The Variability of Stars—Supernovae Precursors

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Abstract Many types of stellar variability are connected with mass-loss processes. Strong variable winds ejected by supernova precursors are revealed in early supernova spectra, radio, and X-rays. The geometry of the circumstellar shells around the exploding stars is surprisingly regular at different scales. The formation of shells is a universal process for colliding winds in a series of astrophysical objects, and is detected as a quasi-periodic variability.

1. Introduction

An impressive number of observations of supernovae (SNe) (radio, X-ray, optical) give evidence of matter being ejected before the SN explosion. Thus, at the moment of the explosion, the progenitor is already surrounded by an envelope. SNe are observed only after the explosion, when the wind matter is in a state of interaction with the emission of the explosion itself. The stellar wind can be subjected to the following kinds of interaction: 1) UV pulse of radiation due to outcoming shock wave; 2) emission of the expanding supernova envelope; 3) fast particles; 4) direct collision of the SN envelope with the wind matter.

The variability of the winds of antique SNe precursors was proven by radio observations of SNe over both long (SN 1979C) and shorter (SN 1993J) time scales.

Spectral observations of SNe were not systematic, unfortunately. Hence, we do not have a complete dynamic picture of the evolution of spectral features. There are several key observational results thus far: Dopita *et al.* (1984) discovered the so-called "superwind" ejected at extremely high velocities (3,000 km/s) immediately prior to the SN event. The fascinating changes of the velocity shifts in SNe 1983K (Niemela *et al.* 1985) and 1990M (Polcaro and Viotti 1991) witness to the existence of complicated, but rather regular structures in the wind at scales of less than 10^{16} cm. A few years ago these observational facts were united in common dynamical model (Tsiopa 1995).

2. Regular structures at large scales

One very famous result of the interaction process of winds as a SN precursor is the "Napoleon's Hat" around 1987A (Wang and Mazzali 1992), formed by the slow, dense, asymmetrical wind and the following fast wind. Though everybody has seen the beautiful three-ring picture of SN 1987A, the origin of this circumstellar structure is still under discussion. Burderi and King (1995) proposed that the two outer rings are part of the shell brightened by the interaction of a double beam of relativistic particles emitted from a young pulsar formed after the explosion.

But it is not impossible that such regular structures can be formed exclusively by interacting winds. Lloyd *et al.* (1995) presented the results of numerical calculations which showed that this effect could be reached by frictional interaction of a low-mass binary companion with the wind of the progenitor star.

Even in the case of a single progenitor with highly variable wind, one can easily imagine the formation of such structures. It is quite common to speak about the interaction of two winds: the slow wind of a red supergiant phase and the fast wind of a blue supergiant. But the real picture may prove to be a little more complicated. If the velocity of the blue supergiant wind is not constant, the wind is ejected as a system of shells. Let us assume that the wind produced later is much faster than the wind which has already formed the hour-glass structure. Then the winds must collide. And the shock can occur when the fast wind is decelerated at the boundary of the hour-glass structure. For a spherically-symmetric fast wind, one will observe two excited rings.

Finally, it should be mentioned that this axially-symmetric shell is quite similar to well-known planetary nebulae and to those surrounding luminous blue variables (in shape and even in size $= 10^{18}$ cm), and can be related to structures around Wolf-Rayet stars. Unfortunately, this is the only example of a direct photographic image available. The other wind-formed structures were revealed just in the SN spectra.

3. Small-scale regular structures in the winds of supernovae Type II and Type Ia

Though the SN envelope velocities of SNe Type II are slower than in SNe Type I, their winds are extremely fast (up to 2,000–4,000 km/s). The wind, being highly variable and dense, can generate pronounced colliding wind-formed structures close to the SN progenitor. The development of the system of interacting wind layers with different deviations of symmetry and increasing velocities may result in three general types of shell geometry: quasi-spherical, oblate, and prolate. The SN envelope expands inside the wind shell formed by the SN progenitor just before the explosion. As the SN envelope velocity is much higher than the wind velocity (about ten times), the wind-formed shell is swept outward by the envelope, starting from the inner parts. The wind-originated lines are generated in the region about to be swept outward. These parts of the wind matter are excited by the fast electrons produced by the SN expanding envelope. The outer regions of the wind shell cannot exhibit Balmer lines, because hydrogen cannot be excited up to the second level there. The general picture of wind-originated line formation depends on the the line-of-sight position for oblate and prolate shells.

The presence of a distinct prolate ellipsoidal shell can explain the narrow Hα absorption lines observed in the spectra of SN 1983K. The lines are forming in the parts of the shell closest to the expanding SN envelope, where hydrogen is excited up to the second level (previous regions already having been swept outward by the SN envelope). According to our line-of-sight position, the velocity shift had increased during the two-month period of observation, accelerating 40 km/s per day due to the velocity distribution in the ellipsoidal wind-formed shell.

The quasi-spherical shell may be responsible for "superwind" P Cyg lines observed in SN 1984E. The line-of-sight orientation is not important in this case.

The pre-supernova winds of SN Type I are very difficult to detect: they are less massive, slower by hundreds of km/s, and are swept away almost immediately by the SN envelope's expansion at very high speed. In the case of SN 1990M, the model implies the existence of a shell formed by matter with a maximum velocity of 1,200 km/s and a minimum of 600 km/s, with an inclination to the line-of-sight of 40°.

The hydrogen emission line observed by Branch *et al.* (1983) can also find its place within the framework of the same model. The small narrow feature was located at the rest wavelength of $H\alpha$. Pure emission with zero velocity shift implies that the ellipsoid axis of the wind is perpendicular to the line-of-sight, with most of the shell already swept away by the SN envelope. Such a spectral line is supposed to disappear in a very short time; the feature was not detected five days later.

4. Discussion

Judging from the SN envelope expansion velocity, the wind formed structures under consideration are situated at the radii of the explosion center of 10^{14} –10^{15} cm for SN 1983K, and $3–6 \times 10^{15}$ cm for SN 1990M. The time of shell ejection can be estimated as 6×10^{6} seconds for SN 1983K, and 5×10^{7} seconds for SN 1990M. Such rather small distances and short periods of regular structure formation imply the presence of a high initial gradient of density and velocity in the wind matter.

Thus extraordinary activity of the precursor can be expected even for a single star. During periods of interior reconstruction (preceding a SN Type II event, for example), even the outer parts of the star are likely to be in an unstable state. Strong pulsation with different modes can be evoked. Such processes as several-mode resonant coupling are likely to determine the mass-loss rates in critical periods of stellar evolution (it is even possible that the SN explosion itself is encouraged by the resonance pulsation). When expanding, the star throws away the very outer part of its envelope (or, in other words, the stellar wind increases dramatically) and a shell is ejected. In this case the precursor would be surrounded by a system of interacting shells (Tsiopa 1990).

One type of steady stellar wind flow is changed to another (with different wind velocity and density)—and not in a smooth way. During the period of reconstruction the star produces a strongly inhomogeneous wind.

It should be noted that the majority of the pulsating stars are located in the same place on the Hertzsprung-Russell diagram as Type II SN precursors are thought to be.

As for the SN Type Ia precursors, some other mechanisms are certainly to be proposed. However, close systems buried in a common envelope (or one compact object inside the extended atmosphere of the other component) are in some sense indistinguishable from a rotating pulsating star. The formation of the circumstellar environment may be rather similar. Perhaps the eccentricity of the orbit in a binary system can be treated as a trigger generating instabilities and resonance effects.

In the close binary supernova precursor the shell ejections can be more closely connected with the mass-losing component (a red giant in its final period of evolution, for example), than with the mass-accreting white dwarf. The strongly variable accretion rate might cause the degenerate object to approach the Chandrasekhar limit.

Recurrent ejections of matter with different velocities can result in the formation of axial colliding wind-formed structures. A very energetic individual pulsation of a supernova precursor just before the explosion event produces a shell, perhaps discovered in the early spectra of SN 1984E.

The only way to find a supernova progenitor in the Galaxy before an explosion is to understand the structure of its wind and to compare its variability with data on known peculiar wind-producing stars.

5. Addendum, 2006

During the last nine years great progress was made in the SNe investigations. New beautiful structures were observed in the famous remnant of SN 1987A. Gamma-ray bursts were connected with Type Ib/c SNe. The amount of discovered SNe per year has dramatically increased. Still the mean number of bright new supernovae discovered each year is not changed, naturally. Though the better quality of modern receivers provides more opportunities for spectral investigation of fainter objects, supernovae observations are not regular and detailed enough yet. The light curve variations caused by the interaction of the matter ejected prior to the SN explosion and the SN envelope itself look very promising to help further understanding of SN progenitor surrounding. There was a great discussion on the presence of hydrogen lines in Type Ia early spectra originated in the matter ejected prior to the SN explosion. Such lines were observed again in SN 2002IC (Hamuy *et al.* 2003). Nowadays SNe precursors are thought to be more variable than it was common to suppose nine years ago. Even small telescopes can be fruitfully used to help to find small-scale variations in the SNe light curves caused by the interaction of the matter ejected prior to the explosion with the expanding SN envelope.

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