








Supernovae with the Square Kilometre Array

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This chapter presents the science potential of the Square Kilometre Array (SKA) for studying all classes of supernovae and their environments. It substantially updates and extends the earlier work of Pérez-Torres et al. (2015), originally published in the 2015 Advancing Astrophysics with the SKA (AASKA14) volume, reflecting the dramatic progress in time-domain astronomy and radio instrumentation over the past decade.

We outline how SKA1 and its pathfinders will transform the radio study of core-collapse supernovae (CCSNe) through sensitive, commensal wide-field surveys capable of discovering hundreds of events per year, providing a dust-unbiased census of massive-star deaths and direct measurements of the volumetric CCSN rate. The same data will probe ejecta–circumstellar-medium (CSM) interaction, shock microphysics, and progenitor mass-loss histories.

Deep, triggered observations of thermonuclear supernovae (SNe Ia) will allow the SKA to test competing progenitor scenarios by detecting—or definitively excluding—the prompt radio emission expected from single-degenerate systems. The chapter further explores superluminous supernovae (SLSNe), delayed interaction supernovae and synergies with facilities such as ALMA, ngVLA, CTA, IceCube-Gen2, and ULTRASAT. Collectively, these studies will turn radio supernova astrophysics from a discovery-limited field into one governed by population statistics.

1 Introduction

Supernovae are among the most energetic explosions in the Universe. In the thermonuclear pathway, a sufficiently massive carbon–oxygen white dwarf in a binary system may accrete material from its companion and approach the Chandrasekhar mass, triggering a runaway nuclear fusion instability and producing a Type Ia supernova (Whelan and Iben, 1973; Nomoto, 1982). Massive stars, on the other hand, end their lives through the gravitational collapse of their cores, giving rise to the diverse family of CCSNe; Bethe and Wilson 1985; Woosley et al. 2002. Both SNe Ia and CCSNe exhibit several observational subclasses, primarily distinguished by their optical spectroscopic and photometric properties. Classical SNe Ia are characterized by the absence of hydrogen and the presence of prominent Si II $\lambda 6355$ Å absorption (Filippenko, 1997). A subset of SNe Ia show narrow hydrogen emission features caused by interaction between the ejecta and dense, unshocked H-rich circumstellar material (CSM), forming the class of SNe Ia-CSM (Hamuy et al., 2003). Within the CCSN population, the presence or absence of hydrogen defines Types II and I, respectively. Type II SNe are further separated into IIP and IIL events based on whether their optical light curves exhibit a plateau or a more linear decline. Type I CCSNe are subclassified as Ib or Ic depending on whether helium is detected or not, respectively. Transitional Type IIb supernovae bridge the gap between hydrogen-rich (Type II) and hydrogen-poor (Type I) events. Collectively, the sequence IIP \rightarrow IIL \rightarrow IIb \rightarrow Ib \rightarrow Ic is interpreted as reflecting progressively greater stripping of the progenitor’s outer layers prior to explosion (Filippenko, 1997). In addition, CCSNe that interact strongly with dense CSM are designated with the suffix “n,” producing subclasses such as Types IIn, Ibn, and Icn. For a comprehensive classification overview, we refer the reader to Fig. 1 of Chandra (2025).

Massive stars, progenitors of supernovae, shed material from their outer layers throughout their evolution, thereby creating a CSM that encases the star. The mass-loss can be driven by radiation, binary interactions, and/or wave-driven processes (Puls et al., 2008). In the most massive stars, the mass-loss rates can exceed those of solar-type stars by several orders of magnitude. Although such extensive and often episodic mass loss complicates a one-to-one mapping between supernova classes and the zero-age main sequence (ZAMS) masses of their progenitors, the resulting CSM preserves valuable information about the progenitor’s evolutionary history. Consequently, detailed studies of ejecta–CSM interaction (see § 2), which is most relevant for SKA frequencies, offer a powerful means to trace supernova properties back to their progenitor systems and to probe the physical mechanisms governing late-stage stellar mass loss.

2 Circumstellar interaction and radio emission in supernovae

When the supersonically expanding SN ejecta encounters the slower-moving CSM, it generates a forward shock that propagates outward into the CSM and a reverse shock that travels back into the expanding ejecta. These two shocks are separated by a contact discontinuity, a region prone to Rayleigh–Taylor and other hydrodynamic instabilities that can amplify magnetic fields (Fig. 1). The shocks heat the plasma to high temperatures and accelerate electrons to relativistic energies; these relativistic electrons, interacting with the amplified magnetic fields, produce non-thermal synchrotron emission that is most prominently observed at radio wavelengths (Chevalier, 1982a,b). The hot shocked gas also emits thermal and non-thermal X-rays, while X-ray-excited

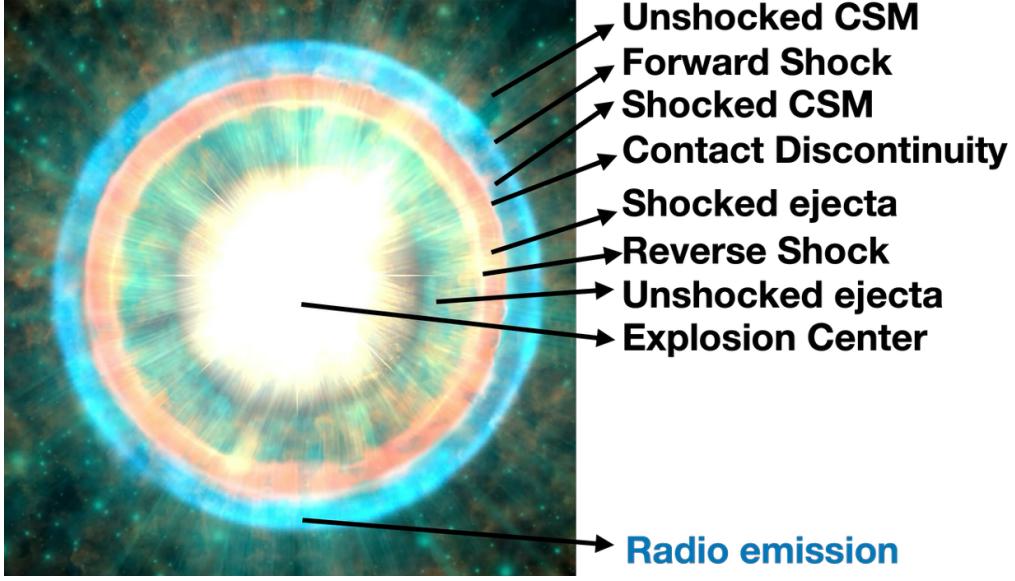


Figure 1: Circumstellar interaction picture in a typical SN. The image shows ejecta-CSM interaction and the formation of various shocked and unshocked regions. The radio emission typically originates from the forward shock.

unshocked ejecta or emission from the vicinity of the contact discontinuity can generate additional optical features such as H α emission (Chugai et al., 2007). Among these diagnostics, however, radio emission provides the cleanest and most direct probe of the CSM density structure and, by extension, the progenitor’s mass-loss history.

Radio emission, which is synchrotron in nature, is absorbed at early times, either via synchrotron self-absorption (SSA) and/or free-free absorption (FFA) (Chevalier, 1998). The flux density under SSA and FFA can be written, respectively (Chandra, 2025):

$$F_\nu(t) = K_1 v^{5/2} t^a [1 - \exp(-\tau_\nu^{\text{SSA}})], \quad (1)$$

$$\tau_\nu^{\text{SSA}} = K_2 v^{-(p+4)/2} t^{-(a+b)},$$

and

$$F_\nu(t) = K_1 v^{-\alpha} t^{-\beta} \exp[-\tau_\nu^{\text{FFA}}(t)], \quad (2)$$

$$\tau_\nu^{\text{FFA}}(t) = K_2 v^{-2.1} t^{-\delta},$$

Here K_1 and K_2 are the flux density and absorption normalization parameters, respectively; and τ_ν^{SSA} and τ_ν^{FFA} are SSA and FFA optical depths, respectively. Parameters a , b , α , β , δ are power law indices, with p being the electron energy index, related to α as $\alpha = (p-1)/2$ and δ upon ejecta density structure, $\rho_{\text{ej}} \propto r^{-n}$, as $\delta = (n-3)/(n-2)$. Thus radio emission typically rises as the expanding shock becomes optically thin to its absorption/s, peaks, and then decays. The radio spectrum evolves from steeply absorbed (optically thick) to a power-law (optically thin) phase. As high frequencies become transparent earlier than low frequencies, hence, multi-frequency monitoring allows us to

trace shock evolution and yields important parameters. Radio observations map the CSM density profile and time variability, and enable us to constrain shock physics, magnetic fields, forward shock velocity, and shock microphysics. High cadence early- to late-time radio observations also reveal light-curve bumps and re-brightening events, thought to be caused by shock interaction with discrete shells or clumps of CSM (e.g.; [Anderson et al., 2017](#); [Rose et al., 2024](#)).

SKA is an ideal telescope for SN studies owing to its unprecedented sensitivity and large field of view (FoV). The SKA capabilities will allow us to conduct both targeted follow-up observations and wide-field, high-cadence surveys via commensal use. The SKA will be essential in probing SN-CSM interaction at early to late times to constrain their progenitors. Furthermore, its capability for unbiased wide-area surveys makes the SKA a suitable instrument to discover hard-to-find supernovae in dusty regions where optical surveys fail. In the next several sections, we lay out the topics which will be important to study with SKA in this field.

3 Radio emission from thermonuclear supernovae

3.1 Constraining progenitor models

Despite the ubiquity of SNe Ia as cosmological distance indicators, the nature of their progenitor systems remains unsettled. The two main paradigms—the single-degenerate (SD) channel, in which a carbon–oxygen white dwarf accretes material from a non-degenerate companion until reaching the Chandrasekhar mass, and the double-degenerate (DD) channel, involving the merger of two white dwarfs—predict fundamentally different circumstellar environments ([Maoz et al., 2014](#)). SD systems should exhibit detectable CSM and thus prompt radio and X-ray emission from ejecta–CSM interaction, whereas DD systems should be radio-silent at early times. Radio non-detections therefore provide direct upper limits on pre-explosion mass loss and can, in turn, rule out entire regions of SD parameter space ([Pérez-Torres et al., 2014](#)).

SNe Ia have eluded radio detections until recently. Deep VLA and eMERLIN observations of nearby events such as SNe 2011fe and 2014J yielded 3σ upper limits of $\dot{M} \lesssim (6\text{--}7) \times 10^{-10} (v_w/100 \text{ km s}^{-1}) M_\odot \text{ yr}^{-1}$ ([Pérez-Torres et al., 2014](#)). These results seem to exclude symbiotic systems, optically thick accretion winds, and most recurrent-nova configurations as viable progenitors. They leave only very tenuous or quiescent systems consistent with observations, strengthening the case for DD progenitors in at least a fraction of SNe Ia.

The Ia-CSM SN 2020ejj was the first and the only SN Ia of any subtype to have shown radio emission ([Kool et al., 2023](#)). The radio emission was detected on 605 and 741 days, post-optical discovery, with 5 GHz radio spectral luminosity in the range $1.2\text{--}1.6 \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$. The lack of radio emission from other SNe Ia-CSM is therefore intriguing, despite detections at other wavelengths indicating presence of dense CSM. One reason could be excessive absorption which can lead to non-detectable radio emission due to progressively decreasing synchrotron strength with time. Another possibility is different microphysics of shocks in thermonuclear SNe compared to that in CCSNe, which may alter the efficiency of synchrotron production. SKA radio limits and detections of SNe Ia combined with SKA VLBI will be able to probe the parameter space of the microscopic physics.

3.2 SKA capabilities and Observing strategy of SNe Ia

The sub- μJy sensitivity of SKA1-Mid (AA4 configuration; $\sigma_{1\text{h}} \simeq 0.7 \mu\text{Jy}$ at 1.7 GHz) will push these limits one order of magnitude deeper. A non-detection at this level for an SN Ia at the distance of M82 ($D \simeq 3.5 \text{ Mpc}$) would constrain the wind-density parameter to $\dot{M}/v_w \lesssim 5 \times 10^{-13} M_{\odot} \text{ yr}^{-1} \text{ km s}^{-1}$, effectively excluding all single-degenerate channels with hydrogen-rich companions. Conversely, a detection of early radio emission would provide the physical parameters and, when combined with the optical and X-ray data, directly measure the density, composition, and microphysical parameters of the surrounding medium, providing the first definitive identification of an SD progenitor. The full SKA will reach $\sim 70 \text{ nJy h}^{-1/2}$, enabling detections or limits on prompt emission out to $\sim 25 \text{ Mpc}$, where ~ 2 SNe Ia per year are expected, yielding a statistically meaningful sample within a decade of operation, sufficient to carry out population synthesis studies of SNe Ia.

In the double-degenerate scenario, merger ejecta expanding into the tenuous interstellar medium may yield slowly rising radio emission on decade timescales as the shock sweeps up ambient material (Harris et al., 2016; Griffith et al., 2025). Regular SKA monitoring of decades-old SNe Ia will therefore test this prediction and may reveal the delayed onset of synchrotron radiation characteristic of merger-driven explosions.

For Type Ia SNe, the ideal strategy is to trigger within 1–3 days of explosion, in order to probe the very compact CSM structure. For example SN 2011fe was observed in radio beginning about 2 days after explosion, and those data set definitive limits on the immediate environment (Horesh et al., 2012). A practical approach of triggering nearby and very young SNe Ia is likely to result in best constraints. Despite radio non-detection at early times, if the optical spectra shows presence of interaction or time-variable narrow absorption, then additional efforts need to be made to monitor it at later times, say until a year.

4 Radio emission from Core-collapse supernovae

4.1 Clues to the progenitor

Massive stars can experience multiple channels of mass loss during their lifetimes. The dominant mechanisms include radiation-driven winds, binary interaction-induced stripping, and wave-driven mass loss (Puls et al., 2008; Smith, 2014). Because mass loss shapes the CSM, different progenitor systems produce markedly different CSM structures and densities. Studying the CSM across various spatial and temporal scales provides crucial insight into the nature and evolution of SN progenitors (Chandra, 2025). Radio light curves and spectra are particularly powerful probes of this connection. The epoch of radio turn-on, the nature of absorption, the timing and strength of the radio peak, and the overall extent of emission each encode distinct physical processes associated with specific progenitor environments (Fig. 2). Historically, most radio studies have concentrated on higher frequencies, where sensitivity to the evolving CSM density profile is reduced. Low-frequency observations, however, allow the emission to be followed over longer timescales, thereby revealing a more extended record of the progenitor’s mass-loss history. This is where SKA stands.

Since supernova shock velocities are typically 100–1000 times greater than those of the CSM winds

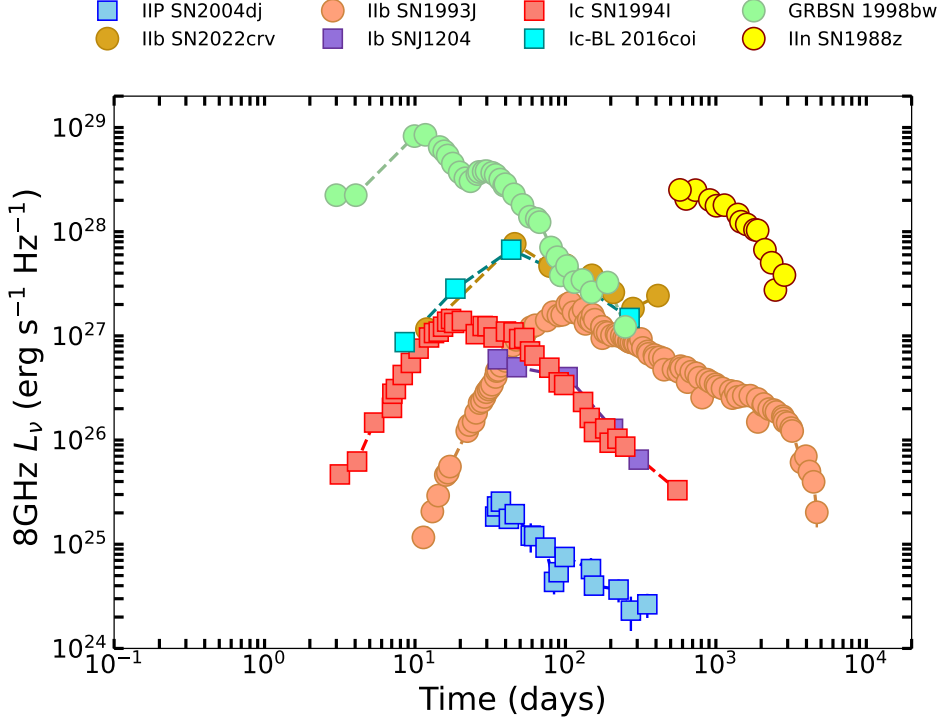


Figure 2: Plot of 8 GHz radio light curve for various types of CCSNe. The diversity in the radio luminosity, time to peak and extent of the radio emission is apparent in different classes and indicate towards diversity in progenitors. The data are taken from [Nayana et al. \(2018\)](#); [Weiler et al. \(2007, 2011\)](#); [Kulkarni et al. \(1998\)](#); [Gangopadhyay et al. \(2023\)](#); [Chandra et al. \(2019\)](#); [Nayana and Chandra \(2020\)](#).

([Chevalier and Fransson, 2003](#)), the expanding shock effectively samples material ejected hundreds to thousands of years before explosion. This makes ejecta-CSM interaction an invaluable “time machine” for reconstructing the pre-SN evolution and mass-loss history of massive stars during their advanced nuclear-burning phases. The pronounced observational diversity in radio bands among supernovae exhibiting ejecta-CSM interaction underscores the complex mass-loss histories of their progenitors, involving multiple channels such as steady winds, binary mass transfer, and eruptive pre-SN outbursts. The ejecta-CSM interaction remains the most effective diagnostic of progenitor mass-loss rates and CSM densities over timescales ranging from the final year to several centuries before explosion.

4.2 Confined CSM, shock breakout

Recent progress in optical wide-field transient surveys has enabled the discovery of supernovae within hours of explosion. Rapid optical follow-up spectroscopy has revealed transient, high-ionization narrow emission lines emerging shortly after the explosion (e.g., [Yaron et al., 2017](#)). These so-called “flash” features indicate the presence of a denser CSM at small radii (i.e., confined CSM) located very close to the progenitor, typically within $\lesssim 10^{15}$ cm. Such confined CSM implies that the progenitor star experienced an episode of enhanced mass-loss during the final years to

decades before core collapse, reaching the mass-loss rates of $\gtrsim 10^{-3} M_{\odot} \text{ yr}^{-1}$, which is several orders of magnitude higher than the steady wind of a typical red supergiant ($\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$) (e.g., Goldman et al., 2017). Statistical studies further suggest that a significant fraction of Type II SNe show evidence for such confined CSM (e.g., Förster et al., 2018).

While optical “flash” spectroscopy probes the innermost region, radio observations trace the interaction with the more extended CSM. However, the confined CSM can strongly absorb the synchrotron emission via free–free absorption at early times, particularly at lower frequencies, where the optical depth is higher. This often results in non-detections in the low-frequency bands during the first few days, or in some cases up to hundreds of days, after the explosion. Such early non-detections themselves provide valuable constraints on the optical depth and density of the confined CSM. As the shock expands and the medium becomes optically thin, radio emission emerges, revealing the density structure beyond the confined region. Therefore, high-cadence, multi-frequency, long-term radio monitoring – from the earliest phases at higher frequencies with SKA-Mid through to the later evolution at lower frequencies, employing SKA-Low is essential to capture the transition from absorption-dominated to emission-dominated phases, and to map the density variations that record the progenitor’s final mass-loss history. In § 4.5, we expand on observing strategies.

4.3 Supernovae in dense CSM: secondary leptons

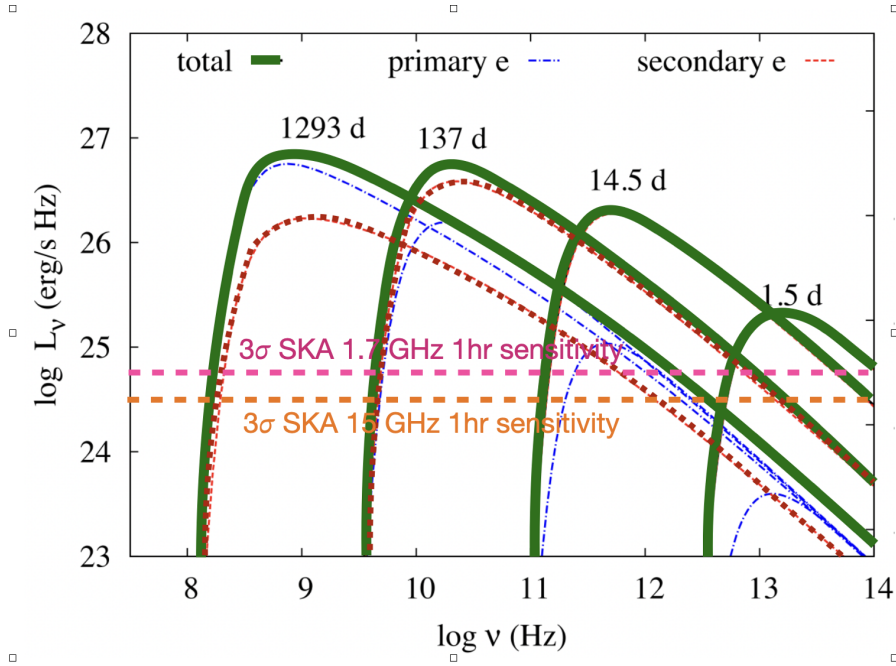


Figure 3: The contribution of the primary (blue dash–dotted lines) and secondary (red dashed lines) electrons to the total synchrotron emission (green solid line) for a wind density CSM for parameters mentioned in Petropoulou et al. (2016), the paper from which this figure is adapted and a distance of 40 Mpc is assumed. We also show 3- σ SKA-Mid sensitivities at 1.7 GHz and 15 GHz at 40 Mpc.

There are growing pieces of evidence for dense CSM shells around CCSNe. The collision of the SN shock with such dense environments results in efficient conversion of shock kinetic energy to

radiation which has been proposed as one possible powering source of superluminous supernovae (SLSNe; Falk and Arnett, 1973; Ofek et al., 2007; Smith and McCray, 2007; Quimby et al., 2011, and see Section 5). These interaction-powered supernovae can act as efficient cosmic ray accelerators for a range of CSM parameters (Murase et al., 2011; Katz et al., 2012; Kashiyama et al., 2013). The accelerated protons undergo pp collisions and experience pion losses that will produce gamma-rays, neutrinos, and secondary leptons. While primary electrons are injected at shock, the secondary electrons are injected throughout shocked region and can emit detectable synchrotron radiation. The actual synchrotron spectrum and flux densities depend on various parameters including ejecta velocity and mass, and physical location of the CSM shell with respect to the progenitor star. The emission could peak with flux density $\approx 0.01\text{--}1$ mJy at 3–3000 GHz for an SN like SN 2006jd at distances of hundreds of Mpc (Murase et al., 2014). In Fig. 3, we show radio light curves taken from Petropoulou et al. (2016), decomposed into contributions from primary and secondary electrons and their relative importance with time. Secondary electrons dominate early radio emission, but their contribution declines faster than primaries, leading to a break/flattening in the light curve. There is no confirmed detection of synchrotron emission from secondary leptons from supernovae as of yet. Nayana et al. (2025) reported millimeter emission from SN 2023ixf in excess to the standard synchrotron spectrum and attributed it to possible emission from secondary leptons. The sensitivity of current radio arrays is a limiting factor in detecting this emission, and the SKA era, mainly SKA-Mid combined with upgraded ALMA, will make significant progress towards detecting/placing robust limits on synchrotron emission from secondary leptons.

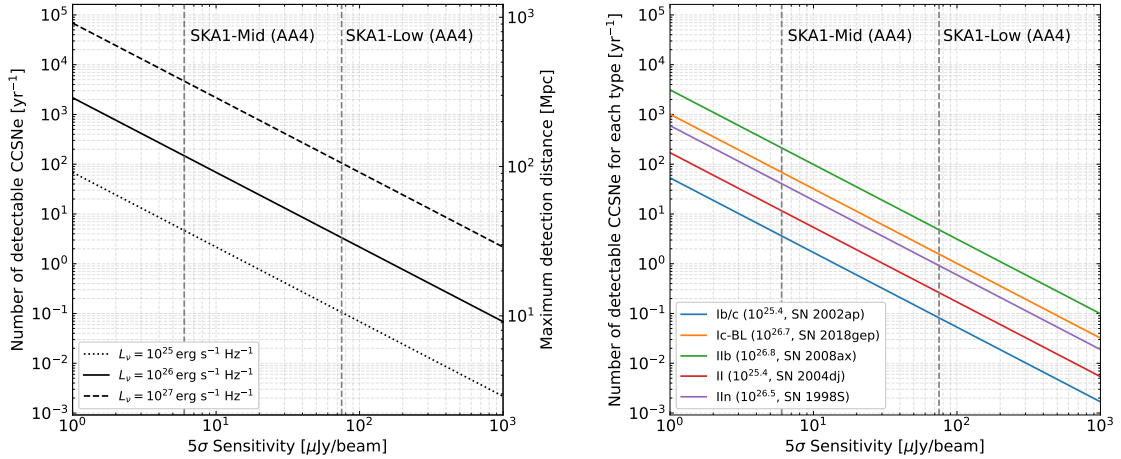


Figure 4: (Left) Estimated number of detectable CCSNe per year and the maximum observable distance. Three cases of the peak spectral luminosity are shown: $L_v = 10^{25}$, 10^{26} , and $10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$. Vertical lines indicate the assumed 1-hour (5σ) sensitivities of SKA1-Low and SKA1-Mid for the AA4 configuration. (Right) Same as the left panel, but divided by SN type. The assumed SN fraction of each type is taken from Ma et al. (2025). The average peak luminosities (from Bietenholz et al. 2021) and representative SN events corresponding to those luminosities (from Pérez-Torres et al. 2015) are shown in the labels. Both panels assume a CCSN rate of $N \approx 10(D/30 \text{ Mpc})^3 \text{ yr}^{-1}$ and a yearly survey area of $10,000 \text{ deg}^2$.

4.4 Late time radio emission from core-collapse supernovae

Radio emission from CCSNe is typically monitored for $\approx 1\text{--}2$ years except for a few very nearby events. The radiation is synchrotron in origin and displays high brightness temperatures, and is often attenuated by free-free absorption by the ionized medium in the line of sight and/or synchrotron self-absorption by the same plasma. As a result of the temporal evolution of combined emission and absorption processes, the radio light curves trace a general pattern of a steep rise to a maximum flux density (F_{pk}) followed by a power-law decay ($F_{\nu} \propto t^{\beta}$) with decay index of range $\beta \approx -1$ to -3 . The time to peak radio emission (t_{pk}) ranges from a few days to several years, and the corresponding peak spectral luminosities (L_{pk}) cover $\sim 10^{23}\text{--}10^{29}$, $\text{erg s}^{-1}, \text{Hz}^{-1}$ (Bietenholz et al., 2021), with both quantities exhibiting large variation across different SN types. The follow-up observations of individual supernovae are usually carried out to trace the evolution of this radio emission and as the light curve decays, the emission is expected to become undetectable with the current generation radio telescopes.

However, late time studies have thrown some surprises. Stroh et al. (2021) reported late-time (1–60 yrs post explosion) radio emission from 19 CCSNe by cross-matching optical positions of known SN with the first data release of the VLA Sky Survey (VLASS; Lacy et al., 2020). The luminosities of this sample spans $L_{\text{pk}} \approx 10^{26}\text{--}10^{29}$ $\text{erg s}^{-1} \text{Hz}^{-1}$, reaching the peak luminosities of early radio light curves. Similar work was conducted by Rose et al. (2024), who found radio emission from 29 archival SNe using the Variables and Slow Transients (VAST; Murphy et al., 2013, 2021) pilot survey conducted with the SKA precursor Australian SKA Pathfinder telescope (ASKAP; Hotan et al., 2021). The VAST detections covered a similar range of luminosities to the VLASS sample and identified five late-time radio re-brightening events. Broadly speaking, there are three possible scenarios to explain the late-time bright radio emission – (i) SN shock interaction with a dense CSM shell possibly ejected at an earlier phase of mass-loss in the progenitors life (Chevalier and Fransson, 2006), (ii) Emission from relativistic jets launched at the time of explosion which was initially off-axis and coming to the line of sight as the jet decelerates (Granot et al., 2002), and (iii) Emission from the central compact object left behind by the core-collapse like a newly born pulsar wind nebula (Slane, 2017). The sample of CCSNe with late-time radio emission offers an unique opportunity to explore these different scenarios.

While the VLASS and VAST samples cover opposite celestial hemispheres and are limited by an rms noise of $\approx 120 \mu\text{Jy}$ and $\approx 250 \mu\text{Jy}$, respectively, SKA’s unique sensitivity and coverage will unravel a significantly bigger sample of these late-time radio emitters. Low-frequency is particularly interesting as the emission component from the initial blast wave might be still bright in addition to the late-time component, as evidenced by (Rose et al., 2024). With one hour 5σ sensitivities of $6 \mu\text{Jy}/\text{beam}$ (SKA1-Mid) and $75 \mu\text{Jy}/\text{beam}$, (SKA-Low) in AA4, we can extrapolate the Rose et al. (2024) VAST scaled estimate to expect $10^3\text{--}10^4$ detectable re-brightening events and each year with the SKA. A systematic study of such a statistically significant sample will answer questions about the off-axis jets in relativistic supernovae (Type Ic-BL), complex mass-loss history of progenitors, and emission from the youngest compact remnants. SKA, when used in VLBI mode, will be able to reach sensitivity $0.5\text{--}1 \mu\text{Jy}$ in a few hours, and provide mas resolution (Rioja et al., 2026). We note here that the angular resolution of SKA-VLBI will not be improved beyond what is achievable

with current facilities, hence we realistically expect to resolve CCSNe out to a distance of ~ 30 Mpc. Furthermore, the better sensitivity of the SKA1 (see Fig. 4) will allow the derivation of meaningful size constraints for recently exploded CCSNe out to about 100 Mpc (An et al., 2026). Given the volumetric CCSN rate of $\sim 7 \times 10^{-5} \text{ yr}^{-1} \text{ Mpc}^{-3}$ (Pessi et al., 2025), the potential number of targets to be resolved per year is about 8 supernovae, which is a sensible number of targets for specific follow-up with SKA-VLBI within 30 Mpc, and amounts to ~ 280 within 100 Mpc, which leaves room to select the brightest and most relevant targets. We note here that the limiting issue is the time needed to resolve the expanding shell of a CCSN. Indeed, at least 15 yr would be needed to barely resolve a CCSN at 100 Mpc (at 15 GHz). For this reason, targeted SKA-VLBI observations should be done only on the closest and brightest targets of each subtype. In addition, SKA-Mid and SKA-Low, in VLBI fashion, will allow us to image old exploded CCSNe, which current VLBI arrays cannot resolve out due to sensitivity limitations.

4.5 SKA capabilities and observing strategies for CCSNe

Untargeted and commensal surveys by SKA will find hundreds of CCSNe per year with SKA-1 and an order of magnitude more with SKA-2, including heavily obscured events in dusty environments that optical surveys miss. Such surveys will help resolve the “missing SNe” problem and provide robust measurements of the volumetric CCSN rate and the subtype distribution. Fig. 4 shows the estimated number of detectable CCSNe per year. If we assume a peak luminosity of $10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$, SKA-1 Mid would detect $\sim 100 \text{ SNe yr}^{-1}$ within a maximum distance of ~ 100 Mpc. While the majority of these detections will rely on cross-matching with optically discovered SNe, image-plane slow transient searches across multiple epochs could also yield a population of radio-only detected SNe. Even without optical counterparts, these radio transients can potentially be identified as SNe if their peak radio luminosities and the shape of the light curve (or the characteristic evolutionary timescales) can be adequately constrained (e.g., Brunthaler et al., 2009). This approach opens a pathway to construct an unbiased sample of radio SNe. When estimating the number of detectable supernovae by subclass, using the average peak luminosity (Bietenholz et al., 2021) and relative occurrence rate for each type (Ma et al., 2025), Type IIb events are predicted to be the most numerous, with approximately hundreds of sources expected to be detectable per year (see right panel of Fig. 4). These estimates depend on several uncertain parameters and particularly on the peak luminosity: for subclasses whose peak luminosities are close to the detection threshold, detection is feasible only if the source is observed near its peak. On the other hand, low-frequency light curves evolve over much longer timescales, which increases the likelihood that sources can be detected.

For CCSNe the trigger strategy depends upon not just how young it is, but the subtype of a supernova. A large compilation of radio light curves has indicated that the characteristic peak times of roughly $10^{1.1} - 10^{1.5}$ days for SNe Ib/Ic to SNe IIb, $10^{1.6}$ days for non-IIc SNe II and 10^3 days for SNe IIc (Bietenholz et al., 2021). Hence the optimum trigger strategy is to trigger SNe IIb, Ib and Ic within 2–7 days, SNe IIP within 5–10 days and SNe IIc from a couple of weeks to a month. The follow up should be longer for SNe showing signs of structured CSM, strong $H\alpha$, luminous X-rays, or optical bumps/rebrightenings. A systematic compilations of detected supernovae and statistical study of their peak luminosities will improve correlation between typical radio peak luminosities and rise

times across CCSNe subtypes and emphasize diversity (Bietenholz et al., 2021). To this end, a near ideal practical strategy is to carry out an untargeted survey with SKA-Low (wide-field) and SKA-Mid (high-sensitivity), and then multi-band follow-up with 3–5 SKA bands. A logarithmic cadence will be crucial, given the power-law time evolution of SNe (e.g., Weiler et al., 2010). In addition, follow-up observations with other radio facilities will provide essential complementary coverage, both by accessing frequency ranges not available to the SKA and by enabling rapid, flexible scheduling (e.g., Iwata et al., 2025).

5 Superluminous supernovae with the SKA

Superluminous supernovae (SLSNe) represent a relatively recent, observationally defined class of explosions whose peak luminosities exceed those of canonical supernovae by more than an order of magnitude (Gal-Yam, 2012, 2019; Moriya, 2024). Although SLSNe may arise from various stellar death pathways, their extreme luminosities are thought to be powered by one or more of three primary mechanisms: (i) radiation from CSM interaction, (ii) energy injection from a central engine such as magnetar spin-down or fallback accretion, or (iii) radioactive decay associated with the pair-instability mechanism (Gal-Yam, 2019; Moriya, 2024). To date, only two SLSNe—both hydrogen-poor SLSNe-I—have been detected in the radio: PTF10hgi (Eftekhari et al., 2019, 2021; Mondal et al., 2020) and SN 2017ens (Margutti et al., 2023). In PTF10hgi, radio emission was discovered approximately seven years after explosion; modeling indicated that the event was magnetar-powered, with the radio emission arising from a pulsar wind nebula confined by the surrounding CSM. In contrast, SN 2017ens exhibited Balmer emission lines in its optical spectra about 100 days post-explosion (Chen et al., 2018), and its radio detection nearly three years later revealed strong ejecta-CSM interaction as the dominant power source. Because SLSNe are typically found at large cosmological distances—and their early-time radio emission is often absorbed—the steadily declining synchrotron flux makes them challenging to detect once the optical depth to absorption drops below unity at late epochs and low frequencies. SKA will prove to be a diagnostic machine that can separate the powering channels as the each mechanism is likely to imprint a distinct radio timescale and evolution. While magnetar powered SLSNe are expected to show a slow rise and evolution, the off-axis jet will show a sharper rise on months to years timescales followed by the decay. If CSM interaction is powering SLSNe, then it is not possible to have a smoothly decaying CSM and one is likely to see bumps and wiggles in the radio lightcurve. The enhanced sensitivity of the SKA will be critical for uncovering and characterizing such faint, late-time radio counterparts.

6 Multiwavelength, multi-messenger synergies with SKA

With the advent of next-generation facilities, multiwavelength and multimessenger studies of supernovae will enter a transformative era. The launch of ULTRASAT in 2027 will provide an unprecedented wide field of view and rapid public alerts (Ben-Ami et al., 2022). ULTRASAT will routinely capture the earliest ultraviolet signatures of stellar explosions, including shock breakout and flash-ionization phases. When combined with SKA observations of early-time radio emission—particularly the radio turn-on that encodes the circumstellar density structure—joint modeling will enable us to break long-standing degeneracies in ejecta-CSM interaction models. The SKA

will operate synergistically with both ALMA (upgraded) and the ngVLA, together covering a broad swath of the radio-to-millimeter spectrum. ngVLA frequencies will be highly complementary to those of the SKA, providing wide-band spectral coverage that is crucial for diagnosing cooling processes and the evolving microphysics (Kadler et al., 2026). ALMA’s millimeter observations will probe the high-frequency synchrotron tail as well as thermal free–free and dust emission, while SKA measurements at centimeter wavelengths will tightly constrain absorption processes. Taken together, ALMA, ngVLA, and SKA will allow us to disentangle contributions from primary and secondary electrons in dense CSM environments (Petropoulou et al., 2016).

Nearby core-collapse supernovae are also expected to be sources of high-energy (\gtrsim TeV) gamma rays and neutrinos, neither of which has been detected yet (unlike the MeV neutrinos observed from SN 1987A). As explained in § 4.3, hadronic collisions in the shock–CSM interaction region accelerate protons to relativistic energies, generating neutral and charged pions whose decay produces gamma rays and neutrinos, respectively. In the SKA era, the Cherenkov Telescope Array (CTA) will be fully operational, and the next-generation neutrino facility IceCube-Gen2 is expected to commence observations, offering the exciting possibility of coordinated multimessenger detections of supernova explosions.

7 Summary

The coming decade will revolutionize supernova astrophysics through the combined power of wide-field discovery surveys and deep, broadband radio follow-up with the SKA. High-cadence time-domain specific will deliver unprecedented samples of nearby and early-phase explosions, providing timely triggers for SKA observations. SKA’s exceptional sensitivity will transform our ability to measure pre-supernova mass loss across all core-collapse subtypes, uncover episodic or eruptive mass-loss episodes, and probe the poorly understood circumstellar environments of stripped-envelope supernovae—including the possible role of central engines. For thermonuclear SNe Ia, SKA’s stringent non-detections will decisively rule out most single-degenerate progenitor channels, while any detection would provide rare, direct constraints on circumstellar density and progenitor physics. Together with complementary facilities such as ALMA, ngVLA, IceCube-Gen2 etc., SKA will enable a comprehensive, multiwavelength and multimessenger view of stellar death, fundamentally reshaping our understanding of how massive stars evolve, explode, and enrich the Universe.

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References

- T. An et al. In *Advancing Astrophysics with the SKA – II (AASKAII)*. 2026. arXiv search: Report number AASKAII/TaoAn02.
- G. E. Anderson et al. *MNRAS*, 466(3):3648–3662, Apr. 2017. doi: 10.1093/mnras/stw3310.
- S. Ben-Ami et al. In J.-W. A. den Herder, S. Nikzad, and K. Nakazawa, editors, *Space Telescopes and Instrumentation 2022: Ultraviolet to Gamma Ray*, volume 12181 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 1218105, Aug. 2022. doi: 10.1117/12.2629850.
- H. A. Bethe and J. R. Wilson. *ApJ*, 295:14–23, Aug. 1985. doi: 10.1086/163343.
- M. F. Bietenholz et al. *ApJ*, 908(1):75, Feb. 2021. doi: 10.3847/1538-4357/abccd9.
- A. Brunthaler et al. *A&A*, 499(2):L17–L20, May 2009. doi: 10.1051/0004-6361/200912327.
- P. Chandra. *arXiv e-prints*, art. arXiv:2510.20913, Oct. 2025. doi: 10.48550/arXiv.2510.20913.
- P. Chandra et al. *ApJ*, 877(2):79, June 2019. doi: 10.3847/1538-4357/ab1900.
- T. W. Chen et al. *ApJL*, 867(2):L31, Nov. 2018. doi: 10.3847/2041-8213/aaeb2e.
- R. A. Chevalier. *ApJ*, 258:790–797, July 1982a. doi: 10.1086/160126.
- R. A. Chevalier. *ApJ*, 259:302–310, Aug. 1982b. doi: 10.1086/160167.
- R. A. Chevalier. *ApJ*, 499(2):810–819, May 1998. doi: 10.1086/305676.
- R. A. Chevalier and C. Fransson. Supernova interaction with a circumstellar medium. In K. W. Weiler, editor, *Supernovae and Gamma-Ray Bursters*, volume 598 of *Lecture Notes in Physics*, pages 171–194. Springer, Berlin, Heidelberg, 2003. doi: 10.1007/3-540-45863-8_10.
- R. A. Chevalier and C. Fransson. *ApJ*, 651(1):381–391, Nov. 2006. doi: 10.1086/507606.
- N. N. Chugai, R. A. Chevalier, and V. P. Utrobin. *ApJ*, 662(2):1136–1147, June 2007. doi: 10.1086/518160.
- T. Eftekhari et al. *ApJL*, 876(1):L10, May 2019. doi: 10.3847/2041-8213/ab18a5.
- T. Eftekhari et al. *ApJ*, 912(1):21, May 2021. doi: 10.3847/1538-4357/abe9b8.
- S. W. Falk and W. D. Arnett. *ApJL*, 180:L65, Mar. 1973. doi: 10.1086/181154.
- A. V. Filippenko. *ARA&A*, 35:309–355, Jan. 1997. doi: 10.1146/annurev.astro.35.1.309.
- F. Förster et al. *Nature Astronomy*, 2:808, Sept. 2018. doi: 10.1038/s41550-018-0563-4.
- A. Gal-Yam. *Science*, 337(6097):927, Aug. 2012. doi: 10.1126/science.1203601.
- A. Gal-Yam. *ARA&A*, 57:305–333, Aug. 2019. doi: 10.1146/annurev-astro-081817-051819.
- A. Gangopadhyay et al. *ApJ*, 957(2):100, Nov. 2023. doi: 10.3847/1538-4357/acfa94.
- S. R. Goldman et al. *MNRAS*, 465(1):403–433, Feb. 2017. doi: 10.1093/mnras/stw2708.
- J. Granot, A. Panaitescu, P. Kumar, and S. E. Woosley. *ApJL*, 570(2):L61–L64, May 2002. doi: 10.1086/340991.
- O. Griffith et al. *ApJ*, 995(1):54, Dec. 2025. doi: 10.3847/1538-4357/ae17b0.
- M. Hamuy et al. *Nature*, 424(6949):651–654, Aug. 2003. doi: 10.1038/nature01854.
- C. E. Harris, P. E. Nugent, and D. N. Kasen. *ApJ*, 823(2):100, June 2016. doi: 10.3847/0004-637X/823/2/100.
- A. Horesh et al. *ApJ*, 746(1):21, Feb. 2012. doi: 10.1088/0004-637X/746/1/21.
- A. W. Hotan et al. *PASA*, 38:e009, Mar. 2021. doi: 10.1017/pasa.2021.1.
- Y. Iwata et al. *ApJ*, 978(2):138, Jan. 2025. doi: 10.3847/1538-4357/ad9a62.
- M. Kadler et al. In *Advancing Astrophysics with the SKA – II (AASKAII)*. 2026. arXiv search:

- Report number AASKAII/Kadler02.
- K. Kashiyama et al. *ApJL*, 769(1):L6, May 2013. doi: 10.1088/2041-8205/769/1/L6.
- B. Katz, N. Sapir, and E. Waxman. In P. Roming, N. Kawai, and E. Pian, editors, *Death of Massive Stars: Supernovae and Gamma-Ray Bursts*, volume 279 of *IAU Symposium*, pages 274–281, Sept. 2012. doi: 10.1017/S174392131201304X.
- E. C. Kool et al. *Nature*, 617(7961):477–482, May 2023. doi: 10.1038/s41586-023-05916-w.
- S. R. Kulkarni et al. *Nature*, 395(6703):663–669, Oct. 1998. doi: 10.1038/27139.
- M. Lacy et al. *PASP*, 132(1009):035001, jan 2020. doi: 10.1088/1538-3873/ab63eb. URL <https://doi.org/10.1088/1538-3873/ab63eb>.
- X. Ma et al. *A&A*, 698:A305, June 2025. doi: 10.1051/0004-6361/202452684.
- D. Maoz, F. Mannucci, and G. Nelemans. *ARA&A*, 52:107–170, Aug. 2014. doi: 10.1146/annurev-astro-082812-141031.
- R. Margutti et al. *ApJL*, 954(2):L45, Sept. 2023. doi: 10.3847/2041-8213/acf1fd.
- S. Mondal, A. Bera, P. Chandra, and B. Das. *MNRAS*, 498(3):3863–3869, Nov. 2020. doi: 10.1093/mnras/staa2637.
- T. J. Moriya. *arXiv e-prints*, art. arXiv:2407.12302, July 2024. doi: 10.48550/arXiv.2407.12302.
- K. Murase, T. A. Thompson, B. C. Lacki, and J. F. Beacom. *Phys. Rev. D*, 84(4):043003, Aug. 2011. doi: 10.1103/PhysRevD.84.043003.
- K. Murase, T. A. Thompson, and E. O. Ofek. *MNRAS*, 440(3):2528–2543, May 2014. doi: 10.1093/mnras/stu384.
- T. Murphy et al. *PASA*, 30:e006, Feb. 2013. doi: 10.1017/pasa.2012.006.
- T. Murphy et al. *PASA*, 38:e054, Jan. 2021. doi: 10.1017/pasa.2021.44.
- A. J. Nayana and P. Chandra. *MNRAS*, 494(1):84–96, May 2020. doi: 10.1093/mnras/staa700.
- A. J. Nayana, P. Chandra, and A. K. Ray. *ApJ*, 863(2):163, Aug. 2018. doi: 10.3847/1538-4357/aad17a.
- A. J. Nayana et al. *ApJ*, 985(1):51, May 2025. doi: 10.3847/1538-4357/adc2fb.
- K. Nomoto. *ApJ*, 253:798–810, Feb. 1982. doi: 10.1086/159682.
- E. O. Ofek et al. *ApJL*, 659(1):L13–L16, Apr. 2007. doi: 10.1086/516749.
- M. A. Pérez-Torres et al. *ApJ*, 792(1):38, Sept. 2014. doi: 10.1088/0004-637X/792/1/38.
- T. Pessi et al. *A&A*, 703:A34, Nov. 2025. doi: 10.1051/0004-6361/202556799.
- M. Petropoulou, A. Kamble, and L. Sironi. *MNRAS*, 460(1):44–66, July 2016. doi: 10.1093/mnras/stw920.
- J. Puls, J. S. Vink, and F. Najarro. *A&ARv*, 16(3-4):209–325, Dec. 2008. doi: 10.1007/s00159-008-0015-8.
- M. A. Pérez-Torres et al. In *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, page 60, 2015. URL <https://pos.sissa.it/215/060>.
- R. M. Quimby et al. *Nature*, 474(7352):487–489, June 2011. doi: 10.1038/nature10095.
- M. Rioja et al. In *Advancing Astrophysics with the SKA – II (AASKAII)*. 2026. arXiv search: Report number AASKAII/Rioja01.
- K. Rose et al. *MNRAS*, 534(4):3853–3868, Nov. 2024. doi: 10.1093/mnras/stae2289.
- P. Slane. Pulsar Wind Nebulae. In A. W. Alsabti and P. Murdin, editors, *Handbook of Supernovae*, page 2159. 2017. doi: 10.1007/978-3-319-21846-5_95.
- N. Smith. *ARA&A*, 52:487–528, Aug. 2014. doi: 10.1146/annurev-astro-081913-040025.

- N. Smith and R. McCray. *ApJL*, 671(1):L17–L20, Dec. 2007. doi: 10.1086/524681.
- M. C. Stroh et al. *ApJL*, 923(2):L24, Dec. 2021. doi: 10.3847/2041-8213/ac375e.
- K. W. Weiler et al. *ApJ*, 671(2):1959–1980, Dec. 2007. doi: 10.1086/523258.
- K. W. Weiler et al. *Mem. SAIIt*, 81:374, Jan. 2010.
- K. W. Weiler et al. *ApJ*, 740(2):79, Oct. 2011. doi: 10.1088/0004-637X/740/2/79.
- J. Whelan and I. Iben, Jr. *ApJ*, 186:1007–1014, Dec. 1973. doi: 10.1086/152565.
- S. E. Woosley, A. Heger, and T. A. Weaver. *Reviews of Modern Physics*, 74(4):1015–1071, Nov. 2002. doi: 10.1103/RevModPhys.74.1015.
- O. Yaron et al. *Nature Physics*, 13(5):510–517, Feb. 2017. doi: 10.1038/nphys4025.