論文内容の要旨

論文題目 Supernovae in Three Dimensions
(超新星爆発の三次元構造)

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Supernova (SN) is one of the most important objects to understand the current universe, our Galaxy, and the earth: SNe synthesize and eject heavy elements, which are seen in our life, and inject huge kinetic energy to the interstellar medium. However, the explosion mechanism of SNe is not yet clarified. This is one of the most important questions in astrophysics. We explore the explosion mechanism of SNe by studying the explosion geometry, which is a key to understand the mechanism.

As a theoretical approach, we perform the first multi-dimensional radiative transfer simulations for photospheric phase spectra (<50 days after the explosion) of aspherical hyper-energetic SNe. We show that observational properties do depend on the line of sight, reflecting the aspherical element distribution in the SN ejecta and the anisotropic ionization structure. We show that the kinetic energy is overestimated if a polar-viewed SN is analyzed under the assumption of spherical symmetry. In fact, the kinetic energy of SN 1998bw associated with GRB 980425 is found to be ~20 x 10^{51} erg, which is smaller than that estimated by spherical models (30-50 x 10^{51} erg).

However, because of the complexity in the SN ejecta, it is shown to be difficult to observationally study the explosion geometry only with photospheric phase spectra, without independent information of the line of sight. With simple spectroscopy, observations at nebular phases (~1 yr after the explosion) are more powerful since the emission line profile traces the element distribution.

We perform nebular phase observations of SN 2008D associated with the X-ray transient 080109 with Subaru telescope. This SN is a rare and important object in that it was discovered soon after the explosion by the luminous X-ray emission. We find that the [O I] emission line shows a double-peaked profile while the [Ca II] line does not show such a profile. The double-peaked profile clearly shows that the explosion is not spherically symmetric. The double-peaked profile can be expected when an expanding torus is viewed from near the equatorial direction. We suggest that SN 2008D is a bipolar explosion viewed from off-axis direction, > 50 degree from the pole. Thus, the X-ray emission detected soon after the explosion is unlikely to be caused by highly relativistic jets.

We show polarization measurement is also a powerful and, in fact, the most robust method to study the explosion geometry. We perform a spectropolarimetric observation of SN 2007gr. It is found that the Ca line has a high polarization level while the O and Na lines do not have a comparably strong polarization. The results clearly indicate that explosively synthesized elements (such as Ca) have a different distribution from pre-supernova elements (such as O and Na). These properties can be explained by an axisymmetric jet-like explosion viewed from near the polar direction.

We also show our spectropolarimetric observation of SN 2005bf. This SN has been observed at two different epochs. The polarization spectra at two epochs clearly show the enhancement of polarization at the lines of Ca, Fe, and He (excited in coexistence with ^{56}Ni). These properties indicate the aspherical distribution of the explosively synthesized elements. In addition, changes in the polarization angle are seen at these lines at both epochs. The change in the polarization angle indicates non-axisymmetric distribution of the elements. It is suggested that the explosion of SN 2005bf possibly has two axes, in analogy with a pulsar, which has independent rotational and magnetic axes.

By our observational studies, the aspherical nature of SN explosion has become apparent. Especially, axisymmetric, two dimensional explosion models are successful in

understanding the spectroscopic and spectropolarimetric observations. However, detailed spectropolarimetric observations are providing deeper information: three dimensional nature of the explosion is becoming apparent.