Radio Supernovae:
Circum-Stellar Investigation (C.S.I.) of Supernova Progenitor Stars

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1 Why are Radio Observations of Supernovae Important?

Supernovae (SNe) are among the most energetic phenomena in the Universe, releasing $\geq 10^{51}$ erg in a few seconds with shock speeds ranging from a few 1,000 km s^{-1} to $\sim 230,000$ km s^{-1} (for the extreme Type Ic SN 1998bw). They are integrally linked to many phenomena of importance to modern astrophysics – formation of black holes and neutron stars, at least some types of gamma-ray bursters, powering starburst galaxies, nucleosynthesis, cosmology probes, and distribution of heavy elements and energy into the interstellar medium (ISM).

SNe come in two basic types, type Ia (thermonuclear detonation of white dwarfs) and types Ib/Ic/II (resulting from the core-collapse of massive stars). While no radio emission has ever been detected from type Ia SNe (Panagia et al. 2006), 75% of detected radio SNe are type II and 25% are type Ib/Ic. Type II SNe are thought to be the deaths of stars between $8M_\odot$ and $40M_\odot$, while type Ib/Ic SNe generally thought to be exploding Wolf-Rayet stars ($M > 40M_\odot$; Conti et al. 1987; Humphries et al. 1985) or lower mass stars in interacting-binary systems (Uomoto 1986; Podsiadlowski et al. 1992).

In the $\sim$10,000 years prior to explosion, the progenitor star is believed to undergo a period of enhanced mass-loss creating a dense region of circumstellar material (CSM) which is propagating outward at ~ 10 km s^{-1} (Chevalier 1982a). The UV flash from the SN explosion ionizes the CSM through which the SN blastwave propagates and heats the CSM to $T_{CSM} \sim 10^5$ K. In the early phase after the SN explosion, the average blastwave speed is on the order of $\sim 10^4$ km s^{-1}. In the forward shock created at the interface where the blastwave overruns the CSM, radio emission is generated by relativistic electrons swept up in the intense magnetic fields associated with the blastwave (Chevalier 1982a; Weiler et al. 1986, 2002, 2005). A reverse shock is also created with a typical "inward" speed of $\sim 10^3$ km s^{-1} relative to the forward shock. The reverse shock propagates back into the rapidly outward-moving SN ejecta, resulting in X-Ray emission. A detailed discussion of X-Ray Supernovae has been submitted in a white paper prepared by Dave Pooley.

Progenitor stars have been identified in only a few cases, and none have been the subject of extensive monitoring prior to explosion (Li et al. 2007). Further, optical observations only sample the SN photosphere and ejecta at early times after the explosion. Figure 1 identifies significant regions to the emission of radio and X-rays associated with the SN blastwave interacting with the CSM.

The modeling of the SN blastwave interaction with the CSM allows the determination of a number of physical properties of SNe from radio observations. One of these is the mass-loss rate from the SN progenitor prior to explosion. From the Chevalier (1982a,b) model, the turn-on of the radio emission for RSNe provides a measure of the presupernova mass-loss rate to wind velocity ratio ($\dot{M}/v_w$). Weiler et al. (1986) derived this ratio for the case of pure, external absorption by a homogeneous medium. There are several possible physical mechanisms responsible for the absorption of the radio emission by the CSM, characterized the the effective optical depth at a given radio frequency τ_{eff}. The generalized equation (16) of Weiler et al. (1986) relates the mass-loss rate at given epoch to the radio determined optical depth as

$$\frac{\dot{M}(M_\odot \text{ yr}^{-1})}{(v_w/10 \text{ km s}^{-1})} = 3.0 \times 10^{-6} < \tau_{eff}^{0.5} > m^{-1.5} \left(\frac{v_s}{10^4 \text{ km s}^{-1}}\right)^{1.5} \times$$
$$\left(\frac{t_i}{45 \text{ days}}\right)^{1.5} \left(\frac{t}{t_i}\right)^{1.5m} \left(\frac{T}{10^4 \text{ K}}\right)^{0.68}. \tag{1}$$

Weiler et al. (2002) and Sramek et al. (2003) discuss in the detail how radio light curves of supernova can be fit to a parameterized model accounting for the nature of the CSM. Weiler et
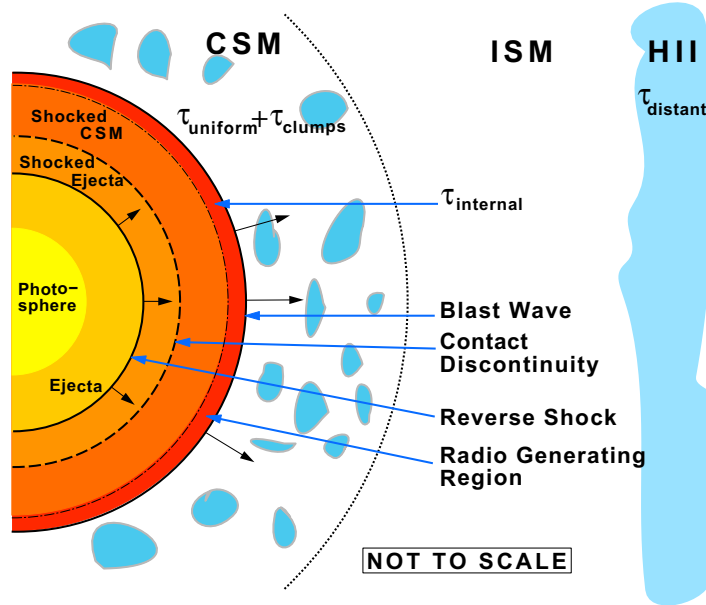
Figure 1 *Cartoon image of the SN blastwave interacting with the CSM (Stockdale et al. 2007). The radio emission originates just behind the blastwave and the X-ray emission is dominated by emission from the shocked CSM and ejecta, heated by the reverse shock.*

al. (2002) were able to identify at least three possible absorption regimes: 1) absorption by a homogeneous external medium, 2) absorption by a clumpy or filamentary external medium with a statistically large number of clumps, and 3) absorption by a clumpy or filamentary medium with a statistically small number of clumps. Each of the three cases requires a different formulation for $< \tau_{\text{eff}}^{0.5} >$. Only with a well-sampled radio light curve is it possible to robustly model the CSM and determine the appropriate mass-loss history for a given SNe.

Radio observations probe the SN blastwave's interaction with the CSM and the absorbing properties of the CSM in the radio emitting region and in the region along the line of sight to the observer. Using the radio observations, it is possible to map the circumstellar density profiles and to measure and compare mass-loss rates of the SN progenitor stars. Studying the radio emission from core-collapse SNe, astronomers can explore these three key questions:

1. How do the massive progenitor stars of core-collapse SNe evolve in the thousands of years prior to their explosion?

2. What are the physical processes of the absorbing medium of the early radio emission?

3. Do these SNe simply transition smoothly into Supernova Remants (SNRs) or is there a fading as they overrun their CSM and later re-brightening as the blastwave begins to encounter the ISM?

These questions can be explored through an active program that searches for radio emission from nearby core-collapse SNe and the subsequent long-term monitoring of radio SNe. The early observations, those made within 1-2 months of explosion, probe the mass-loss history of the progenitor in the hundreds of years immediately preceding the SN explosion. Later observations probe the evolution of the CSM at progressively earlier epochs of the progenitor star's pre-explosion evolution. The multi-frequency radio light curve transitions from optically thick to optically thin are
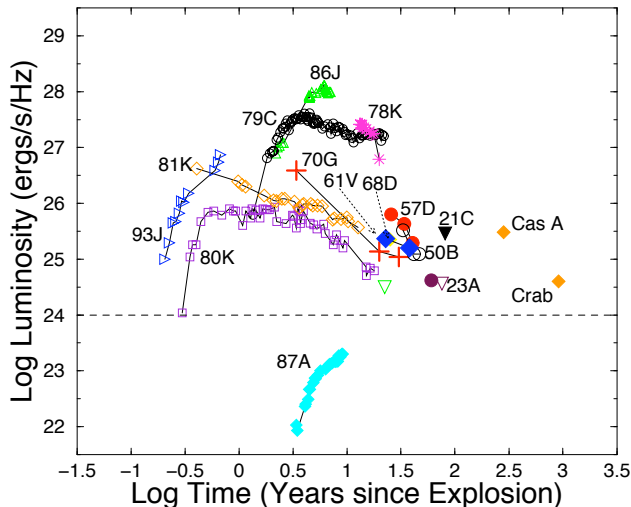
Figure 2 *L-band (20 cm) radio light curves for a number of historical radio SNe, plotting the log of the spectral luminosity vs. the log of the time since explosion. The dashed line indicates a typical sensitivity of 10^{24} erg s^{-1} Hz^{-1}, roughly 12 hours of VLA observation for a source at $\sim$5 Mpc. There is a 300 year gap between SN 1923A, the oldest radio SN, and the youngest SNRs! See Stockdale et al. 2006 and references therein for the data regarding each SN.*

an important probe of the absorption physics of the CSM (Chevalier 1982; Weiler et al. 1986, 2002, 2005). The key observational objectives of an effective radio SN program include:

- an aggressive, but selective Target-of-Opportunity Program); and

- detect and chart the rapid evolution of radio emission from new core-collapse SNe within 25 Mpc (weekly to monthly); and

- monitor the radio evolution of SNe within the last 20 yrs (semi-annually).

Because only a few SNe are detectable at reasonable observing times ($<$ 1 hr per frequency measurement) using the Very Large Array (VLA)[1], a carefully-planned and aggressive Target-of-Opportunity program is essential for identifying which SNe are candidates for further radio study. This complements the Long Term Monitoring which follows the evolution of the radio emission for as long as 75 years after explosion, as is the case of SN 1923A in the spiral galaxy M83 (Stockdale et al. 2006; Eck et al. 1998). Prior to SN 1923A, the last observed SNe with detected radio emission were Cas A (dated to the late 17th century) and SN 1604 (observed by Kepler). Due to the scarcity of observational evidence, the evolution of SNe into supernova remnants (SNRs) is poorly understood. Because the non-thermal radio emission from the blastwave/CSM interaction persists for decades, radio observations are the only feasible method to study this transition phase. Figure 2 illustrates the lack of measurements of 100-300 year old SNe probing this transition Stockdale et al. 2006).

Together, Radio and X-Ray measurements provide a deeper insight in the pre-explosion evolution of core-collapse supernova progenitors.

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[1]The VLA telescope of the National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc. under a cooperative agreement with the National Science Foundation.

2 The Current State of Radio Supernovae Studies

At present, there are on-going RSN observing programs on six continents at a variety of facilities, including the Giant Metrewave Radio Telescope (India) and the Australia Telescope Compact Array, but the VLA remains the most sensitive and useful instrument for the detection and monitoring of these transient sources. The VLA has been monitoring SNe for more than 25 years initiated by K. W. Weiler, N. Panagia, and R. A. Sramek. The VLA observing programs have detected dozens of new radio SNe. After discovery, the radio emission is monitored at multiple frequencies until the emission has completed faded under a Long Term Monitoring Program. This may take anywhere from months to decades, depending on the nature of the progenitor. Because many of these sources evolve over such long time-scales, a complete analysis of the radio evolution often requires years of observations to yield significant results.

2.1 Target of Opportunity Program

In the last eight years, seven new type II radio SNe have been discovered, and there have also been more than a dozen unsuccessful searches. An excellent example of the need for early detection and frequent radio observations of new SNe is SN 1993J. As shown in Figure 3, SN 1993J represents the most complete set of radio observations from its initial radio detection to the sudden decline as the CSM becomes optically thin. For SN 1993J, Weiler et al. (2007) have been able to determine that both synchrotron self-absorption and free-free absorption by the CSM contribute to the radio optical opacity. This determination was only possible because of early and daily monitoring (< 10 days after explosion).

2.2 Long Term Monitoring of Monitoring of Recent Supernovae

Following the their initial detections, these SNe, which span a variety of optical classifications, are now the subject of on-going VLA observations. SNe 2001gd, 2004et, and 1986J are three SNe that are currently being monitored by the VLA.

SN 2001gd: Stockdale et al. (2007) indicate that the evolution of SN 2001gd [a type IIb SN] diverges from the simple Chevalier (1982a) model of constant, wind-driven CSM. The radio light curves of SN 2001gd, shown in Figure 4, suggest a similar evolution to that of SN 1993J (see Figure 3), typified by a dramatic decline in their radio emission at all frequencies in VLA observations near day ~ 550 (Stockdale et al. 2007). SNe 1993J and 2001gd are both type IIb SNe, and their declines indicate abrupt increases in mass-loss just prior to the explosion that stripped the hydrogen shells from the progenitors (Stockdale et al. 2007; Weiler et al. 2007). In Figure 4, the radial density of the CSM (assuming a typical 10 km s-1 pre-explosion wind velocity) for SN 1993J and SN 2001gd is presented. For both SNe, Stockdale et al. (2007) and Weiler et al. (2007) interpret the abrupt change in the radio evolution as indication of a substantially enhanced wind developing no earlier than 8,000 years prior to the explosions of the progenitor stars. Future VLA observations will continue to probe this exponential decline.

SN 2004et: SN 2004et [a type II-P SN] was thought to be a fairly intact hydrogen envelope with a relatively low mass progenitor star. Chugai et al. (2007) predicted the radio evolution of SN 2004et and other type IIP SNe should follow the Chelavier (1982) model. Kelley et al. (2009) reported the recent observations of SN 2004et that indicate an abrupt change in the progenitor mass-loss rate, the nature of which is yet to be determined. Future VLA observations will provide critical confirmation as to whether (**1.**) this decline continues to persist indicating an abrupt cessation to the CSM which may be an indication of significant change in the mass-loss history of
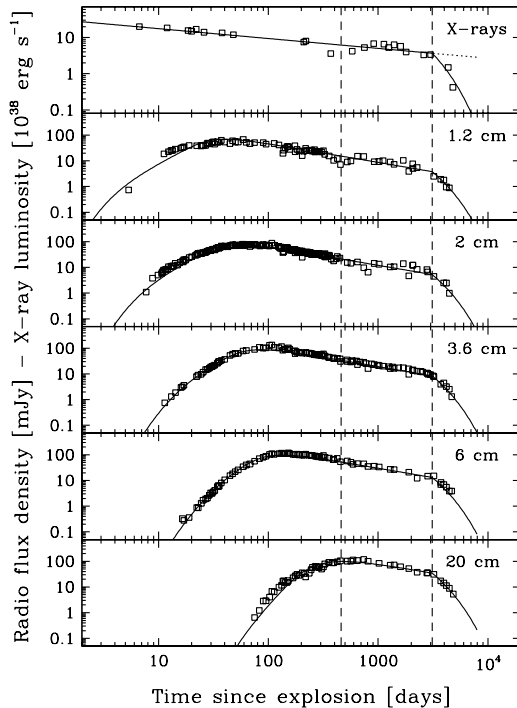
Figure 3 *SN 1993J is the most well studied radio SN outside of the Local Group, with over 650 radio observations taken mostly with the VLA, the Ryle telescope, and the Giant Meter-wave Radio Telescope (GRMT). The wavelengths for each light curve are shown in the figure. There is a slight increase in flux density as compared to the model prediction at 20 cm following the turn-over, also present in the other bands. There is a clear correlation between the X-ray and radio light curve evolution. Also, note the achromatic drop at day $\sim$ 3,100 (Weiler et al., 2007).*

the progenitor stars or (**2.**) this is a fluctuation in the CSM due to a previously undetected binary companion akin to the behavior of SNe 2001ig (Ryder et al. 2004, 2005) and 1979C (Montes et al. 1998) . From these preliminary measurements, Kelley et al. (2009) estimated the progenitor mass loss rates to the order of 10^{-5} $M_{\odot}$ yr^{-1}for both SNe, assuming a constant velocity, filamentary medium as described in Weiler et al. (2002).

   SN 1986J: Recent Very Long Baseline Interferometry (VLBI) observations of SN 1986J have yielded new insight into the study of core-collapse SNe. Bartel et al. (2007) have completed a series of high-resolution radio imaging of this type IIn SN, the first ever detected in the radio, prior to an optical detection. Bartel et al. (2007) indicate the likely formation of a neutron star, the first historical SN in the last 100 years to make this transition. The initial analysis of the recent VLA data appears to support this discovery, reporting an inversion of the spectral index at higher frequencies. A thorough analysis of the VLA observations is warranted to determine how the VLA observations can be used to distinguish between radio emission from blastwave/CSM interactions and the formation of pulsar wind-nebula in other SN observations where VLBI measurements are not feasible.
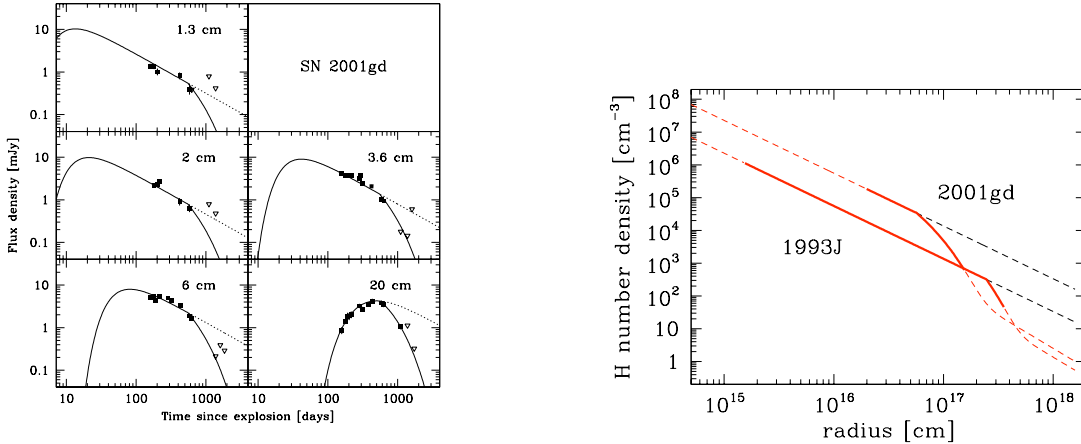
Figure 4 *Left, the VLA light curves of SN 2001gd in the five main VLA bands. Note the achromatic break at day ∼ 550, similar to that SN 1993J. Right, the ionized hydrogen density plots as a function of radius for SNe 2001gd and 1993J. (Stockdale et al. 2007; Weiler et al. 2007)*

3   The Future of Radio Supernovae

Current observing programs with the VLA typically yield 1-2 new radio detections per year. Because past observations have shown that astronomers only detect in the radio a small percentage of newly discovered SNe (currently $< 5\%$), only those objects which have a peak optical $m_v < 13$ or a distance < 25 Mpc have been observed to maximize our use of the VLA observing allocation. With the soon to be commissioned Expanded VLA (EVLA), we will be able to expand our investigation to include SNe out to 75 Mpc, which would increase our detection of new radio SNe by more than an order of magnitude. This will allow astronomers to explore the evolution of a broad variety of SNe for a longer time. We will be able to discern the comprehensive mass-loss histories of the SN progenitor stars, as done for SN 1993J, for at least one SN per year, rather than one per decade. There are only one, or at best two, well sampled radio SNe of any given optical classification. This is insufficient to make any true determinations concerning the CSM structure for an entire optical classification. It is essential that we study all core-collapse SNe as a unified class, as the zoology of optical classifications (Ib, Ic, IIP, IIn, IIL, IIb...) has already begun to blur with SNe evolving from one optical type into another.

With the EVLA, astronomers will study of a broad variety of types of core-collapse SNe, observationally determining the detailed mass-loss rates that are essential in discriminating models for progenitor evolution. A database of a variety of SN types and their early pre-explosion evolutionary stages will be built. The research performed with the EVLA will consist of the most comprehensive studies available on the evolution of the radio emission of supernovae. This will allow a unique insight into the evolution of high-mass, SN-progenitor stars. **With the EVLA, astronomers will be able to probe the eventual transition of SNe from explosion into SNRs and will be to study the galactic environments in which SNe are formed.**

With the Square Kilometer Array (SKA), normal radio SNe would be detectable to ∼ 200 Mpc. It may even become possible to detect radio emission from type Ia SNe, or at least to establish more stringent constraints on wind-driven, mass-loss rates of the white dwarfs' companion stars.

REFERENCES:

Bartel et al. 2007, ApJ, 668, 2, 924

Chevalier 1982a, ApJ, 258, 302

Chevalier 1982b, ApJ, 259, L85

Chevalier & Fransson, 2006, ApJ, 651, 1, 381

Chugai et al. ApJ, 662, 2, 1136

Conti et al. 1983, ApJ, 274, 302

Eck et al. 1998, ApJ, 508, 664

Filippenko 1997, ARAA, 35, 309

Humphreys, Nichols, & Massey 1985, AJ, 90, 101

Kelley, et al. 2009, in prep.

Li et al. 2007, ApJ, 661, 2, 1013

Montes et al. 1998, ApJ, 532, 2, 1124

Panagia et al. 2006, ApJ, 646, 369

Podsiadlowski, Joss, & Hsu 1992, ApJ, 391, 246

Ryder et al. 2004, MNRAS, 349, 1093

Ryder et al. 2005, IAU Colloquium, 192, 123

Sramek, & Weiler 2003, Lecture Notes in Physics, 598, 145

Stockdale et al. 2006, AJ, 131, 2, 889

Stockdale et al. 2007, ApJ, 671,1, 689

Uomoto 1986, ApJ, 310, L35

Weiler et al. 2002, ARAA, 40, 387-438

Weiler et al. 1986, ApJ, 301, 790

Weiler et al. 2005, ASP Conference Series 342, 290

Weiler, et al. 2007, ApJ, 671, 2, 1959