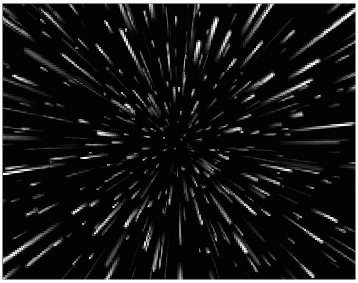
UNVEILING THE SECRET *of the Universe with neutrinos,* GRAVITATIONAL WAVES *and gamma rays*

Por TAKAAKI KAJITA
Premio Nobel de Física 2015
Instituto de Investigación en Rayos Cósmicos, ICRR.
Universidad de Tokio, Japón.



En 1912 se descubrieron los rayos cósmicos: partículas de alta energía, como protones, helio o núcleos atómicos más pesados. Es un misterio el cómo y dónde estas partículas han sido aceleradas. El descubrimiento de los rayos cósmicos también ha sugerido que hay fenómenos de alta energía que no pueden entenderse solamente a partir de observaciones astronómicas. Se espera que los estudios sobre neutrinos, ondas gravitacionales y rayos gamma desvelen los misterios del Universo a altas energías.

Invitado por la Fundación Ramón Areces y la Unidad de Excelencia María de Maeztu CIEMAT-Física de Partículas, Takaaki Kajita, Premio Nobel de Física 2015, pronunció esta conferencia en la que explicó el interés y la expectación generada por los estudios acerca del Universo con estos mensajeros.

Neutron stars are a kind of special stars, which typically have a radius of 10 kilometers and a mass of about 1.4 solar masses; subsequently, very dense and very small stars.

Even 1,000 years ago, people were interested in new stars in the universe. In his diary, Teika Fujiwara wrote what he had heard about a new bright star. One of the descriptions is about the very bright new star that appeared on May 1st 1006, more than 1,000 years ago. Another description is about a bright new star that appeared in May 1054. This clearly indicates that people were interested in looking at the universe even 1,000 years ago.

About 100 years ago, Victor Hess discovered that there is a radiation coming from the universe. For this discovery, he took some kind of gondola ride and took a flight up to five kilometer from the ground. Then he discovered that radiation level increases with the height, and that was the discovery of cosmic radiation or cosmic rays. This observation clearly indicated there are phenomena in the universe that cannot be observed with optical telescopes. From the early days the question was where and how these particles are accelerated.

This is still a major question. And by the way, Teika Fujiwara's diary and Victor Hess's discovery might be related and I want to talk about the phenomena related with them.

Now, I will move on to the neutrinos. We love to understand the universe with neutrinos, but of course, you may not know what neutrinos are. Neutrinos are fundamental particles like electrons and quarks, so they are very small particles. Neutrinos are something like electrons without electric charge. In fact, this has a substantial consequence, and neutrinos can easily pass through even the Earth. This fact indicates that neutrinos can bring information of the center of the stars, so we could use neutrinos to study the universe.

The first experiment that contributed to the neutrino astrophysics was the Kamiokande experiment. It was located in Japan and the experiment began in July 1983. If we look at the inside of the Kamiokande experiment, we can see a 3,000-ton water detector where we can see many dots. These dots are photodetectors, which detect photons that are emitted by the neutrino interactions. That way, this detector observed neutrinos. I was a member of this experiment together with professor Koshiba, who was my physics advisor and also the Nobel Prize laureate in 2002. I remember when we were constructing the Kamiokande detector. Every morning we went into the mine and worked in the mine 1,000 meters from the surface, where the detector was being constructed. We had to construct the detector, which means we had to install the photodetectors onto the inner surface of the Kamiokande tank. We were happy that we were successful in constructing the detector.

Another experiment that contributed to the neutrino astrophysics was the IMB experiment in the United States. This experiment began one year earlier than Kamiokande, in 1982. These experiments were designed to detect proton decays that were predicted by the Grand Unified Theory of the '70s. Unfortunately, these experiments did not observe proton decays, although they were sensitive to neutrinos.

Then, several years later an event happened. Now we have to think about the life of a star. If the mass of the star is not heavy, then the star will continue shining for an extremely long period, I would say more than 10 billion years. If the star has the mass of about our sun, then its life will be around 10 billion years and after finishing the shining, there will be a white dwarf remaining. But if the mass of the star is much heavier than our sun, its life would be rather short. And at the end of its life, there is an extremely large explosion that is called supernova explosion. This is really a major event. After that, neutrons stars are typically remaining there.

This was the expectation in the '70s and '80s. Then in 1987, there was a supernova explosion that happened in the Large Magellanic Cloud, which is about 160,000 light years away from our Solar System. We have images that show the Large Magellanic Cloud before and after the supernova explosion. We can see a very bright star after the explosion. At the time, the Kamiokande and the IMB experiments were taking data. The total number of neutrino events observed by these experiments was only 24, but these numbers were already enough to understand the basic mechanism of the supernova explosion. And because of this observation, Professor Koshiba received the Nobel Prize in Physics in 2002. We expected to observe a supernova explosion and the neutrinos.

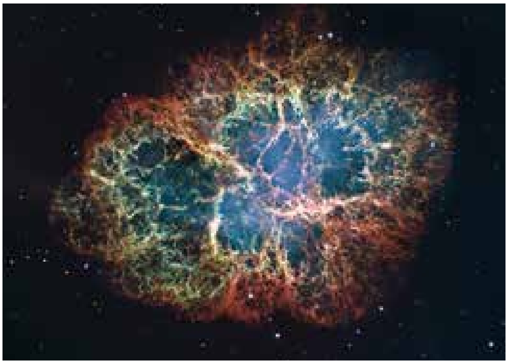
In 1987, it was not possible to simulate the supernova explosion with computers. However, this observation triggered the theoretical community to seriously study this supernova explosion. Finally, after almost 30 years, we were able to somehow reproduce a supernova explosion by computer simulation. Actually this computer simulation is not a simple one. We could see a nuclear fusion process going on and, with time, at the center of the star, heavy elements are accumulated. If the iron is produced, then the star can no more shine. Then the materials surrounding the center core come to the center, and then the center core shrinks producing a very heavy center core. Then there is still outer material coming to center, but there is a bounce and then some kind of explosion begins. This simulation, which has not spherical symmetry, is rather complicated. Nonetheless, you need this kind of three-dimensional simulation in order to make this star explode. So this kind of detailed simulation is needed to reproduce the supernova explosion.

Since the detection of neutrinos is extremely important, even after the previous measurement that was 30 years ago, we are trying to observe the subsequent neutrino burst from a supernova explosion. And the main detector is the Super-Kamiokande Detector. It is a 50-kiloton water detector. The diameter of the detector is about 40 meters and the height is also 40 meters. This detector began the operation in 1996. In the last 20 years we have been waiting for the next supernova to happen. Unfortunately, so far, we had no supernova detection, which means I cannot show new data. Instead, today I want to show you what will happen if the next supernova happens nearby.

We have simulated supernova neutrino interactions in Super-Kamiokande. There is the dark noise, and then, the supernova came. For about 10 seconds, Super-Kamiokande should observe a lot of neutrino interactions. If a supernova explodes at the center of our Milky Way, Super-Kamiokande should detect about 10,000 neutrino interactions in 10 seconds. That is what we are expecting to observe. We actually continue searching for these neutrinos. Anyway, it is true that we have been waiting for 20 years and, so far, we have no observation of the second supernova neutrino burst. Therefore, in Super-Kamiokande, we are thinking in a different way now.

In the history of the universe, there have always been supernovas. And with these supernovas, neutrinos are emitted. Now, we are thinking to detect supernova neutrinos that were created by past supernova explosions. This would be a very important observation. However, the present Super-Kamiokande is not powerful enough to detect these supernova neutrinos. Therefore, we need to improve our Super-Kamiokande detector. And in fact, Super-Kamiokande has decided to improve the detector in next year. We would like to start the observation of these neutrinos maybe two years from now. That is our new project.

The next topic is gamma rays. Supernova explosions were recorded in a diary. We also have the present image of the super-explosion that happened in 1054. And we think that these supernova remnants are a part of the source of cosmic rays. In that sense, all the supernova and cosmic rays could be related. Then the next question is how we can prove



that these supernova remnants are the source of cosmic rays. Well, we know where the source and the Earth are. Now, if a cosmic ray is accelerated in the source, we also know how the trajectory may look like. Cosmic ray particles cannot propagate straight because they are just particles and, as we know, there are magnetic fields in the universe. Therefore, even if we have a very precise measurement of the cosmic ray coming direction, we cannot get any information of the cosmic ray source. Then, what shall we do? We should observe gamma rays. If a cosmic ray is accelerated, then cosmic ray interactions with matter produce gamma rays and these gamma rays go straight. Therefore, if we measure these gamma rays and measure the direction, then we know the source and the location of these cosmic ray accelerators.

Of course, neutrinos can also be used to know the source of the cosmic rays. But unfortunately, I think gamma rays studies are more advanced. The question is how we can measure these gamma rays. Actually, these gamma rays have extremely high energies. Therefore, if these gamma rays come into the Earth or Earth's atmosphere, they produce a lot of particles that actually emit photons. If we have a telescope, we can detect these photons and from these observations we can say from what direction those gamma rays are coming from. That way, we detect very high-energy gamma rays.

There are several gamma ray telescopes, like the one located at the Roque de los Muchachos in La Palma (Canary Islands, Spain), which has already produced significant scientific results. Now, what will happen if we observe the supernova remnants after 1,000 years by very high-energy gamma rays? We know that gamma rays are coming from certain locations, clearly indicating that supernova remnants could be a source of the cosmic rays. So it's clear that very high-energy gamma rays are a very important tool to understand the high-energy phenomena in the universe. In fact, there are many potential sources that should be studied with very high-

We are in the era of multi-messenger astronomy. Neutrinos, gamma rays, and gravitational waves play very important roles. Thus, I believe new messengers will tell us the secrets of the universe that cannot be studied by optical telescopes.

energy gamma rays, for instance, supernova remnants, super heavy black holes at the center of galaxies, and gamma ray bursts. Finally, these gamma ray studies may also tell us about the nature of dark matter particles. Science is focusing on high-energy gamma rays because it is very important. Therefore, the world community has been thinking to improve our gamma ray measurement. In fact, the next-generation telescope called the CTA is planned and the construction has begun.

The Cherenkov Telescope Array (CTA) will be constructed in both the North and South hemispheres by a collaboration of more than 1,000 scientists from 32 countries. The one at the north is at La Palma. We are expecting a lot of important results from this observatory. The CTA construction site at La Palma is in progress and, before the end of 2018, we expect that the mirror of the first Large Size Telescope will be installed there.

I finally move onto the gravitational waves. The story of the gravitational waves is a little bit different. About 100 years ago, gravitational waves were predicted by Einstein based on his theory of general relativity. We made a simulation of the merger of two black holes. It included the expected gravitational wave signal and the deformation of the space-time. With these black holes orbiting around each other, the gravitational waves are emitted, and with the emission of the gravitational waves, they come closer and begin to merge. As a result, a new heavier black hole was formed. If we look at the space, we can see that gravitational waves propagate across space. This is what we expect to observe. But you may ask how we can detect these gravitational waves. Well, the effect of the gravitational wave is essentially a length change. If a gravitational wave comes, the distance between two objects will change. We use a laser interferometer to measure if the relative length travelled by light changes. By doing so, we can detect these gravitational waves. That was the principle. Finally, last year in February, there was an announcement of the detection of a gravitational wave. In fact, there were two waves overlaid which showed a very good agreement. This agreement showed us that this couldn't be a false signal. This must be true.

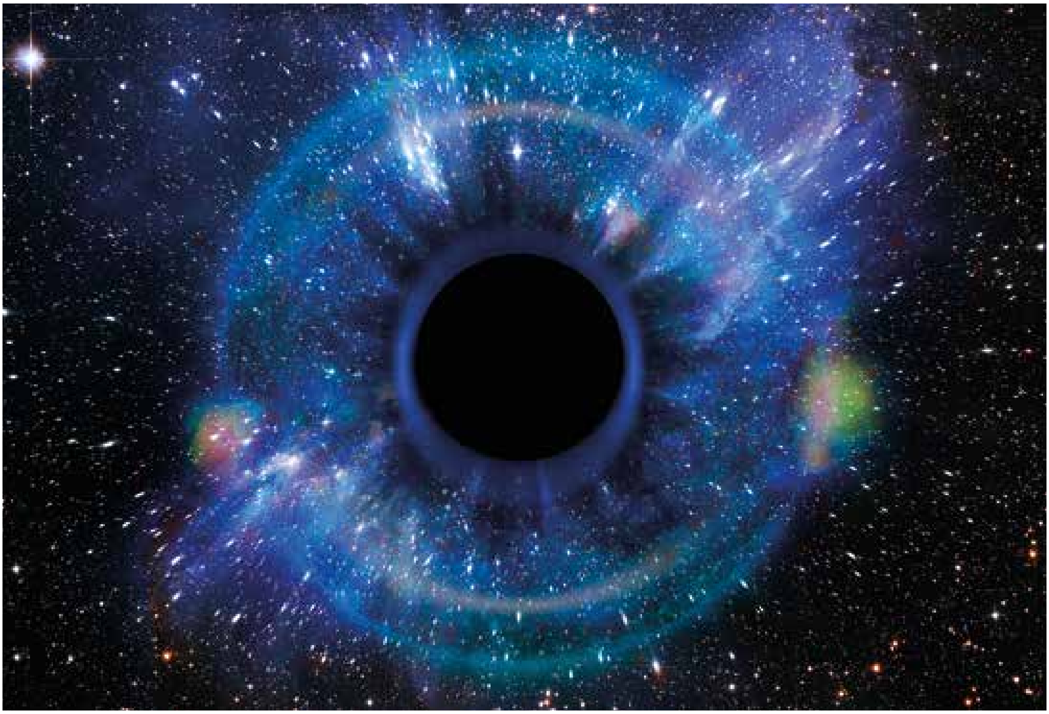
From this data, we get information about what happened in the far universe. This data told us that two black holes of 36 and 29 solar masses respectively mashed at a distance of 1.3 billion light years, newly forming a 62 solar masses black hole. This conclusion was reached by analyzing this data. You may have noticed something strange: 36 plus 29 must be 65 but the newly formed black hole has a mass of 62 solar masses. That means that 3 solar masses disappeared during this merger and an equivalent energy of 3 solar masses was converted to the energy of gravitational waves and propagated through the universe, and I believe this must be the most violent phenomenon we have ever observed.

This discovery was awarded with the Nobel Prize in Physics this year. Now, we think that we really are in a stage to use gravitational waves to study the universe. By the way, the detectors that detected these gravitational waves are located in United States. They have a big laser interferometer whose arm length is four kilometers.

That was in fact a very big discovery. Then, a few weeks ago, there was an announcement of another big discovery. The same interferometer observed the merger of two neutron stars. Neutron stars are a kind of special stars, which typically have a radius of 10 kilometers and a mass of about 1.4 solar masses; subsequently, very dense and very small stars. The gravitational waves signal showed the merger of these neutron stars in August 17th this year.

The merger was actually also observed by detecting gamma rays and later on by observations with optical telescopes. In fact, the data from optical telescopes suggest that with this merger lots of heavy metals, such as gold or platinum, were generated. This was a mystery. Before this event, we did not understand how these metals were generated in the universe. So clearly, this single event answered one of the mysteries in the universe.

Since last year, we had several observations of gravitational waves, but it is not so easy. We know the distance between the Sun and the Earth is about 150 million kilometers. Now, let us assume that a gravitational wave comes to the Solar System. Then of course, the distance between the Sun and the Earth changes. The question is how much change we expect. The expected change is about 10^{-8} centimeters. That is about the size of the hydrogen atom. So, if a gravitational wave comes to the Solar System, the distance between the Sun and the Earth changes by 10^{-8} centimeters. Therefore, every gravitational wave detector has to be sensitive to this length change. Unfortunately, the present gravitational wave detectors have interferometer arm lengths of only 3 to 4 kilometers. That means these detectors must be sensitive to a length change with too many zeros, 10^{-16} in 3 to 4 kilometers. That is the sensitivity these detectors must have.



For science, these detectors have become a clear target, and scientists have been working for many years to achieve this kind of sensitivity. Of course, we already know that binary black holes merge. However, we know that we do not understand something. The gravitational waves observed with the merger of the black holes showed us that these black holes are a little bit heavier than we expected. So we would like to understand how these black holes are created. I think there could be a very important science behind this new question. Now, we know that binary neutron stars merged and we also know that heavy metals are created with this merger. Finally, we would like to observe the supernova explosion with gravitational waves, and understand how the heavy stars finish their life.

Although here I discussed gravitational waves, in many cases it is important to have follow-up observations by optical telescopes. Therefore, it is very important to tell astronomers the sky location of the gravitational wave event. However, any single gravitational wave detector does not get the directional information. We can only get directional information, if we have a worldwide network of the gravitational wave detectors. Therefore, at present, there are two interferometers, LIGO, in the United States and one interferometer, VIRGO, in Italy. In addition, we are in the process of building the KAGRA interferometer in Japan. And also, the construction of LIGO India was recently approved. In the next seven or eight years, we will have this kind of detector network, and that way we will improve the sky localization substantially. Consequently, we can further enhance the gravitational wave astronomy in collaboration with optical telescopes.

Now, I just want to introduce the project in which I am currently involved: the KAGRA project. KAGRA is under construction in Kamioka, Japan. In fact, it is actually located in Kamioka's underground mine. We think the underground environment is very important because underlying floors are much more stable. For instance, seismic noises are approximately two orders of magnitude smaller than the seismic noises at the surface. Therefore, we have much better working conditions in the underground. In addition, we are going to use cryogenic temperature mirrors, 20 kelvin, in order to reduce the thermal noise. Since these interferometers require such an extremely high sensitivity, even the thermal noise of a mirror is an issue. Therefore, we decided to cool down these mirrors. These are the key features of the KAGRA interferometer, and actually, we are in the middle of the construction.

It has a vacuum pipe of three kilometers. The connection and dig test of the three-kilometer by three-kilometer beam tubes already finished in February 2015. Now we are installing various elements into the vacuum tank, for example, the beam splitter and its seismic attenuation system, in June this year, or the test of the suspension of the cryogenic mirror, in July this year. This kind of construction work is going on in KAGRA, and we plan the first operation with reasonably good sensitivity in 2019 to 2020. So we are excited with this new observation facility.

Finally, I want to talk about the synergy. If a supernova explodes at the center of the Milky Way, then gravitational wave interferometers should observe this signal, and at the same time Super-Kamiokande neutrino detector should observe a lot of neutrinos. By combining these two pieces of information, we will get the detailed understanding of the supernova explosion and we could compare the data with the simulation of the supernova explosion. Therefore, gravitational waves and neutrinos are related. Finally, this supernova should be observed by gamma rays, maybe 1,000 years later, but anyway, this is still relevant.

Bio

TAKAAKI KAJITA

En 2015 Takaaki Kajita fue galardonado con el premio Nobel en Física junto con el físico canadiense Arthur B. McDonald "por el descubrimiento de las oscilaciones de neutrinos, lo que demuestra que los neutrinos tienen masa". El hallazgo de ambos físicos "ha cambiado nuestra comprensión del funcionamiento más profundo de la materia y puede ser crucial para nuestra visión del universo", según la Academia de Ciencias Sueca.

Nombrado director del Centro para Neutrinos Cósmicos del Instituto para la Investigación de Rayos Cósmicos (ICRR), en 1999, desde 2015 trabaja en el Instituto de Física y Matemáticas del Universo en Tokio y es Director del ICRR.

We are in the era of multi-messenger astronomy. Neutrinos, gamma rays, and gravitational waves play very important roles. Thus, I believe new messengers will tell us the secrets of the universe that cannot be studied by optical telescopes.