Polarization Signals of Luminous Supernovae by Jet-driven Bipolar Explosions Postprint

Authors: Xudong Wen, Zongkai Peng and He Gao

Date: 2025-06-13T16:50:50+00:00

Abstract

Superluminous supernovae (SLSNe) and luminous supernovae (LSNe) exhibit extreme luminosities, which require additional energy supply mechanisms such as central engines or circumstellar interaction. In the central-engine scenario, jets inject energy into the polar ejecta, modifying its evolution and shaping the explosion geometry. This study investigates the polarization signatures of jet-driven bipolar explosions in SLSNe/LSNe, where the asymmetric ejecta structure and differential photospheric evolution imprint distinct observational features. We develop a two-component ejecta model, consisting of fast-expanding polar ejecta (powered by jets) and slower equatorial ejecta. We find that polarization exhibits complex temporal evolution, where the ejecta geometry and flux asymmetry between the two regions jointly produce a double-peaked feature. In addition, the line opacity in the polar region further enhances the wavelength dependence of the polarization. Spectropolarimetric observations, particularly during early phases, can constrain the geometry and energy sources of SLSNe/LSNe, advancing our understanding of their explosion mechanisms.

Full Text

Preamble

Research in Astronomy and Astrophysics, 25:065016 (7pp), 2025 June https://doi.org/10.1088/1674-4527/add565 CSTR: 32081.14.RAA.add565 aaaaaaa Polarization Signals of Luminous Supernovae by Jet-driven Bipolar Explosions Xudong Wen[1,2], Zongkai Peng[1,2], and He Gao[1,2] [1] Department of Astronomy, Beijing Normal University, Beijing 100875, China; zkpeng@bnu.edu.cn, gaohe@bnu.edu.cn [2] Institute for Frontier in Astronomy and Astrophysics, Beijing Normal University, Beijing 102206, China Received

2025 April 4; revised 2025 April 22; accepted 2025 April 28; published 2025 June 2

Abstract

Superluminous supernovae (SLSNe) and luminous supernovae (LSNe) exhibit extreme luminosities that require additional energy supply mechanisms such as central engines or circumstellar interaction. In the central-engine scenario, jets inject energy into the polar ejecta, modifying its evolution and shaping the explosion geometry. This study investigates the polarization signatures of jet-driven bipolar explosions in SLSNe/LSNe, where the asymmetric ejecta structure and differential photospheric evolution imprint distinct observational features. We develop a two-component ejecta model, consisting of fast-expanding polar ejecta (powered by jets) and slower equatorial ejecta. We find that polarization exhibits complex temporal evolution, where the ejecta geometry and flux asymmetry between the two regions jointly produce a double-peaked feature. In addition, the line opacity in the polar region further enhances the wavelength dependence of polarization. Spectropolarimetric observations, particularly during early phases, can constrain the geometry and energy sources of SLSNe/LSNe, advancing our understanding of their explosion mechanisms.

Key words: (stars:) supernovae: general -polarization -methods: numerical

1. Introduction

Optical surveys have identified a growing population of exceptionally luminous transients, classified as superluminous supernovae (SLSNe) with peak r-band magnitudes of M_r < −20 and luminous supernovae (LSNe) with M_r = −19 to −20 (Gomez et al. 2022). These events, which are significantly brighter than ordinary core-collapse supernovae (CCSNe), exhibit unique observational characteristics that challenge CCSN models. The extreme luminosities and rapid optical evolution of SLSNe and LSNe require far more radioactive Ni than predicted by CCSN models, suggesting the existence of an additional energy supply mechanism (Nicholl et al. 2013). This has stimulated further exploration of the underlying astrophysical processes.

There are two primary channels commonly invoked to explain the observed lightcurves of SLSNe. The first involves the interaction of supernova ejecta with a dense circumstellar medium (Ginzburg & Balberg 2012). The thermalized shock energy is effectively trapped due to the high optical depth of the medium, and is eventually released through radiative diffusion, producing the observed extreme luminosity (Smith & McCray 2007; Woosley et al. 2007; Chevalier & Irwin 2011; Moriya et al. 2011). The second channel posits that the ejecta from a standard supernova explosion is continuously reheated by energy injection from a long-lived central engine. This engine could be a rapidly rotating, highly magnetized neutron star (Kasen & Bildsten 2010; Woosley 2010) or an accreting black hole (Dexter & Kasen 2013). Both mechanisms provide plausible explanations for the extreme brightness and prolonged emission observed in SLSNe (Liu et al. 2017; Nicholl et al. 2017; Yu et al. 2017). Some SLSNe exhibit characteristics of both interaction-driven and central-engine-powered mechanisms (Wang et al. 2016), though the exact nature of the energy source remains an active area of investigation. In the latter scenario, some studies suggest that formation of the central engine likely involves the launch of jets during the explosion, and in some cases, these jets may also be emitted post-explosion, potentially carrying significant additional energy (Soker 2016, 2017; Kaplan & Soker 2020a).

Jets can significantly alter the geometry of the ejecta, as evidenced by observations of bipolar protrusions ("Ears") in images of certain CCSNe, as well as by the detection of polarization in some CCSN events (Wang et al. 2001; Maund et al. 2007; Milisavljevic et al. 2013; Inserra et al. 2016; Mauerhan et al. 2017). Kaplan & Soker (2020a) developed a toy model of jet-driven bipolar ejecta, demonstrating that the rapid evolution of the photosphere in the polar regions can lead to a sharp decline in the lightcurve or, in some cases, the formation of a distinct "knee" feature. This model provides a plausible explanation for the observed rapid lightcurve evolution in SLSN 2020wnt and LSN 2018don (Kaplan & Soker 2020b; Soker 2022). Polarimetry provides a powerful diagnostic of the SN explosion geometry (Shapiro & Sutherland 1982; Höflich 1991; Kasen et al. 2003; Wang & Wheeler 2008). Jet-driven bipolar ejecta exhibit faster evolution in the polar regions compared to the slower-evolving equatorial ejecta. This two-component radiation would produce an observable polarization signal that is dependent on the viewing angle and the distribution of the emitting zone on the photosphere (Wen et al. 2023). In this study, we construct a toy model of a bipolar explosion (Section 2) and subsequently estimate the resulting lightcurves and polarization signatures (Section 3). In our conclusion, we discuss how polarization can serve as a powerful diagnostic tool for identifying bipolar explosions.

2.1. Luminosity

We follow the toy model proposed by Kaplan & Soker (2020a), which assumes that jets enhance the energy of the polar ejecta. We simplify the ejecta by dividing it into two distinct regions, both expanding as part of a spherical explosion but with different energies. The polar ejecta, characterized by a half-opening angle of (measured from the symmetry axis), can be treated as a portion of a spherical explosion with mass M_ej = 13M_ , which carries a very high explosion energy E_po. The mass and energy of the polar ejecta are treated as independent parameters respectively. The expanding equatorial ejecta can also be seen as part of a spherical explosion with mass M_ej, but with a relatively low explosion energy E_eq. The mass and energy of the equatorial ejecta are similarly treated as independent parameters respectively.

The ejecta density profiles in the two regions follow a spherical explosion with energy E_ej and mass M_ej. Following Matzner & McKee (1999), we adopt a broken power law to describe the radial density profile of the SN ejecta, i.e.,

$$\rho_{SN}(r,t) = \begin{cases} \frac{1}{4\pi(n-\delta)} \frac{M_{ej}}{R_{tr}^3} \left(\frac{r}{R_{tr}}\right)^{-n} & \text{for } r > R_{tr} \\ \frac{1}{4\pi(n-\delta)} \frac{M_{ej}}{R_{tr}^3} \left(\frac{r}{R_{tr}}\right)^{-\delta} & \text{for } r < R_{tr} \end{cases}$$

where the transition radius R_tr of the ejecta is expressed as

$$R_{tr} = \left[\frac{3(3-\delta)(n-3)}{4\pi(3-n)}\right]^{1/3} \left(\frac{M_{ej}}{\rho_{core}}\right)^{1/3}$$

The coefficients can be obtained from the normalized continuity condition, namely

$$\int_0^\infty 4\pi r^2 \rho_{SN}(r,t) dr = M_{ej}$$

For a red supergiant progenitor, the typical values of the density power indices are = 1, n = 12 (Matzner & McKee 1999). The radius of the photosphere R_ph satisfies

$$R_{ph} = \frac{2}{3} \frac{1}{\kappa \rho_{SN}(R_{ph}, t)}$$

Since the polar ejecta has higher energy and lower density, the polar photosphere initially expands more rapidly and then begins to recede more quickly than the equatorial photosphere.

After the progenitor star experiences an explosion, a rapidly rotating magnetar is formed. This magnetar loses rotational energy through a magnetic dipole spin-down process and has a luminosity of

$$L_{mag}(t) = \frac{L_{mag,i}}{(1 + t/t_{sd})^2}$$

where the initial luminosity is

$$L_{mag,i} = \frac{E_{rot,i}}{t_{sd}}$$

and the spin-down timescale is

$$t_{sd} = \frac{3Ic^3}{B^2 R^6 \Omega_i^2}$$

where B, I, R are the polar magnetic field, the moment of inertia, and the radius of the magnetar. For ejecta in the polar region, we calculate the luminosity produced from magnetar heating by the standard SN diffusion equation that includes the effects of gamma-ray leakage

$$L_{po}(t) = \frac{2}{3}\frac{1}{\kappa_{po}}\frac{R^2_{ph,po}}{t^2_{d,po}}\int_0^t \frac{L_{mag}(t')}{1+t/t_{d,po}}e^{-(t-t')/t_{d,po}}dt'$$

where gamma-ray leakage and _ ,po is the effective gamma-ray opacity for the polar ejecta (Arnett 1982). The effective diffusion time is

$$t_{d,po} = \sqrt{\frac{2\kappa_{po}M_{ej,po}R_{ph,po}}{13.8v_{po}c}}$$

accounts ej,po where _po is the opacity of the polar ejecta, = 13.8 is a constant for the density distribution of the ejecta, v_po is the velocity of the polar ejecta (Nicholl et al. 2017). Similar to Equation (8), the lightcurve from the equatorial direction can be written as

$$L_{eq}(t) = \frac{2}{3}\frac{1}{\kappa_{eq}}\frac{R^2_{ph,eq}}{t^2_{d,eq}}\int_0^t \frac{L_{mag}(t')}{1+t/t_{d,eq}}e^{-(t-t')/t_{d,eq}}dt'$$

The effective diffusion timescales in Equation (10) have the same expression as in Equation (8), and only require replacing _po, M_ej, v_po with the opacity of the equatorial ejecta _eq, M_ej and the velocity of the equatorial ejecta v_eq.

Research in Astronomy and Astrophysics, 25:065016 (7pp), 2025 June Wen, Peng, & Gao Table 1 Elemental Abundances

2.2. Polarization

We performed three-dimensional calculations of the polarization evolution using a Monte Carlo polarization simulation code (Wen et al. 2023). Each photon packet carries polarization information which can be described by a useful convention, namely the Stokes vector S = (I, Q, U, V), where I gives the total intensity, Q and U describe the linear polarization, and V specifies the state of circular polarization.

Since the signal of the V component has not yet been observed, implying that the projectile does not have a strong magnetic field (Kasen et al. 2003), we ignore the V component in our calculations in this paper. The polarization degree (P) and the position angle ( ) can then be given in terms of the Stokes parameters, namely

$$P = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi = \frac{1}{2} \arctan \frac{U}{Q}$$

For the sake of convenience, for the case of the orthogonal components of U, which is balanced in the projection plane along the line-of-sight to the observer, the polarization degree can be simplified to P = Q/I.

Unpolarized photon packets are emitted from the photosphere with random propagation directions and propagate through the medium. Following the prescriptions in previous studies (e.g., Mazzali & Lucy 1993; Code & Whitney 1995; Lucy 1999; Kasen et al. 2003; Whitney 2011; Bulla et al. 2015), photon packets with zero polarization were prepared at the emitting layer, whose initial traveling directions were set randomly. For a photon packet traveling through the medium, a certain probability of electron scattering is assigned. When electron scattering occurs, the polarization state and the direction of propagation of the photon packet after being scattered will be calculated, following which the photon packet continues to propagate in the new direction. The line interaction will have a depolarizing effect on the photon packet. We set the electron scattering opacity in the two ejecta regions to be $= 0.1$ cm^2 g^{1} and estimate the line opacity distribution from the TARDIS radiative transfer code (Kerzendorf & Sim 2014). We used the composition of ejected material proposed by Mazzali et al. (2016) as shown in Table 1. We destroy the photon packages that enter the interior of the photosphere. For photon packets in the computational domain outside the photosphere, we treat them as free to propagate in two regions. The observer frame was set at 100 Mpc from the SN center. The final collection of the photon packets is carried out within each $1° \times 180°$ latitudinal bin.

3. Results

In the case of a central energy source with isotropic radiation, the evolution of the luminosity mainly depends on the dynamics of the two ejecta, which in turn depends on the mass and energy of each region of the ejecta, as well as on the half-opening angle that divides the two ejecta regions. To facilitate comparison with observed SLSN (SN 2015bn), we adopt a parameter set consistent with SN 2015bn observational data (Inserra et al. 2016): E_po = 5×10^{2} erg, E_eq = 5×10^{1} erg, $= 35°$, R = 10 cm, I = 10 g cm^2, B = 0.2×10^1 G, and the rotation period of the magnetar P_mag = 1.7 ms.

Figure 1 [Figure 1: see original paper] illustrates the dynamical evolution of the photosphere. Initially, the ejecta in the polar region expanded outwards more rapidly than the ejecta in the equatorial region. Subsequently, because of its higher kinetic energy, the polar photosphere began to recede earlier than the equatorial photosphere. This differential evolution continued until about 180 days after the explosion, when the polar photosphere receded inwards to within the radius of the equatorial photosphere.

Each of the two regions produces different luminosity levels. The evolution of the luminosity of each region is shown in Figure 2 [Figure 2: see original paper]. The rapid evolution of the polar region ejecta results in a rapid early reduction and a steep post-peak drop of the luminosity. The total luminosity (L_eq + L_po) of the two regions has a weak enhancement compared to the luminosity produced from the equatorial region (L_eq) before the peak. The observed lightcurve is strongly dependent on the viewing angle (_los, 0° from the north pole) as shown in Figure 3 [Figure 3: see original paper]. A higher peak level will be observed from the equatorial direction due to the larger projection area of the two regions than that observed from _los = 0°. The lightcurve along the _los = 0° viewing direction exhibits a "shoulder" or plateau feature before the peak of its time evolution. The "shoulder" is primarily dominated by the rapidly brightening photosphere from the polar regions, where the large expansion area of the polar photosphere partially obscures the equatorial region, resulting in only a fractional luminosity contribution from the latter. As the polar photosphere expansion velocity and its luminosity decline, the dominant radiative contribution shifts toward the redder spectral bands. Around 100 days, continued expansion of the photosphere and increased luminosity in the equatorial region provide an additional contribution to the flux, leading to the peak. The spectra of the two regions are predominantly distributed at the blue end of the spectrum during the lightcurve peak, until the spectra start to evolve toward the red end after 150 days (shown in Figure 4 [Figure 4: see original paper]).

The level of polarization strongly depends on the viewing angle, the luminosity levels of the two regions, and the geometry of the ejecta. In contrast to the lightcurve, polarization exhibits a very rich variation in the time evolution from the beginning (as shown in Figure 5 [Figure 5: see original paper]). At early times, the rapidly expanding polar ejecta makes the whole ejecta geometry exhibit a bipolar-long equatorial-narrow shape. During this phase, there is no significant flux asymmetry between the two regions, so this polarization is mainly due to geometric effects. When the polar region luminosity reaches its peak, a significant flux asymmetry between the two regions leads to a decrease in polarization. The rapid decrease in luminosity in the polar region is accompanied by a corresponding significant increase in polarization. During this phase, while the global ejecta geometry remains largely unchanged, the relative luminosity contribution shifts substantially as the polar regions fade and the equatorial emission brightens, ultimately causing the equatorial component to dominate both the polarization level and its sign. After the luminosity peak in the equatorial region (about day 100), the luminosity and temperature differences between the two regions do not increase, and the radiative flux is mainly contributed by the equatorial region. At this point, the polarization level evolves in the direction of a positive sign due to the flux from the equatorial region. As the polar region photosphere recedes, the geometry of the whole ejecta gradually changes to a bipolar concave equatorial oblate shape, at which point the polarization starts to be dominated by the geometry and is maximal in the direction of _los = 90°. As the equatorial photosphere continues to expand, the level of polarization gradually begins to increase.

The polarization level is significantly dependent on the viewing angle. As shown in Figure 5 [Figure 5: see original paper], the polarization level tends to be minimum with _los = 0° and reaches a maximum in the equatorial direction. This is due to the fact that under the axisymmetric assumption, the geometry of the ejecta gradually converges to a symmetric disk shape when viewed from the polar direction, which causes the polarization vectors in each direction to cancel each other out, eventually resulting in no significant net polarization. Therefore, a significant geometry in the equatorial direction leads to a net polarization and reflects an upper limit of the polarization level.

Line opacity depends on wavelength, which can affect the dependence of polarization with wavelength to some extent. We used TARDIS to calculate the value of the Sobolev optical depth for each transition in each region, and used this to calculate a table of wavelength-dependent expansion opacities. For instance, the opacity of the layer near the photosphere on day 75 is shown in Figures 6 and 7 [Figure 6: see original paper] [Figure 7: see original paper]. In our calculations, we use a polynomial fit to the line opacity distribution to represent the pseudo-continuous absorption component. The polar region ejecta has the same level of opacity at the blue end of the spectrum as electron scattering. The opacity of equatorial ejecta has a weak wavelength dependence in the visible wavelength band. Under the effect of line opacity depolarization, the polarization exhibits a wavelength dependence (shown in Figure 8 [Figure 8: see original paper]). The blue end of the spectrum is affected by the higher line opacity from the polar region, resulting in a decrease in polarization level. The red end of the spectrum is weakly affected by depolarization and produces a higher polarization degree from the geometry. However, wavelength dependence has an additional contribution from the flux difference between the two regions in addition to the effect of line absorption. The low-temperature polar photosphere contributes polarized photons mainly to longer wavelength bands, while more polarized photon energy in the equatorial region is distributed at shorter wavelengths. We compute the wavelength-dependent polarization distribution governed by both photospheric geometry (P__geo) and flux asymmetry (P__flux) between the two regions (red curve in Figure 8 [Figure 8: see original paper]). The blue curve in Figure 8, representing purely geometry-induced polarization, demonstrates significant blue-band depolarization caused by line absorption, while maintaining nearly constant polarization level across 5000–9000 Å. We shift the blue line in Figure 8 to the red line for comparison (as shown by the green curve in the figure), and we find that the flux asymmetry between the two regions introduces an additional polarization component, leading to an increase in the net polarization in the blue band.

4. Conclusions

This study explores the polarization signatures of SLSNe and LSNe arising from bipolar ejecta driven by a central engine. By constructing a toy model that divides the ejecta into distinct polar and equatorial regions with differing energies, we simulate the dynamical evolution of the photosphere, lightcurve behavior, and polarization characteristics. The polar ejecta, characterized by higher energy, exhibit rapid expansion and early recession compared to the slower-evolving equatorial ejecta. This differential evolution leads to a photospheric geometry that transitions from an initially prolate to an oblate structure, imprinting unique signatures on the observed lightcurves and polarizations. The total luminosity displays a mild post-peak decline compared to a spherical explosion, with viewing-angle-dependent features such as "shoulder" or plateau-like lightcurves when observed along the polar axis. Polarization serves as a powerful diagnostic of the ejecta geometry, revealing complex temporal evolution tied to the changing luminosity contributions and photospheric shapes.

During the phase when polar radiation dominates, the early peaks of polarization come from the geometry of the polar bulges. Subsequently, as the equatorial radiation flux increases and the polar radiation flux decreases, the overall polarization level begins to decrease. As the relatively faint photosphere in the polar regions continues to expand, a secondary polarization enhancement occurs. The wavelength-dependent polarization arises from line opacity variations between the polar and equatorial regions, exhibiting strongest depolarization in the blue band—a finding consistent with the polarization interpretation by Inserra et al. (2016). Furthermore, the flux asymmetry between these regions generates an additional polarization component. These findings highlight how spectropolarimetry can disentangle the geometric and radiative contributions to SLSNe emission, providing critical constraints on central engine models and jet-driven explosions.

Such polarization signatures become particularly discriminative when comparing different energy injection scenarios. Comparative analysis of polarization characteristics reveals a fundamental distinction between jet-driven and companion-fed SLSNe models (Gao et al. 2020). In the companion-fed scenario, where a black hole or neutron star injects energy through accretion feedback, it produces polarization peaks that are temporally coupled with either the lightcurve maximum or plateau phase—a direct consequence of the accretion processes. This characteristic timing behavior provides a clear observational discriminant from the polarization evolution predicted by jet-driven models. These results underscore the importance of polarization observations in distinguishing between competing energy sources for powering SLSNe. Future high-cadence polarimetric campaigns, particularly during the early phases of SLSN lightcurves, will be essential for testing the predicted signatures of bipolar ejecta. Additionally, advancements in radiative transfer modeling, incorporating more detailed treatments of line opacity and 3D ejecta structures, will refine the interpretation of polarization data. By further combining these tools with multi-wavelength observations, we can advance our understanding of the extreme physics governing SLSNe and their role in stellar evolution.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Projects 12373040 and 12021003), the National SKA Program of China (2022SKA0130100), and the Fundamental Research Funds for the Central Universities.

Research in Astronomy and Astrophysics, 25:065016 (7pp), 2025 June Wen, Peng, & Gao

References

Arnett, W. D. 1982, ApJ, 253, 785 Bulla, M., Sim, S. A., & Kromer, M. 2015, MNRAS, 450, 967 Chevalier, R. A., & Irwin, C. M. 2011, ApJL, 729, L6 Code, A. D., & Whitney, B. A. 1995, ApJ, 441, 400 Dexter, J., & Kasen, D. 2013, ApJ, 772, 30 Gao, H., Liu, L. D., Lei, W. H., et al. 2020, ApJL, 902, L37 Ginzburg, S., & Balberg, 2012, ApJ, 757, 178 Gomez, S., Berger, E., Nicholl, M., Blanchard, P. K., & Hosseinzadeh, G. 2022, ApJ, 941, 107 Höflich, P. 1991, A&A, 246, 481 Inserra, C., Bulla, M., Sim, S. A., & Smartt, S. J. 2016, ApJ, 831, 79 Kaplan, N., & Soker, N. 2020a, MNRAS, 492, 3013 Kaplan, N., & Soker, N. 2020b, MNRAS, 494, 5909 Kasen, D., & Bildsten, L. 2010, ApJ, 717, 245 Kasen, D., Nugent, P., Wang, Lifan, et al. 2003, ApJ, 593, 788 Kerzendorf, W. E., & Sim, S. A. 2014, MNRAS, 440, 387 Liu, L.-D., Wang, S.-Q., Wang, L.-J., et al. 2017, ApJ, 842, 26 Lucy, L. B. 1999, A&A, 345, 211 Matzner, C. D., & McKee, C. F. 1999, ApJ, 510, 379 Mauerhan, J. C., Van Dyk, S. D., Johansson, J., et al. 2017, ApJ, 834, 118 Maund, J. R., Wheeler, J. C., Patat, F., et al. 2007, MNRAS, 381, 201 Mazzali, P. A., & Lucy, L. B. 1993, A&A, 279, 447 Mazzali, P. A., Sullivan, M., Pian, E., Greiner, J., & Kann, D. A. 2016, MNRAS, 458, 3455 Milisavljevic, D., Soderberg, A. M., Margutti, R., et al. 2013, ApJL, 770, LL38 Moriya, T., Tominaga, N., Blinnikov, S. I., Baklanov, P. V., & Sorokina, E. I. 2011, MNRAS, 415, 199 Nicholl, M., Guillochon, J., & Berger, E. 2017, ApJ, 850, 55 Nicholl, M., Smartt, S. J., Jerkstrand, A., et al. 2013, Natur, 502, 346 Shapiro, P. R., & Sutherland, P. G. 1982, ApJ, 263, 902 Smith, N., & McCray, R. 2007, ApJL, 671, L17 Soker, N. 2016, NewA, 47, 88 Soker, N. 2017, ApJL, 839, L6 Soker, N. 2022, ApJ, 935, 108 Wang, L., & Wheeler, J. C. 2008, ARA&A, 46, 433 Wang, L. F., Howell, D. A., Höflich, P., & Wheeler, J. C. 2001, ApJ, 550, 1030 Wang, S. Q., Liu, L. D., Dai, Z. G., et al. 2016, ApJ, 828, 87 Wen, X.-D., Gao, H., Ai, S.-K., et al. 2023, ApJ, 955, 9 Whitney, B. A. 2011, BASI, 39, 101 Woosley, S. E. 2010, ApJL, 719, L204 Woosley, S. E., Blinnikov, S., & Heger, A. 2007, Natur, 450, 390 Yu, Y.-W., Zhu, J.-P., Li, S.-Z., et al. 2017, ApJ, 840, 12

Note: Figure translations are in progress. See original paper for figures.