

MULTIWAVELENGTH VIEWS OF THE FINAL DECADES PRECEDING AN EXOTIC HELIUM-RICH EXPLOSION

RAPHAEL BAER-WAY ^{1,2}, POONAM CHANDRA ², AND MARYAM MODJAZ ¹

¹*Department of Astronomy, University of Virginia, Charlottesville VA 22904-4325, USA*

²*National Radio Astronomy Observatory, 520 Edgemont Rd, Charlottesville VA 22903, USA*

ABSTRACT

Supernovae that interact with hydrogen-poor, helium-rich circumstellar material (CSM), known as Type Ibn supernovae (SNe Ibn), present a unique opportunity to probe mass-loss processes in massive stars. In this work, we report the first radio detection of a SN Ibn, SN 2023fyq, and characterize the mass-loss history of its stellar progenitor using the radio and X-ray observations obtained over 18 months post-explosion. We find that the radio emission from 58–185 days is best modeled by synchrotron radiation attenuated by free-free absorption from a CSM of density $\sim 10^{-18}$ g/cm³ ($\sim 10^6 \rho_{\text{ISM}}$) at a radius of 10^{16} cm, corresponding to a mass-loss rate of $\sim 4 \times 10^{-3}$ M_⊙ yr⁻¹ (for a CSM velocity of 1700 km/s from optical spectroscopy) from 0.7 to 3 years before the explosion. CSM configuration inferred from multiwavelength observations, we invoke binary interaction as the most plausible mechanism for the mass-loss history before this explosion. These results suggest a shell-like CSM from at most 4×10^{15} to 2×10^{16} cm ($\sim 10^5 R_{\odot}$) with a CSM density that is roughly consistent with predictions from a merger model for this object. Future radio observations of a larger sample of SNe Ibn will provide key details on the extent and density of their helium-rich CSM.

1. INTRODUCTION

Massive stars lose significant amounts of mass as they approach the ends of their lives (Woosley et al. 1993; Smith 2014; Chiosi & Maeder 1986; Langer 2012; Puls et al. 2008). Observations of certain supernovae (SNe) reveal extensive interaction between the ejecta and dense circumstellar material (CSM) formed by this mass loss (see e.g., Chevalier & Fransson 2017; Margutti et al. 2017; Chandra 2018; Jacobson-Galán et al. 2024; Brethauer et al. 2022; Maeda et al. 2013; Baer-Way et al. 2025). In particular, certain objects reveal interaction between the ejecta and helium-rich CSM (Matheson et al. 2000; Hosseinzadeh et al. 2017; Pastorello et al. 2016; Moriya & Maeda 2016; Foley et al. 2007; Smith 2017), suggesting the star has almost fully lost its hydrogen and lost at least some of its helium layer but experienced this mass loss close enough to the explosion to retain a meaningful amount of nearby high-density helium-rich material.

These objects, known as type Ibn supernovae (SNe Ibn) as they are hydrogen-deficient but their optical spectra contain narrow helium emission lines (~ 1000 km/s FWHM (Hosseinzadeh et al. 2017)) from unshocked CSM (Gal-Yam 2017; Modjaz et al. 2019), make up 1% (by local volumetric rate) of the Core Collapse Supernova (CCSN) population (Perley et al. 2020). It

has been somewhat difficult to observationally constrain this class of objects due to their relative scarcity. SNe Ibn are characterized by fast-declining (relative to any other supernova subtype) lightcurves (Moriya & Maeda 2016; Hosseinzadeh et al. 2017; Khakpash et al. 2024), with the ~ 0.1 mag/day decay in the first month post-explosion driven by changes in the shock emission mechanism from radiatively cooling to adiabatic. This occurs in SNe Ibn due to the high shock velocities (which lower the CSM densities by quickly propagating to large radii and allowing for a faster cooling transition) characteristic of the subtype (Maeda & Moriya 2022). By definition, all SNe Ibn interact with some type of helium-rich CSM, but optical spectral diversity in line-width and shape (i.e., P Cygni profiles vs. solely narrow emission lines) may suggest different optical depths or viewing-angle effects (Shivvers et al. 2017; Hosseinzadeh et al. 2017). Viewing-angle effects would imply that there are large deviations from spherical symmetry in the explosion/CSM itself.

Some SNe Ibn show narrow-line emission (order 1000 km/s speed) that persists out to late times and is indicative of continued interaction into the nebular phase ~ 200 –300 days post-explosion (Foley et al. 2007; Smith et al. 2008). Others, such as the target we analyze in this paper, evolve to look more like a classical stripped-envelope SN at later phases, potentially due to a less

extended helium shell of CSM (Dong et al. 2024). Given the diversity within the subclass, it is possible that there are intrinsic differences between these explosions/their progenitors. This implies that they should not be grouped as one subclass, or that the mass-loss mechanism can act on varying timescales. The time frame over which the intensive mass-loss occurs ($> 10^{-3} M_{\odot} \text{ yr}^{-1}$ as has been seen in all SNe Ibn for which a mass-loss rate was measured (Pellegrino et al. 2024)) is much shorter (on the order of years) than in hydrogen-rich interacting objects, where the mass loss can occur for hundreds of years (Smith et al. 2009). There are various possibilities for these short-lived mass loss episodes of SNe Ibn, such as mass ejections due to pulsational instabilities near core collapse (Woosley 2017), or mass loss due to unstable mass transfer during inspiral in a binary system on the way to a merger-driven explosion (Wu & Fuller 2022; Tsuna et al. 2024; Schröder et al. 2020).

Roughly 70–100 SNe Ibn have been discovered at optical wavelengths (Dong et al. 2024). Of these, three have shown evidence for pre-explosion outbursts, detected as flares or excess emission in pre-explosion lightcurves (Gangopadhyay et al. 2020; Foley et al. 2007; Brennan et al. 2024), one of these being the object we explore in this work. Beyond SNe Ibn, there have been a few tens of cases of precursor emission observed in CCSNe (Strotjohann et al. 2021; Pastorello et al. 2013; Elias-Rosa et al. 2016; Ofek et al. 2014). In most cases, including the Ibn subclass, these precursors are interpreted as compelling evidence for mass ejection before the explosion that creates dense CSM. (Gagliano et al. 2025; Jacobson-Galán et al. 2022; Bilinski et al. 2015; Ofek et al. 2013; Pastorello et al. 2010).

As the supernova explodes, the ejecta will run into the CSM, causing non-thermal radio synchrotron emission given the strong magnetic field and fast ($\sim 10,000 \text{ km/s}$) shock (Chevalier 1982). The hot shocked material can also generate thermal X-rays (Chevalier 1982). Three type Ibn SNe have been detected at X-ray wavelengths: SN 2006jc (Immler et al. 2008), SN 2010al (Ofek et al. 2013) (initially classified as a type II_n) and SN 2022ablq (Pellegrino et al. 2022). These X-ray observations revealed that these SNe likely had an intense outburst of mass-loss ~ 1 -2 years pre-explosion. While roughly 100 CCSNe have been detected at radio wavelengths (Bietenholz et al. 2021), a SN Ibn has never been detected despite attempts for multiple different objects (Shivvers et al. 2017; Smith et al. 2008). Given that very few objects have been sampled out to late times (beyond ~ 30 days-meaning the mass loss was only probed out to ~ 1 year pre-explosion given characteristic 10,000/1000 km/s shock/wind speeds) and/or with high sensitivity

$< 10^{26} \text{ ergs s}^{-1} \text{ Hz}^{-1}$, these non-detections are not particularly constraining for the subclass as a whole.

In this work, we report the first radio detection of an SN Ibn, SN 2023fyq. We use the radio emission of SN 2023fyq to constrain the mass-loss history of its progenitor system. SN 2023fyq has been studied extensively at optical wavelengths even before explosion: SN 2023fyq showed evidence for optical precursor emission indicative of pre-explosion outbursts for at least 1500 days (Dong et al. 2024; Brennan et al. 2024). The object then rose dramatically in brightness, and the explosion date (in our frame) was inferred as 16 July 2023 (Brennan et al. 2024). Brennan et al. (2024) estimated this explosion date relative to the time of maximum through blackbody fits. We take all epochs in this work relative to this explosion date. We note that our results are robust even with an explosion date error of $\sim \pm 15$ days. The SN is roughly 15" offset from the center of its host galaxy, NGC 4388 – which is at a distance of 18 ± 3.7 Mpc using the most recent Tully-Fisher estimate (Dong et al. 2024). This galaxy has attracted interest on its own as a unique radio and X-ray-bright active galactic nucleus (AGN) (Sargent et al. 2024; Gediman et al. 2024).

SN 2023fyq is one of the first objects for which pre-explosion spectra were acquired of the outbursting material (Brennan et al. 2024). Dong et al. (2024) and Brennan et al. (2024) have combined the optical pre- and post-explosion spectra and lightcurves (which showed that this SN was unambiguously a terminal transient-meaning the core was disrupted and the progenitor destroyed) to characterize SN 2023fyq. They interpreted their optical dataset of this object as an explosion originating from a binary system with a low-mass ($\sim 3 M_{\odot}$) helium star orbiting a neutron star that they claim eventually experienced either runaway mass loss triggering core collapse, or a merger that directly triggered the explosion (Dong et al. 2024).

2. ANALYSIS

2.1. *Radio Data Analysis*

In general, radio emission from CCSNe is non-thermal synchrotron radiation that arises due to the interaction of the SN forward shock with the CSM. The emission is suppressed via synchrotron self-absorption (SSA) by the synchrotron-emitting electrons themselves and/or via free-free absorption (FFA) by the dense medium external to the shock (Chevalier 1998). Both absorption mechanisms can work in tandem, and radio light curves can be represented in parametrized forms that describe the optically thick (F_{ν} -rising) and thin (F_{ν} -declining) spectral and temporal evolution, as well as the opti-

cal depth normalization. In an FFA model, the radio flux density ($F(\nu, t)$) can be parametrized as [Chevalier \(1982\)](#); [Chandra et al. \(2020\)](#); [Weiler et al. \(2002\)](#):

$$F(\nu, t)_{\text{FFA}} = K_1 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-\alpha} \left(\frac{t}{1000 \text{ days}} \right)^{-\beta} e^{-\tau_{\text{FFA}}(\nu, t)}, \quad (1)$$

Here, α is the spectral index and β is the temporal index of the flux density evolution. α is related to the electron energy index p by $p = 2\alpha + 1$ ([Chevalier 1998](#)). We note that this is true only when the self-absorption frequency is less than both the cooling and minimum electron energy frequency, but we confirm this is the case using the scale of the B-field (~ 0.5 G) derived self-consistently in section 2.2. The FFA optical depth is given by

$$\tau_{\text{FFA}}(\nu, t) = K_2 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left(\frac{t}{1000 \text{ days}} \right)^{-\delta} \quad (2)$$

δ describes the evolution of the optical depth, and is related to the density gradient in the CSM $\rho_{\text{CSM}} \propto r^{-s}$ by $m = \frac{n-3}{n-s}$ (where the ejecta density profile $\rho_{\text{ejecta}} \propto r^{-n}$), where $\delta = m(2s - 1)$. We can also use this m to characterize the evolution of the CSM radius $R \propto t^m$. K_2 is the optical depth normalization.

In the SSA model, the flux density is parametrized as ([Weiler et al. 1986](#); [Chevalier 1998](#))

$$F(\nu, t)_{\text{SSA}} = K_1 \left(\frac{\nu}{5 \text{ GHz}} \right)^{2.5} \left(\frac{t}{1000 \text{ days}} \right)^{-\beta'} \times \left(1 - e^{-\tau_{\text{SSA}}(\nu, t)} \right) \quad (3)$$

The SSA optical depth is parametrized by

$$\tau_{\text{SSA}} = K_2 \left(\frac{\nu}{5 \text{ GHz}} \right)^{(-\alpha-2.5)} \left(\frac{t}{1000 \text{ days}} \right)^{(-\beta'+\beta)} \quad (4)$$

K_2 corresponds to the SSA optical depth normalization. β' and β denote the temporal evolution of flux densities in the optically thick ($F \propto t^{\beta'}$) and thin phase ($F \propto t^{\beta}$), respectively. The SSA model can be rewritten at a specific temporal epoch to reduce the model to 3 free parameters and measure their evolution as: ([Chevalier 1998](#); [Soderberg et al. 2006](#))

$$F_{\nu, \text{SSA}} = 1.582 F_p \left(\frac{\nu}{\nu_p} \right)^{5/2} \left(1 - \exp \left[- \left(\frac{\nu}{\nu_p} \right)^{-2.5-\alpha} \right] \right) \quad (5)$$

where α again is the optically thin spectral index, ν_p is the frequency at which the SSA spectrum peaks (frequency at which $\tau_{\text{SSA}} \approx 1$), and F_p is the corresponding peak flux density. ν_p and F_p can be used to estimate the shock radius (R) and magnetic field (B) ([Chevalier](#)

[1998](#)). For $p \sim 2.5$ (given the optically thin spectral slope that we measure as detailed later in this section), we find ([Pacholczyk 1970](#))

$$R = 3.7 \times 10^{15} f_{eB}^{-1/18} \left(\frac{f}{0.5} \right)^{-1/18} \left(\frac{F_p}{\text{Jy}} \right)^{17/36} \times \left(\frac{D}{\text{Mpc}} \right)^{17/18} \left(\frac{\nu}{5 \text{ GHz}} \right)^{-1} \text{ cm} \quad (6)$$

$$B = 0.70 f_{eB}^{-2/9} \left(\frac{f}{0.5} \right)^{-2/9} \left(\frac{F_p}{\text{Jy}} \right)^{-1/9} \times \left(\frac{D}{\text{Mpc}} \right)^{-2/9} \left(\frac{\nu}{5 \text{ GHz}} \right) \text{ G} \quad (7)$$

where $f_{eB} = \frac{\epsilon_e}{\epsilon_B}$ denotes the ratio between the energy density of relativistic electrons (ϵ_e) and the magnetic field energy density (ϵ_B). f is the volume filling factor, which we assume to be 0.5 as is standard for radio SNe with $n \sim 10$ and $s \sim 2$ ([Weiler et al. 1986](#)) – although other values could be considered up to $f=0.1$ or 1 (considering the asymmetry seen in the optical dataset ([Dong et al. 2024](#))) without changing R and B by more than 10 %. D is the angular distance to the SN.

As seen in Figure ??, the data do not cover the peak of the SED at any epoch: at 58 days, the entire SED is in the optically thick phase, and the data are optically thin at all other epochs. We still attempted to fit an FFA-dominated and SSA-dominated model to the full dataset using equations 1 and 3. We carry out fits using `emcee` ([Foreman-Mackey et al. 2013](#)), with 200 walkers and 10000 iterations. In the FFA model, we kept $\alpha, \beta, \delta, K_1, K_2$ as free parameters, while for SSA we kept $\alpha, \beta, \beta', K_1, K_2$ as free parameters. We find similar reduced χ^2 $\chi_{\nu, \text{FFA}}^2 = 1.41$ and $\chi_{\nu, \text{SSA}}^2 = 1.81$. We find $\alpha = 0.87_{-0.10}^{+0.10}$ for FFA and $\alpha = 0.76_{-0.03}^{+0.02}$ for SSA. We also find for FFA that $\delta = 2.11_{-0.08}^{+0.15}$. This δ value implies that $s \sim 2$ for reasonable m values from 0.6–1 with the relation $\delta = m(2s - 1)$. We find $\beta' = 3.67_{-0.30}^{+0.23}$ for SSA. Finally, we have $\beta = 1.32_{-0.2}^{+0.18}$ for SSA and $\beta = 1.86_{-0.14}^{+0.09}$ for FFA. From the similar χ^2 values and visual inspection of the best-fitting models, we conclude that we cannot favor a pure FFA or SSA model for the full dataset but find preference for $s \sim 2$.

However, the fact that at $\Delta t = 58$ days, the SED is best sampled in the optically thick regime allows us to constrain the dominant absorption process. The flux densities rise by a factor ~ 2 between 9–11 GHz, suggesting a very steep optically thick slope of $F_{\nu} \sim \nu^4$. In an SSA model, the optically thick spectral slope would be $F_{\nu} \propto \nu^{2.5}$ (given the ordering of cooling/electron/SSA frequencies we confirmed) ([Rybicki & Lightman 1979](#)). The observed optically thick spectral slope is steeper

than this and suggests that FFA must be dominant at this epoch. We thus fit each SED with equation 1 (fixing t at each epoch).

We freeze $\delta = 3$ (as $\delta = (2s - 1)m$) as we assume constant shock velocity $m = 1$ and $s=2$. We note that with $s = 2, m = \frac{n-3}{n-s}$ can only be approximately 1, but we assume $m = 1$ for simplicity and given the poor constraint on s . We also fix $\beta = 1.86$ from the FFA fits to the full dataset as β should not vary across individual epochs (as it sets the temporal evolution). As one further motivation for fitting with FFA, we note that given the 10 GHz peak, a Chevalier diagram (Chevalier 1998) as shown in Figure 2 suggests a shock speed ~ 4000 km/s, which is a clear underestimate based on optical estimates, meaning SSA alone is not the primary absorption mechanism and there is a significant contribution from FFA. We use $V_{sh} = 8500$ km s $^{-1}$ from the late-time optical spectra (Dong et al. 2024). This likely corresponds to the fastest ejecta speed, which is not the same as the shock speed and is often an underestimation (Chevalier & Fransson 2017). We proceed assuming a non-decelerating shock speed, given that we lack the data to accurately model the evolution of this speed.

We perform FFA fits at each epoch using equation 1 keeping K_1, K_2 and α as free parameters. The results for these three parameters are shown in Table 1. We note the relatively high α at early epochs, but also emphasize that the error bars are quite large and there are degeneracies in the fitting. We show the single-epoch FFA fits to the data in Figure ???. We caution that our results in general are only approximations given the s and m we assume.

2.2. Intrinsic SSA+FFA

We proceeded to find the intrinsic SSA emission suppressed by the FFA self-consistently by estimating the radius and B-field accounting for the density profile. We use the CSM densities from single epoch FFA fits. We estimate τ_{FFA} using equation 2 with the best-fit K_2 and assumed $\delta=3$. The CSM density is then given by $\rho_{\text{FFA}} = \frac{\dot{M}_{\text{FFA}}}{4\pi r^2 v_w}$, where (Chandra et al. 2020)

$$\frac{\dot{M}_{-3,\text{FFA}}}{v_{\text{CSM},1}} = 7.5 \times 10^{-2} \left(\frac{\tau_{\text{eff/FFA}}}{1 + \left[\frac{n(\text{He})}{n(\text{H})} \right]} \right)^{0.5} \left(\frac{\nu}{\text{GHz}} \right)^{1.06} \times \left(\frac{T_{\text{CSM}}}{10^4 \text{ K}} \right)^{0.67} \left(\frac{v_{\text{sh}}}{10^4 \text{ km s}^{-1}} \right)^{1.5} \left(\frac{t}{1000 \text{ days}} \right)^{1.5} \quad (8)$$

here τ_{eff} is the effective optical depth considering all absorption components (here, we consider FFA optical depth), T_{CSM} is the electron temperature of the CSM,

and v_{sh} is the shock speed in km s $^{-1}$. $\frac{\dot{M}_{-3,\text{FFA}}}{v_{\text{CSM},1}}$ denotes the mass-loss rate in units of $10^{-3} M_{\odot} \text{ yr}^{-1}$ for a wind speed of $v_w = 10$ km s $^{-1}$. We use $v_w = 1700$ km s $^{-1}$ from the P Cygni absorption trough of He I 5876 Å seen in the optical spectra (Brennan et al. 2024; Dong et al. 2024).

We assume $n(\text{He})/n(\text{H}) \approx 10$ given that the CSM is helium rich (Dong et al. 2024; Brennan et al. 2024). This ratio could be even higher and the derived mass-loss rate would then be lower. We also assume the CSM temperature to be high at 10^5 K considering high ionization indicated by the strong presence of helium (Lundqvist & Fransson 1991). We note that the \dot{M} we estimate will be an effective value, given both that we do not assume an unchanging K_2 and thus do not fix the mass-loss rate as constant directly, and we assume our line of sight is representative of the total distribution of matter. Using the τ_{FFA} and the radius of the CSM $V_{sh}t$ (where we use $V_{sh} = 8500$ km/s), we find ρ_{FFA} at each epoch.

Using the CSM density derived from FFA modeling, we can then constrain B using the magnetic field scaling relation (Chevalier 1998).

$$\frac{B^2}{8\pi} = \epsilon_B \rho_{\text{FFA}} V_{sh}^2 \quad (9)$$

V_{sh} is again the constant shock speed where $R = V_{sh}t$. Using the estimated B from equation 9 and R , we can constrain the SSA F_p and ν_p at each epoch using equations 6 and 7. However, we need ϵ_B and f_{eB} . From running MCMC fits using an SSA model attenuated by FFA (equation 10) with f_{eB} and ϵ_B as free parameters, it is clear that there are degeneracies between these values and α . However, at the fourth epoch where we have the most datapoints, we find $\epsilon_B = 0.0016^{+0.0001}_{-0.0001}$ and $f_{eB} = 1.2^{+0.2}_{-0.2}$ for the frozen α from the FFA single-epoch fit. We thus fix $\epsilon_B = 0.0016$ and $f_{eB} = 1$ given the degeneracy with α . This gives good fits as seen in Figure ?? except at the second epoch, where the FFA α and the f_{eB} and ϵ_B that work well for other epochs do not provide a good fit. We attribute this to degeneracies in the fitting. We fix $\alpha = 0.75$ at this epoch for the SSA+FFA plotting (this does not affect any derived parameters) given the fit to the optically thin points between 15–30 GHz at all epochs as detailed below.

We note that we assumed $p \approx 2.5$ in equations 6 and 7, motivated by the shallow spectral slope derived from an overall fit to the optically thin points between 15–30 GHz (an MCMC fit yields a spectral index of $\alpha = 0.75^{+0.17}_{-0.18}$). Having found τ_{FFA} and F_p/ν_p through ρ_{FFA}/V_{sh} we construct an SSA+FFA model with the α

from the single-epoch FFA fits.

$$F_{\nu, \text{SSA+FFA}} = e^{-\tau_{\text{FFA}}} 1.582 F_p \left(\frac{\nu}{\nu_p} \right)^{5/2} \left(1 - \exp \left[- \left(\frac{\nu}{\nu_p} \right)^{-\alpha-2.5} \right] \right) \quad (10)$$

The 1.582 factor carries over from the SSA formulation (Chevalier 1998). We did attempt fits where τ_{FFA} is a free parameter along with α , f_{eB} and ϵ_B . There are clear degeneracies between all these values, so we opted to freeze α and τ_{FFA} from the single-epoch FFA fits and then f_{eB}/ϵ_B from reasonable values obtained from fitting equation 10 at the fourth epoch with more datapoints. We plug in all our values to this equation 10 at each epoch. We note that at > 125 days, there seems to be an uptick in CSM density. Given the assumptions and uncertainties, we suggest these variations are within error bars and cannot be attributed to true variations within the CSM. As described, we find $\epsilon_B = 0.0016$ and $f_{eB} \sim 1$ allows for the best fit to the flux density values. Given the R values we assume and the B values we find in Table 1, we use equation 1 of Chevalier (1998) to find the density of relativistic electrons N_0 and thus U_E . We find $U_E \sim 0.8U_B$, suggesting that the equipartition implied by our best-fit $f_{eB} = 1$ is a reasonable assumption. However, these microparameters are quite difficult to ascertain from the limited data we have and have degeneracies with other parameters i.e., shock radius/ α (Fransson et al. 1996). These values differ from the often-assumed $\epsilon_E = \epsilon_B = 0.1$ (Soderberg 2006). Recent studies suggest such deviations are plausible due to shock acceleration effects (Park et al. 2015; Gupta et al. 2024). The inferred value of ϵ_B is also consistent with measurements from other radio-bright interacting SNe such as SN 2023ixf (Nayana et al. 2025).

Results from Our derived SSA+FFA models are plotted in Figure 1 and all relevant parameters are listed in Table 1. Given we have constrained the frequency ν_p where $\tau_{\text{SSA}} = 1$, we find the overall τ_{eff} at this frequency using equation 2 (adding 1 to the FFA optical depth for the SSA contribution), and estimate the mass-loss rate at each spectral epoch again using equation 8. Using the 1700 km/s CSM speed, we obtain the mass-loss rates at each epoch with detections seen in Figure 1. The effective mass-loss rate is relatively constant at $\sim 4 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$ as expected given the assumed $s = 2$ in equation 8. The variations seen are within error bars. We convert to pre-explosion epoch by taking the ratio of the assumed shock to the CSM speed and plot this as well in Figure 1.

While we have assumed a standard r^{-2} CSM density profile based on the FFA fitting, SNe Ibn are expected to have an r^{-3} CSM density profile (Maeda & Moriya 2022), at least for the first ~ 100 days. Given the limited data, it is difficult to model in an $s = 3$ scenario, especially because at $s = 3$ the self-similar solutions derived by Chevalier (1982) are no longer valid. However, we find the r^{-3} mass-loss rate at each epoch from the relation in Fransson et al. (1996) (equation 2.1 in their work), using our initial mass-loss value as the base mass-loss and adjusting for the evolution of the radius of the shock as needed for non- r^{-2} profiles.

Recent work on stars in binary systems undergoing high rates of mass loss (Wu & Tsuna 2025) has developed an approach that uses a given explosion energy and shock speed as well as an assumed electron power-law index p to obtain estimates of the flux from interaction between the SN ejecta and CSM density profile (Wu & Tsuna 2025). This model uses the M2.467.P100d $\rho_{\text{CSM}} \sim \alpha r^{-3}$ density profile (where the density profile is directly extracted from simulations, i.e., no functional form assumed). The model has ejecta kinetic energy of 10^{51} erg, ejecta mass $1.25 M_{\odot}$, shock velocity of 8970 km s^{-1} , CSM filling factor 1 (meaning a symmetric CSM), $\epsilon_e = 10^{-4}$, $\epsilon_B = 10^{-3}$, and $p = 2\alpha + 1 = 2.1$.

The shock velocity from this modeling is consistent with our estimate, despite the difference in p /small difference in ϵ_e/ϵ_B . The model does not provide as good a fit to the light curve as SSA/FFA (although data at day ~ 100 would truly have allowed us to distinguish between the models). However, it is noteworthy that our derived density values are relatively consistent (despite our assumption of an r^{-2} profile) with the density profile (the M2.P467100D model specifically) developed by Tsuna et al. (2024) for these radio models (e.g., see Fig. 1). Furthermore, the Tsuna et al. (2024) model assumes there is no significant mass-loss beyond 2×10^{16} cm, which is consistent with our late-time upper limits that suggest a sharp decline in radio flux density.

2.3. X-Ray Data Analysis

We also did not detect the supernova at 542 days post-explosion in NASA *Chandra* images, with a limit on the 0.3-10 keV luminosity of $L_X < 2 \times 10^{38}$ ergs/s. We can convert the limit on luminosity to a limit on mass loss at this epoch. Using the cooling formulas detailed in Chevalier & Fransson (2017) (equations 14/18), we find from the mass-loss rate inferred from radio modeling ($< 0.0025 M_{\odot} \text{ yr}^{-1}$) that at 542 days, the reverse shock will be adiabatic and there will no longer be significant absorption from the dense shell between the shocks. We thus can use equation 3.10 from Fransson et al. (1996)

Table 1. SN 2023fyq fitting results

Epoch (Days)	K_1 (FFA)	K_2 (FFA)	ρ_{FFA} (g/cm ³)	B (G)*	R (cm)*	α (FFA)
58	$0.055^{+0.021}_{-0.027}$	$0.0023^{+0.0002}_{-0.0002}$	$5.0^{+0.6}_{-0.2} \times 10^{-18}$	0.408	4.26×10^{15}	$1.46^{+0.36}_{-0.36}$
125	$0.029^{+0.006}_{-0.008}$	$0.0019^{+0.0007}_{-0.0008}$	$1.3^{+0.4}_{-0.3} \times 10^{-18}$	0.180	9.18×10^{15}	$1.29^{+0.22}_{-0.27}$
139	$0.041^{+0.016}_{-0.016}$	$0.0038^{+0.0014}_{-0.0016}$	$1.3^{+0.2}_{-0.3} \times 10^{-18}$	0.193	1.02×10^{16}	$0.97^{+0.26}_{-0.32}$
165	$0.054^{+0.019}_{-0.018}$	$0.0066^{+0.0025}_{-0.0020}$	$1.2^{+0.4}_{-0.5} \times 10^{-18}$	0.187	1.21×10^{16}	$0.85^{+0.20}_{-0.25}$
185	$0.033^{+0.01}_{-0.01}$	$0.0047^{+0.0028}_{-0.0028}$	$8.2^{+4.3}_{-6.3} \times 10^{-19}$	0.153	1.36×10^{16}	$0.84^{+0.18}_{-0.17}$

NOTE—Starred values (*) are fixed from the FFA single-epoch fit + assumed shock velocity (using equations 6/7 and 9) and thus are not reported with associated error bars. All FFA parameters are from single-epoch fits with equation 1 with frozen $\delta = 3/\beta = 1.86$. We fixed $K_1 < 0.25$ at the first epoch due to unphysically large values obtained from fits where it was not constrained.

(which gives the prediction for the 1 keV reverse shock spectral luminosity given some mass-loss rate) to find the mass-loss limit given the limit on the X-ray luminosity. Assuming a 5 keV temperature of the shock, the 8500 km/s shock speed, and converting our X-ray 0.3-10 keV luminosity to a spectral luminosity, we find $\dot{M} < 3 \times 10^{-3} M_{\odot} \text{yr}^{-1}$. This is consistent with the limit obtained at radio wavelengths at a similar epoch.

3. INTERPRETATIONS

The detection of radio emission from SN 2023fyq allows for the first constraints on mass-loss up to 8 years pre-explosion in a SN Ibn. There are two clear results from our modeling:

1. The best-fit model to the radio emission suggests mass loss at a rate $\sim 0.004 M_{\odot} \text{yr}^{-1}$ from 0.7–3 years before the explosion for a CSM velocity of 1700 km/s as measured in optical spectra (Dong et al. 2024). This mass-loss rate translates to constraints on CSM density from $(0.4\text{--}1.4) \times 10^{16}$ cm.
2. The non-detections at $\Delta t = 525$ days suggest that there was a drop in CSM density at $R \sim 2 \times 10^{16}$ cm (suggesting a drop by a factor > 2 in progenitor mass-loss rate). This is confirmed by an X-ray non-detection at $\Delta t = 542$ days, which gives a similar limit on the mass-loss rate and implies a shell-like CSM.

From an analysis of the optical spectroscopy and lightcurves, Dong et al. (2024) and Brennan et al. (2024) determined that SN 2023fyq was surrounded by a highly dense torus of CSM created by intensive mass loss (at a rate of $\sim 1 M_{\odot} \text{yr}^{-1}$) in the last 40 days before explosion that caused the sharply rising precursor emission. Assuming our CSM speed of 1700 km/s, this would only create CSM out to $R \approx 3 \times 10^{15}$ cm, which is a smaller radius than the CSM radius at any epoch at which we

obtained detections. The authors also suggest that there was further mass loss at earlier times before the explosion caused by less intensive precursor outbursts that may have created a shell of less dense CSM (with no specifics on the density) at larger radii ($R \gtrsim 3 \times 10^{15}$ cm). This shell could correspond to the material traced by our radio observations, whereas the mass loss immediately preceding the explosion may have caused strong radio absorption consistent with our early non-detections up to $\Delta t = 58$ days ($R \lesssim 4 \times 10^{15}$ cm).

On the nature of the progenitor, Dong et al. (2024) concluded that SN 2023fyq was a helium star in a binary system with a compact object which either merged or experienced runaway core collapse very close to explosion. This merger-precursor scenario has been considered and modeled in detail by Tsuna et al. (2024), and the mass-loss rate we measure in these initial phases up to 1 year pre-explosion is generally consistent with the mass-loss values they find. However, it does not match the increase in mass-loss rate (as we assume a standard r^{-2} profile given that our data do not fully constrain the density profile) as seen in Figure 1. This short mass-loss timescale (< 10 years before the explosion) is common in type Ibn supernovae (Smith 2014), and the merger scenario does provide a clear explanation in this case for why the mass-loss would only occur at an elevated rate for such a limited time frame.

In more detail, the sharp drop in CSM density at 2×10^{16} cm is only feasible in a scenario where there were limited mass ejections or some late-stage mass loss explicitly triggered by changes in the progenitor system. The merger model can account for the uptick in mass loss, with the beginning of mass-loss caused by the onset of non-conservative mass transfer preceding merger (Tsuna et al. 2025, 2024). The mass-loss rate measured from 0.7-3 years at $0.004 M_{\odot} \text{yr}^{-1}$ is, in fact, relatively low (by an order of magnitude) compared to

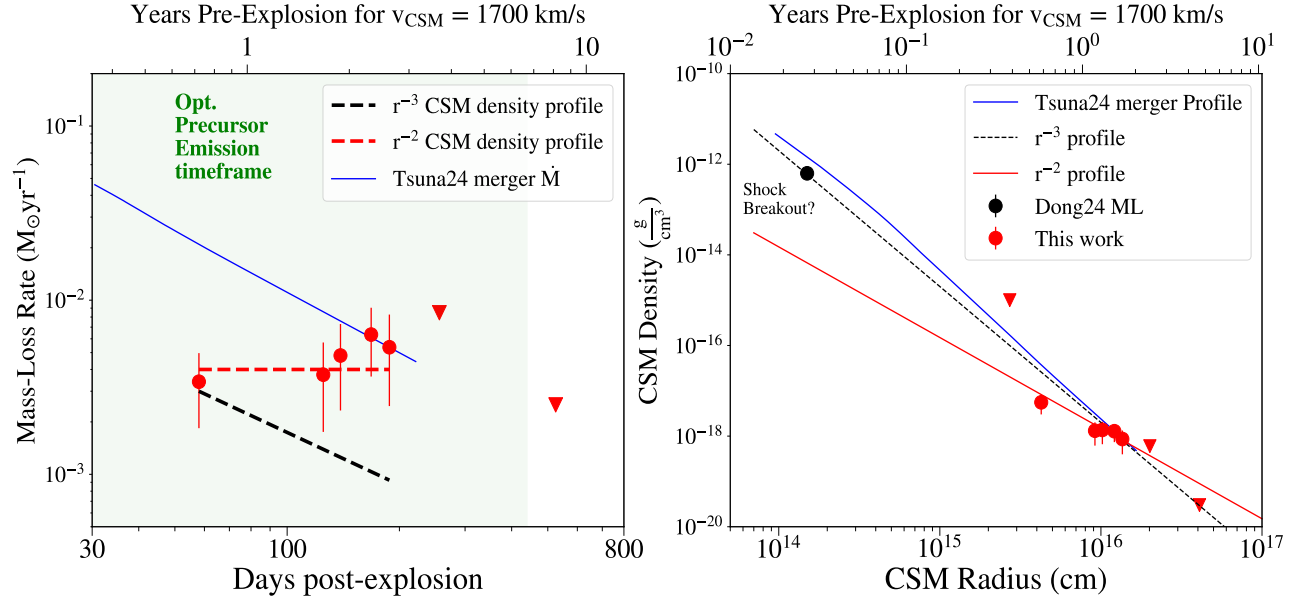


Figure 1. The mass-loss picture of SN 2023fyq that we derive based on our radio modeling. *Left* : Derived effective mass-loss rate as a function of days after explosion, as well as years before explosion, assuming the observed CSM speed of 1700 km/s. We denote the period over which optical precursor emission (at $S/N > 3$) was detected (Brennan et al. 2024) to illustrate how the precursor outbursts may have been creating the CSM we observe in the radio. No precursor data could be obtained beyond 7 years before the explosion, since the ZTF/ATLAS surveys have not started then. *Right* : CSM density associated with the mass-loss rate as a function of the CSM radius. We also show r^{-3} & r^{-2} density profiles along with profiles from merger simulations by Tsuna et al. (2024). Our data suggests enhanced mass-loss with a sudden drop between 5-8 years before the explosion revealed by our upper limit. We emphasize that some jump in density, potentially due to shock breakout, would be needed to consistently explain our datapoints and the early datapoint from (Dong et al. 2024) in the r^{-2} case. Our last 3σ upper limits are consistent with the Tsuna et al. (2024) density profile extrapolation, given that this profile assumes that the mass loss starts directly at 4 years before the explosion (for our assumed CSM speed).

the huge outbursts from mass ejections seen in SN 2006jc or 2022ablq, which may suggest that the merger model for SN 2023fyq is more likely than mass ejections. The elevated mass-loss just before the explosion, suggested by the rise in precursor emission seen at optical wavelengths in the last 40 days, also means that there would have to have been multiple outbursts at varying mass-loss rates in the ejection scenario. Additionally, the consistent optical emission over > 5 years suggests continuous energy injection and perhaps disfavors the ejection scenario (Dong et al. 2024). Given the extremely short timescale and the high mass-loss rate, a stellar wind cannot explain our measurements. However, our data cannot explicitly distinguish between distinct ejections leading to the optical/radio discrepancy at different times or a continuous outflow driven by the merger inspiral, given the cadence of our data/uncertain constraints on density profile. We also note that our data does not fully distinguish between our preferred CSM shell vs. torus/clumps; however, clumps would be expected to give rise to elevated X-ray emission/a potentially shallower density profile that we do not see.

The timescale of mass loss in SN 2023fyq differs from other SNe Ibn with confirmed multi-wavelength emission that allowed for a constraint on the mass-loss evolution across time. In SN 2006jc, detailed modeling of the X-ray light curve and the optical data revealed a massive outburst two years before explosion at $\dot{M} \sim 10^{-2} M_{\odot}\text{yr}^{-1}$ that was preceded by extremely quiescent mass-loss at > 5 orders of magnitude lower (Tominaga et al. 2008). SN 2022ablq revealed even more intensive mass loss at $\dot{M} \sim 10^{-1} M_{\odot}\text{yr}^{-1}$ for the 2-3 years pre-explosion (Pellegrino et al. 2024).

While the mass-loss rate has ramped up pre-explosion in SN 2023fyq as shown by the optical analysis (Dong et al. 2024; Brennan et al. 2024), the radio results suggest the increase was only by ≈ 2 orders of magnitude. It thus seems that the mass loss acted on a different timescale and at a different magnitude in SN 2023fyq, emphasizing that SNe Ibn can originate from a wide range of progenitor channels. While initially it was thought that most SNe Ibn came from Wolf-Rayet stars (Pastorello et al. 2016), certain objects showed potential evidence for more exotic progenitors such as white dwarf binary systems (Sanders et al. 2013). Other work has

suggested that certain pair instability supernovae could appear as SNe Ibcn with hydrogen-free ejecta (Woodsley 2017; Renzo et al. 2020) due to the intense mass ejections.

SN 2023fyq is the first type Ibcn object to be detected in the radio, but it is not the first object for which observations were attempted. SNe Ibcn 2019aaajs and SN 2019qav were observed but not detected with the VLA and NOEMA (IRAM Northern Extended Millimeter Array) from 15-400 days post-explosion at 10/90 GHz (Ho et al. 2023). SN 2020bqj was observed but not detected with AMI-LA at 15.5 GHz at 6 days post-explosion (Kool et al. 2021). SN 2015G (Shivvers et al. 2017) and the aforementioned SN 2006jc (Soderberg 2006) were both observed at VLA frequencies from 4–22 GHz at ~ 1 week for SN 2006jc and out to 120 days for SN 2015G. The dates of discovery/explosion are taken from optical estimates for all of these SNe.

For SN 2015G, the non-detection was analyzed to obtain a limit on the mass-loss rate at $< 10^{-4} M_{\odot} \text{yr}^{-1}$, while for SNe 2006jc, 2019aaajs, 2019qav and 2020bqj the results were less constraining, given that the non-detections were either early at 7-40 days post-explosion or were at a high luminosity limit given the large distance to the SN. SN 2015G had a 10 GHz non-detection at $3 \times 10^{25} \text{erg s}^{-1} \text{Hz}^{-1}$ at 120 days, which is a factor of 5 below the luminosity of the 10 GHz detection of SN 2023fyq at 125 days. We display the radio light curve of SN 2023fyq and the upper limits for the other SNe Ibcn in Figure 3. The fact that the SN 2015G radio emission must have been at least one order of magnitude less luminous implies that 2015G may come from a progenitor with a different mass-loss history.

When comparing with other interacting SNe, SN 2023fyq is less luminous and peaks slightly earlier than most radio-detected SNe Ibcn as shown in Figure 2. Another difference from SNe Ibcn is in the non-detections at later times and/or potentially steeper density profile. While SN 2023fyq may have experienced mass loss for longer than other SNe Ibcn, it appears that it definitely did not lose mass at enhanced rates on the decade-centuries timescales that SNe Ibcn do (see i.e. Smith (2017)). SN 2023fyq provides compelling evidence for continuing to observe a larger sample of SNe Ibcn at radio wavelengths to try to understand the subclass.

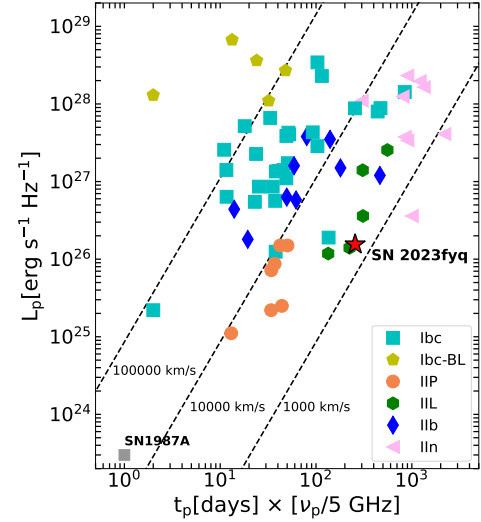


Figure 2. The peak spectral luminosity vs. peak time for SN 2023fyq (taken at 10 GHz) in context with a variety of other radio-detected SNe (Nayana et al. (2025) and references therein). The speeds noted on diagonal lines are shock velocities for pure SSA. 2023fyq is distinct from most other stripped-envelope SNe, likely due to denser CSM, but does not reach the peak spectral luminosity of many SNe Ibcn.

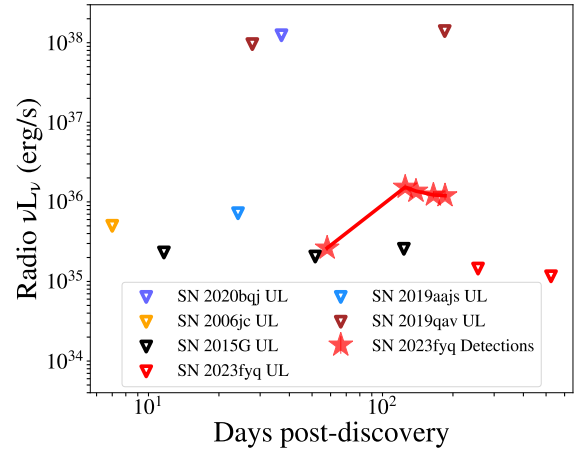


Figure 3. A view of all previous radio-observed type Ibcn SNe and the upper limits on luminosities, including 10 GHz detections and non-detections for SN 2023fyq. Non-detections are shown with downward-facing triangles, and are all 3σ limits.

4. CONCLUSIONS

We observed SN 2023fyq from 1–35 GHz with the VLA and GMRT over 1.5 years post-explosion. We also analyzed data over the same time period at X-ray wavelengths from *Swift-XRT* and *Chandra* (finding

non-detections). Our detections at radio wavelengths constitute the first ever radio detection and long-term radio follow-up of a type Ibn supernova. We obtain constraints on the mass-loss rate from the best-fitting free-free absorbed + intrinsic synchrotron self-absorbed models. The magnitude of the mass-loss rate and CSM density/upper limits measured suggest a drop in CSM density at $\sim 2 \times 10^{16}$ cm that can be explained by enhanced ($\sim 4 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$) mass loss that only occurred for roughly 5 years before the explosion and must have ramped up by ~ 2 orders of magnitude in the final months pre-explosion based on the optical evolution (Brennan et al. 2024; Dong et al. 2024). Our derived mass-loss history is roughly consistent with early mass-loss predictions from the binary merger scenario explored in depth by Tsuna et al. (2024). We emphasize that further monitoring of SNe Ibn at radio wave-

lengths within 1-2 years post-explosion is needed to constrain their progenitor systems and understand objects like SN 2023fyq in the context of the larger SN Ibn population.

5. ACKNOWLEDGMENTS

R.B.-W. and P.C. acknowledge NASA award GO3-24056X. R.B.-W. acknowledges support from a VSGC Fellowship. M.M. and the METAL group at UVa acknowledge support in part from ADAP program grant 80NSSC22K0486, from NSF grant AST-2206657, and from *HST* program GO-16656.

Facilities: GMRT, VLA, LBT, MMT, Lick Observatory, Keck, LCO, Chandra, Swift (XRT)

REFERENCES

- Baer-Way, R., Chandra, P., Modjaz, M., et al. 2025, ApJ, 983, 101, doi: [10.3847/1538-4357/adc00a](https://doi.org/10.3847/1538-4357/adc00a)
- Bietenholz, M. F., Bartel, N., Argo, M., et al. 2021, ApJ, 908, 75, doi: [10.3847/1538-4357/abccd9](https://doi.org/10.3847/1538-4357/abccd9)
- Bilinski, C., Smith, N., Li, W., et al. 2015, MNRAS, 450, 246, doi: [10.1093/mnras/stv566](https://doi.org/10.1093/mnras/stv566)
- Brennan, S. J., Sollerman, J., Irani, I., et al. 2024, A&A, 684, L18, doi: [10.1051/0004-6361/202449350](https://doi.org/10.1051/0004-6361/202449350)
- Brethauer, D., Margutti, R., Milisavljevic, D., et al. 2022, ApJ, 939, 105, doi: [10.3847/1538-4357/ac8b14](https://doi.org/10.3847/1538-4357/ac8b14)
- Chandra, P. 2018, SSRv, 214, 27, doi: [10.1007/s11214-017-0461-6](https://doi.org/10.1007/s11214-017-0461-6)
- Chandra, P., Chevalier, R. A., Chugai, N., Milisavljevic, D., & Fransson, C. 2020, ApJ, 902, 55, doi: [10.3847/1538-4357/abb460](https://doi.org/10.3847/1538-4357/abb460)
- Chevalier, R. A. 1982, ApJ, 259, 302, doi: [10.1086/160167](https://doi.org/10.1086/160167)
- . 1998, ApJ, 499, 810, doi: [10.1086/305676](https://doi.org/10.1086/305676)
- Chevalier, R. A., & Fransson, C. 2017, in Handbook of Supernovae, ed. A. W. Alsabti & P. Murdin (Springer), 875, doi: [10.1007/978-3-319-21846-5_34](https://doi.org/10.1007/978-3-319-21846-5_34)
- Chiosi, C., & Maeder, A. 1986, ARA&A, 24, 329, doi: [10.1146/annurev.aa.24.090186.001553](https://doi.org/10.1146/annurev.aa.24.090186.001553)
- Dong, Y., Tsuna, D., Valenti, S., et al. 2024, ApJ, 977, 254, doi: [10.3847/1538-4357/ad8de6](https://doi.org/10.3847/1538-4357/ad8de6)
- Elias-Rosa, N., Pastorello, A., Benetti, S., et al. 2016, MNRAS, 463, 3894, doi: [10.1093/mnras/stw2253](https://doi.org/10.1093/mnras/stw2253)
- Foley, R. J., Smith, N., Ganeshalingam, M., et al. 2007, ApJL, 657, L105, doi: [10.1086/513145](https://doi.org/10.1086/513145)
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306, doi: [10.1086/670067](https://doi.org/10.1086/670067)
- Fransson, C., Lundqvist, P., & Chevalier, R. A. 1996, ApJ, 461, 993, doi: [10.1086/177119](https://doi.org/10.1086/177119)
- Gagliano, A., Berger, E., Villar, V. A., et al. 2025, ApJ, 978, 110, doi: [10.3847/1538-4357/ad9748](https://doi.org/10.3847/1538-4357/ad9748)
- Gal-Yam, A. 2017, in Handbook of Supernovae, ed. A. W. Alsabti & P. Murdin (Springer International Publishing AG), 195, doi: [10.1007/978-3-319-21846-5_35](https://doi.org/10.1007/978-3-319-21846-5_35)
- Gangopadhyay, A., Misra, K., Hiramatsu, D., et al. 2020, ApJ, 889, 170, doi: [10.3847/1538-4357/ab6328](https://doi.org/10.3847/1538-4357/ab6328)
- Gediman, B., Miller, J. M., Zoghbi, A., et al. 2024, ApJ, 966, 57, doi: [10.3847/1538-4357/ad2fa3](https://doi.org/10.3847/1538-4357/ad2fa3)
- Gupta, S., Caprioli, D., & Spitkovsky, A. 2024, ApJ, 976, 10, doi: [10.3847/1538-4357/ad7c4c](https://doi.org/10.3847/1538-4357/ad7c4c)
- Ho, A. Y. Q., Perley, D. A., Gal-Yam, A., et al. 2023, ApJ, 949, 120, doi: [10.3847/1538-4357/acc533](https://doi.org/10.3847/1538-4357/acc533)
- Hosseinzadeh, G., Arcavi, I., Valenti, S., et al. 2017, ApJ, 836, 158, doi: [10.3847/1538-4357/836/2/158](https://doi.org/10.3847/1538-4357/836/2/158)
- Immler, S., Modjaz, M., Landsman, W., et al. 2008, ApJL, 674, L85, doi: [10.1086/529373](https://doi.org/10.1086/529373)
- Jacobson-Galán, W. V., Dessart, L., Jones, D. O., et al. 2022, ApJ, 924, 15, doi: [10.3847/1538-4357/ac3f3a](https://doi.org/10.3847/1538-4357/ac3f3a)
- Jacobson-Galán, W. V., Dessart, L., Davis, K. W., et al. 2024, ApJ, 970, 189, doi: [10.3847/1538-4357/ad4a2a](https://doi.org/10.3847/1538-4357/ad4a2a)
- Khakpash, S., Bianco, F. B., Modjaz, M., et al. 2024, ApJS, 275, 37, doi: [10.3847/1538-4365/ad7eaa](https://doi.org/10.3847/1538-4365/ad7eaa)
- Kool, E. C., Karamahmetoglu, E., Sollerman, J., et al. 2021, A&A, 652, A136, doi: [10.1051/0004-6361/202039137](https://doi.org/10.1051/0004-6361/202039137)
- Langer, N. 2012, ARA&A, 50, 107, doi: [10.1146/annurev-astro-081811-125534](https://doi.org/10.1146/annurev-astro-081811-125534)

- Lundqvist, P., & Fransson, C. 1991, *ApJ*, 380, 575, doi: [10.1086/170615](https://doi.org/10.1086/170615)
- Maeda, K., & Moriya, T. J. 2022, *ApJ*, 927, 25, doi: [10.3847/1538-4357/ac4672](https://doi.org/10.3847/1538-4357/ac4672)
- Maeda, K., Nozawa, T., Sahu, D. K., et al. 2013, *ApJ*, 776, 5, doi: [10.1088/0004-637X/776/1/5](https://doi.org/10.1088/0004-637X/776/1/5)
- Margutti, R., Kamble, A., Milisavljevic, D., et al. 2017, *ApJ*, 835, 140, doi: [10.3847/1538-4357/835/2/140](https://doi.org/10.3847/1538-4357/835/2/140)
- Matheson, T., Filippenko, A. V., Chornock, R., Leonard, D. C., & Li, W. 2000, *AJ*, 119, 2303, doi: [10.1086/301352](https://doi.org/10.1086/301352)
- Modjaz, M., Gutiérrez, C. P., & Arcavi, I. 2019, *Nature Astronomy*, 3, 717, doi: [10.1038/s41550-019-0856-2](https://doi.org/10.1038/s41550-019-0856-2)
- Moriya, T. J., & Maeda, K. 2016, *ApJ*, 824, 100, doi: [10.3847/0004-637X/824/2/100](https://doi.org/10.3847/0004-637X/824/2/100)
- Nayana, A. J., Margutti, R., Wiston, E., et al. 2025, *ApJ*, 985, 51, doi: [10.3847/1538-4357/adc2fb](https://doi.org/10.3847/1538-4357/adc2fb)
- Ofek, E. O., Sullivan, M., Cenko, S. B., et al. 2013, *Nature*, 494, 65, doi: [10.1038/nature11877](https://doi.org/10.1038/nature11877)
- Ofek, E. O., Sullivan, M., Shaviv, N. J., et al. 2014, *ApJ*, 789, 104, doi: [10.1088/0004-637X/789/2/104](https://doi.org/10.1088/0004-637X/789/2/104)
- Pacholczyk, A. G. 1970, *Radio astrophysics. Nonthermal processes in galactic and extragalactic sources*
- Park, J., Caprioli, D., & Spitkovsky, A. 2015, *Phys. Rev. Lett.*, 114, 085003, doi: [10.1103/PhysRevLett.114.085003](https://doi.org/10.1103/PhysRevLett.114.085003)
- Pastorello, A., Mattila, S., Zampieri, L., et al. 2008, *MNRAS*, 389, 113, doi: [10.1111/j.1365-2966.2008.13602.x](https://doi.org/10.1111/j.1365-2966.2008.13602.x)
- Pastorello, A., Botticella, M. T., Trundle, C., et al. 2010, *MNRAS*, 408, 181, doi: [10.1111/j.1365-2966.2010.17142.x](https://doi.org/10.1111/j.1365-2966.2010.17142.x)
- Pastorello, A., Cappellaro, E., Inzerra, C., et al. 2013, *ApJ*, 767, 1, doi: [10.1088/0004-637X/767/1/1](https://doi.org/10.1088/0004-637X/767/1/1)
- Pastorello, A., Wang, X. F., Ciabattari, F., et al. 2016, *MNRAS*, 456, 853, doi: [10.1093/mnras/stv2634](https://doi.org/10.1093/mnras/stv2634)
- Pellegrino, C., Howell, D. A., Vinkó, J., et al. 2022, *ApJ*, 926, 125, doi: [10.3847/1538-4357/ac3e63](https://doi.org/10.3847/1538-4357/ac3e63)
- Pellegrino, C., Modjaz, M., Takei, Y., et al. 2024, *ApJ*, 977, 2, doi: [10.3847/1538-4357/ad8bc5](https://doi.org/10.3847/1538-4357/ad8bc5)
- Perley, D. A., Fremling, C., Sollerman, J., et al. 2020, *ApJ*, 904, 35, doi: [10.3847/1538-4357/abbd98](https://doi.org/10.3847/1538-4357/abbd98)
- Puls, J., Vink, J. S., & Najarro, F. 2008, *A&A Rv*, 16, 209, doi: [10.1007/s00159-008-0015-8](https://doi.org/10.1007/s00159-008-0015-8)
- Renzo, M., Farmer, R., Justham, S., et al. 2020, *A&A*, 640, A56, doi: [10.1051/0004-6361/202037710](https://doi.org/10.1051/0004-6361/202037710)
- Rybicki, G. B., & Lightman, A. P. 1979, *Radiative processes in astrophysics*
- Sanders, N. E., Soderberg, A. M., Foley, R. J., et al. 2013, *ApJ*, 769, 39, doi: [10.1088/0004-637X/769/1/39](https://doi.org/10.1088/0004-637X/769/1/39)
- Sargent, A. J., Fischer, T. C., Johnson, M. C., et al. 2024, *ApJ*, 961, 230, doi: [10.3847/1538-4357/ad11d4](https://doi.org/10.3847/1538-4357/ad11d4)
- Schröder, S. L., MacLeod, M., Loeb, A., Vigna-Gómez, A., & Mandel, I. 2020, *ApJ*, 892, 13, doi: [10.3847/1538-4357/ab7014](https://doi.org/10.3847/1538-4357/ab7014)
- Shivvers, I., Zheng, W., Van Dyk, S. D., et al. 2017, *MNRAS*, 471, 4381, doi: [10.1093/mnras/stx1885](https://doi.org/10.1093/mnras/stx1885)
- Smith, N. 2014, *ARA&A*, 52, 487, doi: [10.1146/annurev-astro-081913-040025](https://doi.org/10.1146/annurev-astro-081913-040025)
- Smith, N. 2017, *Interacting Supernovae: Types II_n and Ib_n* (Springer International Publishing), 403–429, doi: [10.1007/978-3-319-21846-5_38](https://doi.org/10.1007/978-3-319-21846-5_38)
- Smith, N., Foley, R. J., & Filippenko, A. V. 2008, *ApJ*, 680, 568, doi: [10.1086/587860](https://doi.org/10.1086/587860)
- Smith, N., Silverman, J. M., Chornock, R., et al. 2009, *ApJ*, 695, 1334, doi: [10.1088/0004-637X/695/2/1334](https://doi.org/10.1088/0004-637X/695/2/1334)
- Soderberg, A. 2006, *The Astronomer's Telegram*, 917, 1
- Soderberg, A. M., Chevalier, R. A., Kulkarni, S. R., & Frail, D. A. 2006, *ApJ*, 651, 1005, doi: [10.1086/507571](https://doi.org/10.1086/507571)
- Strotjohann, N. L., Ofek, E. O., Gal-Yam, A., et al. 2021, *ApJ*, 907, 99, doi: [10.3847/1538-4357/abd032](https://doi.org/10.3847/1538-4357/abd032)
- Tominaga, N., Limongi, M., Suzuki, T., et al. 2008, *ApJ*, 687, 1208, doi: [10.1086/591782](https://doi.org/10.1086/591782)
- Tsuna, D., Fuller, J., & Lu, W. 2025, arXiv e-prints, arXiv:2508.21116, doi: [10.48550/arXiv.2508.21116](https://doi.org/10.48550/arXiv.2508.21116)
- Tsuna, D., Wu, S. C., Fuller, J., Dong, Y., & Piro, A. L. 2024, *The Open Journal of Astrophysics*, 7, 82, doi: [10.33232/001c.123897](https://doi.org/10.33232/001c.123897)
- Weiler, K. W., Panagia, N., Montes, M. J., & Sramek, R. A. 2002, *ARA&A*, 40, 387, doi: [10.1146/annurev.astro.40.060401.093744](https://doi.org/10.1146/annurev.astro.40.060401.093744)
- Weiler, K. W., Sramek, R. A., Panagia, N., van der Hulst, J. M., & Salvati, M. 1986, *ApJ*, 301, 790, doi: [10.1086/163944](https://doi.org/10.1086/163944)
- Woosley, S. E. 2017, *ApJ*, 836, 244, doi: [10.3847/1538-4357/836/2/244](https://doi.org/10.3847/1538-4357/836/2/244)
- Woosley, S. E., Langer, N., & Weaver, T. A. 1993, *ApJ*, 411, 823, doi: [10.1086/172886](https://doi.org/10.1086/172886)
- Wu, S. C., & Fuller, J. 2022, *ApJL*, 940, L27, doi: [10.3847/2041-8213/ac9b3d](https://doi.org/10.3847/2041-8213/ac9b3d)
- Wu, S. C., & Tsuna, D. 2025, arXiv e-prints, arXiv:2507.19613, doi: [10.48550/arXiv.2507.19613](https://doi.org/10.48550/arXiv.2507.19613)