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Type Ib/c supernovae: new observational data

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1. Introduction

The evolution of stars of certain classes ends up with a supernova explosion after which the star disappears or transforms into a qualitatively different state. Supernova explosions (SN) are observed in galaxies as a sudden appearance of a star with luminosity comparable with the total luminosity of the host galaxy.

In recent years, the interest in supernova studies has grown strongly. Twenty years ago less than 20 supernovae were discovered per year, ten years ago this number increased to 60, and in 2001 a record number of supernovae (282) were discovered. The total number of extragalactic supernovae discovered since 1885 is already more than 2000. To search for supernovae, special fully automatic systems have been elaborated. Amateur astronomers also actively participate in SN searches.

Observational astrophysics studies the dependence of the SN emission power on time — the light curves in various spectral bands, and their spectral changes with time.

Statistical studies of the SN population, such as the explosion rate determination, the spatial distribution inside the host galaxies, etc., are also carried out.

Theoretical light curve and spectra modeling, as well as the statistical characteristics, allow astronomers to conclude which stars explode as supernovae and what may be supernova remnants.

2. Classification of supernovae

Even at the very beginning of supernova studies it became clear that they do not represent a homogeneous class of objects. The existing classification is mainly based on the spectral shape near the maximum brightness. Supernovae were subdivided in two main types, I and II. The spectra of the type II supernovae demonstrated bright emission hydrogen lines, while SN I did not. SN I occur in all types of galaxies, including ellipticals, where the star formation has almost stopped by now, while SN II reside only in spiral galaxies and clearly demonstrate concentration towards spiral arms. The principal features in the type I supernova spectra near the maximum brightness were broad absorption lines of single-ionized elements of intermediate mass, such as silicon, calcium, magnesium, sodium, and iron. One of the most prominent features was the absorption line of Si II at the wavelength 6150 Å. As early as in the 1960s, it was noted that in the spectra of some SN I this line is weak or almost absent. Those supernovae were termed peculiar type I supernovae. Only in the middle of the 1980s did it become clear that these supernovae constitute a special class notably different from SN I. The spectra of these supernovae were obtained with digital detectors which allowed exact measurements of the line intensities. But most significant were studies of spectra obtained at the late (> 200 days after the maximum) stage after the explosion. These spectra proved totally different from most SN I. They were dominated by forbidden emission lines of oxygen and calcium, while in spectra of usual SN I at these phases blends of the iron and cobalt lines are most prominent. It was also established that these 'peculiar' SN I occur only in spiral galaxies and demonstrate a close relation to star forming regions inside them. Therefore, these supernovae were shown to be not a variety of SN I, but constitute a special supernova type, whose presupernova evolutionary status is rather like SN II. This type was named Ib, and 'ordinary' type I supernovae were designated as Ia. A more detailed investigation of the SN Ib spectra revealed that the most prominent absorption lines in their spectra near the maximum brightness at wavelengths around 5700 Å belong to helium. Lines of calcium, silicon, and iron, typical for SN Ia, were also present. As the number of studied SN Ib grew, differences in their spectra became apparent. The most clear difference was in the helium line intensities; in some SN Ib they were almost absent. Those supernovae were proposed to be called type Ic. However, at the late nebular stage, they showed no spectral differences with SN Ib. It was also shown that in the SN Ic spectra helium is present, so most likely there are not separate type Ib and Ic SNs, but a continuous sequence of spectral characteristics related to different helium abundance in the envelope.

3. Possible relation of SN Ib/c with gamma-ray bursts

On April 25, 1998, the detectors onboard the BeppoSAX and CGRO satellites registered a gamma-ray burst with coordinates $\alpha = 19$ h 34 m 54 s; $\delta = -52°49.9'$ with a probable error of $8'$. Optical observations of the burst region started as early as on April 26 and revealed a fairly bright nearby spiral galaxy ESO 184-G82 $1.6'$ away from the gamma-ray burst error box center. The distance to the galaxy is about 34 Mpc. In this galaxy, a supernova (1998bw) was visible at the ascending brightness phase which reached the maximum on May 12 [1]. Thus, the spatial and temporal coincidence of the supernova and gamma-ray burst was apparent. However, studies of the gamma-ray burst area by the NFI camera onboard the BeppoSAX satellite revealed the presence of two X-ray sources, one of which was practically coincident with SN 1998bw and another located $\sim 4'$ away but still within the error box of the gamma-ray burst [1]. The second source faded away very rapidly, and the first source had been observed for a long time. It is quite possible that it is the second source that was the X-ray afterglow of the gamma-ray burst, and the first source and the supernova were just spuriously detected at this site, though the probability of such a coincidence is estimated to be $\sim 10^{-4}$. This assumption is also supported by a very low value of the gamma-ray burst luminosity, of about 10^{-6} of the typical values, if it indeed were at such a close distance.

However, SN 1998bw proved unusual, which, of course, argues for its relation to the gamma-ray burst.

The SN 1998bw spectrum, although it can be classified as related to type Ic, was notably different from the usual SN Ic spectra at the maximum brightness, and the main reason for the difference could be a very high expansion velocity of the SN 1998bw envelope [2]. It turned out that one more type Ic supernova, SN 1997ef discovered at the end of November of 1997, displayed a similar spectrum at the maximum brightness [3]. The high expansion velocity of the envelope, its possible large mass, and the high luminosity at the maximum of SN 1998bw are evidence for an enhanced explosion energy.

4. Light curves of supernovae

SN Ia light curves are sufficiently similar to each other and demonstrate a rapid increase to the maximum, which lasts for about 20 days and is followed by a slower brightness decrease. In 30 – 40 days, it strongly slows down and continues at a constant rate expressed in units of stellar magnitudes per unit time, which corresponds to an exponential luminosity decay. The light curves of type II supernovae are very different, which reflects the diversity of characteristics of envelopes of stars-supergiants at late evolutionary stages. Some of them have sufficiently close form to SN Ia, some of them are drastically different by showing a prolonged (up to 100 days) plateau with almost persistent brightness.

The SN Ib/c light curves in the B and V bands, for which most data are available, resemble those of the SN Ia, however they have a large dispersion in the brightness decay rates after the maximum, in the peak widths, and in the linear part starting times. For them the parameter Δm_{15} which is used to describe the brightness decay rate after the maximum, takes the value from $0^m.3$ to $1^m.8$, and the starting time of the linear part varied from 20 to 40 days.

The absolute magnitudes at the maximum brightness of SN Ib/c also vary in a broad range from -16^m to -20^m. SN 1998bw shows the largest luminosity $M_V = -19^m.4$ among the well-studied SN Ib/c, however SN 1997ef with similar spectrum has a strongly different form of the light curve and a low luminosity at the maximum of about -17^m. The recent study [4] showed that two separate groups of SN Ib/c are likely to exist: the 'bright' ones with an absolute magnitude of around -20^m, and the 'weak' ones whose absolute magnitude varies from -16^m to -18^m.

Observations and analysis of the SN Ib/c light curves have been also carried out at the P K Sternberg Astronomical Institute (SAI): photometrical observations of 14 SN Ib/c were performed, of which data for 8 SNs were published [5 – 7].

5. Statistical characteristics of SN Ib/c

Type Ib/c supernovae are fairly rare events. Of almost 2000 SNs discovered since 1885, only 83 were related to this type. Of 282 SNs discovered in 2001, only 9 supernovae are of type Ib/c.

Statistical studies of supernovae include investigation of their spatial distribution in the host galaxies, including the distribution relative to such structural details as spiral arms and H II regions, as well as the explosion rate studies.

The recent supernova rate determination based on joint results of several SN searching programs [8] revealed that the SN Ib/c rate is significantly smaller than the SN II and SN I rates. In units of SNu (the number of SNs/$10^{10} L_{\odot}$/100 years), the SN Ib/c rate in type Sbc-Sd spiral galaxies is around 0.14, while for SN Ia it amounts to 0.21 and for SN II it is 0.86. According to these data, in our Galaxy one SN Ib/c must occur approximately once per 400 years, and the total SN rate of all classes is about once per 50 years, i.e. SN Ib/c constitute one eighth of all SNs. However, the recent study [9] showed that in Seyfert galaxies with active nuclei the SN Ib/c rate can be appreciably enhanced with respect to the SN II rate.

Studies [10] of the spatial distribution of supernovae carried out several times revealed a strong concentration of SN Ib/c towards spiral arms of galaxies and H II zones, i.e. towards active star formation sites. Undoubtedly, young massive stars whose age does not exceed 10^7 years explode as supernovae Ib/c, and the initial mass of their progenitors on the main sequence is above 8 – 10 $M_{\odot}$.

The radial distribution of SN Ib/c in galaxies [11] resembles that of young objects, such as OB-associations and H II zones. Matching the radial distributions of gamma-ray burst sites inside galaxies with SN Ib/c, however, showed a notable difference.

6. Radio emission from type Ib/c supernovae

Studies of radio emission from SNs can establish some important physical characteristics of the explosion, such as the velocity and deceleration of the shock wave expanding after the explosion; peculiarities in the circumstellar matter distribution; and the mass loss rate of the presupernova [12].

Observations indicated that radio emission from SN Ib/c is non-thermal synchrotron radiation with a high brightness temperature. The radiation absorption decreases with time, which results in the maximum first occurring at shorter wavelengths. After the maximum, the radiation intensity decreases by a power law. Relativistic electrons and magnetic fields which are a prerequisite for the radiation to form, are produced in the supernova shock wave interaction with a sufficiently dense circumstellar matter ionized and heated up by an ultraviolet and X-ray flash that appears during the shock wave break out on the stellar surface. It is conjectured that the circumstellar matter is formed by the stellar wind from the presupernova or its companion emanating with a constant mass loss rate and velocity. The ionized circumstellar matter absorbs radio emission. The rapid increase in the flux is explained by the shock wave passing through the matter; as a result, the thickness of the absorbing layer rapidly decreases.

This model allows one to estimate the presupernova mass loss rate. For example, the typical value for an SN Ib/c is $\dot{M} \sim 10^{-6}\, M_{\odot}$ per year.

7. Radio emission from SN 1998bw

SN 1998bw was studied in detail in the radio band, and its properties proved quite unusual. A very large radio luminosity at the wavelength 6 cm of 7.9×10^{28} erg s^{-1} Hz^{-1} [13], which is about 30 times as large as the mean SN Ib/c value, was reached very shortly after the explosion. Assuming a constant brightness temperature of $10^{11.5}$ K, this implies a very high expansion velocity of the 'radiosphere' of about 200,000 km s^{-1}.

Radio light curves show two maxima at short wavelengths 3.5 and 6.3 cm, whereas only one maximum is seen at 21.7 cm. In the framework of the model with synchrotron emission and thermal bremsstrahlung absorption, the presence of two maxima on the radio light curves is explained by the shock wave passing through interstellar matter zones with different densities. Modeling also suggests that the interstellar matter should be clumpy, with almost all its mass concentrated in separate clumps with a filling factor of 0.1 – 0.25. This helps to explain the high shock wave speed which then propagates virtually in vacuum. It can also be concluded that the matter density maxima are separated by a distance of around 3×10^{17} cm, which is possibly due to the presupernova mass loss rate variations or results from the presupernova wind interaction with the wind from its companion in a binary system. The presupernova mass loss rate was also estimated to be $\dot{M} \sim 3.5 \times 10^{-5}\, M_{\odot}$ per year [12].

8. Theoretical models of SN Ib/c explosions

The statistical characteristics together with the observations of light curves and spectra of SN Ib/c allow us to make some conclusions on the nature of presupernovae. These must be young massive stars that lost their hydrogen and, fully or partially, helium envelopes in the course of evolution. Envelopes can be lost either by stellar wind or during the evolution in a close binary system, or in some combination of these processes.

Theoretical calculations of light curves and spectra of supernovae allow the estimation of such important parameters as the energy of the explosion, the mass of the ejection, the characteristic presupernova radius, and the mass of ^{56}Ni ejected.

For the narrow-peaked light curve SN Ic 1994I the most appropriate model is a C + O star with mass $2.1 M_{\odot}$. The mass of ^{56}Ni is $M_{\rm Ni} \approx 0.07\, M_{\odot}$, the mass of the ejecta is $0.9\, M_{\odot}$, the explosion energy is $E = 1 \times 10^{51}$ erg [14].

At SAI and at the Institute of Theoretical and Experimental Physics, a special numerical code STELLA has been devised for SN light curve modeling. This code describes the energy and momentum exchange between matter and radiation assuming no stationarity and allows realistic SN light curves in different filters to be reproduced. Using this code, models of SN Ib/c were also investigated [15]. In paper [16] the evolution of a massive star with mass loss was calculated. One of these models, mt60, was proposed as a presupernova. This model originally has a mass of $60\, M_{\odot}$ on the main sequence and becomes a Wolf – Rayet star after powerful stellar wind mass loss. Before the collapse, its mass is as low as $4.25\, M_{\odot}$, with hydrogen fully lost. The presupernova radius is $R_0 \approx 0.56 R_{\odot}$. The calculations assumed a core with a mass of $1.6\, M_{\odot}$ to collapse, such that the mass of the ejecta is $\sim 2.65\, M_{\odot}$. The mass of ^{56}Ni is $M_{\rm Ni} \approx 0.22\, M_{\odot}$. The kinetic energy of the ejecta is $E_{\rm kin} \approx 1.37 \times 10^{51}$ erg. A comparison of the obtained light curves with observations of one of type Ib/c supernovae, SN 1962L, indicates that overall qualitative agreement is observed near the maximum, but the tail of the theoretical curve is too high. It can be decreased by decreasing the amount of ^{56}Ni, but then the maximum also decreases. Possibly, this discrepancy will be ruled out by taking into account non-LTE effects,which are very strong in SN Ib/c already near the maximum brightness.

Most attention recently has been given to modeling explosions of SN 1998bw and 1997ef. For SN 1997ef, a model of an explosion of a C + O star with the mass $\sim 6 M_{\odot}$, explosion energy $E = 1 \times 10^{51}$ erg, mass of ^{56}Ni $M_{\rm Ni} \approx 0.15\, M_{\odot}$ has been considered, as well as a model with an enhanced mass of $M_{\rm ej} = 9.5\, M_{\odot}$ and energy $E = 1.9 \times 10^{52}$ erg; the light curve is fairly well reproduced by both models, but the second model better reproduces the spectra and the envelope expansion velocity [17]. For SN 1998bw, the best agreement with observations was obtained in the model of a carbon-oxygen star with $M_{\rm MS} \approx 40 M_{\odot}$, $M_{\rm fin} = 13.8 M_{\odot}$, $M_{\rm ej} = 10\, M_{\odot}$, $M_{\rm Ni} \approx 0.4 M_{\odot}$, $E = 5 \times 10^{52}$ erg. The compact remnant in this model has a mass exceeding $3\, M_{\odot}$, and hence could be a black hole [18].

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