FEATURE

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Research Area: Astronomy

Measuring the Universe with the Ancient Supernovae

Tycho Brahe's supernova and the observation of its echo

About 12,000 years ago, one star made a big explosion in our Galaxy. The light emitted from the explosion reached the Earth in November, 1572 AD. This "new" star was observed as a "guest star" in Korea and then China. About a week later, a famous Danish astronomer, Tycho Brahe observed this star in Constellation Cassiopeia. Tycho noticed that this was a "new" star, changing its color and brightness with time. He continued his naked-eye observation of the star until it disappeared in March 1574 AD. This observation of change in the sky was a challenge to Aristotle's view of the "constant" universe.

After Tycho's observation, the telescope was invented, and Galileo made astronomical observations using the telescope. Recently, with modern instruments, astronomical observations in other wavebands, such as radio, infrared, X-rays, and gamma-rays, became possible. Similar bright new stars have been observed in very distant galaxies. Zwicky and Baade coined "supernova" for those especially bright novae. At the location of Tycho's star, a nebula has been found and named "Tycho's supernova remnant," and X-ray and infrared observations revealed heavy element abundances (Fig. 1). The optical light emitted in 1572, however, could not be observed with telescopes, so that it was impossible to study the detailed nature of the supernova in 1572 AD itself.

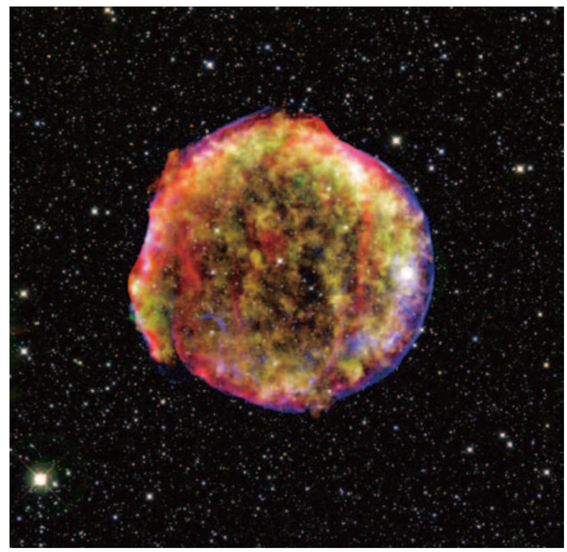

Figure 1: Tycho's supernova remnant (Max-Planck-Institut für Astronomie).

However, surprisingly enough, in 2008, 436 years after Tycho's observation, the optical light from SN 1572 was observed. It was an echo. The optical echo occurs when the light emitted from the source is scattered by the dust in the surrounding interstellar cloud, and it reached the Earth some time later. The observed echo brought the information of SN 1572 itself. In a sense, the echo is a video tape that shows the past.

How to find the echo? If there exist dusty materials distributed outward, then the echo spot seems to move quickly outward. By identifying the echo from such a quickly moving spot of light with a telescope in Spain, our team of NAOJ, IPMU, and MPE successfully conducted spectroscopic

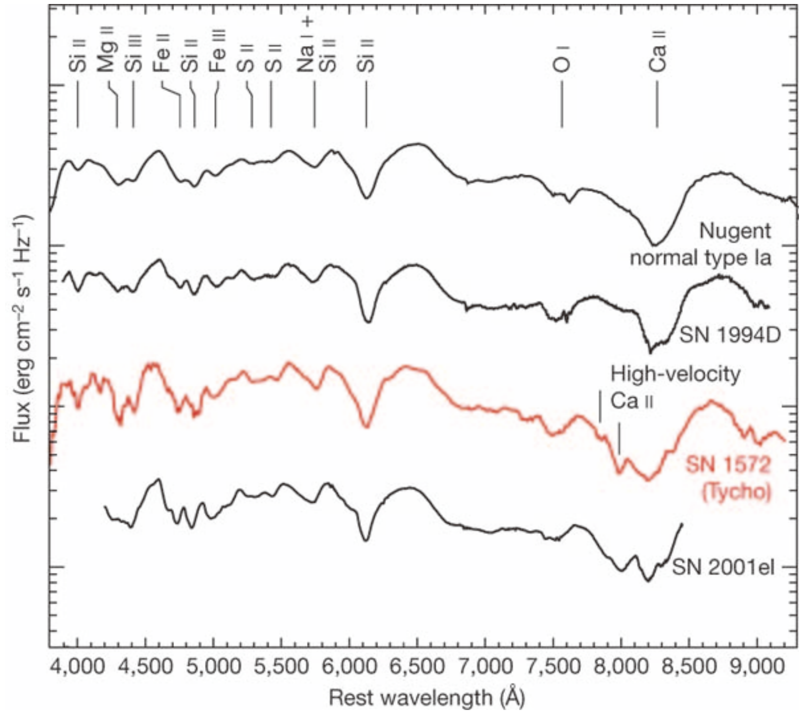

Figure 2: The spectrum of the echo of Tycho's supernova (SN 1572) (red) compared with the spectra of several type Ia supernovae (black) (Krause et al. 2008 Nature **456**, 617).

observation of the echo with the Subaru Telescope in September 2008. It is just amazing that the supernova light observed by Tycho with only the naked eye was observed now, 436 years later, with the modern telescope.

We have found that the observed spectrum of SN 1572 (the red line in Fig. 2) is very similar to the spectra of Type Ia supernovae (SNe Ia) (black lines in Fig. 2). Absorption lines in the spectra are identified with those of iron, silicon, magnesium, oxygen, etc. This implies that these supernovae created those elements in the explosion. (Note that no hydrogen line is seen, despite the fact that hydrogen is the most abundant element in the universe.) This similarity means that SNe Ia are strikingly similar, irrespective of the very distant galaxies in which they appeared.

The question, then, is what kind of stars explode as SNe Ia. When I started working on SNe Ia in the early 1980s, we could not even identify the elements in the spectra of SNe Ia seen in Figure 2. It was only evident from the spectra that there was no hydrogen in SNe Ia, so the progenitor stars had undergone unusual evolution. We had two candidates of the progenitor: a helium star with about 2 solar mass and a white dwarf (WD). The WD model for SNe Ia has been established only after further development of observations and theories.

What are white dwarfs?

Stars like the Sun shine by burning hydrogen into helium in the central region. When hydrogen is exhausted, the envelope of the star expands to a radius as large as almost an orbital radius of Venus, and the star becomes a red giant. In the central region of the star, helium burns into carbon and oxygen. When the helium is exhausted, the

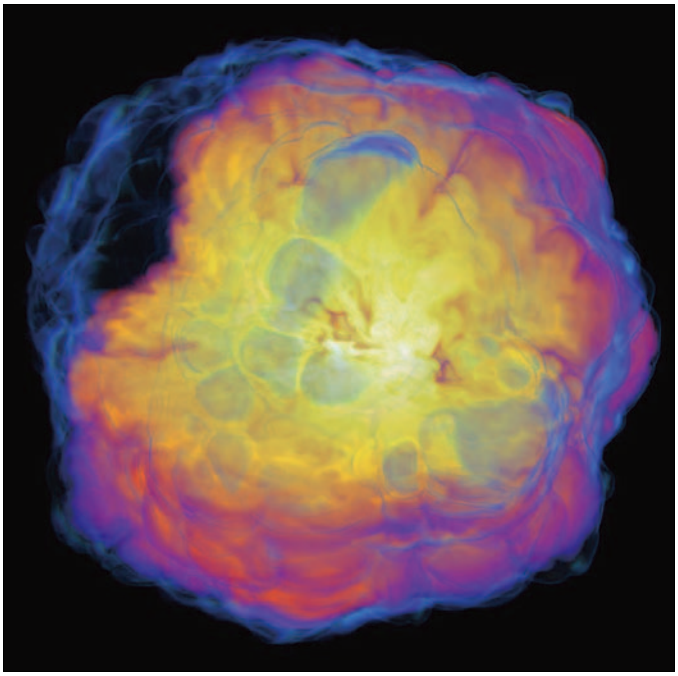

Figure 3: Simulation of the exploding white dwarf. The various colors indicate the various heavy elements (e.g., Fe) synthesized in the interior (W. Hillebrandt).

stellar envelope expands further even to the orbital radius of the Earth. Eventually, the outer envelope is separated from the core of the star to form a so-called planetary nebula. The remaining stellar core is composed of carbon and oxygen. Its radius is as small as the size of the Earth. Its surface temperature is so high that it is called a white dwarf (WD).

The WD is very different from an ordinary star. In ordinary stars, the thermal motion of gas particles provides sufficient pressure against gravity. In the WD, electrons are degenerate, where electrons at high densities need to occupy high energy states due to Pauli's exclusion principle in quantum mechanics. Such degenerate electrons provide the pressure against gravity.

A typical WD star has a mass of about 0.5–1 solar mass and a radius that is about one hundredth of the solar radius, which is as small as the radius of the Earth. Its central density is extremely high—about 1 ton per cubic centimeter. There is an upper limit to the mass of a WD—the so-called Chandrasekhar mass (1.4 solar mass)—because the velocity cannot exceed the speed of light according to the special theory of relativity. As the WD's mass approaches this limit, the central density becomes infinitely high. This is an important mass limit for SNe Ia to be standard candles.

Nuclear explosions of white dwarfs

The evolution of a single WD is simply a cooling process. However, if the WD is a member of a close binary system, its ultimate fate could be very different. Because of the mass transfer from the companion star, the mass of the WD could increase to the Chandrasekhar mass. The central density of the WD then becomes high enough for a carbon fusion reaction to increase the central temperature.

Figure 4: Type Ia supernova SN 1994D (lower-left) (NASA).

Since the degenerate pressure does not depend on the temperature, the pressure stays constant and the WD does not expand. Then the temperature does not drop but continues to increase. It accelerates the carbon fusion reaction, which eventually leads to thermonuclear runaway. Such a WD is a veritable carbon bomb (Fig. 3).

Thermonuclear runaway increases the temperature up to 5 to 10 billion degrees, and most of the carbon and oxygen burn to nickel 56. The burned central region forms a bubble, which heats up the surrounding layer to burn more carbon. This creates more bubbles and the burning front propagates outward. Under certain conditions, a shock wave may form to induce detonation, which could give rise to an asymmetric explosion.

Nickel 56 is radioactive and decays into cobalt 56 with a half-life of about a week. Cobalt 56 is also radioactive, decaying into stable iron 56 with a half-life of 78 days. Gamma-rays emitted from these radioactive decays have high enough energy to excite the surrounding gas and emit optical light. Therefore, supernova brightness depends on how much nickel 56 is synthesized. The observation of SNe Ia is witnessing the creation of iron in the universe. Since the mass of the WD at the explosion is close to the Chandrasekhar mass, the synthesized mass of nickel 56 is about 0.6 solar mass which is virtually constant among SNe Ia. This is the reason why the brightness of SNe Ia is nearly uniform.

Acceleration of the expansion of the universe

An SN Ia shines as bright as a whole galaxy which contains 10–100 billion stars—so it can be observed even at a distance of 10 billion light years—and the brightness of SNe Ia is nearly uniform. Therefore SNe Ia are good standard candles to provide evidence of

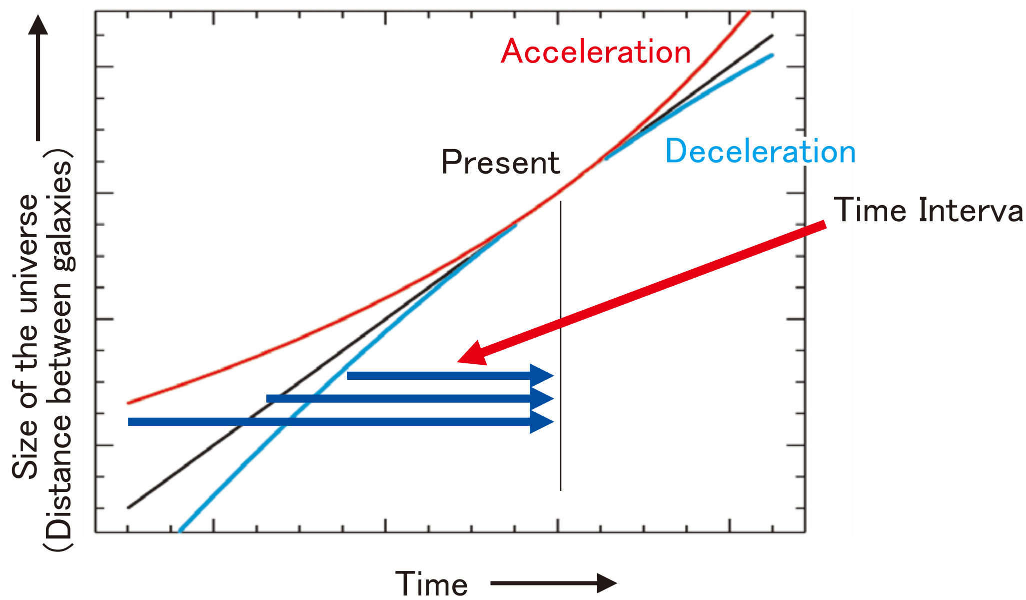

Figure 5: The size of the expanding universe vs. time. The red, blue, and black lines show the universe with acceleration, with deceleration, and without acceleration or deceleration.

the acceleration of cosmic expansion.

How has the acceleration of cosmic expansion been discovered? Figure 5 shows that the separation between galaxies (i.e., the size of the universe) is increasing with time due to cosmic expansion. The slope indicates the rate of expansion, and the red (blue) line shows cases of deceleration (acceleration) of cosmic expansion.

As the size of the universe increases, the wavelength of the light emitted in the past is stretched, so that the light is red-shifted (z). The universe was smaller in the past by a factor of 1/(1+z).

If cosmic expansion has accelerated, then the rate of expansion must have been slower in the past and gradually accelerated to reach the current rate. With acceleration, it takes more time for the light from the past SN Ia to reach us, i.e., the SN Ia is more distant, and thus dimmer, compared to cases with no acceleration.

If the expansion has decelerated, on the other hand, the rate of expansion in the past was faster, so the distance to the past SN is shorter compared to cases without deceleration. Therefore the SN Ia is brighter than in cases with no deceleration.

Dark Energy

The abscissa of Figure 6 shows the brightness of an SN Ia at a certain redshift (z) compared to the empty universe with no acceleration or deceleration. The observed points are obtained by averaging the brightness of many SNe Ia. It is clear that SNe Ia around z = 0.5 are fainter than in the empty universe.

In contrast, the SN Ia around z = 1.7 is brighter. This implies that the cosmic expansion was decelerated in the past but turned to acceleration some 6 billion years ago.

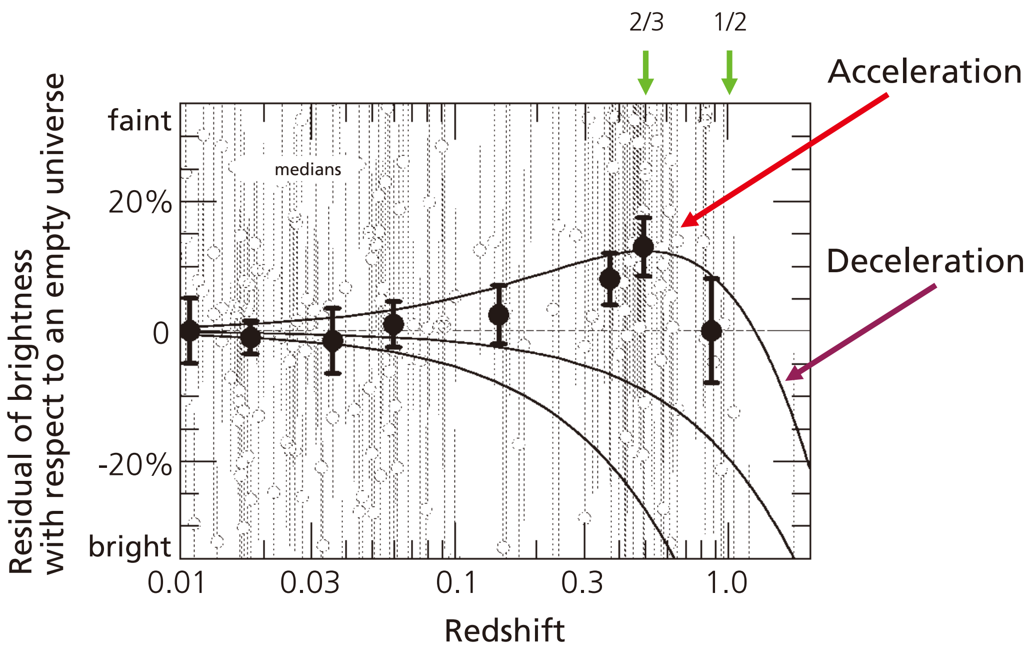

Figure 6: The brightness of distant supernovae at high redshift. The differences from an empty universe with no acceleration or deceleration are shown (Tonry et al. 2003 ApJ **594**, 1).

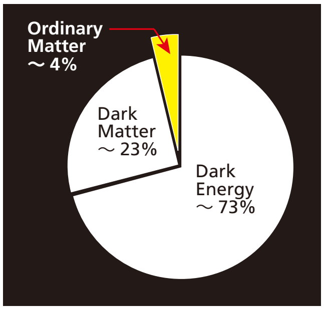

Figure 7: Composition of the universe.

The deceleration of cosmic expansion can be understood as a result of the gravitational force exerted by matter in the universe. The reason why the acceleration started should be the effect of anti-gravity that causes repulsive force. The nature of the source of this repulsive force is unknown, and it is thus referred to as "Dark Energy." The observations of cosmic background radiation combined with some other observations have revealed that the composition of the current universe comprises about 73% dark energy, 23 % dark matter, and only 4% ordinary matter. Amazingly, 96% of the universe consists of "dark."

What this "Dark Energy" is, what its equation of state is, and whether it is the cosmological constant introduced by Einstein are fundamental questions in physics. In order to answer these questions, we need to construct "precision cosmology" by more detailed observational and theoretical studies. By observing a larger number of distant supernovae, we should be able to investigate how the nature of SNe Ia depends on their host galaxies and redshift and reduce systematic errors. We need more accurate observations using next generation astronomical satellites, space telescopes, and 30 m class giant ground-based telescopes.

At the IPMU, we are studying SNe Ia by combining the observational and theoretical approaches, where we are trying to identify the progenitor binary star systems that produce SNe Ia, to clarify the nature of host galaxies, and to simulate aspherical explosions and associated nucleosynthesis. By revealing the nature of SNe Ia, we are approaching "precision cosmology."