

Radio Supernovae in the Local Universe

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ABSTRACT

In the last three decades, about 50 radio supernovae have been detected as a result of targeted searches of optically discovered supernovae in the local universe. Despite this relatively small number some diversity among them has already been identified which is an indication of the underlying richness of radio supernovae waiting to be discovered. For example, comparison of star formation and supernova discovery rate imply that as many as half of the supernovae remain undetected in the traditional optical searches, either because of intrinsic dimness or due to dust obscuration. This has far reaching consequences to the models of stellar and galaxy evolution. A radio sky survey would be ideal to uncover larger supernova population. Transient radio sky would benefit significantly from such a survey. With the advent of advanced gravitational wave detectors a new window is set to open on the local Universe. Localization of these gravitational detectors is poor to identify electromagnetic counterparts of the gravitational wave sources. However, the longer lasting radio emission accompanied in these sources could be effectively identified in a radio sky survey. We advocate a medium area (\approx a few thousand deg^2) radio sky survey at C-band. Alternatively, a survey at S-band has advantage of larger sky coverage without serious loss of the science case as presented here. Understanding the background in radio sky will be of paramount importance for the upcoming sensitive radio facilities including the Square Kilometer Array.

1. Introduction

A full characterization of the transient sky is one of the key observational frontiers in modern astronomy as underscored by the Astro2010 Decadal Survey. It is driven by the fact that transient phenomena generally result from a rapid and violent release of

energy and therefore provide a unique window into extreme physics, massive star outbursts and deaths, and the diverse behavior of compact objects (white dwarfs, neutron stars, and black holes). Very Large Array (VLA) radio telescope has been a pioneer in the transient astronomy over decades especially through its targeted observations of novae, supernovae (SNe), gamma ray bursts (GRBs) and, recently, tidal disruption events (TDEs). Moreover, it has enabled a systematic characterization of the radio properties of SNe. Detailed comparison of radio observations with optical and other wavebands has revealed a rich diversity among SNe such as a broad luminosity distribution, SNe powered by a central engine and some without optical or high energy counterparts to state a few. A radio sky survey would be ideal to address some of these issues and to uncover and systematically study a larger supernova population.

With the advent of synoptic sky surveys astronomy is on the brink of revolution and radio astronomy is finally gearing up for that era, which had until now been largely the domain of optical and other high-frequency bands. Several upcoming and operational radio facilities, such as ASKAP-VAST ¹, MWA ², GMRT-TGSS ³, LOFAR ⁴ etc., are well positioned to do the low frequency (≤ 1.5 GHz) whole sky survey and will map the radio sky at those frequencies at regular intervals. VLA should, therefore, concentrate on its unique strength at high-frequencies (around 5 GHz) with an eye on future facilities (SKA, ⁵, LSST ⁶, Advanced-LIGO ⁷, Zwicky Transient Facility etc.) and the skies that they open up (novae, SNe, GRBs, TDEs and other transients).

2. Radio Emission from Supernovae

On physical grounds SNe could be broadly classified in two branches: core collapse (type Ib, Ic and type II) and thermonuclear (type Ia). The gravitational collapse of stellar core is accompanied by the ejection of outer stellar shells at very high velocities ($\approx 10,000$ km/s) which upon interaction with the circum-stellar material launches a shock-wave propagating at a fraction of the speed of light ($v \approx 0.1-0.2 c$). The material swept by the shock gets heated to high temperatures. Relativistic electrons in this plasma gyrate

¹<http://www.physics.usyd.edu.au/sifa/vast/index.php>

²<http://www.mwatelescope.org/>

³<http://tgss.ncra.tifr.res.in/>

⁴<http://www.lofar.org/>

⁵<https://www.skatelescope.org/>

⁶<http://www.lsst.org/lsst/>

⁷<https://www.advancedligo.mit.edu/>

in the shock amplified magnetic field generating synchrotron radiation which peaks in the radio frequency bands. Largely similar description would be applicable in the case of thermonuclear SNe although to-date no radio emission has been seen from the site of type-Ia SNe. Environmental reasons could be strongly to blame for those non-detections.

The theory of radio emission due to SN shock wave has been developed by Chevalier (1982). A significant progress in observations has been achieved due to the work of several groups, notably by Weiler et al. (2002); Berger et al. (2003); Soderberg (2007); Stockdale et al. (2006).

The synchrotron radio luminosity of a SN could be described in a semi-empirical form

$$f_\nu(\nu, t) = K_1 \left(\frac{\nu}{5\text{GHz}} \right)^{\beta_f} \left(\frac{t}{\text{day}} \right)^{\alpha_f} e^{-\tau_\nu} \quad (1)$$

with the optical depth due to the external absorption

$$\tau_\nu(t) = K_2 \left(\frac{\nu}{5\text{GHz}} \right)^{\beta_\tau} \left(\frac{t}{\text{day}} \right)^{\alpha_\tau} \quad (2)$$

where β_τ and β_f describe spectral evolution of flux and optical depth, respectively. Similarly, α_τ and α_f describe temporal evolution of flux and optical depth, respectively.

In addition to the external source of absorption, radiating electrons acts as a source of internal absorption via the well known process of synchrotron self-absorption. This prominent spectral feature cascades down in frequencies with time. Its detection and evolution is crucial for estimating density of circum-stellar material and the shock speed. Along with the estimation of peak brightness these observed parameters are used to infer shock wave kinetic energy.

Figure 1 is an effective way of looking at the diversity in the population of RSNe. The peak radio spectral luminosity ($L_{\nu,p}$) at 5 GHz and its epoch (t_p) are related to the shock velocity (β_{sh}) expressed in the units of speed of light (Chevalier 1998).

$$L_{\nu,p} = 1.2 \times 10^{28} \beta_{sh}^{36/17} \left(\frac{\nu_p}{5 \text{ GHz}} \right)^{36/17} \left(\frac{t_p}{10 \text{ day}} \right)^{36/17} \quad (3)$$

Supernovae are formed during the collapse of massive star, and merely 1% ($= 10^{51}$ erg) of the total gravitational energy released during the collapse is coupled to the SN ejecta moving at $\approx 10,000$ km/s. Even smaller fraction $\lesssim 10^{-5}$ of the total energy is coupled to the fastest moving shock wave responsible for synchrotron emission shining in radio. Although formed under similar circumstances, GRBs are much rarer events. In contrast to SNe, shock waves of GRBs are highly relativistic and orders of magnitude more energetic. According to the widely accepted scenario, this difference stems from the

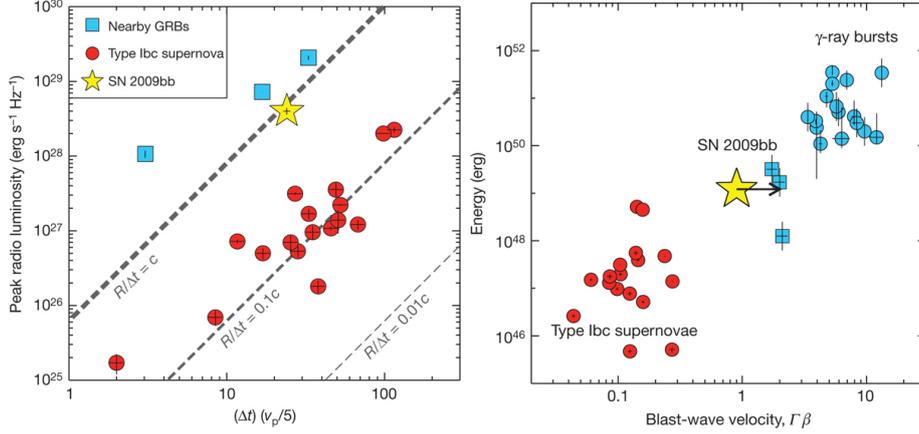


Fig. 1.— *Left Panel* The peak spectral luminosity at 5 GHz is plotted against the epoch of peak brightness. These observed quantities are related to the shock speed racing down the circum-stellar medium through equation 3. The dashed lines corresponds different shock speeds ($\beta_{sh} = 0.01, 0.1, 1$). As can be seen a large population of radio supernovae (red points) drive sub-relativistic shock wave while Gamma-ray burst, which are powered by central engine lead to bright radio afterglows due to relativistic shock waves. Engine driven supernovae, such as SN 2009bb with mildly relativistic shock wave, occupy the large gap in the middle. *Right Panel* Kinetic energy in the fastest moving ejecta is plotted against shock wave speeds and compared for SNe and GRBs. It can be seen that the normal supernova shock wave carries a few orders of magnitude less energy than a GRB shock wave. Similar to the velocity space, energy distribution of SN and GRBs also appear bimodal. Events similar to SN 2009bb populating this parameter space remain to be discovered. These figures have been taken from Soderberg et al. (2010).

way SNe and GRBs derive their energy. SNe derive their energies from the asymmetric core collapse and is coupled to the massive stellar ejecta. GRBs, on the other hand, derive most of their energy from the central engine formed during the core collapse and drives relativistic jet. Appearance of SN 1998bw/GRB 980425 with bright radio emission and relativistic ejecta in the intermediate velocity-energy parameter space implies that stellar collapse can produce diverse explosions. Subsequent discovery of mildly relativistic SN 2009bb, possibly driven by central engine but without a gamma ray trigger, strongly supports this inferred diversity and has deep significance for the theories of stellar evolution and explosion.

As a result of several targeted searches and subsequent monitoring campaigns key properties of radio emission from SNe have been established which will be helpful in guiding future observations. Figure 2 summarizes two of the most important observational properties of RSNe i.e. observed distributions of peak luminosities and their epochs. Core-collapse RSNe have peak luminosities of $L_{\nu,p} = 2 \times 10^{27}$ erg/s/Hz and they attend those peak luminosities around $T_p = 31.6 \pm 1.9$ days after the SN.

3. Motivation

The targeted observations have significantly improved our understanding of the properties of RSNe. At the same time, they have revealed some deep gaps in our knowledge about them. For example, what are the progenitors of type Ia SNe ? Where are the off-axis afterglows of GRBs and what’s the true census of engine driven SNe ? Below we identify some important gaps and key questions in ours understanding of radio supernovae which also form the motivation for proposing this VLA sky survey.

1. Relativistic SNe: The association of SN 1998bw with GRB 980425 brought about a significant advancement in our understanding of these relativistic transients. On one side this association was the first proof that long duration GRBs originate in the collapse of massive stars, which was conclusively established subsequently by GRB030329/SN2003dh. On the other hand, it opened up a possibility that due to the collimated nature of GRBs, although many such triggers could be missed, associated SNe which are more isotropic could be detected. Such SNe powered by the “central engine” are considered the missing link in the core collapse scenario. Figure 1 shows this picture clearly. GRBs are relativistic ($\Gamma\beta \sim$ several) and have energies $\approx 10^{50} - 10^{52}$ erg. Normal RSNe have lower energy budgets $\approx 10^{46} - 10^{48}$ erg and non-relativistic blast waves ($\beta \sim 0.1$). It was expected that SNe with intermediate energies and mildly relativistic velocities, similar to some SN associated with low energy GRBs, should be detectable without associated

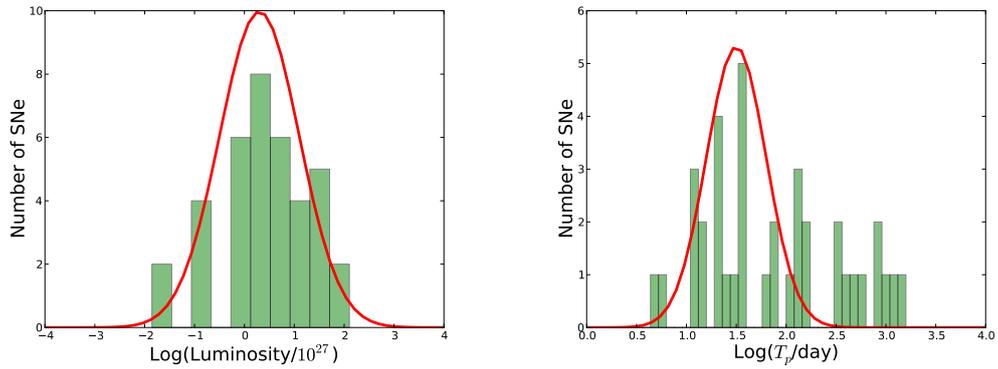


Fig. 2.— Peak radio luminosity distribution of core collapse SNe is shown in the *left panel*. The mean of the log-normal distribution is around $\log_{10}(L/10^{27}) = 0.3$ and $\sigma = 0.8$. Distribution of the epochs of peak brightness in the *right panel* shows significantly delayed peaks, some of them several hundred days after the supernova. Most of the delayed peaks, such as in the case of SN 1996cr and 2001em for example, are thought to be due to the interaction of shock wave with dense circum-stellar medium or shell. The red curves in both the plots are not a result of fits to the data. The mean of the log-normal curve for the peak times has mean corresponding to $T_p = 31.6$ days and standard deviation of 2 days.

GRB. SN 2009bb with energy $\sim 10^{49}$ erg and $\beta \sim 0.9$ just turned out to be such an object without a gamma ray trigger. Naturally, it is expected that several such relativistic SNe should be out there waiting to be discovered.

2. Type Ia supernovae: Despite several deep searches, none of the type Ia supernova has been detected to date. Some of the strong upper limits on the radio luminosities of type Ia SNe have been presented by Panagia et al. (2006) which cover time scales of a few to several days from SN constraining luminosities to $L_\nu < 10^{25}$ erg/s/Hz. Optical sky surveys have become efficient not only in SN detections but also in classification, thus opening up possibilities of early observations of SN Ia. As an exciting outcome of this a nearby type Ia SN PTF11kly/SN2011fe was detected at a age < 1 day and was searched for radio emission by VLA. The non-detection provided one of the strongest constraints on the radio luminosity and circum-stellar matter density (Horesh et al. 2012; Chomiuk et al. 2012). Such detections will be possible more often in the near future by the upcoming optical transient surveys.
3. Transients without high energy triggers: Horiuchi et al. (2011) pointed out that the SNe rate measured largely from the optical observations does not match the cosmic massive star formation rate. They estimate that as many as half the SNe are never discovered. A possible reason could be heavy obscuration due to dust in the regions where SNe occur. Interestingly, a nearby RSN SN 2008iz was discovered serendipitously in the galaxy M82 which reached the peak luminosity $L_\nu > 10^{27}$ erg/s/Hz (Brunthaler et al. 2009). Another radio transient was discovered soon afterwards in the same galaxy (Muxlow et al. 2010). Luminosity of the later transient $L_\nu \approx 10^{25}$ erg/s/Hz is consistent with SNe, although its nature is being debated. These cases lend support to the claim that not all SNe could be discovered through optical and some might actually be detected only via radio emission. A radio sky survey is the most efficient way to uncover this hidden population of SNe.
4. GW sources: A new window on the Universe is set to open when the merging compact binaries, involving neutron stars and black holes, will be detected through the emission of gravitational waves (GW). Advanced GW detectors such as ALIGO and VIRGO will be able to detect such emission from sources within about 300 Mpc. Their localization, however, is going to be coarse with the positional uncertainty being of the order of several tens of degrees. Therefore, identifying these transients through their associated electromagnetic signatures, having orders of magnitude better localization capabilities will be of crucial importance. It has been shown by several authors, e.g. Nakar & Piran (2011); Kamble & Kaplan (2013), that mergers of binary neutron stars as well as binary supermassive black holes could result in subsequent bright radio emission. A snap-shot of the entire

radio sky, at a sensitivity of 0.1 mJy should be able to detect from a few to a dozen such transients within a horizon of size similar to that of ALIGO.

4. Rate Estimates

A radio SN of typical luminosity $\overline{L_\nu}$ will be detectable from as far away as $d_L = \sqrt{\overline{L_\nu}/4\pi F_{\nu,lim}}$ for the assumed survey sensitivity $F_{\nu,lim}$. Based on the previous observations and surveys the log-normal distribution of peak spectral luminosities of RSNe peaks at $\overline{L_\nu} \approx 2 \times 10^{27}$ erg/s/Hz as shown in Figure 2. For the fiducial sensitivity of $F_{\nu,lim} = 0.1$ mJy per VLA pointing a typical RSN should therefore be detectable out to about ≈ 125 Mpc or redshift ≈ 0.03 . This corresponds to the detectable volume in the local universe $V_{detect} \approx 8.2 \times 10^6$ Mpc³. As far as RSNe are concerned, it is clear that the VLA will typically be detecting those events in the local universe. Effects of cosmological redshift could therefore be ignored from the rate calculations.

If \mathfrak{R} is the volumetric rate of supernovae in the local universe, then in an all sky snap-shot VLA survey should be able to detect about $N_{all-sky} = \mathfrak{R}V\Delta t$ radio SNe within the detectable volume V and lasting for time Δt above the VLA sensitivity. It is clear from the past experiences, as shown in Figure 2, that most of the RSNe reach their peak brightness around 30 days after the burst. Therefore, we will use $\Delta t \approx 30$ days.

The volumetric rate of core-collapse SNe have been estimated from observations, and ranges from $10^{-3} \leq \mathfrak{R} \leq 10^{-4}$ SNe yr⁻¹ Mpc⁻³. Using $V = V_{detect}$ and $\Delta t \approx 30$ days as described above, one gets $700 \leq N_{all-sky} < 70$. In other words, about one SN per month should be detectable for every 60 deg² of the sky scanned.

5. Survey Strategy

RSNe reach peak brightness in around 30 days at 5 GHz or VLA ‘C’ band. The spectral peak of the radio emission from SNe cascades to lower frequency bands with time. The peak brightness of RSNe, however, remains largely steady in most cases which is to be expected when a freely expanding shock wave is ploughing through the circum-stellar wind.

Given these characteristics of the RSNe, VLA-C band appears to be an optimum choice for carrying out radio sky survey for SNe and similar transients mentioned above. According to the reference guide for Jansky VLA capabilities for sky surveys, scanning rate of $SS \approx 7.2$ deg²/hr of the sky could be achieved at C-band for the nominal sensitivity of $F_{\nu,lim} = 100\mu\text{Jy}$. In order to confirm variability, a suitable cadence will be

necessary. The natural choice for RSNe would be 30 days, roughly the timescale required for RSNe to reach peak brightness. In order to achieve a sky coverage of about 1000 deg^2 with a cadence of 30 days, VLA would need to invest about 3.3 hr of observation time on a daily basis. With the inclusion of 25% overhead time for calibration etc. about 4.1 hr/day would be required to achieve the sky coverage of 1000 deg^2 . This translates to detection of about 16 RSNe per month, conservatively, assuming lower end of the SN rate.

Alternatively, surveying at a lower frequency S-band has the advantage of faster or equivalently, larger sky coverage. For the same sensitivity at S-band, survey speed of $SS = 16.53 \text{ deg}^2/\text{hr}$ is attainable which is more than twice as fast compared to the C-band. This would require a little over 2 hr-per-day for the coverage of 1000 deg^2 with the cadence of 30 days. No serious losses would be inflicted as a result of moving to lower than C-frequency band as far as supernova science case is concerned. Radio spectral peak of supernovae cascades down to lower frequencies with time as $(\nu_{\text{peak}}/5 \text{ GHz}) = (t/30 \text{ day})^{-1}$. Thus, the spectral peak would appear in S-band in about ≈ 45 days, allowing longer cadence and therefore larger sky coverage for the survey. We estimate that more than 3000 deg^2 of sky coverage could be achieved at S-band, compared to 1000 deg^2 at the C-band, for 4.1 hr/day of VLA observations owing to longer cadence allowed and faster survey speeds achievable.

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