Supernovae at Various Wavelengths

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Abstract We review some of the main features of supernovae (SNe) observed at different wavelengths. Included here are discussions of observations in the gamma-ray, X-ray, optical, infrared and radio domains of energy.

Key words: types of SNe – light curves, spectra: radio: X-rays: gamma-rays: infrared: dust

1 INTRODUCTION

It hardly needs saying that supernovae (SNe) of different classes behave quite differently at various wavelengths. Even within a class there can be different observable characteristics. It is therefore worth reviewing how SNe are classified since these classifications, no matter how general, give an immediate insight into the basic mechanisms that are responsible for their occurrence and appearance. SNe are divided into two broad categories Type I and Type II on the basis of visibility of hydrogen Balmer emission lines in the latter and their absence in spectra of the former. However Type I SNe are subdivided into two types Ia and Ib,c. This division is on the basis of the presence of a strong SiII 6355 absorption line in the former, and weak or absent SiII absorption in the latter.

It is now commonly believed that SN Ia originate from deflagration or detonation of an accreting white dwarf which has reached the Chandrasekhar limit thus becoming unstable. They are called thermonuclear SNe. The SN Ib and Ic show very little identifiable hydrogen but differ from one another in that SN Ib show optical absorption lines of helium while SN Ic show weak or no helium lines. Intermediate cases exist. However we should note here recent work (Elmhamdi et al. 2005) which demonstrates weak high velocity hydrogen absorption lines in virtually all Type Ib SNe at early phases. Together with all Type II SNe these SNe are believed to result from core-collapse in the interior of a massive evolved star whose nuclear fuel is exhausted. In fact because of the absence of hydrogen and helium (in SN Ic), these Type I SNe are believed to have originated from stars that reached the main sequence with masses in excess of $30 - 40 M_\odot$ and have lost considerable mass prior to explosion owing to a wind or binary interaction. Wolf-Rayet stars are considered possible progenitors. These SN Ib,c develop very strong emission lines of [OI] at the nebular phase (about 100 days after maximum light) suggesting that copious amounts of oxygen are produced. Some objects of this type of object, possibly with higher energies, are now known to be associated with $\gamma-$ray bursts (GRB).

Type II SNe are thought to originate from the core-collapse of massive stars. This type is subdivided into classes IIP, IIL, IIn depending on the shape of the light curve and other spectral characteristics. SN IIP are arguably the best understood theoretically seemingly originating from the explosion of a late-type supergiant and having a plateau shaped light curve following maximum that results from the extended envelope. SN 1987A is sometimes included in this class although the light curve is not a typical plateau resulting from its explosion as a blue supergiant.

Type IIL SNe have linearly decaying light curves following maximum but little in the way of a physical understanding has been published for these objects. Type IIn SNe are recognised by the presence even at early stages of narrow hydrogen emission lines undoubtedly coming from the circumstellar material excited by the impact of the SN ejecta. The resulting light curve does not follow the normal decay expected from

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radioactive decay because the kinetic energy of the ejecta is being converted into radiative energy thus enhancing the light curve. An example, of which there are now many, is SN 1995G. There are other objects such as SN 1993J which start as Type II with visible hydrogen lines that eventually fade, with the late spectra resembling more that of a SN Ib,c.

2 GENERAL PROPERTIES

Here a qualitative understanding of these types may be briefly summarized.

1. SN Ia occur in galaxies of all types. Core-collapse occur only in spirals and irregulars.
2. The presence of Ia in E, S0 galaxies suggests that some of the progenitors must be highly evolved low mass stars. Their abundance also in star forming galaxies (Mannuci et al. 2005) might indicate that there some may come from a relatively younger population. Core-collapse SNe have masses $> 8\ M_\odot$.
3. Although the SN Ia explosion results from mass accretion onto a white dwarf which then reaches the Chandrasekhar limit, there is no agreement on whether this accretion involves a white dwarf and a close normal red giant companion, or whether it involves the coalescence of 2 white dwarfs. In massive stars the core-collapse events occur because when iron (Fe) is synthesized in the core of a massive star more energy cannot be extracted by fusion and collapse begins followed by a bounce.
4. Differences among SN Ia exist but are smaller than differences among the full range of core-collapse SNe. For example, the range in absolute magnitude for SN Ia at maximum light is approximately 2.5 magnitudes, while for core-collapse objects it is more than 5 magnitudes. Fainter SN Ia are statistically more prevalent in early-type galaxies. There is a correlation between intrinsic brightness and mass of iron produced. The rate of fading after maximum light of SN Ia is inversely correlated with the intrinsic brightness. For progenitors of Type II SNe there are indicative masses now spanning the range 9–$20\ M_\odot$.
5. Radioactive decay of ^{56}Ni $-\ ^{56}$Co $-\ ^{56}$Fe powers the light curves for both thermonuclear and core-collapse SNe for the first 3 or 4 years (with the exception of Type IIn). Later other isotopes such as ^{57}Co will predominate.
6. Radio emission has not been detected from SN Ia. It has been detected from some but not all core-collapse objects.
7. X-ray emission has not been detected from SN Ia, but has been detected from some core-collapse objects.
8. SN Ia produce ^{56}Fe in the range 0.1–1.1 $M_\odot$. Evidence for this comes from modelling of their light curves and quantitative analyses of their nebular spectra which are dominated by emission lines of ions of Fe and Co. Core-collapse objects produce ^{56}Fe in the range 0.004–0.7 $M_\odot$. Here light curves are the most important tool for determining absolute masses. The masses of other elements are less well determined.

3 LIGHT CURVES

Early light curves, i.e. those embracing the first 3–4 months, when modelled provide information about the mass of the envelope, the radius of the exploding star and the energy of the explosion. There is also information less obviously revealed about the abundances of the elements. Unfortunately bolometric light curves are available for very few SNe of which SN 1987A is the outstanding example. Even so for SN 1987A there are competing models of apparently equally good fit where the the mass of the ejected envelopes vary more than 30 percent. Here we cannot discuss detailed models but make only some general remarks focussed on observations.

For all SNe there are two conspicuous parts of the light curves viz. the regions embracing maximum light and the exponential tail. SN Ia have a range in shape of the region around maximum, as mentioned earlier (Phillips 1993), but the physical reason for the variation of the rate of decay immediately after maximum and its correlation with absolute brightness is still a matter of debate. SN Ia on the exponential decay do not follow the rate that might be expected from the ^{56}Co decay rate because the envelope is small and thin allowing a higher and higher proportion of γ-rays to escape. What has gone largely unremarked is that the decay rate on the exponential tail is also faster for intrinsically fainter objects.

This is presumably the same reason why SN Ib,c light curves at late times decay faster than those of Type II. The SNe of Type IIP were thought to come from stars with extended envelopes having masses

$> 10\,M_\odot$. There are however two important points arising from observations. SN IIP have plateau phases of varying lengths indicating variations within this class, of envelope masses, explosion energies and possibly chemical abundances. They also have varying rates of decay from maximum light which correlate with the mass of ^{56}Co produced and deduced from the luminosity of the exponential decay (Elmhamdi et al. 2003). There is increasing evidence that the progenitors of some SN IIP have masses as low as 8–9 $M_\odot$ (Smartt et al. 2004). On the basis of some modelling (Arnett 1995), there is some suggestion that the envelope masses for SN IIL are considerably smaller than those for SN IIP. However the progenitor masses are as yet a mystery.

SN IIn have light curves of varying shape. It seems likely that these variations in shape and luminosity depend on the distance of the CSM from the SN, its density and its linear extent. Systematic properties hardly exist, but these objects are normally those that produce radio and X-ray emission.

4 RADIO LIGHT CURVE

The radio emission from SNe can be understood with a model (Chevalier 1982) in which a synchtron source (generated by the blast wave or by a pulsar) interacts with an optically thick CSM which eventually becomes optically thin. Synchrotron self-absorption may also play a role in what is observed. Most of the observed radio SNe have been modelled (Weiler et al. 2002) with satisfactory results. One important product of this modelling is the mass loss rate generated by the wind which constitutes the CSM. As might be expected one sees in general the higher frequencies rise more rapidly and then also fade more rapidly.

Radio emission has been observed as early as a day or two after explosion, SN 1987A, SN 1993J and SN 1998bw being the main examples, and as late as years afterwards, SN 1988Z, SN 1979C, and again SN 1987A being good examples. It should be noted that the prompt radio outburst of SN 1987A, which probably resulted from synchrotron interaction with the blue stellar supergiant wind (which is expected to have a quite high velocity) faded quickly in tens of days (Turtle et al. 1987). The modelling described above gives an adequate fit to the observations. It was only detected because of the near proximity of SN 1987A and could not have been detected in any other modern SN.

However SN 1987A has a possibly more complex CSM surrounding it than many of the other radio SNe. There appear to be 3 rings surrounding the SN, all of which must be associated with a mass loss period when the progenitor was a red supergiant. The possibility that a binary system existed only adds to the complexities. After about 3 years the radio emission started to increase again and continues to the present time, presumably as the outward propagating shock starts to interact with the inner ring. Some effects on the ring will be discussed later. The blast wave would be expected to decelerate as it impacts on the denser ring and this has been measured (Manchester et al. 2002). A more gradual deceleration has been measured for SN 1993J (Marcaide et al. 1997). Apart from mass loss rates and deceleration effects, well sampled radio light curves offer one of the few ways of mapping the structure in the CSM. Such effects resulting from density changes have been reported.

5 X-RAYS & γ-RAYS

If one judges from the best observed SN 1987A at X-ray energies there are 2 scenarios for production of X-rays not necessarily contemporaneous. In SN 1987A γ-ray lines and associated Comptonised continuum and hard X-rays (16–28 keV), also a result of Comptonisation, were detected starting at about 180 days and continuing for almost 2 years. All of this radiation is believed to originate with the radioactive β-decay of ^{56}Co which emits 8 detectable lines in the 0.8–3.5 MeV range. These lines have been detected from SN 1987A (Leising et al. 1990) and their strength when they appeared required a model with significant mixing of the radioactive material in the envelope. A line from ^{57}Co was also subsequently detected (Kurfess et al. 1992). These observations consisted of one of several independent methods of fixing the mass of radioactive material synthesized in SN 1987A and equally importantly the final mass of stable ^{56}Fe produced. The Type Ia SN 1991T is at present the only other SN from which the 2 strongest lines from ^{56}Co have been detected.

Soft X-ray emission was detected after about 4 years from SN 1987A (Beuermann et al. 1994) at about the same time that radio emission started to be detected. Emission at both energy ranges has continued to rise since then but not at the same rate. There are about 12 SNe for which soft X-ray detections have been made. Most detections begin at least a month after the explosion and are spasmodic preventing an easy comparison

and correlation with radio emission. This comparison is desirable because it is thought that the emission at both wavelengths is associated with the ejecta-wind interaction outlined for radio emission. Apart from SN 1897A the only object with good early coverage at both energies is SN 1993J. In this case, while the radio (6 cm) emission is rising dramatically starting 15 days after explosion, the soft X-ray luminosity is gradually decreasing. It will be seen from the example of SN 1987A that complex structures in the CSM, not resolvable at extra-galactic distances, might play an important role in understanding the detailed shape of light curves at various wavelengths.

6 SN 1987A

Because of its proximity and the more detailed data, including resolved imaging, that is available it is important to combine and jointly discuss recent data in order now to understand the interaction of the envelope with CSM. In fact mid-IR imaging made in 2003 (Bouchet et al. 2004) has resolved the inner ring. This mid-IR emission near 10 and 18 μm has been plausibly assigned to dust present in the ring at a temperature of approximately 180 K. The imaging photometry at 2 wavelengths near 10 and 20 μm also suggested a variation in the temperature of the dust possibly a bit higher closer to the SN. This temperature is based on a black-body assumption and will be revised somewhat when the dust grain type is better known. At present there is further observational evidence that silicate grains are present. It is believed that this dust is heated by electron and ion collisions with grains, the energy coming from the forward shock (Dwek 1987).

The resolved imaging also allowed the detection of the central source at 10 μm. The flux from this unresolved source is consistent with the decreasing trend extrapolated from 4000 days, qualitatively consistent with decreased heating from the decay of ^{56}Co and ^{57}Co. This dust now has a temperature of approximately 100 K and probably has existed since most dust formed immediately after 530 days (Lucy et al. 1989).

The observations of the IR luminosity after 6000 days extrapolated backwards in time suggest that near 3800 days interaction of the ejecta with the inner more tenuous part of the ring was beginning. In fact an increase in the rate of X-ray brightening was also noted (Park et al. 2004). The associated increase in the rate of radio brightening seems to have been a short term trend, since in the long term, it has continued evenly upward and more slowly than the most recent X-ray brightening. More recent data, still under consideration, show that near or just after day 6000 a further dramatic brightening in the IR and X-rays has occurred possibly because the low velocity forward shock has entered the main part of the ring (Bouchet et al. 2005). There must be a reverse shock propagating into the extended envelope. If the density is lower then the velocity will be higher and possibly cause a major contribution to the hard X-rays. Whether it can be responsible for some component of the radio radiation is not clear at the moment. The behavior of the radio emission at various frequencies, which is quite varied, might help our understanding particularly if multi-frequency observations are continued at reasonable intervals for the foreseeable future.

7 CONCLUSIONS

This small limited review is intended to show not only the successes in SN research but also the areas where more concentrated and extensive observations co-ordinated over the full energy range can shed light on physical processes that are still being debated. It seems mandatory to continue this for SN 1987A because although this SN is only one of a broad array of types, it does, because of its proximity, allow us to directly see interactions that we can only infer for more distant objects. We will need this experience to help decode much of what occurs in more distant SNe. Even SN 1987A is sufficiently far and our techniques and sensitivities too limited to study many aspects in detail. Obviously we should be ready for the next Galactic SN.

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