Supernovae and Radio Supernovae

Zongwei Li [1] & Xiaofeng Wang[1,2]

(1 *Department of Astronomy, Beijing Normal University, Beijing* 100875)
(2 *National Astronomical Observatories, Chinese Academy of Sciences, Beijing* 100012)

Abstract One of the most energetic explosive events known is a supernova. This occurs at the end of a star's lifetime, when its nuclear fuel is exhausted and it is no longer supported by the release of nuclear energy. As calibrated standard candles, type Ia supernovae now provide the main route to determine the main cosmological parameters, such as the Hubble constant, the cosmological density parameters. The study of radio supernovae has been briefly reviewed. Radio supernovae may also be promising objects to determine the distances, with an empirical relation between the turn-on time and peak flux density at 6 cm. Current study in radio supernovae is rather limited by the sensitivity of radio telescopes.

1 Supernovae

The study of supernovae (SNe) is in vogue today. They are at the confluence of many different streams of astronomical researches. As the final episode of the life of many kinds of stars, SNe allow crucial tests of stellar evolution theories. During and immediately after the explosions, there are a variety of fundamental physical mechanisms which can be probed, such as neutrino and gravitational wave emissions, flame propagation and explosive nucleosynthesis, radioactive decays and shocks with circumstellar medium (CSM). SNe play a vital role in galactic evolution through chemical enrichment, through energy input into the interstellar medium, through production of stellar remnants such as neutron stars, pulsars, and black holes. SNe are also being utilized as a powerful distance probes to determine various cosmological parameters, such as the Hubble constant and the density parameters.

SNe have three basic types: Ia, Ib/c and II. Both SNe Ia and SNe Ib/c lack hydrogen lines in their optical spectra, while SNe II all show hydrogen in their optical spectra with varying strengths and profiles (Filippenko 1997). SNe Ib and SNe Ic do not show the deep Si II absorptions trough near 6150 Å (blueshifted) that characterizes SNe Ia, and SNe Ib show moderately strong He I lines, especially at 5876 Å, while SNe Ic do not. Additionally, SNe II can also be further subdivided into SNe II-P (plateau) and II-L (linear) according to the shape of their light curves.

The spectral differences may indicate the differences in progenitors. SNe Ia generally believed to originate from the thermonuclear explosions of accreting white dwarfs in close binary systems. The central carbon ignition would take place when the mass of the primary white dwarf approaches to the Chandrasekar limit M_{ch} (e.g. 1.39 $M_\odot$). However, the propagation of the burning in the star and the progenitor systems are still debated. In contrast, SNe II are likely the core-collapse induced explosions of massive stars ($> 8M_\odot$). SNe Ib and Ic are also believed to be core-collapse supernovae because they share most properties with SNe II except for the deficit of H lines. The hydrogen envelope of their massive progenitors may be stripped through stellar winds or binary interactions. Possible progenitors for SNe Ib/c are exploding Wolf-Rayet stars that evolve from stars with $M > 40M_\odot$. An alternative candidate is exploding, relatively less-massive helium stars in interacting binary system.

Possible variants of normal SNe II are the "Type IIn" and the "Type IIb", which both show unusual optical characteristics. SNe IIn are characterized by very narrow emission lines superposed on top of broad Balmer emission lines. The narrow component presumably arises from interaction with a dense ($n > 10^7 \mathrm{cm}^{-3}$) CSM surrounding the SN. SNe IIb look optically like normal SNe II at early time, but evolve to more closely resemble SNe Ib at late time. It may represent a transitional subclass between SNe II and Ib (e.g. SNe 1993J and 1996cb).

2 Type Ia Supernovae as Distance Indicators

2.1 SNe Ia as Standard Candles

SNe Ia has long been proposed as good distance indicators for cosmology, first through their standard candle character, i.e., identical peak luminosity, and later normalized by corrections from light curve shapes. Their Hubble diagram (i.e. magnitude-redshift relation) can be used to trace the expansion history of the universe. The linear part of the Hubble diagram with absolute magnitude calibration determines the Hubble constant (see Branch 1998 for a review); curvature in the diagram probes evolution in the expansion rate, e.g. acceleration or deceleration, and different combinations of cosmological parameters (Riess et al 1998; Perlmutter et al 1999; Leibundgut 2001 for a recent review). It is generally accepted that brighter SNe Ia have broader light curves around optical maxima. The peak luminosity-decline rate relation (Phillips 1993; Hamuy et al. 1996) or width luminosity relation (Riess et al. 1996; Perlmutter et al. 1997) has been proposed to further reduce the scatters of maximum brightness. We briefly call this kind of relation WLR in this report. This relation now becomes the basic law for the use of SNe Ia as cosmological yard-stick.

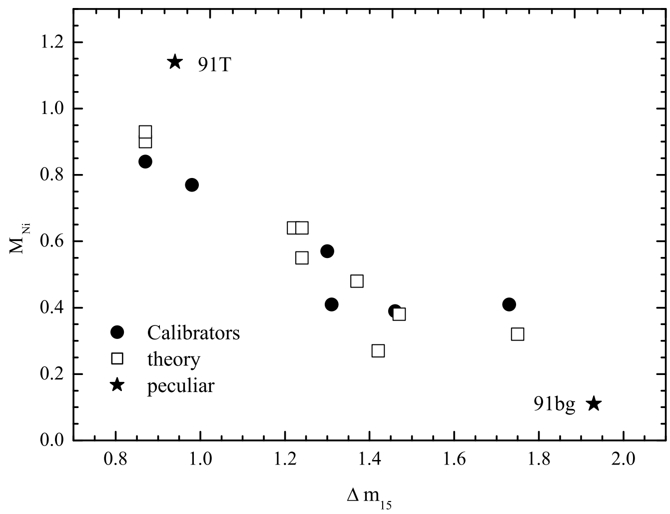

Fig. 1 The plot of the amount of ^{56}Ni produced in SN Ia explosion vs. decline rate Δm_{15}. The open squares correspond to calculations made by varying the ^{56}Ni mass in DD4. The filled circles show measurements from nearby SNe Ia with independent distance calibrations.

The WLR has been very well substantiated observationally, yet it is an empirical relation that needs to be understood from the physical point of view. A priori, the light curve may depend on many parameters, such as the total mass M of the exploding star, the explosion energy E, the ^{56}Ni mass synthesized in the explosion and the opacity k etc. Since the light curves of SNe Ia are believed to be powered by the radioactive decay chain $^{56}\mathrm{Ni} \rightarrow ^{56}\mathrm{Co} \rightarrow ^{56}\mathrm{Fe}$ (Kuchner 1994; Bowers et al. 1997), it is reasonable to attribute the variation in peak luminosity to different amounts of ^{56}Ni produced in the explosions (see Figure 1). The WLR may be a natural consequence of the radiation transport in SNe Ia explosion (Höflich P et al. 1996; Pinto & Eastman 2001). The ^{56}Ni yield sets the scale of the peak luminosity and the heating rate of the gas. The resulting temperature determines the ionization and hence the cooling rate of the gas. More ^{56}Ni leads to more heating, higher temperature, less efficient cooling, and hence broader and brighter light curves. Note that an additional physical parameter that regulates the WLR may be the r-ray escape fraction, which sets the evolution rate of the energy deposition and therefore influences the light curve declines. Greater r-ray escape fractions would result in a narrower light curve even for bright SNe Ia. This may explain why some luminous SNe Ia have relatively faster decline rates while their colors remain bluer, e.g.SN 1992bp. On the other hand, the observed correlation between the peak luminosity and maximum B-V color of SNe Ia is also expected, since the color at maximum light is a measure of the opacities in the ejecta, which is an indicator of the temperature (Khokholov, Muller&Wheeler 1993). More ^{56}Ni would cause higher temperature and opacities that are contributed primarily by particular species (such as cobalt, iron and sulfur) (Bowers et al. 1997), and consequently, bluer color at maxima. Note that, under the delayed detonation models, Höflich P et al.(1996) reproduced well the observed $M_{max} - (B - V)$ correlation.

The dispersion of the Hubble diagram could be reduced to ~ 0.08 mag when applying the combined $M_{max}(\Delta m_{15}, (B - V))$ relation to the peak luminosity of an extinction-free SN sample.Such a small luminosity dispersion is now the same order as the observational error, which leaves little room for other possible correlations such as the type (or color) of the host galaxies (Hamuy et al. 1996b; 2000) as well as the galactocentric distances (Wang, Höflich & Wheeler 1997; Ivanov et al. 2001).

2.2 The Absolute Magnitudes of SNe Ia and the Hubble Constant

As the best distance indicators beyond the Virgo cluster, SNe Ia now provide the main route to determine the Hubble constant (H_0). The distance dispersion inferred from standardized luminosity of SNe Ia is only 5%. Although other distance indicators are still discussed, in most cases they enter the analysis with lower weight.

Knowing their absolute magnitudes at maxima is the premise to determine the H_0 value by SNe Ia. Sandage/Saha Type Ia SNe HST calibration Program has provided us accurate Cepheid-based distances to some nearby galaxies that hosted SNe Ia. In a series of papers, Saha and Sandage have published the Cepheid distances to IC 4182 (SN 1937C), NGC 5253 (SNe 1895B, 1972E), NGC 4536 (1981B), NGC 4496A (SN 1960F), NGC 4639 (SN 1990N), NGC 3627 (SN 1989B), NGC 3982 (SN 1998aq), and NGC 4527(SN 1991T) (see Saha et al. 2001 and references therein). Tanvir et al(1995) and Turner (1998) gave the Cepheid distances to NGC 3368 (SN 1998bu) and NGC 4414 (SN 1974G). Using all or some of these distances, the absolute magnitudes of normal SNe Ia are estimated to be -19.55 ± 0.08(statistical) mag in V band, which is in agreement with the result predicted by theoretical models with equal decline rate and color (Höflich P et al. 1996).

The Hubble constant is estimated to be $64\pm2\,\mathrm{km\,s^{-1}\,Mpc^{-1}}(1\sigma)$ by matching the local calibration value to the distant Hubble-flow SNe Ia. The errors only account for statistical errors. The possible systematic errors include the specific photometry (i.e. ALLFRAME vs. DoPHOT) and associated method of detecting variable stars; the metal dependence of the P-L relation; the shape of Cepheids' P-L relation; the zero point of the P-L relation.

Considering the those systematic effects discussed above, the final result for the Hubble constant could be $64{\pm}2{\pm}6\,\mathrm{km\,s^{-1}\,Mpc^{-1}}(1\sigma)$ (see Wang et al. 2001). Further improvement of the accuracy would rely on the full understanding of various systematic effects that possibly influence the calibration value of the absolute magnitudes for Type Ia supernovae.

2.3 The Accelerating Expansion Implied from SNe Ia

Using SNe Ia as distance indicators to trace the history of the cosmic expansion, a deviation from the linear Hubble flow can be measured at higher redshift which is related to the (de)acceleration of the local Universe. For a precision of Δm in distance modulus at redshift z, the deceleration can be measured to an accuracy of $\Delta q_0 \approx 0.9\Delta\mathrm{m/z}$. Statistical accuracies of 0.1 mag in an ensemble of supernovae at z$\approx$0.5 can lead to a error in q_0 of less than 0.2 units, which is adequate to determine the sign of the acceleration.

Spectacular and surprising claims have been made about the detection of an acceleration away from the linear local Hubble flow, which is interpreted as a positive cosmological constant Ω_Λ(Riess et al 1998; Perlmutter et al 1999). After the initial excitement, the reliability of above results needs to be further tested. For example, the peak $B-V$ colors of high-redshift SNe Ia seem to be bluer than the local counterparts (e.g. -0.15 ± 0.03 vs. -0.04 ± 0.01), which may imply evolution of peak luminosity or systematic errors in extinction correction. The most direct method of testing systematic effect is to further extend the m-z relation of SNe to z$\geq$1, since there exists a transition from decelerated expansion (where the energy density was dominated by matter) to accelerated expansion if current universe is Λ-dominated. In a flat Universe model Ω_Λ=0.2, Ω_M=0.8, this transition occurred at z$\sim$1, where the SNe become less faint relative to an empty universe. If the current SN data were explained by evolution or extinction, for instance a systematic uncertainty which grows linearly with redshift, we would expect that SN Ia results at higher redshift to diverge significantly from the cosmological prediction. Thus, observations of SN Ia at z$\sim$1 will provide an excellent test to confirm or refute the current cosmological paradigm.

3 Radio Supernovae

The radio emitting supernovae (RSNe) have been extensively searched for since at least 1970 and several weak detections of SN 1970G have been obtained. The radio emission is an indicator of the presence of CSM. Therefore, analysis of the radio emission provides vital insight into the interaction of the SN shock with preexisting CSM lost by the progenitor star or progenitor system, and, therefore, into the nature of pre-supernova evolution. Moreover, because of their high radio luminosities and slow decay time, RSNe may be significant contributors to the total radio flux of starburst galaxies, and hence it is of interest in studying the FIR-radio correlation. Finally, if some RSNe are optically dim or invisible (as SN1986J appears to have been), and if these are also the most massive stars (with a corresponding large yield of processed stellar material), there will be important consequences for our understanding of the chemical enrichment history of galaxies.

Radio emission has been observed for some supernovae in SNe Ib/c (e.g. 1983N), IIb (i.e.1993J, 1996cb), IIn (1986J, 1988Z), II-L and now II-P. However, due to low resolution, background confusion, and sensitivity limitations of the radio telescopes, less than 30 RSNe have been detected and even small number of them have been extensively studied in detail at multiple radio frequencies. The SN IIpec 1987A was observed in the radio, but it probably would not have been observed at the distance of a few megaparsecs (Mpc). The sole II-P observed near the time of its explosion in the radio is SN 1999em (Lacey et al. 1999); additionally the SN II-P 1923A has recently been detected in the radio (Eck et al. 1998). The

SN IIn are usually not only in the optical, but also in the radio, being exceptionally powerful radio sources ($\geq 10^{28}$ erg s^{-1} Hz^{-1}). Note that radio emission has not been observed from SNe Ia, but certain models of SNe Ia (i.e. Hachisu et al. 1999a, b) propose radio emission at some level before maxima. To determine whether this absence of radio emission in SNe Ia is real or if it merely represents the limitations of existing observations has to rely on the future observations (e.g., an improvement by two orders of magnitude will give a definite answer).

3.1 The Light Curves and the Model

All RSNe appear to share the common properties of 1) non-thermal synchrotron emission with high brightness temperature; 2) a decrease in absorption with time, resulting in a smooth, rapid turn-on first at shorter wavelengths and later at longer wavelengths; 3) a power-law decline of the flux density with time at each wavelength after maximum flux density is reached at that wavelength; and 4) a final, asymptotic approach of spectra index α to an optically thin, non-thermal, and constant negative value.

A "mini-shell" model is usually used to describe the observed RSNe, which involves the acceleration of relativistic electrons and enhanced magnetic field necessary for synchrotron emission, arising from the SN shock interacting with a relatively high-density CSM that has been ionized and heated by the initial SN UV or X-ray flash. The rapid rise in radio flux density results from the shock overtaking progressively more of the ionized wind matter, leaving less of it along the line-of-sight to absorb the emission from the shock region. While the slow decline in flux density at each wavelength after the peak is then due to the SN shock expanding into generally lower density regions of the optically thin CSM. The observed variation in density flux of RSNe can be represented by a relatively complex function of the time after the explosion, which consists of the unabsorbed flux density, the power law term, and two terms describing uniform external absorption and clumpy absorption respectively. The readers can refer to Weiler et al. (1986; 1990) for the detailed parameters of this model.

3.2 RSN Distance Determination

Evidence has recently been presented that the radio emission from SNe may have quantifiable properties which allow for distance determinations. Using a small sample of 12 Type II RSNe, Weiler et al. (1998) showed that these objects appear to obey a relation $L_{6\,\mathrm{cm\,peak}} \approx 5.5\times10^{23}(t_{6\,\mathrm{cm\,peak}}\text{-}\ t_0)^{1.4}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$, with time in days. If these relations are supported by further observations, they provide a means for determining distances to supernovae, and thus to their parent galaxies, from purely radio continuum observations. The H_0 determination could be made independent of optical observations. Furthermore, if some bright SNe could be radio detected to z$\sim$1, the estimation of other cosmological parameters, such as q_0 and Ω, might be possible.

However, due to the sensitivity limitations, the studies of most RSN can only be restricted to distances smaller than the Virgo cluster, a cosmologically insignificant distance. In order to be able to detect the brightest of RSNe, such as Type IIn SN 1988Z and SN 1986J at the cosmologically interesting distance of z =1, the sensitivity of radio telescope should be improved to the level of 1μ Jy. While for normal Type II RSNe, such as SNe 1979C and 1980K, this sensitivity should reach to the level of 0.1μ Jy.

4 Conclusions

Empirical WLR makes the thermonuclear SNe one of the most powerful tool to measure the distances to distant galaxies. However, the determination of the Hubble constant is still greatly affected by the accuracy of Cepheid calibrations for nearby SNe Ia. While the cosmological results from high-z SNe Ia should experience more strict test against some systematic effects. Observation of SNe Ia at $z > 1$ would help to give judgements. On the other hand, the RSNe study is severely sensitivity limited by the radio telescopes, even by VLA. For RSNe study, one would like to see that the sensitivity should be at the level of 1μ Jy rms or better in 30 minutes. The Square Kilometer Array (SKA), a VLA Expansion, holds possibility to reach such an accuracy. The SKA would improve SN environment/progenitor studies, would lead to improvement in our understanding of galactic chemical and dynamical evolution, and would provide independent distance and cosmological parameter estimates.

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