Principal Investigator Katsuhiko Sato
Research Area: Astrophysics

Exploring Star Deaths and the Early Universe by Detecting Supernova Neutrinos and Gravitational Waves

Neutrino astronomy's early days

On February 23, 1987, astronomers on Earth spotted a supernova in the Large Magellanic Cloud, a galaxy neighboring our own galaxy, the Milky Way. Later, it turned out that Kamiokande, the neutrino observatory led by Professor Koshiba at that time, had detected neutrinos emitted from this stellar explosion, the SN1987A supernova at 4:35 pm (Japan Standard Time), more than three hours prior to the optical observation. Until then, traditional astronomers had been exploring the universe through observations using visible light and radio waves. The 1987 observations at Kamiokande marked the birth of 'neutrino astronomy.' Mankind acquired a new probe, the neutrino, for observing the universe.

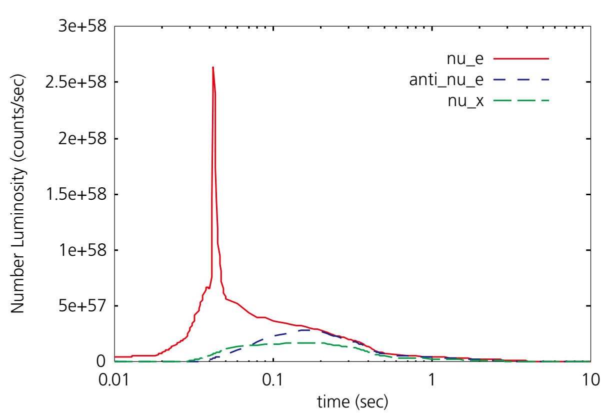


Figure 1: An example of a calculation of the intensity of the neutrinos emitted from a supernova. The effect of the neutrino oscillations, the back-and-forth transmutations of the emitted neutrinos into three neutrino types, are not taken into account in this calculation. (Totani, Sato, Dalhead, and Wilson, 1998)

The supernova in the Large Magellanic Cloud resulted from the death of a star roughly 10 times or more heavier than the Sun. The illumination of the Sun and stars is powered by nuclear fusion reactions in their central cores, where hydrogen burns into helium which is then fused into carbon and oxygen. This nuclear burning chain, in which the ash produced in the earlier stage is converted into fuel by increasingly high temperatures and pressures in the latter stage, stops with the production of iron. Iron does not burn, hence the nuclear energy can no longer be extracted. When the star reaches this stage, it starts to collapse under its own gravitational force. Eventually, the star explodes: the star's matter bursts outward into the cosmos, leaving either a black hole or neutron star at the center. A neutron star has a radius of only about 10 km, but an extremely high density. The density is so high, in fact, that a mere spoonful of matter weighs on the order of 100 million tons.

Our group analyzed observational data from Kamiokande from a theoretical point of view, taking full advantage of the information directly supplied by the group of Professor Koshiba, working side-by-side with us at the Physics Department of the University of Tokyo. Through this work, we were able to present estimations on the total energy of the emitted neutrinos, the mass of the progenitor star (the star

SN1987A is the supernova observed in the Large Magellanic Cloud on February 23, 1987. Kamiokande detected the neutrinos emitted from this supernova. (©Anglo-Australian Observatory)

that exploded), and the mass of the resulting neutron star prior to other groups. Subsequently, similar analyses were reported around the world including the neutrino data from the IMB experiment in the US, which was reported soon after the Kamiokande's announcement, and these were mostly in agreement with our results.

An approach combining observations and theory

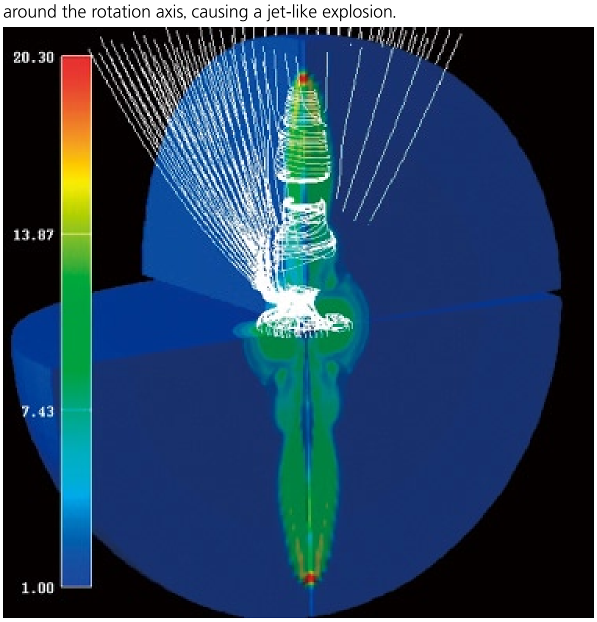
But Kamiokande and IMB observed only 11 and 8 neutrinos, respectively: too few to allow us to pin down the exact mechanism of the stellar explosion. Fortunately, Super-Kamiokande is currently operating with a sensitivity 30 times higher than that of its forerunner Kamiokande. If a supernova occurs in the central part of the Milky Way, we should be able to observe roughly 10,000 neutrinos. Our group has been theoretically investigating the expected neutrino signals from supernovae for many years. We performed one of our investigations jointly with J. Wilson's group at the Los Alamos National Laboratory in the US. Through this collaboration, we were able to make realistic predictions for the neutrino spectrum that Super-Kamiokande would observe within a short time span of 10 seconds, should a supernova occur near the center of our galaxy. Of course, we need to know the properties of neutrinos in order to precisely predict how neutrinos are emitted from a supernova and detected on earth.

In 1988, the Super-Kamiokande group reported, for the first time ever, that neutrinos were not mass-less, but had finite mass and went through neutrino oscillations, that is, back-and-forth transmutations into other types of neutrinos. We know there are three types of neutrinos, namely, the electron type, the muon type, and the tau type.

The interactions of neutrinos with matter are subtly dependent on these types. Since all three types are emitted from the center of a supernova, we expect that they go through oscillations within matter that spreads outward after the explosion. They also go through oscillations inside the Earth before reaching Super-Kamiokande.

We still have no clear understanding, however, of how these neutrinos oscillate. First of all, we do not know if their masses get heavier in the order of electron-type, muon-type, and tau-type (this is called the normal hierarchy), or in the order of the tau-type, electron-type, and muon-type (this is called the inverted hierarchy). Different mass hierarchies certainly result in marked differences in the behavior of the neutrino oscillations. Second, we do not know the value of θ_{13}, one of the mixing angles that represent the extent of the mixture among the three types of neutrinos (this mixture of the neutrino causes the oscillations). Differences in mass ordering and the mixing angles will result in strong differences in the appearances of neutrino signals from a supernova. If we can make precise measurements of supernova neutrinos, we will be able to deduce these unknown properties of neutrinos.

Figure 2: Computer simulation of a rotating progenitor star with magnetic fields as it collapses and starts to explode. The white lines are magnetic field lines. Colors indicate the amount of thermal energy. The magnetic field lines are strongly wound up around the rotation axis, causing a jet-like explosion.



In further collaboration with the Los Alamos group, we studied how the neutrinos would oscillate inside the supernova and how they would look when observed in Super-Kamiokande. We ought to be able to obtain information on the mass hierarchy and the mixing angles by comparing the observed signals and theoretical calculations, should a supernova occur in our Galaxy.

Messages arriving from the Universe's distant past

Confoundingly, past statistics indicate that a supernova is only likely to occur in the Milky Way once every 50 to 100 years. This may be too long to wait. On a brighter note, the universe is filled with neutrinos emitted from supernovae that have exploded earlier in the history of the universe. These neutrinos will be observed not as a 10-second burst of signal from a supernova, but as "background neutrinos" with a constant flux in time. The Super-Kamiokande group is trying to detect these relic supernova neutrinos by filtering out the known signals, such as the atmospheric neutrinos produced by cosmic ray interactions in the atmosphere.

An upper limit of the relic supernova neutrino flux obtained from the observation is now close to the value calculated with one of our theoretical neutrino models. With an improved sensitivity, it may become possible to test this neutrino model. The flux of the background supernova neutrinos should also show how frequently supernovae have occurred in the past. We therefore want to use this observation to study the history of the universe.

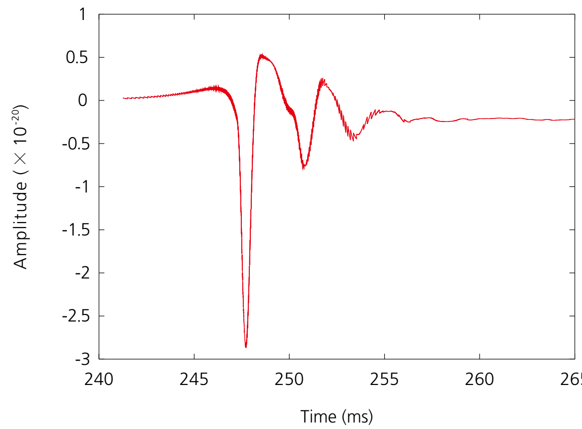


Figure 3: An example of gravitational waves emitted from a supernova explosion. For a slower rotation speed of the exploded star, the oscillation period is shorter. Observation of the gravitational waves will help us understand the explosion mechanism.

Gravitational wave observations are no longer just a dream

Astronomers have recently recognized more diverse and complex mechanisms of supernovae. Theory holds that if a progenitor star before an explosion rotates fast or has strong magnetic fields, the explosion will be jet-like along the rotation axis. This would be very likely to result in directional variation of the neutrino emission. For the moment, our group is seeking to understand the types of supernovae that occur when the effects of rotation or magnetic fields are strong. This study is expected to reveal the intensity of neutrino emissions from these supernovae.

Supernovae emit not only neutrinos, but also gravitational waves. A gravitational wave is a distortion of space that propagates as a wave, as predicted by Einstein's theory of general relativity. A large gravitational wave detector called the LIGO is now at work in the US, and Japan has its own smaller-scale detector (TAMA) at work at the National Astronomical Observatory.

If a supernova occurs in the Milky Way or a neighboring galaxy, these detectors are very likely to detect the gravitational waves. Also, as in the case of the neutrino, gravitational waves emitted from earlier supernovae are probably coming in from all directions in the universe. In the early universe, when the very first stars and galaxies were born, large mass stars were probably formed. If this was so, black holes with masses on the order of 10 or even a few 100 times the solar mass must have been formed. Theory holds also that gravitational waves emitted during this period fill the present universe. We look forward to observing these gravitational waves from the early universe in the near future. This is not a dream, rather a matter of time.

Furthermore, our colleagues are now considering a proposal to build a Hyper-Kamiokande, a neutrino observatory 20 times larger in mass than the Super-Kamiokande. In the near future we will explore parts of the universe that cannot be seen with light, such as the insides of supernovae, by observing neutrinos and gravitational waves.

References
Statistical Analysis for the Future Detection of Supernova Neutrino Burst
Astrophys. J. **496** (1998) 216-225,
T. Totani, K. Sato, S. Dalhed and J. Wilson
Relic Neutrino Background from Cosmological Supernovae
New J. Phys. **6** (2004) 170 (27p),
S. Ando and K. Sato
Explosion Mechanism, Neutrino Burst, and Gravitational Wave in Core-Collapse Supernovae
Reports on Progress in Physics **69** (2006) 971-1144,
K. Kotake, K. Sato, and K. Takahashi