RADIO SUPERNOVAE AND THE SQUARE KILOMETER ARRAY

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Abstract. Detailed radio observations of extragalactic supernovae are critical to obtaining valuable information about the nature and evolutionary phase of the progenitor star in the period of a few hundred to several tens-of-thousands of years before explosion. Additionally, radio observations of old supernovae (>20 years) provide important clues to the evolution of supernovae into supernova remnants, a gap of almost 300 years (SN ∼1680, Cas A, to SN 1923A) in our current knowledge. Finally, new empirical relations indicate that it may be possible to use some types of radio supernovae as distance yardsticks, to give an independent measure of the distance scale of the Universe. However, the study of radio supernovae is limited by the sensitivity and resolution of current radio telescope arrays. Therefore, it is necessary to have more sensitive arrays, such as the Square Kilometer Array and the several other radio telescope upgrade proposals, to advance radio supernova studies and our understanding of supernovae, their progenitors, and the connection to supernova remnants.

1. Supernovae

Supernovae (SNe) play a vital role in galactic evolution through explosive nucleosynthesis and chemical enrichment, through energy input into the interstellar medium, through production of stellar remnants such as neutron stars, pulsars, and black holes, and by the production of cosmic rays. SNe are also being utilized as powerful cosmological probes, both through their intrinsic luminosities
and expansion rates. A primary goal of supernova research is an understanding of progenitor stars and explosion mechanisms for the different SNe types. Unfortunately, little is left of the progenitor star after explosion, and only the progenitors of four (SNe 1987A, 1978K, 1993J, and 1997bs), out of more than 1560 extragalactic SNe, have been directly identified in pre-explosion images. Without direct information about the progenitors, thorough examination of the environments of SNe can provide useful constraints on the ages and masses of the progenitor stars.

SNe come in three basic types (e.g., [1]): Ia, Ib/c, and II. Both SNe Ia and SNe Ib/c lack hydrogen lines in their optical spectra, whereas SNe II all show hydrogen in their optical spectra with varying strengths and profiles [2]. SNe Ib and SNe Ic subclasses do not show the deep Si II absorption trough near 6150 Å that characterizes SNe Ia, and SNe Ib show moderately strong He I lines, while SNe Ic do not.

These spectral differences are theoretically explained by differences in progenitors. SNe Ia are currently thought to arise from the total disruption of white dwarf stars, which accrete matter from a binary companion. In contrast, SNe II, SNe Ib, and SNe Ic are likely the explosions of massive stars. SNe II presumably result from the core collapse of massive, hydrogen-rich supergiant stars with masses \( 8 \lesssim M (M_\odot) \lesssim 40 \). On the other hand, SNe Ib/c are believed to arise from a massive progenitor which has lost all of its hydrogen envelope prior to explosion (e.g., [3]). One candidate progenitor for SNe Ib/c is exploding Wolf-Rayet stars (which evolve from stars with \( M \gtrsim 40 M_\odot \); e.g., [4,5]). An alternative candidate is exploding, relatively less-massive helium stars in interacting binary systems [6,7].

Possible variants of normal SNe II are the “Type IIn” [8], and the “Type IIb” [9], which both show unusual optical characteristics. SNe IIn show the normal broad Balmer line profiles, but with a narrow peak sitting atop a broad base. The narrow component presumably arises from interaction with a dense \( (n \gtrsim 10^7 \text{ cm}^{-3}) \) circumstellar medium (CSM) surrounding the SN. SNe IIb look optically like normal SNe II at early times, but evolve to more closely resemble SNe Ib at late times.

2. Radio Supernovae

Radio emitting supernovae (RSNe) have been extensively searched for since at least 1970 [10] and several weak detections of SN1970G were obtained [11]. However, due to low resolution, background confusion, and sensitivity limitations, only with the Very Large Array (VLA)\(^1\) was the first example found which could be studied in detail at multiple radio frequencies (SN 1979C; [12]; see also [13,14,15,16]). So far, about 27 RSNe have been detected with the VLA and other radio telescopes and only \(~17\) objects have been extensively studied, including the SNe II 1980K [13,17,18] and 1979C [14,15], the SNe Ib/c 1983N [13], 1990B [19], and 1994I [20], the SNe IIn 1986J [21] and 1988Z [22], and the

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\(^{1}\)The VLA is operated by the National Radio Astronomy Observatory of the Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.
Figure 1. Light curves at multiple radio frequencies for SN 1983N (Type Ib) in M83, SN 1979C (Type II) in M100, and SN 1988Z (Type IIn) in MCG +03−28−22.

SN IIb 1993J [23]. The SNe IIn are unusual not only in the optical, but also in the radio, in being exceptionally powerful radio sources (≥10^{28} \text{ erg s}^{-1} \text{ Hz}^{-1}, or several thousand times the luminosity of Cas A, at 6 cm).

Figure 1 shows several examples of detailed RSN light curves. Figure 2 shows an example of a particularly well-measured RSN, the SN IIb 1993J, which is only 3.6 Mpc distant, in M81.

Analysis of the radio emission provides vital insight into the interaction of the SN shock with preexisting circumstellar matter lost by the progenitor star or progenitor system, and, therefore, into the nature of presupernova evolution.

All RSNe appear to have the common properties of 1) nonthermal 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 (optical depth ≈1) is reached at that wavelength; and 4) a final, asymptotic approach of spectral index α to an optically thin, non-thermal, constant negative value [13,21].

The observed RSNs can in general be represented by the “mini-shell” model [24,25], 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, which has been ionized and heated by the initial SN UV/X-ray flash. The CSM is presumed to be the pre-SN mass lost in the late stages of the progenitor’s evolution. 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. 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 now-optically thin CSM.

This model has been parameterized by [13,21] as:
Figure 2. Light curves at multiple radio frequencies for a recent, nearby Type IIb, SN 1993J in M81 (NGC 3031), only 3.6 Mpc distant.

\[ S = K_1(\nu/5 \text{ GHz})^\alpha (t - t_0)^\beta e^{-\tau} \left( \frac{1 - e^{-\tau'}}{\tau'} \right) \text{ mJy}, \]  

(1)

\[ \tau = K_2(\nu/5 \text{ GHz})^{-2.1}(t - t_0)^\delta \]  

(2)

and

\[ \tau' = K_3(\nu/5 \text{ GHz})^{-2.1}(t - t_0)^{\delta'} \]  

(3)

$K_1$, $K_2$, and $K_3$ formally correspond to the unabsorbed flux density ($K_1$), uniform ($K_2$) and non-uniform ($K_3$) optical depths, respectively, at 5 GHz one day after the explosion date $t_0$. The term $e^{-\tau}$ describes the attenuation of a local medium with optical depth $\tau$ that uniformly covers the emitting source ("uniform external absorption"), and the $(1-e^{-\tau'})\tau'^{-1}$ term describes the attenuation produced by an inhomogeneous medium with optical depths distributed between 0 and $\tau'$ ("clumpy absorption"). All absorbing media are assumed to be purely thermal, ionized hydrogen with opacity $\propto \nu^{-2.1}$. The parameters $\delta$ and $\delta'$ describe the time dependence of the optical depths for the local uniform and non-uniform media, respectively.

Normally $0 > \delta > \delta'$, so that $\tau'$ is the dominant opacity when $(t - t_0) \leq (K_3/K_2)^{1/(\delta - \delta')} \text{ days}$. At later times, the dominant opacity is $\tau$ until the CSM becomes optically thin and the radio emission is described by its characteristic power law decline with index $\beta$. In both Figures 1 and 2 we show the model fits to the observed data.

As more radio information has become available, some interesting variations in this model have appeared, including clumpiness in the CSM, variations in mass-loss rates (and, thus, stellar evolution phase) in the last few thousand years before explosion \cite{16,18,23}, and possibly synchrotron self-absorption (SSA) in the earliest phases of the SN evolution \cite{26} – the only example of SSA known outside of compact galactic nuclei and quasars.
However, even with the considerable improvement in VLA sensitivity over the past 20 years, the field of RSN studies is still very much sensitivity limited. More than 100 nearby SN events have been observed in the radio, with a detection rate of only $\sim 1/4$, and we have only been able to develop relatively complete, multi-frequency radio light curves for fewer than half of those detected.

With more than 1300 SNe which have been discovered optically since the first modern SN discovery, SN 1885A (S Andromeda) in M31, there is insufficient radio sensitivity, even with the VLA, to have a chance of detecting even a small fraction of them. Such sensitivity limitations restrict the scope of most RSN studies to distances smaller than the Virgo cluster, a cosmologically insignificant distance.

Furthermore, because of sensitivity limitations, the statistics of radio emission from different types of optical SNe is very poor, with only 7 examples of SNe Ib/c and no examples of SNe Ia ever detected. Even the generally radio-brighter Type II SNe have less than two dozen detections, and fewer than half of that number have well measured, multi-frequency radio light curves.

3. New Observations Possible with the SKA

3.1. Radio Emission from Type Ia SNe

With the Square Kilometer Array (SKA) RSN studies would enter a new era. We would be able to monitor RSNe at a practical threshold up to distances ten times further than is currently possible. As a result, statistics for both the Type II and Type Ib/c RSNe would substantially increase giving a better indication of progenitor types and environments.

An aspect where the SKA would greatly advance RSNe studies, and our general understanding of SNe, is in the possible detection of radio emission from Type Ia SNe. These are the luminous objects currently serving as powerful cosmological probes out to $z \sim 1$ and providing interesting constraints on $\Omega_M$ and $\Omega_\Lambda$ [27,28]. Yet, we are still uncertain as to what type of stars are giving rise to Type Ia SNe. We suspect theoretically that they involve the deflagration or detonation of a white dwarf in a mass-transfer binary system, but being able to observe the properties of the mass lost from the presupernova system, through the shock-generated radio emission, could greatly improve our knowledge of the progenitor system’s properties.

Some scenarios for Type Ia SN progenitor systems (see, e.g., [29]) could generate a CSM around the SN sufficiently dense to produce faint radio emission, currently below the sensitivity limit for the VLA. The level of the SN shock/CSM interaction for Type Ia SNe, and its implication for the nature of the progenitor system, thus await a more sensitive radio array.

3.2. RSN Distance Determinations

Evidence has recently been presented [30] that the radio emission from SNe may have quantifiable properties which allow for distance determinations. Type II RSNe, based on a small sample of twelve objects, appear to obey a relation $L_{6 \, \text{cm peak}} \simeq 5.5 \times 10^{23} \left( t_{6 \, \text{cm peak}} - t_0 \right)^{1.4} \text{ erg s}^{-1} \text{ Hz}^{-1}$, with time in days (Figure
Figure 3.  Peak 6 cm luminosity, $L_{6\,\text{cm peak}}$, of RSNe vs. time, in days, from explosion to peak 6 cm flux density ($t_{6\,\text{cm peak}} - t_0$). Type II SNe are plotted as filled triangles. The dashed line is the unweighted, best fit to the 12 available Type II RSNe. The Type II SNe show a large range in times to 6 cm peak ($t_{6\,\text{cm peak}} - t_0$) and in peak 6 cm luminosity, $L_{6\,\text{cm peak}}$, but appear to obey the relation given in the text. Where no error or only a stub of a line is shown, the error in that direction is indeterminate.

3. Thus, measurement of the radio turn-on time ($t_{6\,\text{cm peak}} - t_0$) and peak flux density $S_{6\,\text{cm peak}}$ may yield a luminosity estimate and therefore a distance.

The reality of this relation may be tested simply through the study of more objects, and some examples of the class are bright enough that $\sim1$ per year can presently be detected in the radio to slowly increase the available statistics. For the radio fainter Type II SNe, however, there exists a large gap in our knowledge between the very faint, somewhat oddball SN 1987A ($\sim3 \times 10^{23}$ erg s$^{-1}$ Hz$^{-1}$ at 6 cm peak; which could only be detected in the radio because it was extremely nearby in the LMC), and the faintest of the normal Type II RSNe, such as SN 1980K ($\sim1 \times 10^{26}$ erg s$^{-1}$ Hz$^{-1}$), which can be observed in more distant galaxies with the VLA sensitivity and are more than two orders-of-magnitude radio brighter than SN 1987A at 6 cm peak.

Additionally, the SKA holds the possibility for detection of the very luminous RSNe IIn at quite large distances. Figure 4 illustrates that, at a sensitivity level of 1 $\mu$Jy, one can detect the brightest of RSNe, such as the Type IIn SN 1988Z and SN 1986J, at the cosmologically interesting distance of $z = 1$. At a sensitivity level of 0.1 $\mu$Jy one can even study more normal Type II RSNe, such as SNe 1979C and 1980K, at such cosmologically interesting distances.

If we can extend our horizons to observe SNe up to a redshift of $z \sim 1$ we will fill in the gaps in our knowledge of SN progenitors and improve the statistics for RSNe of all types. Also, RSNe may then provide a powerful and independent technique for investigating the long-standing problem of distance estimates in astrophysics.
Figure 4. A plot of peak C band (6 cm in the observer’s frame) flux density for various well-observed RSNe, if they were moved to higher redshift, assuming a Friedmann cosmology ($\Omega_\Lambda = 0$) with $q_0 = 0.50$ and $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The prototypical RSNe are SN 1980K (open circles), SN 1979C (crosses), and SN 1988Z (asterisk).

3.3. The SN-SNR Connection

Old SNe, such as SN 1968D in NGC 6946, SN 1970G in M101, and SN 1923A in M83, provide a connection to young supernova remnants (SNRs). Currently, a large gap in time exists between the oldest RSNe and the youngest radio SNRs such as Cas A (SN $\sim 1680$), Kepler (SN 1604), Tycho (SN 1572), etc. (See Figure 5.) Bridging this gap and understanding the evolution of SNe into SNRs is vital for our understanding of SNe, their interaction with the CSM, and their energy and chemical input into the ISM — with the resulting influence on star formation and galaxy evolution. The SKA would potentially allow detection of decades-old SNe which may still be radio emitters, but are currently well below the VLA sensitivity limit.

4. Summary

The limitations to our studies of RSNe are intimately tied to the present sensitivity of the VLA, such that: 1) the realistic study limit for short, multi-frequency monitoring is $\sim 1 \text{ mJy}$ peak flux density; 2) we can only detect normal SNe to $\sim$ Virgo Cluster distances ($\sim 20 \text{ Mpc}$); 3) we can only study very luminous RSNe to $\sim 100 \text{ Mpc}$; 4) there is significant delay from observing to mapping; and, 5) no realistic radio SN search modes are possible.

The current RSN study problems are: limitation to optical magnitude $m_V \sim 12 - 14$ for normal Type II SNe; $\sim 1300$ optical SNe are known but there are only $\sim 27$ radio detections; and, $\sim 150$ SNe are discovered each year, but there are only $\sim 1$ to 2 new radio detections yearly. The SKA could extend RSN detections to $m_v \sim 19$, such that $\sim 50$ radio detections per year would become possible. The SKA could possibly provide better SN statistics than the optical by not being limited due to absorption by dust and, as a result, could discover
“hidden” SNe. The SKA could therefore provide better galaxy SN rates, which would yield improved chemical and dynamical galaxy evolution modeling.

Radio data are vital for understanding the nature of SN progenitor stars and stellar systems by probing the pre-SN mass loss in the late stages of the progenitor’s stellar evolution. As a result, radio data place important constraints on the SN progenitor properties and masses. Improved radio data could also extend the monitoring time of young RSNe and provide improved detection of “old” SNe, to bridge the SN-SNR time gap.

With the SKA, normal SNe should be radio detectable to $\sim 200$ Mpc; bright SNe should be radio detectable to $z \sim 1$; and, radio distance estimates could be made from the radio peak luminosity vs. turn-on time relation. $H_0$ determinations could be made independent of optical limitations, and estimation of other cosmological parameters, such as $q_0$ and $\Omega$, might be possible.

5. Conclusions and Recommendations

The current VLA is severely sensitivity limited for SN studies and the current lack of on-line mapping at the VLA precludes RSN searches. Thus, for RSN studies one would like to see:

1) Sensitivity of 1 $\mu$Jy rms or better in 30 minutes;
2) Resolution $\leq 1''$ at 1.4 GHz (preferred also at 327 MHz);
3) Simultaneous, multi-frequency observations;
4) Real-time, on-line editing, calibration, and mapping; and
5) Nearly circular snapshot beam.

The SKA and, for example, a VLA Expansion, would improve SN environment/progenitor studies, would improve SN statistics, would lead to improvements in our understanding of galactic chemical and dynamical evolution, and would provide independent distance and cosmological parameter estimates.
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