Radio Clues to the Progenitors of "Naked" Cosmic Explosions

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Key Goals:

1. Tuning onto the unique diagnostics on cosmic explosions only available through cm band monitoring of the non-thermal emission.
2. Mapping the faint end of the radio luminosity function of SNe Ibc, plowing into low density environments.
3. Revealing the progenitors of stripped-envelope core-collapse supernovae and their connection to those of long-duration gamma-ray bursts.
4. Extending the knowledge of radio SN emission to include thermonuclear Type Ia supernovae and in turn revealing the nature of their progenitors.

Abstract
Throughout history, observational supernova (SN) studies have focused almost exclusively on their strong optical emission that dominates the bolometric luminosity of all SN classes. Yet many of the leading breakthroughs in our understanding of supernovae and their progenitors have been enabled by observations at other wavelengths. For example, through radio observations probing non-thermal emission we now know that less than one percent of all Type Ibc supernovae harbor ultra-relativistic gamma-ray burst jets (GRBs, including those pointed away from us) that are visible to the far reaches of the Universe and enable unique galaxy evolution studies. The progenitors of GRBs must therefore share unusual properties, the nature of which remain hotly debated, and are likely to be revealed only through a detailed study of local SNe Ibc. Similarly, as Type Ia SN studies are extended to higher redshifts and trusted to constrain cosmological parameters, the favored single-degenerate white dwarf model is increasingly called into question by sensitive radio and X-ray observations of nearby SNe Ia that have yet to reveal evidence for a donor star's wind. Theoretical considerations suggest that progenitor mass, metallicity, angular momentum and binary interaction all play a role in the production of GRBs, SNe Ibc and SNe Ia. These clues are only accessible with sensitive radio facilities including the capability to detect and resolve the expanding blastwaves of the nearest cosmic explosions.

Motivation
Massive stars ($M_{ZAMS} > 8\ M_{\odot}$) end their short lives in spectacular explosions that are visible to the far reaches of the Universe. These explosions give birth to extreme compact objects -- black holes (BH), neutron stars (NS), and magnetars -- and play a crucial role in galaxy evolution through the injection of metals and mechanical energy into their environments.

Equally important, through the synthesis of new elements, massive stars help to fuel the formation of stars, planets, and ultimately life.

While our understanding of some basic aspects of stellar death date back several decades, recent findings are forcing us to fundamentally rethink the ways in which massive stars die. In the basic picture, the stellar core exhausts its nuclear fuel and the star collapses spherically to a NS or BH, thereby generating a shock wave that explodes the star. About 99% of the explosion energy is expected to be emitted in neutrinos, with the remaining energy propelling several solar masses of ejecta to velocities of ~10,000 km/s. The radioactive decay of freshly synthesized Nickel-56 gives rise to bright optical emission that peaks days to weeks after the explosion, the observed signpost for a new supernova (SN).

This simple scenario, however, cannot explain the intimate connection observed between ultra-relativistic gamma-ray burst (GRB) jets and spherical SN explosions. Neither can it explain the wide diversity of Galactic compact objects (e.g., the peculiar source in Cas A), or the enormous outbursts observed from some massive stars (e.g., Eta Carina) prior to their eventual demise. Binary companions are frequently invoked to explain some of these puzzles, however, many of the fundamental questions on massive star explosions remain unsolved due, in part, to the historical emphasis on optical data.

Further progress requires a tailored new approach: an observational SN program on several fronts and across the electromagnetic spectrum. Particularly important is the weak non-thermal signal peaking in the radio band and produced as the blastwave plows through the surrounding medium accelerating particles to relativistic energies at the shock front. Providing diagnostics on the fastest ejecta components (e.g. relativistic jets) and mass loss history of the star that are inaccessible at optical wavelengths, radio SN studies are pivotal for progress in a holistic view of the massive star death.

In this context, radio studies of massive star explosions in which the progenitor star's envelope has been stripped, Type Ibc supernovae (SNe Ibc), are of particular interest since they offer an unhampered "naked" view of the massive stellar explosion. Their inferred lack of an extended envelope (based on the spectroscopic non-detection of Hydrogen features) and the observational fact that long-duration GRBs are only accompanied by SNe of Type Ibc [1] leads to a general consensus that these explosions share two possible progenitor models: (i) isolated, massive Wolf-Rayet (WR) stars stripped by radiation pressure driven winds [2], and/or (ii) lower mass helium stars stripped by a close binary companion [3]. In addition, theoretical considerations indicate that several additional parameters (e.g. metallicity, mass, rotation) may affect the explosion properties [4]. Thus, observational guidance is crucial to our understanding of the progenitors and channels by which massive stars die with an overarching goal to map the progenitor properties (mass loss history, binarity), the explosion characteristics (geometry, kinetic energy and velocity, Nickel-56 mass), and ultimately the identity of the compact remnants (NS, magnetar, BH).

In the sections below, we overview the unique diagnostics derived from existing and on-going radio SN Ibc observational efforts, and the major questions left unanswered. We emphasize the observational advancements required to make progress. Finally, we outline how future sensitive radio facility will uncover those explosions expanding into the lowest density media, including both SNe Ibc and the class of thermonuclear Type Ia supernovae providing new clues as to their progenitors. In particular, we discuss how a sensitive radio facility will enable progress on the following outstanding puzzles:

✦ How are the stellar envelopes stripped from SN Ibc progenitors?

✦ What are the progenitors of SNe Ibc and how do they compare to those of GRB-SNe?

✦ What essential physical process enables a small fraction (< 1%) of SNe Ibc to give rise to relativistic gamma-ray burst jets?

✦ What can the environments of SNe Ia tell us about their progenitors (singe vs double degenerate white dwarfs)?

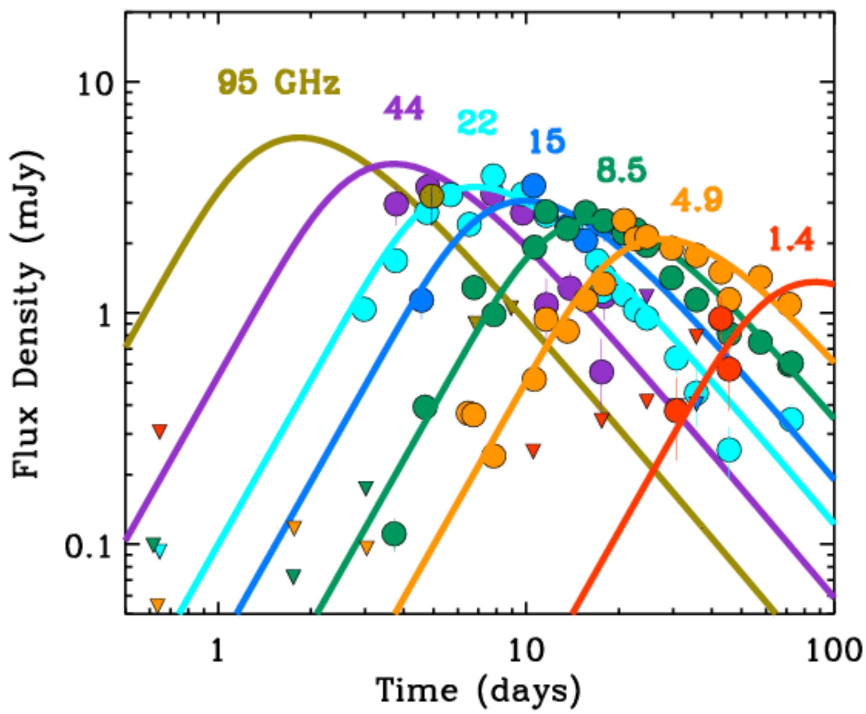

Figure 1: *Radio light-curves of SN 2008D (d~27 Mpc) from [5]. The emission peaks first at higher frequencies and later at lower frequencies as the blastwave expands and the ejecta become optically thin to synchrotron self-absorption.*

Why Radio Observations?

In every homologously expanding supernova explosion, optical data only probe the slow moving bulk ejecta giving rise to strong thermal emission typically powered by the radioactive decay of Nickel-56 [6]. Meanwhile, radio observations uniquely trace the non-thermal emission, produced as the fastest ejecta race ahead and shock material in the circumstellar environment enriched by the progenitor's stellar wind. Shocked electrons gyrate in amplified magnetic fields giving rise to the observed synchrotron spectrum. While extending to higher frequencies, this non-thermal signal is completely masked in the optical bands due to the overwhelming Nickel-56 decay powered emission. As a result these diagnostics are only available in the radio [7] and X-ray bands [8].

Since the fraction of kinetic energy coupled to the fast ejecta is typically less than 1%, the radio emission is several orders of magnitude less luminous than the optical emission. This is compounded by the fact that most massive stars have strong winds that form wind-blown bubbles around the star during their lifetime, with a low density interior, in most cases the blast wave will be expanding into a low density environment [8.5]. Along this line, SNe Ibc reside in relatively low density environments, limiting the amount of material available for shock interaction and therefore requiring a sensitive radio facility. Indeed, as discussed below, even the nearest SNe Ibc (within 10 Mpc) show sub-mJy radio flux densities [e.g., 9] while radio emission from a Type Ia supernova has never yet been seen [10].

In such low density scenarios, the radio light-curves are dominated by synchrotron self-absorption which produces a spectral turnover at low frequencies and determines the peak flux density of the radio emission. The properties of the radio spectral peak -- luminosity ($L_{v,p}$), frequency (v_p), observed time (t_p) -- directly reveal the properties of the fast ejecta and the environment. As shown in Figure~1, the bell-shaped radio light-curves are formed by the cascading spectral peak as the blastwave expands and the ejecta become optically thin to synchrotron self-absorption. The average speed (β) and kinetic energy (E_K) of the fastest ejecta as well as the mass loss rate of the progenitor star (Mdot) simply scale as $\beta \propto L_{v,p}^{9/19} v_p^{-1} t_p^{-1}$, $E_K \propto L_{v,p}^{23/19} v_p^{-1}$, Mdot $\propto L_{v,p}^{-4/19} v_p^{2} t_p^{2}$, where we have made the standard assumption that the post-shock energy density is equally shared by shocked electrons and amplified magnetic fields [11].

To test the assumption of equipartition of energy, a further constraint is required. In this context, the most robust observational constraint is provided by high-resolution (sub-mas) interferometric data (e.g., VLBA) that enables the blastwave radius and expansion speed to be directly measured. This constraint, in turn, reveals the relative energy fractions shared by relativistic electrons and magnetic fields. Moreover, a direct image of the ejecta reveals large-scale asymmetries, seen in the extreme case of collimated GRB jets [12] and Galactic supernova remnants [e.g.,13].

Unique Radio Diagnostics and Progress to Date

Nearly thirty years have passed since Type Ibc supernovae were first recognized as a distinct flavor of core-collapse explosions. Their low discovery rate (15% of all local SNe) and optical heterogeneity (lousy cosmological candles) did not motivate strong observational programs. Over the past decade, however, SNe Ibc have enjoyed a surge of interest thanks to the observation realization that that they are intimately related to gamma-ray bursts.

Motivated by the observational realization of a GRB-SN connection, over the past decade several dedicated efforts have been launched to study the prompt radio properties of local (d < 150 Mpc) SNe Ibc with the Very Large Array (VLA) and Australia Telescope Compact Array (ATCA). Since then, more than 200 SNe Ibc have been observed in the days, weeks and years following the explosion. Several critical results stem from these early efforts. First, the detection fraction of local SNe Ibc with current radio facilities is low, about 10 percent

[14,15,16]. Of the two dozen SNe Ibc with radio detections, the typical spectral luminosities are roughly $L_{\nu,p} \sim 10^{27}$ erg/s/Hz (Figure 2).

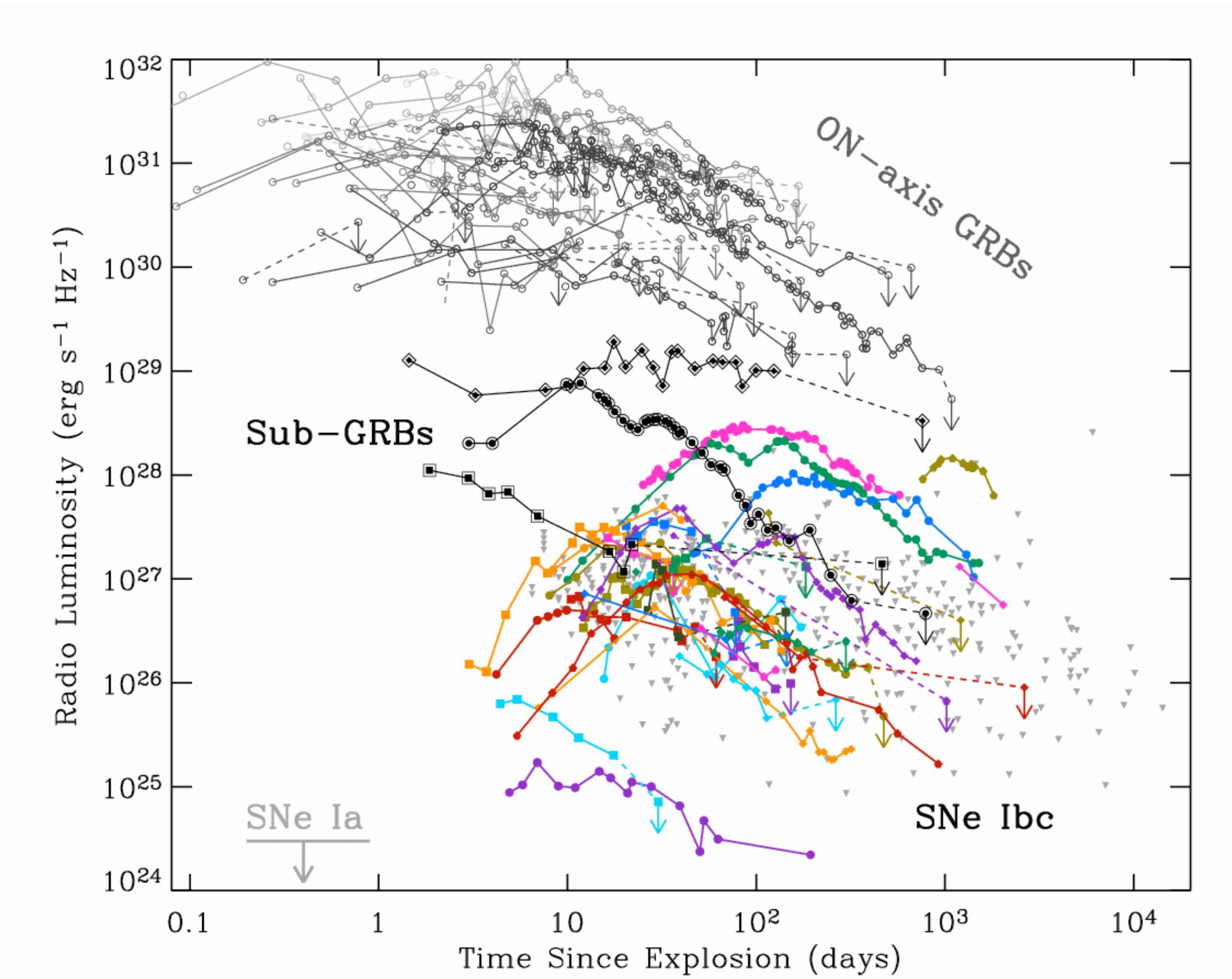

Figure 2: *Radio luminosity light-curves of all SNe Ibc (color) and upper limits observed to date are compared to those of GRB afterglows (grey) and the newly discovered class of sub-energetic GRBs (black). While SNe Ibc are significantly less luminous than both GRBs or sub-GRBs, they also show a surprisingly large spread in radio luminosity suggesting a diversity of progenitors. SNe Ia (grey arrow) have yet to be detected in the radio band though are expected to hover just below current detection thresholds. From [16].*

Next, we find a wide dispersion in the radio properties of SNe Ibc (Figure 2) with peak luminosities spread over four orders of magnitude, implying significant variations in their ejecta properties (β, E_K) and/or circumstellar environments (Mdot). Since the prompt radio emission is produced within 1 pc of the progenitor star and shaped by its mass loss history, a dispersion in radio properties points to a diversity in progenitor properties. Similarly, there is evidence for a dispersion in SN Ibc progenitor mass loss histories spanning four orders of magnitude -- from 10^{-7} to 10^{-3} $M_\odot$ yr^{-1} -- far larger than the distribution measured for Galactic WR stars [17], and thus hinting that binaries must play a key role in the H-envelope stripping of at least some “naked” cosmic explosions [16].

Finally, there is a clear distinction between GRBs and ordinary SNe Ibc using radio luminosity as a probe of the fast ejecta. Even the most powerful radio SNe Ibc are ~10^3 times lower than the afterglow luminosities of classical GRBs on all timescales. GRB jets initially directed away from our line-of-sight eventually spread sideways and decelerate on a timescale of ~1 year, giving rise to an isotropic afterglow signal. Late-time radio observations therefore constrain the true fraction of SNe harboring relativistic jets, currently shown to be less than 3% [15].

In this context, it is intriguing to consider a recently discovered class of sub-luminous GRBs (sub-GRBs) that are less powerful by several orders of magnitude and about ten times more common than classical GRBs (e.g., [18]). With nearly spherical geometry, these "jet-less" and mildy-relativistic explosions are intermediate between GRBs and local SNe Ibc (Figure 2), are only detectable nearby ($z < 0.1$), and hint at an overall continuum. From this effort stems the speculation that there exist a population of SNe Ibc with “suffocated GRB jets” too weak to be detected with current gamma-ray facilities and only accessible through a prompt search for faint radio emission.

Toward Progress: Unveiling Type Ia Supernova Progenitors

With the current detection thresholds of the VLA and ATCA, the sample of radio SN Ibc is complete out to just 10 Mpc while and the detection fraction quickly drops below 30 percent at 50 Mpc. With just a couple dozen objects detected to date, the radio luminosity function of these objects are sparsely sampled, especially at the faint end of the distribution. Such faint radio signals are attributable to low density circumstellar environments and may provide clues as to the nature of the progenitors and the pre-explosion mass loss history. A radio facility with sub-µJy sensitivity and rapid response (hours to days) capability is required for the detection of intrinsically faint SNe Ibc and to catch the fleeting signal predicted to accompany suffocated GRB jets.

In the same fashion that radio observations shed light on the nature of SN Ibc and GRB explosions through probing the local environment enriched by the mass loss history of the progenitor, these same techniques hold perhaps the greatest promise of revealing the progenitors of thermonuclear SNe Ia. Owing to the fact that both SNe Ibc and Ia are devoid of an outer H-envelope at the time of explosion and expanding into relatively low density environs, their non-thermal radio signals should indeed be quite similar [19].

Along this line, additional sensitivity is reasonably argued to enable the first detections of radio emission from SNe Ia. In an age where large optical efforts continue to focus on the utility of SNe Ia as cosmological tools, it is ironic that their progenitors remain largely unknown. Our lack of understanding of the progenitors and their evolution over cosmic time will ultimately challenge the reliability of these objects as calibratable candles as studies push to higher redshift and a lower metallicity Universe.

The two primary progenitor models should be simple to distinguish through radio monitoring: a single WD accreting material from a H-rich donor (e.g., red giant star) explodes into the stellar wind of its companion [20] while a double-degenerate (WD-WD) system explodes into a nearly constant density medium [21]. In the former case, the favored progenitor system of SN Ia, the resulting radio emission is expected to be similar to that of a lowest luminosity SNe Ibc, $L_{\nu,p} \sim 10^{24}$ erg/s/Hz (for Mdot ~ 10^{-8} $M_\odot$ yr^{-1} [22]) while in the latter case the radio luminosity would be even several orders of magnitude lower.

Thus, a radio facility with at least 10 x increased sensitivity over that of the VLA will directly test the single WD progenitor model of SNe Ia and providing the first steps for progenitor identification and in turn clues as to their evolution. Follow-up observations with high resolution interferometry would enable the geometry of the explosion to be imaged directly, a parameter often argued to contribute to the dispersion in Type Ia optical light-curves.

North America Array

The North America Array[1] is a concept for a continent-wide array of telescopes operating at short centimeter wavelengths that will provide images of unprecedented resolution and sensitivity. The North America Array will be built upon the capital investments in the Expanded Very Large Array (EVLA) and Very Long Baseline Array (VLBA), together with new technologies. It is envisioned that the first steps toward the North America Array, primarily prototyping, will be taken during the decade of 2010-2020. In particular, the long term goal is to enable a cm-band sensitivity 30 times greater than that of the current VLA, to extend the baselines of the antennas by an order of magnitude increasing the resolving power significantly, and to increase the sensitivity of the longest VLBA baselines accordingly. These ingredients are critical for solving the open questions in the GRB-SN connection and the race to identify the progenitors of SNe Ia.

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