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# Post-supernova Binary Interactions

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## Abstract

Binary evolution plays a key role in determining the properties of supernova progenitors, while supernova explosions can also significantly impact the evolution of the binary. In this paper I discuss several forms of binary interactions that happen immediately after supernova explosions and their observational consequences. I first discuss energy deposition into the companion envelope through ejecta–companion interaction, that can cause the star to temporarily inflate and become overluminous. I show that we can use this to constrain pre-supernova binary properties if we observe the inflated state of these companions and their later deflation. I then discuss direct collisions between new-born neutron stars and companion stars. Depending on the kick velocity and impact parameter, the neutron star can sometimes penetrate the companion envelope and capture part of the material, causing multiple bumps in the light curve through accretion feedback. I then briefly discuss how to combine these two studies to explain the undulations in the recently discovered SN2022jli.

**Keywords:** supernovae, binary stars, neutron stars

## 1. Introduction

Massive stars are primarily born in multiple systems, and therefore a significant fraction of core-collapse supernovae are expected to occur with the presence of a nearby companion. In particular, the majority of the hydrogen-deficient subtypes (type Ib/c, IIb supernovae) are considered to come from binary-stripped progenitors so should have closeby companion stars [1]. Indeed, there have been a handful of successful detections of surviving companions after stripped-envelope supernovae. These include type IIb SN1993J [2, 3], type IIb SN2001ig [4], type Ibn SN2006jc [5, 6], type IIb SN2011dh [7] and type Ib/c SN2013ge [8]. While there are some counter-examples like Cassiopeia A, which is a type IIb supernova remnant [9] without any trace of a surviving companion [10, 11] (see [12] for a possible binary evolution scenario

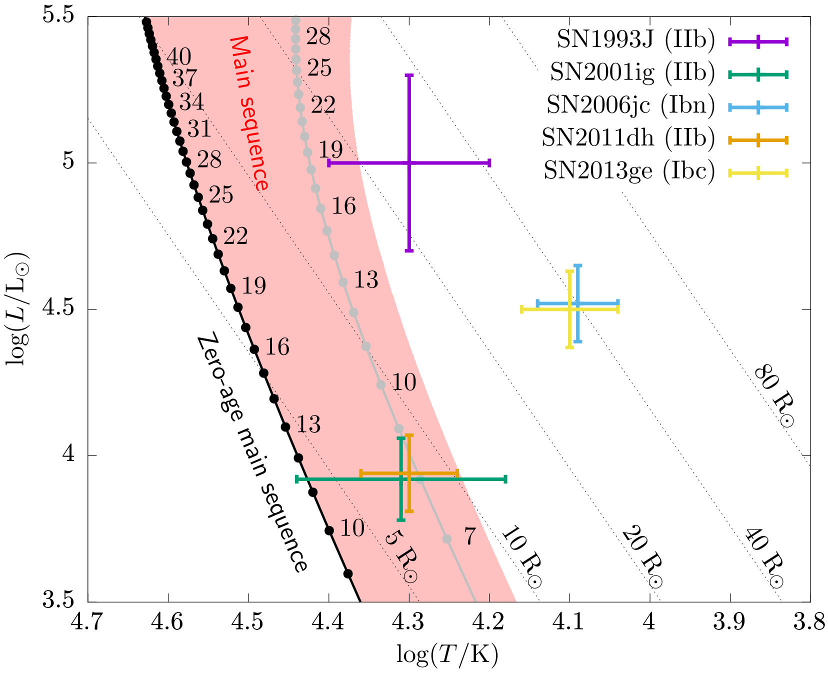

**Figure 1:** Location of detected stripped-envelope supernova companions on the Hertzsprung–Russell diagram. The black curve indicates the zero-age main sequence whereas the grey curve indicates the terminal-age main sequence, and the numbers are masses in solar units. The pink shaded region shows the area that can be covered by main-sequence stars. For SN2013ge, we added error bars similar to SN2006jc for visibility. Credit: Fig. 1 from [16] – CC BY 4.0.

for "lonely" stripped-envelope supernova progenitors), it seems that there is mounting evidence that the majority of stripped-envelope supernovae are occurring in tight binaries (e.g., [13, 14]).

In this paper, I summarize the possible forms of binary interactions that occur straight after supernova explosions in binary systems. This is distinct from traditional binary interactions (e.g. Roche lobe overflow, common-envelope evolution) in many ways, including its timescale and possible consequences. I focus mostly on the observable features from such binary interactions and how it can aid us in constraining binary evolution physics.

## 2. Ejecta–Companion Interaction

When plotted on the Hertzsprung–Russell diagram, some of the observed surviving companions have unexpected properties. Based on binary evolution models, it is expected that the majority of stripped-envelope supernova progenitor companions should be main-sequence stars [15] given the long evolutionary timescale. However, only two or three out of the five detected companions are consistent with being main-sequence stars and in fact the two type Ib/c supernova companions are located in the Hertzsprung gap (Fig. 1). While it is not completely implausible to have companions in this phase of evolution at the point of the first supernova and there is an observational bias against hotter stars, it is still surprising that nearly half of the detected companions are off the main sequence. That is, if these detected stars are regular stars. It could be that the companion is driven out of thermal equilibrium due to previous mass accretion and appears off the main sequence. If so, the mass accretion episode should have occurred within the last $\sim 10^4$–$10^5$ yr (thermal timescale) or so, to still be in an overluminous state, which only occurs in a rather limited parameter space. It is also possible that there is strong extinction due to pre-existing circumstellar material or newly formed dust, causing the star to appear redder. In this case, the intrinsic star could be consistent with being on the main sequence, although it requires much higher luminosities that may contradict the inferred masses from environmental analysis [17]. Here, I argue that "ejecta–companion interaction" may be the most natural explanation for this conundrum.

When a supernova occurs in a binary, the supernova ejecta inevitably collides with the companion star. Such interactions have been proposed to cause bumps in the early light curve as part of the kinetic energy is converted into radiation [18], and several candidates have been discovered for evidence of this occurring in type Ia supernovae. Another predicted feature is that the ejecta forms a shock that injects some energy into the outer layers of the companion envelope [19, 20]. Although the total injected energy is negligible compared to the total binding energy of the star, most of this energy is deposited close to the surface in a layer thin enough that the excess energy is comparable to the binding energy of that layer. This causes the star to swell up and become redder, just like someone who has been slapped in the face. Such supernova-induced envelope inflations may explain why some companions appear to be located off the main sequence in the redder regions. If this is the case, the companions should eventually shrink back to its original state once it radiates away the excess energy and regains thermal equilibrium.

To figure out the companion's response to supernova-heating, we first model the interaction between supernova ejecta and a main sequence companion star in axisymmetric 2D hydrodynamic simulations [19, 21] using the grid-based hydrodynamic code HORMONE [22]. From these simulations, we extract the excess entropy distribution in the companion and how it depends on input parameters like the explosion energy, ejecta mass and orbital separation. We then map that excess entropy distribution in the 1D stellar evolution code MESA [23–25] to follow the long-term evolution [19, 20].

As we can see from Fig. 2, the companion first immediately transitions to an inflated overluminous state. It stays in that state for a few years to decades before abruptly shrinking in radius. The luminosity also abruptly drops but not completely, as it tails off over a much longer duration towards its original luminosity. We find that the maximum luminosity achieved in the inflated state is related to the Eddington luminosity at the base of the surface convection zone, solely dependent on the companion mass, while the duration of envelope inflation strongly correlates with the amount of energy injected.

Based on our numerical models from [19, 20], I constructed an analytical model that accurately describes this companion response given the binary and explosion properties [16]. This allows us to solve the inverse problem in which we can derive the *pre*-supernova binary properties from the *post*-supernova companion photometry in a simple manner. By applying this

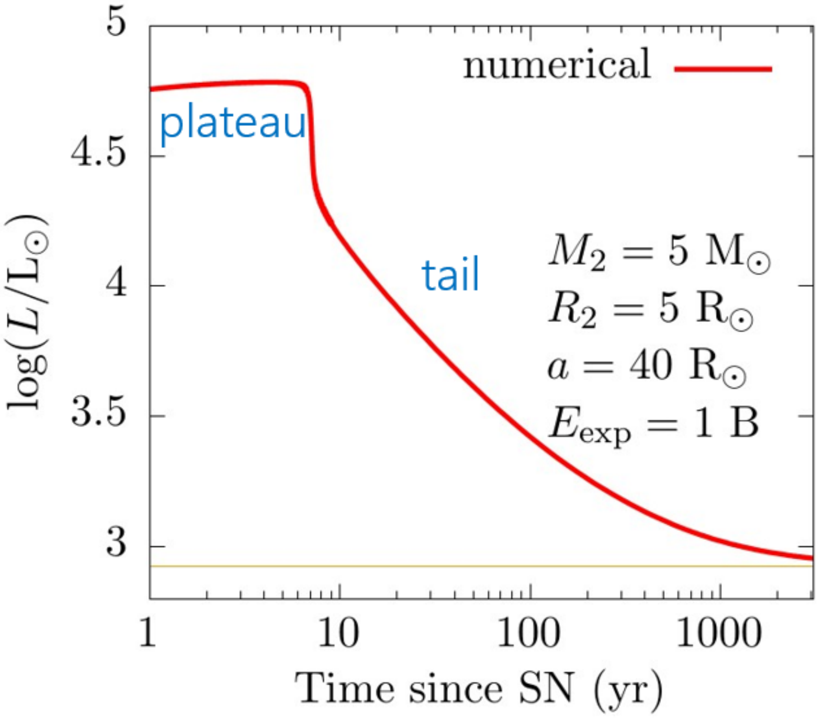

**Figure 2:** Example of the companion response to supernova-heating. The yellow line indicates the pre-supernova luminosity.

to the observed companions, we can constrain their binary properties as in Fig. 3. Combined with other clues like pre-supernova progenitor detections (the progenitor should be contained within its pre-supernova Roche lobe), we can further constrain the parameters as highlighted with star symbols. With more epochs of companion observations, we can draw multiple such curves which should help in further constraining the binary properties. This is one of the only ways to probe pre-explosion binary properties, which is currently otherwise inaccessible. Given that the pre-supernova binary separation reflects the effects of previous binary interactions like common-envelope evolution [26], we propose that post-supernova companion monitoring is an extremely valuable way to constrain binary evolution physics.

## 3. Neutron Star–Companion Interaction

After core-collapse supernovae, neutron stars are born with high proper motions called neutron star *kicks*, which typically have magnitudes of about 300 to 500 $\mathrm{km\,s^{-1}}$ but sometimes reaching more than 1000 $\mathrm{km\,s^{-1}}$. If this kick is directed in certain directions, it can be sent on directly colliding trajectories with the companion. Classically, it was considered that in such cases the two stars will immediately merge and form so-called Thorne–Żytkow objects, which are hypothetical objects that have neutron star cores embedded inside red supergiant-like envelopes [27, 28]. However, the density in the outer layers of stars with radiative envelopes are sufficiently low that gravitational drag may not cause them to immediately merge [29]. To test this, we performed 3D hydrodynamic simulations of collisions between neutron stars and main sequence companion stars with radiative envelopes [30]. We found that even in colliding

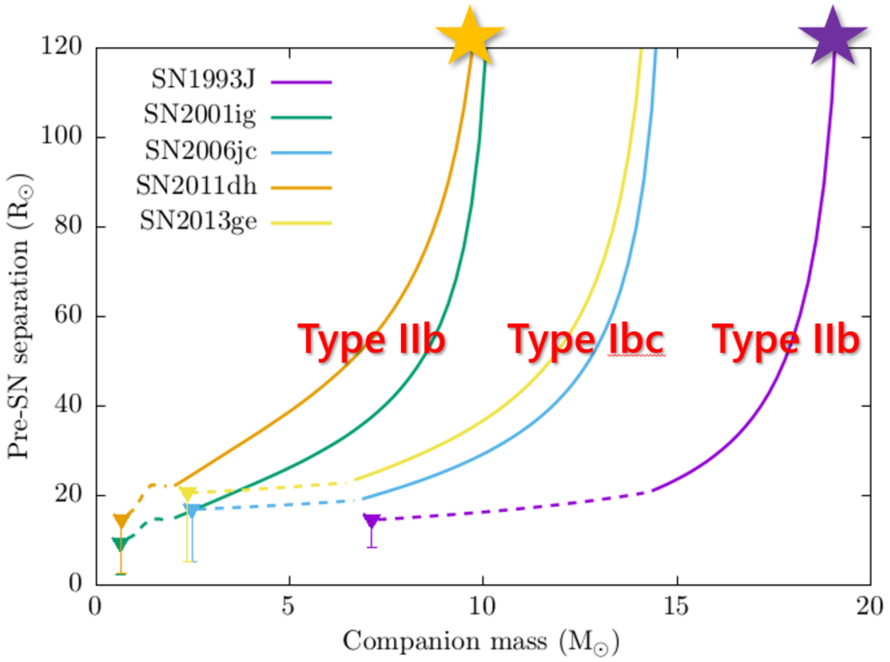

**Figure 3:** Constraints on the pre-supernova binary properties (companion mass and orbital separation) based on post-supernova companion photometry. Solid parts of the curve represent constraints when assuming the current companion is in the tail stage, while the vertical lines assume the companion is in the plateau stage. The dashed part of the curve assumes it is in the drop from plateau to tail, which is highly unlikely. The spectral type of each supernova is indicated by the red labels. Star symbols indicate the likely solutions within these constraints when other independent observational constraints are considered. Credit: adapted from Fig. 4 in [16] – CC BY 4.0.

trajectories, the neutron star can sometimes penetrate the companion envelope, depending on the impact parameter and the relative speed [30]. As the neutron star plunges through, it can carry away part of the envelope material with some angular momentum.

We consider three possible applications where envelope penetration can play an important role. The first example relates to the origin of hypervelocity stars. There is a class of runaway stars that have been discovered with velocities exceeding that of the local escape velocity of the Galaxy (see [31] for a review on hypervelocity stars). Some of these stars can be explained by the "Hills mechanism," where binaries are disrupted by the tidal field of the supermassive black hole in the Galactic centre. Other hypervelocity stars trace back to the Galactic disk, indicating an alternate origin like the "Blaauw mechanism," where binaries are disrupted through supernova explosions. There is a theoretical upper limit to the achievable velocity in the Blaauw mechanism, which is about $540\,\mathrm{km\,s^{-1}}$ for B-stars [32]. This is determined by the escape velocity of the star at the closest approach of the post-supernova trajectory. We find that this upper limit can be exceeded if we allow for envelope penetration, as the closest approach can be made shorter and therefore the velocity gain via the swing-by effect is stronger than the velocity loss through dynamical drag. There are one or two hypervelocity B stars with observed velocities reaching about $600\,\mathrm{km\,s^{-1}}$ [33, 34], which can only be reached by our envelope penetration models.

Another possible application is pulsar planet formation. This may happen if part of the captured material can form protoplanetary disks and the neutron star is on an unbound orbit. In the handful of simulations we performed, the mass captured by the neutron star and the total angular momentum were both sufficiently high to be able to form the planetary system in PSR B1257+12.

While part of the captured material forms planets, part of the captured material could accrete onto the neutron star. The accretion could lead to emission of high-energy radiation or kinetic outflows, which can power the supernova light curve from inside. This could lead to superluminous supernovae and/or bumps in the light curve. Since the majority of envelope penetrations will occur on bound orbits, the penetration could occur multiple times and thus create multiple bumps in the light curve.

## 4. The Tale of SN2022jli

Recently, there was a discovery of a stripped-envelope supernova with periodic undulations in its light curve [35, 36]. The undulation period is $\sim 12.5\,\mathrm{d}$, which carried on for $\sim 15$ cycles before suddenly dropping by $\sim 4$–$5$ mag within $\sim 30\,\mathrm{d}$. This is the most extreme example of bumps in a supernova light curve to date, with many more bumps than predicted in [30].

Instead of full envelope penetrations, we expect this could be a soft interaction where the neutron star interacts with the dilute envelope of a supernova-heated inflated star [20]. The inflated part of the envelope after supernova-heating has extremely low densities, which despite being optically thick, is tenuous enough to avoid orbit shrinkage through dynamical drag. If the post-supernova orbital period is 12.5 d, the orbital separation should be $\sim 30$–$50\,R_\odot$, which is tight enough to be fully embedded in these inflated envelopes. Post-supernova orbits should inevitably be eccentric due to the mass lost in the ejecta, so we naturally expect that there will be periodic undulations due to the variable accretion rate onto the new-born neutron star as it orbits through different density regimes within the envelope.

Further modelling is required to fully understand the main properties of this supernova, but it is already evident that the undulations are caused by binary interactions. Therefore, this supernova should serve as a good probe into binary interaction physics.

## 5. Conclusion

Binary evolution is now becoming widely recognized as being an important ingredient for understanding the diversity of core-collapse supernova progenitors. In this paper, I highlight several forms of binary interactions immediately following supernova explosions that have so far been ignored in the literature. Signatures of such interactions could be found in surviving binary companions or in the supernova light curve itself. With the recent rapidly growing zoo of astronomical transient surveys, we may be able to detect more signatures of such short-duration binary interactions and use them to constrain binary evolution physics.

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## Further Information

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### Conflicts of interest

The author declares that there is no conflict of interest.

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