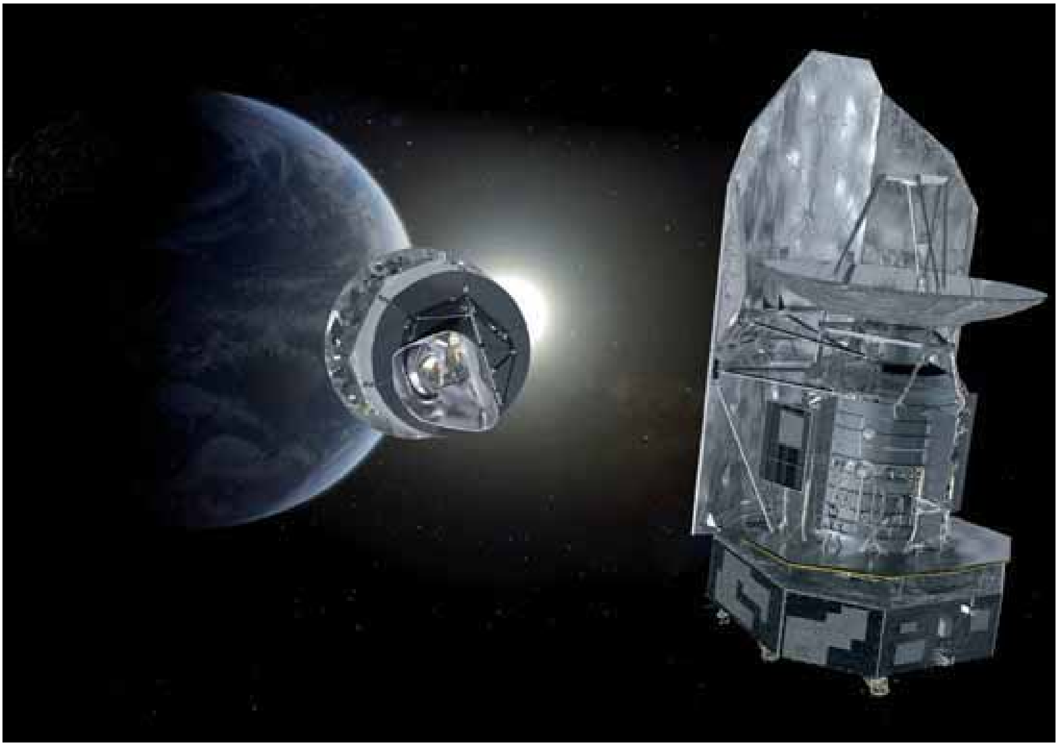


During 2009, the International Year of Astronomy, ESA returned Astronomy to the frontline of its science programme

INTEGRAL

and launched two very ambitious far-infrared and sub-millimetre missions, Herschel and Planck, were launched in May 14 from Kourou in French Guyana. Herschel is the first space facility to completely cover the far infrared and sub-millimetre (57 - 670 λm) range with a large (3.5 m), low emissivity (~ 4%), passively cooled (< 90 K) telescope and three cryogenically cooled science instruments. Operations are planned for more than 3.5 years and Herschel is not only to be considered unique but also complementary. For wavelengths below 200 microns it provides much larger (but warmer) aperture than missions with cryogenically cooled telescopes (IRAS, ISO, Spitzer or AKARI). It offers larger colder aperture, better 'site', and more observing time than balloon- and airborne instruments, as well as larger field of view than interferometers. Active cooling at detectors level will bring them below 1K ensuring a very low background noise.

Herschel is a giant leap forward in the study of star and galaxy formation and evolution. It is the largest telescope ever flown in space, addressing infrared wavelengths never covered before, and details never before seen. Herschel thus provides a sharp focus on star and galaxy formation. A yet unexplored window to the earliest stages of star formation is being opened and it is expected that the youngest stars in our Galaxy can be revealed. Most detailed and complete study of the vast reservoirs of gas in the Galaxy will be possible together with the analysis of planetary formation around other stars. In addition, unprecedented studies of the formation and evolution of galaxies in the Universe, back to 10 billion years ago, are also foreseen.



The Herschel and Planck satellites

Cooperation with Japan in the Akari missions, launched February 2006, has allowed Europeans to have access to observations in the infrared after the end of the operations of ISO so that there is a very active community ready for the exploitation of Herschel. In the longer wavelength millimetre range, the ALMA project consisting of a large array of radio telescopes that is being installed in Atacama (Chile), will certainly complement the scientific results of Herschel.

Planck on the other hand was designed to provide imaging of the whole sky at wavelengths near the peak of the spectrum of the Cosmic Microwave Background (CMB) radiation field with an instrument sensitivity $\sim 10^{-6}$ in temperature variations, an angular resolution ~5', wide frequency coverage, and excellent rejection of systematic effects. Planck is expected to look back to the dawn of time. It is Europe's first mission to study the relic radiation from the Big Bang and should provide more information about the infancy of the Universe than any predecessor mission by means of excellent imaging of the primeval cosmic seeds that led to the structures we see in the Universe today. As a result, detailed census of the Universe's constituents –visible & dark matter, dark energy – and study of its shape and dynamics, will be possible shedding new light on inflation and dark energy. Additional results will be linked to a completely new view of the cosmos and its phenomena at submillimetre wavelengths.

4. The future missions: new tools for new questions

Both Herschel and Planck are being operated in L2 orbit. This has been found to be an excellent location for astronomical missions because of the possibility to block Sun, Earth and Moon light, the use of passive cooling to achieve temperatures around 50 K, it is a stable environment, easy for communications and allowing long uninterrupted observations. Because of these reasons, the coming new astronomy missions of ESA are planned for the L2 orbit, mainly GAIA and the JWST.

GAIA is an astrometric mission to be launched in early 2012 following the experience and leadership achieved earlier with the Hipparcos satellite. Though using the same principles, GAIA uses completely different and much more performing techniques. A large focal plane assembly of multiple CCDs is the essential element in order to measure the position of every source brighter than 21st magnitude in the field of view while scanning the whole sky. In five years of observations every star will be observed at an average of 100 epochs and the accumulated information will allow accurate determination of distances and proper motions for around 1 billion stars with unprecedented precision of 10 to 20 microarcsec. With the addition of photometric information, the database of GAIA will allow a detailed understanding of the structure and evolution of our Galaxy. GAIA will revolutionize stellar astrophysics by providing comprehensive calibrations and physical properties across all types of stars and ages, but it will also add essential information in other fields like minor bodies of the solar system, Kuiper belt objects, extra-solar planets, and many more.

The James Webb Space Telescope (JWST) is the flagship mission of NASA to replace HST and ESA is again contributing to this project with a significant effort which guarantees an access to at least 15% of the observing time for astronomers in ESA Member States. JWST is a 6 m class telescope (25 m2 area) with 18 segments made of Beryllium allowing diffraction-limited observations at 2 µm. The wavelength range of the instruments goes from 0.6 to 28 microns thus enlarging the capabilities in the infrared of HST and approaching the short wavelength limit of Herschel.

The three core instruments are a 0.6-5 microns wide field camera, a 1-5 µm multi-objects spectrometer, and a 5-28 µm camera/spectrometer. A large sunshade (about the size of a tennis court) folded to fit in launch shroud will protect the instruments from the sun light and the design is made to ensure operations for at least 5 years with a 10 year goal. JWST will quest for origins in four major science themes: the end of the dark ages (the first luminous objects from z around 20 up to the epoch of reionization), the assembly of galaxies (from the epoch of reionization to z around 1), the formation of stars and stellar systems (from gas clouds to planetary systems) and the planetary systems (from their physical and chemical properties to their potential for life).

After all these astronomy missions, the science programme of ESA is preparing for new ideas to get deeper into issues raised by the times of large observatories just described. Specific problems need specially designed missions and the new programme of ESA, with the name Cosmic Vision, is being implemented. The missions to be launched before 2020 are being evaluated in a competitive process and some candidates in the field of space astronomy address crucial problems like understanding the nature of dark energy, searching for Earth-like extra-solar planets or following the work of Herschel with even more sensitive instruments. Moreover, a mission to continue with the study of the Sun with better time and spatial resolution, Solar Orbiter, is also being studied.

Euclid, is the name of a dark-energy surveyor project proposed to ESA. Euclid should constrain the dark energy equation of state parameter w to <1% by means of an imaging and spectroscopic survey of the entire extragalactic sky. Euclid is prepared to use two techniques: weak-lensing and baryonic acoustic oscillations. Weak gravitational lensing is a result of matter in front of galaxies distorting their shapes. This “shear” measures amount of matter along the line of sight (dark & normal) to the galaxy. Shear ~1%, must be measured accurately and it is expected to measure the shape of 5x108 galaxies to 24.5 mag. In addition, measurements of distance by photometric redshifts in 3 near IR bands to 24 mag are needed. In the case of baryonic acoustic oscillations the size and distribution of cosmic structures depends on expansion rate and gravity. For this purpose, Euclid will measure spectroscopic distances to σz<0.001 of 33% of all galaxies brighter than 22 mag (~2x10^8 to z = 2). To achieve its goals, Euclid carries a 1.2 m telescope with 0.2" PSF which will perform a 5 years survey using a visible and near-IR imager "DUNE" together with a near-IR spectrograph "SPACE".

Plato is the name of the planet finder proposed to ESA for the next medium size mission. Plato is designed to find and characterise Earth-size planets in 1-AU orbit around 20,000 Sun-like stars. The method to do so is the occultation technique already tested with Corot, i.e. to measure the star brightness to 27 p.p.m. accuracy. Plato will also characterise stars by astroseismology in order to have a complete understanding of the size and mass of the host stars and their planets. For this purpose, Plato needs to survey large sky area for long time monitoring many stars simultaneously. This is done by means of 12 to 54 co-aligned small telescopes that will observe two directions for 2.5 years each. In this way, Plato may find up to 200 earth analogues, sufficiently close for follow-up with future spectroscopic missions.

Finally, Spica is the next generation infrared observatory. Designed to study star and planet formation as well as the birth of galaxies is a follow-up mission of Herschel. It is a joint Japan-Europe collaboration. Japan provides spacecraft, launch and two instruments. Europe provides the telescope and one instrument called "SAFARI". The satellite is like Herschel to be at Sun-Earth Lagrange point L2. The telescope, of 3.5 m diameter (heritage from Herschel) is actively cooled to 6 K allowing much more sensitive measurements. It also includes a coronagraph for imaging exoplanets and the observatory is open to Europe and Japan scientists.

IXO is the International X-ray observatory planned for the study of black holes at the centre of galaxies and their evolution since they were formed as well as the study of the formation and evolution of large-scale structures in the Universe. It is a follow-up of XMM-Newton observatory. Imaging X-rays requires long focal length and IXO design contains a 25 m deployable bench, light-weight X-ray mirrors at one end and 5 X-ray instruments at other. Status from on-going assessment indicates that it is expensive, with cost > 650 M€ requiring the collaboration with NASA and Japan. Light weight mirror technology need long development and cannot be ready for selection in 2010.

On the other hand, LISA is the gravitational wave observatory with the goal of studying mergers of black holes and neutron stars almost since the beginning of the Universe through the gravitational waves they emit. The project consists of 3 interacting spacecraft in an equilateral triangle with 5 million km arms orbiting the Sun. As gravitational waves pass through, they distort space-time and therefore the shape of the triangle. LISA measures this tiny distortion (10-12 m!) by interferometric measurement of the distance between the spacecraft. The project is carried out in collaboration with NASA and most technologies will be validated by LISA Pathfinder in 2011 but can't be ready for selection in 2010.

As a "green dream" for the future, Europeans are working in the necessary technologies to obtain spectra of nearby extra-solar planets using nulling interferometry in space. Several concepts are being studied under the generic name of Darwin mission. The final goal is to find some day the Earth-twin planet looking for indications of the possible existence of life in it.

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Pedro Álvarez

Gran Telescopio CANARIAS - GTC

The GTC instrumentation plan

Abstract
The Gran Telescopio Canarias (GTC) started its regular science operation activity in March 2009. I present here the development plan for the science instruments for this telescope to provide the GTC community with novel and competitive observing modes in the era of large new observing facilities such as ALMA, JWST and the ELTs.

1. Introduction

The GTC is a 10.4 m segmented primary mirror telescope sited at the Observatorio del Roque de los Muchachos, on the Spanish Island of La Palma. It is a partnership between Spain, México and the University of Florida. GTC science operations started in March 2009 with OSIRIS, one of its two first generation instruments.

The GTC primarily serves a specific user community in Spain, México and the University of Florida. This community is broad-based in its scientific interests so that its instrumentation needs are also diverse. The GTC will play an essential role for a large fraction of this community since it will provide prime large telescope access to the northern skies.

It will be no easy task for the GTC to excel among the other large aperture observatories. It can only be made competitive through a judicious combination of its slightly larger aperture with a suite of carefully chosen instruments and telescope capabilities matched to the properties, strengths and plans for growth of the scientific community it has been built to serve.

The GTC's first generation instruments are OSIRIS, now in operation at the GTC, and CanariCam, which is completed and waiting to be installed and commissioned in the coming months.

The GTC inside its dome

Here, I present the GTC instruments currently under development and the plans for future instruments. I also describe second generation instruments that are at various stages of advancement. Of particular interest are CIRCE, a near-infrared camera, planned to be commissioned on the GTC at the end of 2010; EMIR, a wide field multi-object near-infrared spectrograph, which will be starting its assembly phase in autumn; and FRIDA, the Adaptive Optics-fed near-IR integral field unit spectrograph being built in México. FRIDA has undergone its preliminary design review and is now well into its final design phase.

A plan for the further development of new science instruments and telescopic capabilities has been prepared, intensively discussed and finally approved, and is now fully supported. This plan includes the development of two medium resolution MOS spectrographs, one working in the visible and the other one in the near IR. High dispersion optical spectroscopic capabilities could soon be available using the Utrecht Echelle Spectrograph (UES).

2. The GTC's First Generation instruments

2.1 OSIRIS

OSIRIS is a powerful multi-purpose workhorse instrument for imaging and low-resolution spectroscopy operating in the optical waveband (0.36-1.0 μm). It was specifically designed for narrow-band tunable-filter imaging, a uniquely competitive niche among 8-10 m class telescopes. OSIRIS also provides a full set of additional observational modes, including long-slit and multi-object spectroscopy (R<~ 5000), fast photometry and spectroscopy, as well as powerful CCD-transfer modes like fast photometry and fast spectrophotometry, or bracketing line emission frames with continuum frames and subtracting before a read out and reset takes place. The optical design allows for a sizeable field of view (7 x 7 arcmin^2 unvignetted) with a proper oversampling of good ORM seeing conditions. Narrow-band imaging can be continuously tuned from 365 to 1000 nm (FWHM from 12 to 40 Å). Spectroscopically, it samples R = λ/Δλ resolutions from 300 to ~5000 (0.6" slit width), and in MOS mode can accommodate from 40 to several hundred object spectra in fields that depend somewhat on the chosen resolution. OSIRIS delivers a competitive field of view in its spectroscopic modes that is considerably larger than similar instruments of its class, such as GMOS (Gemini) and LRIS (Keck).

The instrument throughput is remarkably competitive. Its optical transmission (excluding dispersive elements and detector) is significantly better at all wavelengths than similar instruments like FORS (VLT), GMOS (GEMINI) and LRIS (Keck). Overall, OSIRIS is a competitive instrument within its class, with the extra advantage of tunable imaging, thus making it quite a competitive and adaptable workhorse optical instrument for broad- and narrow-band imaging and low-to-intermediate (R<~5000) spectroscopy.

OSIRIS's optical design employs a reflective active collimator and a refractive camera. A flat mirror folds the light beam in order to fit it within the Cassegrain envelope. OSIRIS carries two wide format (2048 x 2048) Marconi-EEC detector arrays. Preserving blue sensitiveness has been a constant goal for OSIRIS. U band (365 nm) imaging will therefore be possible for stellar population studies. The array detector sensitivity in the red is also fairly high, thus making OSIRIS ideal for observations of the redshifted Universe, for instance through the study of the [OII] λ372.7 nm line at high redshift. Further details of OSIRIS can be found at http://www.gtc.iac.es/en/pages/instrumentation/osiris.php.

2.2 CANARICAM

CanariCam is the second first generation instrument for GTC and will serve as the facility's mid-infrared instrument. CanariCam is designed for observations in the 8.0–24.0 μm wavelength range. It was built at the University of Florida and represents an evolution of the successful instrument design of T-ReCS, the Gemini South mid-IR imager/spectrometer. CanariCam can perform broad- and narrow-band imaging, long slit spectroscopy, dual beam polarimetry and coronagraphy. The coronagraphy option is, to the best of our knowledge, the first to be made available in the mid-IR on a large ground-based telescope. The detector is a blocked-impurity-band (BIB) arsenic-doped silicon array from Raytheon, with 240 x 320 pixels, 0.08" each on the sky, hence providing a field of view of 19" x 26". CanariCam is designed to get diffraction-limited images across its FOV. CanariCam carries for its imaging mode a large set of broad and narrow-band filters. The coronagraphy mode is selected by inserting an occulting spot in the telescope's focal plane and one of several Lyot stops in the pupil plane. The baseline coronagraphy mode is for the 10 μm window only. In polarimetric mode CanariCam allows polarimetry in the 10 μm atmospheric window. Both the ordinary and the extraordinary rays are observable simultaneously on the detector array, thus allowing much better accuracy even through thin clouds. A Wollaston prism is inserted into the beam after the collimator separates the orthogonally polarized components of the light, which are then imaged separately onto the detector.

Slit-spectroscopy is implemented by inserting a slit in the image plane and one of the four gratings into the pupil plane. There are two gratings for 10 μm spectroscopy, at low (R=100) and High (R= 1300) resolution respectively, and another two for low (R= 60) and High (R= 700) resolution spectroscopy in the 20 μm atmospheric window. Together, the low-resolution gratings span the entire 10μm (8-14μm) and 20μm (approximately 16-25μm) windows. Both high-resolution gratings can be positioned to select the required wavelength within the 10μm and 20μm windows respectively. Two basic slit widths are available: a narrow slit for diffraction-limited observations and a wide slit for twice the diffraction limit.

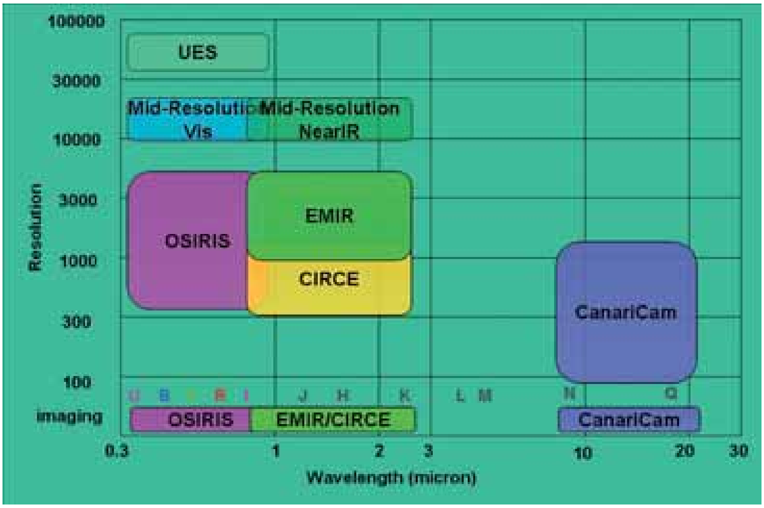
CanariCam has been delivered to the Observatory and will be installed on the GTC in the coming months to start its commissioning. Its use for science observations is expected to be initiated during semester 2010A. Further information on CanariCam and its scientific programmes are available at http://www.gtc.iac.es/pages/instrumentacion/canaricam.php.

3. The GTC's Second Generation instruments

3.1 CIRCE

The Canarias InfraRed Camera Experiment (CIRCE) is a near-infrared (1-2.5 micron) instrument. CIRCE will fill the near-IR gap between the first generation facility instruments OSIRIS and CanariCam. The optics and detector array of CIRCE will provide a pixel scale (0.10 arcsec/pixel), fine enough to sample adequately the excellent images provided by GTC, while at the same time providing a near-IR field of view (3.4x3.4-arcmin) comparable to any currently available on the world's largest telescopes (a real FOV ~25 times larger than NIRC on Keck, and ~3 times larger than NIRI on Gemini).

CIRCE will employ two grisms to provide spectroscopy with two different resolutions. The first grating allows the J, H and K bands to be covered in a single frame at roughly a resolution of R=550 (for a 3-pixel slit). The second grism will cover a single band instantaneously at a resolution of R~1500 (3-pixel slit) in its 3rd order (K-band), 4th order (Hband) and 5th order (J-band). CIRCE will also have a polarimetric mode with the use of a Wollaston prism. It also offers a sub-framing readout mode, for high-speed imaging photometry in any filter (broad or narrow band). The control electronics supports continuous frame rates faster than 1 Hz over fields of view exceeding 1x1 arcmin^2.



GTC Instrumentation coverage of spectral resolution versus wavelength parameter space. FRIDA is not included in order to simplify the picture. It will cover the area covered by CIRCE, EMIR and the Mid-Resolution Near-IR instrument but with a small FOV as it will work in AO mode only with an IFU.

After the delivery of EMIR to the GTC, CIRCE will continue in scientific use on the GTC, where its high imaging quality and resolution, polarimetric capability, high time-resolution readout and lower spectral resolution (useful for very faint targets) will complement the capabilities of EMIR. CIRCE will be a visiting instrument provided to the GTC by the University of Florida. It is expected to be installed and commissioned on the GTC by the end of 2010. Further information on CIRCE and its science drivers are available at http://www.astro.ufl.edu/circe/.

3.2 EMIR

EMIR is a cryogenically cooled wide-field, near-infrared (0.9–2.5 µm) imager and multi-object spectrograph. EMIR is being developed by a consortium of institutes, led by the IAC and including the Universidad Complutense de Madrid (UCM, Spain), the Laboratoire d'Astrophysique des Midi Pyrénées (LAOMP, France) and the Laboratoire d'Astrophysique de Marseille–Provence (OAMP, France). EMIR's optical design allows for a plate scale of 0.2 arcsec/pixel on a Rockwell-Hawaii-2 2Kx2K HgCdTe detector with 18µm pixels. This results in a 6' x 6' field of view.

EMIR is a very versatile near-IR instrument that will become a workhorse for near-IR imaging and multi-object spectroscopy. Apart from its primary mode, which is K-band multi-object spectroscopy with up to 55 slitlets in a 6' x 4' field of view, EMIR is designed to perform broad- and narrow-band imaging. The expected limiting magnitude in the K-band is 23.9 mag in a 1 hour exposure (S/N= 5) within a 0.6" aperture. As for spectroscopy, EMIR is expected to reach 21.2 mag in K-band spectroscopy for a 2 hr exposure (S/N= 5). The Spectroscopic resolution provided by pseudo-grism dispersers ranges from R ~5,000 in the K-band to R ~4,000 in the J-band, allowing observing between the OH telluric lines for better sensitivity to faint objects.

EMIR is a complex instrument. The very wide field of view, relatively high spectral resolution and multi-object capability all add to its overall intricacy. The configuration of slit masks will be performed with a cryogenically cooled robot. EMIR is a general-purpose instrument with a wide range of capabilities and a design optimized for multi-object spectroscopy of high-redshift galaxies in the K-band. Further details on EMIR can be found in the EMIR web page at http://www.ucm.es/info/EMIR/. The current plan is to install EMIR at the GTC at the end of 2012.

3.3 FRIDA

FRIDA and the GTC Adaptive Optics systems (GTCAO) will provide near-diffraction-limited imaging and integral field spectroscopy over the 0.9-2.5 micron bandpass on the GTC. GTCAO will initially provide natural-guide-star correction over the isoplanatic patch with Strehl ratios as high as ~65% in the K-band. A later upgrade of GTCAO will provide a laser guide star with a similar Strehl ratio and dramatically improved sky coverage.

FRIDA uses an image slicer to produce the Integral Field Unit configuration and is based on the successful FISICA design from the University of Florida. FRIDA offers 3D spectroscopy in the 1 to 2.5 micron range, allowing simultaneous imaging and spectroscopy of its field of view. It will therefore deliver data cubes from which images in selected bands can be retrieved. FRIDA employs a Rockwell 2k x 2k Hg-Cd-Te Hawaii II array. Two different plate scales, 0.010"/px and 0.020"/px, will be available for imaging to produce 20.48" x 20.48" and 40.96" x 40.96" fields of view respectively. In spectroscopy three spaxel ratios produce 0.010"/px x 0.020"/slice, 0.020"/px x 0.040"/slice and 0.040"/px x 0.080"/slice respectively. These give a fine scale field of view of 0.66" x 0.66", a medium scale field of 1.32" x 1.20" and a coarse scale field of view of 1.64" x 2.40" respectively. As for spectral resolution, there is a low-resolution mode (R=1500) covering the H and K windows, an intermediate resolution (R= 4000) that allows OH suppression and gives the J, H and K bands independently. Finally, a high-resolution mode (R=30000) can cover selected spectral regions in the H and K bands. This high-resolution mode is a unique feature in FRIDA.

FRIDA is being built at the Institute of Astronomy of the Universidad Nacional Autónoma de México, which leads a large consortium. The other participating institutes are the University of Florida, the IAC and the Universidad Complutense de Madrid (UCM). FRIDA is planned to reach the telescope in 2012. More info on FRIDA can be found in the FRIDA web pages http://www.astroscu.unam.mx/ia_cu/proyectos/frida/index.html.en

3.4 UES

High resolution spectroscopy requires a large number of photons. Except for specific projects, only the largest telescopes at any moment can be really competitive. Therefore, high-resolution spectroscopy is one of the fields in which GTC will be very competitive owing to its large collecting area.

The Utrech Echelle Spectrograph (UES) is being refurbished so that it can be fibre-linked to the OSIRIS mount on the Nasmyth platform of the GTC. The UES will provide the GTC with high optical spectral resolution (R ~ 50000). The former UES, an echelle cross-dispersed spectrograph, had been successfully used for years in one of the Nasmyth focal stations of the WHT. The UES had been decommissioned to free the Nasmyth platform for the ING AO programme. This is a collaborative project between the Isaac Newton Group (ING), owner of the William Herschel and other telescopes on La Palma, and the Instituto de Astrofísica de Canarias.

3.5 Optical medium-resolution spectrograph

A mid-resolution optical spectrograph (R=10000-20000) is planned for the GTC by 2015. An announcement of opportunity has been issued to initiate its development. It is required as a multi-purpose workhorse instrument aimed at giving support to a large number of projects. It will need significant multiplexing capability not only to take advantage of large surveys but also because in current research many results have been reached only after analysing a large number of objects. Possible references (and competitors) would be FLAMES-GIRAFFE and MUSE on the VLT or WFMOS on Subaru. At present, there is no such instrument operating in the northern hemisphere, and only GMOS, with limited resolution, would be a competitor in the blue (DEIMOS at Keck II is also a competitor in the red).

3.6 NIR seeing-limited medium-resolution spectrograph

To fill the gap in near-IR, medium-resolution (10000-20000) spectroscopy, and multiplexing capability over a large field of view an announcement of opportunity has been made to develop a new spectrograph to reach the telescope by 2016. FRIDA provides such spectral resolution in this wavelength range but it is an adaptive-optics instrument and its field of view is consequently limited. No such instrument is yet available or planned for any other 8 to 10 m telescope.

3.7 Feasibility studies towards new AO capabilities

New capabilities need to be developed in the field of high spatial resolution and this will require the upgrading of the GTC AO system.

Feasibility studies for multi-conjugate adaptive optics and ground layer adaptive optics capabilities, and their related instrumentation, need to be initiated to identify new capabilities to be made available on-sky by 2018.

Such capabilities are closely tied to knowledge of the turbulence scale height at the ORM. The GTC will therefore perform a study to provide high-resolution measurements of the ground layer properties and the turbulence scale height at the ORM

4. The GTC and the new large facilities ALMA, JWST and ELTs

From 2012 onwards, new millimeter and sub-millimeter observatories will be operational: ALMA in the southern hemisphere and Large Millimeter Telescope in the northern hemisphere. The GTC will not be the best candidate for ALMA follow-up surveys, but can be a useful tool in dealing with selected samples mostly through NIR spectroscopy and narrow- and broad-band imaging in the optical, NIR and mid-IR. For galactic objects, the GTC can help with AO observations of the closest cool objects detected before the ELTs become fully operational.

The LMT is a better option as it has the same sky coverage as the GTC. Synergies between both instruments can be easily addressed as INAOE is a partner in the GTC and there is an agreement on exchange of observing time and the development of joint programmes around both instruments between the communities.

The James Web Space Telescope (JWST) will be operational from 2014 or 2015 and for a lifetime of 5 to 10 years. It will be an unprecedented step forward in observing the sky, especially in the infrared part of the spectrum. But major ground-based telescopes will complement its observations on studies requiring higher spectral resolution than its limit at R~3000; or at shorter wavelengths than its cutoff around 0.6 microns, which will be particularly important after the HST is decommissioned; or when the higher spatial resolution using AO, in the mid infrared, in good seeing conditions are required. The GTC, like other ground-based telescopes, can benefit from its larger FoV, above the JWST limit of about 3 x 3 arcmin. Multi-IFU capabilities can also be complementary as they are not available at the space telescope. Finally, the upgradability and versatility of the ground-based GTC should be an advantage with respect to the limited flexibility of space facilities to improve and adapt their instrumentation.

After 2018, or probably some years later, the ELTs will become the new unbeatable observing facilities. At that time the 8 to 10 metre telescopes have to adapt to their new roles in the way that 2 to 4 metre telescopes have had to do after the present generation of larger telescopes were built. But there will be fewer ELTs than 8 to 10 metre telescopes. That difference could mean that telescopes like the GTC will play an important role for a longer period of time in complementing the ELTs. By that time the GTC will need to be well equipped with AO observing capabilities as this will be the main observing mode of the ELTs.

In the longer-term it is difficult to identify the best role for the GTC. We need to be open to fundamentally re-assessing our objectives and mission in a time led by multiple ground-based ELTs.

The GTC buildings at the Roque de Los Muchachos Observatory (ORM)

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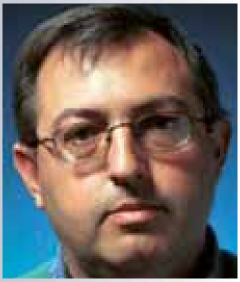

Artemio Herrero

RAPID CONCLUSIONS

1. Rapid Conclusions

First of all, I would like to remind you of the reason why we are here: the GTC is now operating! As a community, I'm sure we all welcome this news, we all congratulate those who made it possible and thank the organizers of this meeting for providing us with an exciting overview of current 8-10 m telescopes and other similar, future, or related facilities.

I have been impressed by the presentations. Impressed, but not surprised, as they referred to some of the best currently available telescopes and instruments and to some of the most promising future facilities.

It is not easy to extract just a few points out of all these excellent presentations, and their corresponding discussions. Of course, this summary is necessarily subjective. It may be that some of those present in the meeting find their ideas here not properly expressed or recognized, or feel that I have skipped important points, comments or conclusions. I can only apologize in advance, and remember an old german saying: *"Wer nichts tut, macht keinen Fehler; wer keinen Fehler macht, wird befördet"* (who does nothing, makes no errors; who makes no errors, is promoted). I have no interest in being promoted, so I'll try to provide this summary, in the hope that it can be of help for you and also for those that couldn't attend the meeting.

I wish to be brief in my conclusions. To this aim, I'll follow the outline provided by the questions presented yesterday in the "Wine and Cheese discussion". This session brings me to my first, zero-order, conclusion:

Conclusion 0: Cheese and wine are really fine!

2. Question 1: Scientific strategies

The first question presented in yesterday's discussion was: What should be the role of the 8-10 m telescopes in the era of the ELT and the JWST (or any other equivalent facility)? In other words, what should be the scientific strategy of these telescopes? To open the discussion, three possible approaches were presented: a) the nurturing approach: start to dedicate a significant amount of observing time to projects that will later be explicitly aimed at ELT and JWST; b) dedicate as much time as possible to individual projects, trying to collect as many new results as possible; and c) maintain competitiveness in the new era, by optimizing the operation efficiency, enlarging the instrument suite or specializing in unique capabilities.

This question was already addressed in his talk by William Smith, who described possible organizational models for observatories, and recommended to carefully select the optimum one in each particular case. An important point of his presentation was that there were successful examples of all models among the 8-10 m telescopes. Taft Armandroff pointed out that observatories should pay attention to all three aspects, but always having the opt priority be scientific merit.

The discussion continued with important comments by other participants. Thomas Henning and Bruno Leibundgut reminded us that the ELTs and the JWST are still a long way from construction. Furthermore, the ELT will need additional time for its instrumental suite to be ready. As pointed out by Jean Rene Roy, "8-10 m telescopes have a decade of scientific freeway ahead", and many participants emphasised the need to make use of all facilities, not just the largest or newest, in order to carry out top-level science (even including telescopes like KELT, the Kilodegree Extremely Little Telescope).

The answer I have chosen for these questions, my conclusion number 1, makes direct use of two sentences expressed during the discussion, one by Bruno Leibundgut and the second one by Phil Charles:

Conclusion 1: do your best science now, do it as well as you can, pushing current telescopes to their limits, and in a natural way these projects will lead the way towards the ELTs when these become available (or are close to completion).

3. Question 2: Science topics

A question that we didn't address during the Cheese and Wine discussion but is clearly in our minds, is that of the hot science topics, those that should guide our way towards the ELT and the JWST.

I would like to mention here an important remark made by Bruno Leibundgut during his talk. He noted that we live in a Golden Age of Astrophysics, as we have access to all possible wavelengths, from gamma-rays to radio, and have access to a large number of excellent telescopes of all sizes, well equipped with modern instruments and sensitive detectors. Combined with powerful number-crunching machines we can study the Universe at any wavelength. At the same time, there is wide public interest in Astronomy (the success of activities during IYA2009 is a nice confirmation) and other communities (like the astro-particle community) are approaching us. This situation is the result of the sustained efforts made during the recent past, and it is our responsibility to preserve and improve it (as difficult as improving a "Golden Age" situation may be…).

Without meaning that they are more important than other topics, Planets and Planetary/Stellar disk systems clearly have dominated the presentations, with interest presently shifting from discovery, to how planetary systems form (see Matt Greenhouse's presentation). Instrumentally, the demands for such research are linked to the AO systems either operating or under development at all major observatories (and which can be applied to many other problems). As examples, AO was explicitly mentioned by Jerry Nelson to be one of the main drivers for TMT, and Taft Armandroff demonstrated how LGS systems can overcome the limitations inherent in NGS. In some cases (VLT, LBT, Keck) interferometry can take such work one step further.

Many other topics were mentioned by several speakers: galaxy formation and evolution, dark matter and dark energy, GRBs and supernovae, the reionization epoch… Actually, the science cases seemed to be quite similar across the presentations, with perhaps the main (still relatively small) differences being between space and ground-based facilities. As a consequence, extensive interest in multiplexing capabilities and broad wavelength coverage can be seen in new and planned instrumentation. Another dimension was present in science cases based on new technological developments, such as high temporal resolution (LSST, SALT), or the combination of high temporal and spectroscopic resolution (LBT), as well as the remarkable microshutter arrays for NIRSpec.

Conclusion 2: We have seen interesting and important science cases covering all areas of astrophysics. It's very difficult to predict which will be the main drivers in ten years. Be prepared for the unexpected.

4. Question 3: Data archives & mining

The comparison of CCD versus mirror growth made by William Smith and Tony Tyson clearly demonstrates the impact large CCDs are having in astronomy. Whereas the mirror area available for observations has increased since 1980 by less than an order of magnitude (which is however very appreciable) the number of detector pixels has increased by more than three orders of magnitude, and is maintaining a substantial growth rate. When we reach the dimensions of the LSST or SASIR projects (see Tony Tyson and José Franco's papers) the handling of such huge amounts of data, in real time, including potentially thousands of alerts per night, may become a problem in its own right.

The importance of Virtual Observatories and Archives is therefore rapidly increasing and there are real efforts at many observatories and institutions to create archives that conform to the International Virtual Observatory Alliance, so that these (expensively) collected photons can be used for the maximum amount of science. According to numbers presented by William Smith, archives in the US already contain 0.5 Pb of data, increasing at a rate of 250 Tb/yr. When fully in operation, LSST will deliver 3 Tb per hour.

Handling and interpreting these gigantic datasets may be an even larger problem. To extract the relevant information will be a very demanding task, even with modern computers and automatic analysis techniques. It is thus important, as pointed out by Phil Charles, to deliver already processed and science-ready data to the community.

Conclusion 3: Important resources and efforts will go in the immediate future into data handling and archives, and related software and infrastructure. When planning our telescopes we must pay attention not only to the instruments, but also to the resultant archives and data handling.

5. Question 4: Collaboration

The issue of collaboration captured the immediate attention of the audience. Actually, several already ongoing collaborations between observatories were mentioned, such as Gemini and Keck for the LGS contract, or the agreement for observing time exchange between Subaru, Keck and Gemini. In future, the potential for other possible collaborations, like that of GTC with LSST, GMT and SASIR, or that of SASIR with LSST, was acknowledged. Moreover, both Álvaro Giménez and Matt Greenhouse emphasized the collaboration possibilities of JWST with ESA missions.

Jean René Roy and Thomas Henning also pointed out the difficulties that always occur in collaborations: the need for clear goals in the collaboration, the different interests of the partners, the asymmetries present in large multi-partner collaborations, the need to recognise all points of view, among others. And strictly focussing on the ELTs, Carme Gallart complained that Americans and Europeans are not really collaborating in the ELT effort, and spoke in favour of such collaborations, as in the cases of HST and JWST.

Generally speaking, there was an extended feeling that any collaboration would be possible and positive, and that it would be worthwhile to work in such direction.

The discussion was particularly interesting when it came to discussing instrumental projects. José Miguel Rodríguez-Espinosa expressed support for a scientific competition; but not a competition in instrument building. He proposed that instruments for large telescopes be built in a complementary manner, trying to avoid duplicity (or at least multiplicity). Phil Charles agreed, but noted the distinction between workhorse instruments and those with a specific scientific objective. Finally, Massimo Tarenghi reminded us how convenient it would be to collaborate also in our relations with industry: we are a small community, more and more left on our own with industry and we are effectively competing with other larger communities: so organization and collaboration are essential to fulfil our goals.

An interesting idea that was raised during the discussion is that of having regular (or semi-regular) meetings to try to find new ways of collaboration. People (particularly observatory directors) should often talk to each other. I personally am very in favour of this, although I recognize that it is very easy for me to say what other people should do with their time!

Conclusion 4: there is a real interest in collaborations. Although they are not easy to establish, they will bring an increasing reward for the astronomical community. Moreover, being in competition with other large communities and industry, fair and equitable collaborations may be the only way for large telescope astronomy to succeed.

6. Question 5: Access, training and young people

If the few big telescopes and top science projects are undertaken more and more in service mode, how are we going to ensure the training of our young observers? This question summarized the worry of many people present in the meeting that led to an open and worthwhile discussion.

Some people, like Alfonso Serrano, found this to be a real problem for the future, and he expressed his concerns. Masahiro Iye and Jean René Roy proposed some ideas about how to train people in large telescopes (through a Visiting Queue Astronomers programme, for example). Bruno Leibundgut looked at the problem a bit more optimistically than others: training in 2 and 4 m telescopes should be enough to train young people and make the jump to larger telescopes easier (and there are many 2-4 m telescopes, and even quite a few 8-10 m telescopes). Tony Tyson stressed the point that young researchers should also be trained in the laboratory, emphasizing the importance of having well-trained people in instrumental development. Related to the training problem, but on a larger scale, Massimo Tarenghi recalled the successful experience of the NTT as a test-bench for the VLT, and supported the idea that 8-10 m telescopes should play a similar role for the ELTs.

William Smith noted "the demise of the lone astronomer": projects (and papers) are carried out by a larger number of scientists than they were in the past. While this is in general positive, as it strengths collaborations and makes it possible to tackle more difficult problems, it also has a negative aspect, as pointed out by Thomas Henning: the lack of personal contribution possibilities and the hierarchical structure of large projects may push young talented people to other scientific areas. Clearly, our community should keep an eye on these issues.

Conclusion 5: There is agreement on the need to train young people, although there are different views on the seriousness of the problem and ways to tackle it (probably all ways are valid). And there is agreement on the (obvious) need to attract talented young people to astronomy!

7. Question 6: Construction of ELTs

The construction of ELTs, although strictly not yet guaranteed, raised several hot topics that provoked a very lively discussion.

The meeting organizers asked who is actually driving the construction of ELTs; astronomers or engineers? After some opinions, Massimo Tarenghi quoted Ricardo Giacconni, about the VLT construction: "Science, technology and politics are required, and in the right order. And there is only one right order: science, technology and politics". I can only agree with this sentence, and therefore the question was settled for me. Of course, it is our responsibility as people interested in the ELTs to guarantee that priorities are kept in the right order.

Participants were confronted with a second question: how many ELTs can be expected to be built? Only 15 years ago, no 8-10 m telescope was operating. Nowadays, there are 10 of them, and LSST will probably join them soon. Presently, 3 telescopes of the ELT-class are planned, two led by Americans (one foreseen for the southern hemisphere, the other in the north) and one by Europeans (without a site decision yet). Probably it is not unreasonable for our community to aim at building 4 ELT-class telescopes. Time and experience will make telescope construction cheaper, and this would allow Americans, Europeans and their partners' full sky access, with one telescope in each hemisphere for each community. This would open many collaborating possibilities, including instrument complementarities.

A final question related to the ELT construction was: are we envisioning the end of the large telescope business? This question got a clear answer from Jean René Roy: No!! And he referred to the many ongoing projects: SASIR, GMT, LSST… and even to the next possible step: OWL wasn't discarded by any clearly insurmountable difficulty. However, it is possible that we have to open our minds and find new ways for our wishes to become reality, as radio astronomers did with ALMA or as segmented telescopes did through Keck.

Conclusion 6: We have as yet no total guarantee that the ELTs will be built, but we should always be ambitious: ELTs do not have to be single entities, nor do they represent the end of the line. We will find, if needed, new ways to look deeper and see better.

Acronyms List

AAT—Anglo-Australian Telescope
AGN – Active Galactic Nuclei
ALMA—Atacama Large Millimeter Array
AO—Adaptive Optics
AOF —Adaptive Optics Facility
APEX —Atacama Pathfinder Experiment
ARC —ALMA Regional Center
AURA—Association of Universities for Research in Astronomy
AzTEC — Astronomical Thermal Emission Camera
BAO —Baryonic Acoustic Oscillations
BOSS —Baryonic Oscillation Spectroscopic Survey
CARMA —Combined Array for Research in Millimeter wave Astronomy
CCD—Charge Coupled Device
CFHT Canada-France-Hawaii-Telescope
CMB —Cosmic Microwave Background
CoRoT—Convection, Rotation and planetary Transits (satellite)
CSO —Caltech Submillimeter Observatory
CTIO —Cerro Tololo Inter-American Observatory
E-ELT—European Extremely Large Telescope
ELT—Extremely Large Telescope (generic term)
ESA —European Space Agency
ESO —European Southern Observatory
FMOS —Fibre Mulit-Object Spectrograph
FIR —Far Infrared
FSBs—Frequency Selective Bolometers
GAIA —Global Astrometric Interferometer for Astrophysics
GMT—Giant Magellan Telescope
GTM —Gran Telescopio Milimétrico
GTC—Gran Telescopio Canarias
HESS—High Energy Stereoscopic System
HET—Hobby-Eberly Telescope
HETDEX—HET Dark Energy eXperiment
HIPPARCOS—High Precision Parallax Collecting Satellite
HRS—High Resolution Spectrograph (on SALT)
HST—Hubble Space Telescope
INAOE – Instituto Nacional de Astrofísica, Óptica y Electrónica
IR—Infrared
IRSF—IR Survey Facility (at SAAO)
ISM – Interstellar Medium
JWST—James Webb Space Telescope
KAT—Karoo Array Telescope (demonstrator for SKA)
KELT—Kilodegree Extremely Little Telescope
LAMOST—Large Mulit-Object Spectroscopy Telescope
LGS—Laser Guide Star
LBT—Large Binocular Telescope

LSST—Large Synoptic Survey Telescope
Monet—MONitoring NETwork (at HET and SALT)
NGAO Next Generation Adaptive Optics
NGS—Natural Guide Star
NIR—Near Infrared
NOAO—National Optical Astronomy Observatory
NTT—New Technology Telescope
OPTICON—Optical and Infrared Coordination Network
OWL—OverWhelmingly Large Telescope
PdBI—Plateau de Bure Interferometer
PRIMA—Phase Reference Imaging and Micro-arcsecond Astrometry
ReSTAR—Renewing Small Telescopes for Astronomical Research
RQQs —Radio Quiet Quasars
RSS—Robert Stobie Spectrograph (on SALT)
SAAO—South African Astronomical Observatory
SAC—Spherical Aberration Corrector (on SALT)
SASIR—Synoptic All-Sky Infrared Survey Telescope
SALT—South African Large Telescope
SALTICAM—SALT Imaging CAMera
SDSS—Sloan Digital Sky Survey
SFR – Star Formation Rate
SKA—Square Kilometre Array
SMA—Sub-mm Array
SMARTS—Small and Medium Aperture Research Telescope System
SMBH—Small Mass Black Holes
SNLS—Supernova Legacy Survey
SOFIA—Stratospheric Observatory for Infrared Astronomy
SPEED – SPEctral Energy Distribution
STScI—Space Telescope Science Institute
SZ —Sunyaev Zel'dovich
TMT—Thirty Meter Telescope
ToO—Target-of-Opportunity
T-ReCS—Thermal Region Camera Spectrograph
TSIP—Telescope System Instrumentation Program
UKIDSS United Kingdom Infrared Deep Sky Surveys
UKIRT United Kingdom Infrared Telescope
UMass – University of Massachusetts
VISTA Visible and Infrared Survey Telescope Assembly
VLBA – Very Long Baseline Array
VLBI – Very Long Baseline Interferometry
VLT—Very Large Telescope
VLTI Very Large Telescope Interferometer
VST VLT Survey Telescope WASP-- Wide Area Search for Planets
WET—Whole Earth Telescope
WFCAM—Wide Field CAMera (on UKIRT)
WFMOS—Wide Field Multi-Object Spectrometer