POSSIBLE SIGNATURES OF EJECTA–COMPANION INTERACTION IN iPTF 13bvn

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ABSTRACT

We investigate the possible effects of the supernova (SN) ejecta hitting the companion star in iPTF 13bvn, focusing on the observable features when it becomes visible. iPTF 13bvn is a type Ib SN that may become the first case in which its progenitor is identified as a binary (by observations in the near future). According to calculations by Bersten et al. the progenitor should have a mass \( \approx 3.5 \, M_\odot \) to reproduce the SN light curve, and such compact stars can only be produced via binary evolution. This is one of the reasons that we expect the progenitor to be a binary, but this should be confirmed by observing the remaining companion after the SN. Bersten et al.’s evolutionary calculations suggest that the companion star will be an over luminous OB star at the moment of SN. With a combination of hydrodynamical and evolutionary simulations, we find that the secondary star will be heated by the SN ejecta and expand to have larger luminosities and lower surface effective temperatures. The star will look like a red supergiant and this should be taken into account when searching for the companion star in the SN ejecta in future observations.

Key words: binaries: close – stars: evolution – supernovae: individual (iPTF 13bvn)

1. INTRODUCTION

Type Ib supernovae (SNe) are one of the hydrogen deficient subtypes of core-collapse SNe, which are the final fates of massive \( (M \geq 8 \, M_\odot) \) stars (Filippenko 1997). Their lack of hydrogen indicates that they explode from stripped-envelope progenitors. Two major scenarios have been proposed to explain the removal of the hydrogen layers. The first scenario involves strong stellar winds for stars with zero-age main-sequence (ZAMS) masses \( M_{\text{ZAMS}} \geq 25 \, M_\odot \) (Maeder 1981). Such stars are called Wolf–Rayet stars, and are known for sometimes shedding their entire hydrogen envelope with the wind. The other possible scenario is mass transfer in close binaries (Podsiadlowski et al. 1992). Outer layers of the more evolved star in a binary can be transferred to its companion via Roche lobe overflow, or removed dynamically in common envelope phases. Debates continue about which is the more likely scenario.

iPTF 13bvn was a recent SN of this particular type, first identified by the intermediate Palomar Transient Factory (Law et al. 2009) on June 16,238 UT 2013. Its host galaxy is NGC 5806, which is at a distance of \( \approx 21 \) Mpc. Pre-explosion images from the Hubble Space Telescope (HST) showed a candidate progenitor within a 2\sigma error of the SN site (Cao et al. 2013). It is not settled whether we were looking at the progenitor star itself or a combined flux of a binary, but nevertheless we can place strong constraints on the exploding star.

Groh et al. (2013) first proposed that a Wolf–Rayet star with a ZAMS mass of 31–35 \( M_\odot \) could be a possible progenitor for iPTF 13bvn. This result was based on the absolute magnitude of the source in the pre-explosion image, and the strict upper limit on the radius of the progenitor (\( \leq 5 \, R_\odot \)) due to early detection. In their case, the pre-SN progenitor mass was \( \approx 10 \, M_\odot \). This possibility was ruled out by observations of the later phases of the bolometric light curve (Bersten et al. 2014; Fremling et al. 2014). Detailed hydrodynamical simulations of SNe with different progenitors showed that the observed light curve cannot be reproduced by a star with \( M \geq 8 \, M_\odot \). Instead, the preferred model was a He star with \( M \approx 3.5 \, M_\odot \), which is difficult to produce by assuming only stellar winds. The limit on the stellar radius was also extended up to \( \leq 150 \, R_\odot \) by an additional set of simulations with extended thin envelopes by Bersten et al. (2014; hereafter B+14). Their results strongly support the binary evolution scenario, and they also showed a possible evolutionary path that can produce such a low-mass progenitor star and match the pre-SN HST observations consistently. The SN is estimated to fade below the brightness of the pre-SN primary star at about three years from explosion.

A fainter secondary star may be observed shortly afterward. If a companion star is really discovered, it will be the first case in which the progenitor for a type Ib SN is confirmed to be a binary.

According to the binary evolution calculations by B+14, the secondary star is predicted to be an over luminous OB-type star. The combined optical flux of the primary and the secondary was consistent with the optical flux from the pre-SN image. However, the SN ejecta may change the observable features of the companion after the explosion by stripping mass, or heating the star to make it swell up (Hirai et al. 2014). This effect was not included in previous predictions although it may significantly alter its appearance.

In this paper we investigate the possible effects of SN ejecta hitting the companion in iPTF 13bvn, and how these effects may affect the observational features. Such events have been thoroughly studied for the single-degenerate scenario of type Ia SNe (Marietta et al. 2000; Podsiadlowski 2003; Liu et al. 2013; Pan et al. 2013; Shappee et al. 2013), but not so much for massive binaries, and relatively wide binaries, which do not fit in the picture of the single-degenerate scenario. Here we first model binary systems that fit within the constraints placed by B+14 via stellar evolution calculations, and then carry out hydrodynamical simulations of the SN ejecta colliding with the companion star. To obtain the stellar structures at the time the companion star becomes visible in the ejecta, we then perform additional stellar evolution simulations with extra heat distributed in the outskirts of the star. The parameters for the artificial heating were evaluated from the hydrodynamical simulations.
This paper is structured as follows. Our choice of model parameters and numerical method is explained in Section 2. The results of our evolution and hydrodynamical simulations are explained in Section 3, and we discuss our results in Section 4. We summarize our conclusions in Section 5.

2. MODELS AND NUMERICAL METHOD

B+14 revealed that the progenitor mass of iPTF 13bvn should be in the range of 3–5 $M_\odot$, presumably $\approx 3.5 M_\odot$. Using detailed binary evolution calculations, they also placed constraints on the initial configuration of the binary system, which can produce such stripped-envelope progenitors in this mass range. According to their estimates, the initial primary star (progenitor) mass should be $15 \lesssim M_1^i \lesssim 25 M_\odot$, and the mass ratio should be $0.8 \lesssim M_2^i / M_1^i \lesssim 0.95$. Note that the lower bound of the mass ratio is not physically motivated, but is set to avoid common envelope phases since they could not handle common envelope evolution with their stellar evolution code. These constraints overlap with the results of Eldridge et al. (2015), where the permitted primary mass was $10 M_\odot \lesssim M_1^i \lesssim 20 M_\odot$. The overlapping range may be the most plausible. They further estimated the possible range of the final secondary mass, calculating $23 \lesssim M_2^f \lesssim 45 M_\odot$ if conservative mass transfer is implied. This range is expanded to $18 \lesssim M_2^f \lesssim 45 M_\odot$ if mass accretion efficiencies are taken in the range $0.5 \lesssim \beta \lesssim 1$, where $\beta$ is the fraction of transferred matter that is accreted onto the secondary star (Benvenuto et al. 2013). The luminosity of the secondary star ended up within the constraint placed by the pre-explosion image of iPTF 13bvn.

In this paper, we first attempt to construct a pre-SN binary model that fits within the observationally permitted range. We utilize the open source stellar evolution code MESA (version 7184; Paxton et al. 2011, 2013) to model each star in the binary. Binary evolution is treated by evolving two spherically symmetric one-dimensional stars with a mass transfer rate applied by the “Ritter formalism” (Ritter 1988). Orbital elements are also evolved consistently. We assume no rotation, no magnetic fields, and circular orbits for all models to maintain simplicity.

It is known that even for identical initial conditions, different stellar evolution codes give different results (Jones et al. 2014; Sukhbold & Woosley 2014). Since the code employed in B+14 (a code by Benvenuto & de Vito 2003; Benvenuto et al. 2013) was different from ours, we could not produce the same binary model as the example case in B+14 by taking the same initial conditions. Here we aim to reproduce similar pre-SN configurations as the one shown in B+14, so we take slightly different initial parameters. We also construct several other binary models for comparison. The selected binary parameters are listed in Table 1, along with the final binary parameters at the moment of SN. For the non-conservative mass transfer models (with $\beta = 0.5$), the angular momentum loss parameter is given as $\alpha = 1$ (Benvenuto & de Vito 2003). All models were calculated until the primary starts producing iron at the center. The primary stars are assumed to explode within hours after iron production, and the binary parameters are unchanged until explosion.

We then apply the same method as in Hirai et al. (2014) to the pre-SN binary model to simulate the SN ejecta hitting the companion. A two-step strategy is employed: (1) artificially explode the primary star on a one-dimensional spherical grid and (2) simulate the effect of SN ejecta hitting the companion star on a two-dimensional axisymmetrical grid. The hydrodynamical code “yamazakura” (Sawai et al. 2013) is used for all hydrodynamical simulations throughout this paper. It is a mesh-based central scheme code with an iterative Poisson solver to solve self-gravity. An ideal-gas equation of state was applied with an adiabatic index $\gamma = 5/3$.

For the first step, $E_{\text{bind}} + E_{\text{exp}}$ of internal energy is added to the inner few meshes of the primary star model placed on a one-dimensional computational domain to initiate an explosion like a thermal bomb (Young & Fryer 2007), where $E_{\text{bind}}$ is the gravitational binding energy of the star and $E_{\text{exp}}$ is the explosion energy. In order to leave a residual neutron star after the explosion, we cut the central $1.4 M_\odot$ of the star out of the computational region, and set a reflective inner boundary condition. Consequently, all the energy applied will be placed just above the neutron star and it will initiate a shockwave that propagates outward through and out of the star. The explosion energy was taken as $E_{\text{exp}} = 8 \times 10^{50}$ erg from the estimate by B+14, which was obtained to fit the peak of the bolometric light curve and photospheric velocity evolution (see also Srivastav et al. 2014 for discussions on the explosion energy). A dilute circumstellar matter is placed around the star due to numerical reasons, with a low density so as not to disturb the propagation of the SN ejecta. An outgoing outer boundary condition is employed so the ejecta can flow out freely. Ejecta profiles are sampled at a point far from the stellar surface (50 times the stellar radius), and we compared the time evolution at different points to check that the profiles follow a homologous expansion.

In the second step, we place the secondary star model onto the origin of an axisymmetric $600(r)\times 180(\theta)$ spherical grid. The axis is taken along the line connecting the center of both stars. Axisymmetry is justified due to the short timescale of SN ejecta flowing past the star (~1 day) compared to the orbital period (~60 days). Unlike Hirai et al. (2014), we do not leave out the central portion of the star because the companion star model is not so centrally concentrated. The density scale height is resolved with at least 10 meshes, with a total ~150 radial gridpoints inside the star. Mesh sizes are then increased monotonically outside the star until the radius of the

| Model$^a$ | Age (Myr) | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $R_2$ ($R_\odot$) | $R_c$ ($R_\odot$) | $P$ (days) | $a$ |
|-----------|-----------|------------------|------------------|------------------|------------------|----------|-----|
| a1.0 | 0.019 | 18.0 | 5.65 | 5.47 | 2.45 | 25.5 |
| 10.4 | 3.48 | 33.5 | 44.7 | 7.72 | 61.7 | 219 |
| a0.5 | 0.019 | 18.0 | 5.65 | 5.47 | 2.45 | 25.5 |
| 10.2 | 3.72 | 18.0 | 47.8 | 10.4 | 62.0 | 203 |
| b1.0 | 0.018 | 17.0 | 5.47 | 5.30 | 3.50 | 31.7 |
| b0.5 | 0.018 | 17.0 | 5.47 | 5.30 | 3.50 | 31.7 |
| c1.0 | 0.015 | 14.0 | 4.93 | 4.74 | 3.30 | 28.7 |
| c0.5 | 0.015 | 14.0 | 4.93 | 4.74 | 3.30 | 28.7 |
| 12.5 | 3.02 | 26.0 | 31.8 | 7.01 | 63.4 | 206 |

Note. All models were assumed to have circular orbits. 
$^a$ Numbers in the model names indicate the values of the accretion efficiency parameter $\beta$ (Benvenuto et al. 2013) that were applied in our evolution calculations.
computational region reaches up to $\sim90\%$ of the binary separation. Then, as in the first step, we again place a low density atmosphere around the star that is dilute enough so that it has negligible mass. Data from the first step are used to place the SN ejecta close to the companion as an initial condition. For the outer boundary condition, the ejecta data are extrapolated as a Dirichlet boundary on the side facing the primary, whereas a free boundary is applied on the opposite side.

Each mesh is marked as bound or unbound using the “Bernoulli criterion,” in which matter is bound when

$$
\frac{1}{2}v^2 + \epsilon + \frac{p}{\rho} + \phi < 0,
$$

where $\epsilon$ is the specific internal energy and $p$ is pressure, $\rho$ is density, and $\phi$ is the gravitational potential. We integrate over the bound region to evaluate the mass and position of the center of mass of the remaining star. In order to see whether matter from the ejecta can mix with the original stellar matter, we also place tracer particles that just follow the fluid motion. Each particle carries information of its mass and origin (stellar or ejecta), and is evaluated on whether it is bound or not at each step.

3. RESULTS

3.1. Stellar Evolution

In this section we show the results of our stellar evolution calculations. Figure 1 shows the evolutionary track on the Hertzsprung–Russell diagram (HR diagram) of both stellar components for models a1.0 and a0.5. They roughly resemble the track of the model presented in B+14. The overall evolution of the primary does not change much for different values of $\beta$, nor does the period of the system. On the other hand, the secondary mass and luminosity strongly depend on the value of $\beta$. However, the optical flux is dominated by the primary, so it is difficult to constrain the secondary luminosity from the HST pre-SN image. All other models followed similar evolutionary tracks on the HR diagram.

Every primary star model was deficient of hydrogen at the point of SN, which is a necessary condition for producing a type Ib SN. Final luminosities of the primary stars range $4.5 \lesssim L_p/L_\odot \lesssim 4.9$, which roughly fits in the allowed range to match the HST pre-SN flux. This is also the case for the companions, with luminosities $4.9 \lesssim L_p/L_\odot \lesssim 5.6$. From the above facts, we assume that all of our models can be progenitor candidates of iPTF 13bvn. Since the progenitor mass is most likely $\approx3.5 M_\odot$, we will take model a1.0 to be our reference model. The b series have primary masses close to the lower limit of the observational constraint and the c series have primary masses close to the upper limit.

Density–radius profiles for each companion star model are compared in Figure 2. All models have similar structures, with steep density gradients near the surface and slightly different radii according to their accretion histories.

Obviously, these are not the only models that can reproduce the observational characteristics of iPTF 13bvn. Common envelope phases may have occurred to produce the compact progenitor, or the orbit may have been eccentric to induce periodic mass loss. Single star models cannot be excluded if we consider stellar rotation (Eldridge et al. 2015). Our stellar evolution calculations do not include these effects, and it is out of the scope of this paper to consider every possible scenario.

3.2. Supernova

Figure 3 shows snapshots of our hydrodynamical simulations of the collision of SN ejecta and the companion star in our reference model. Note that the scales are different in the left and right panels. The whole computational region is displayed in the right panels, whereas we show a close-up view in the left panels. Panel (a) shows our initial condition, where the ejecta is just about to reach the companion surface. As the ejecta hits the surface of the companion, a forward shock is driven into the star, and a reverse bow shock is formed in front of the star, which can be seen as density discontinuities in panel (b). The forward shock heats the outskirts of the star as it proceeds, but the propagation soon stops at a certain point because of the pressure gradient in the star. After the bulk of the ejecta flows past, the bow shock and the heated matter start to expand outward as can be seen in the lower half of panel (c). We can check whether it is the stellar matter or just the bound region that is expanding by looking at the tracer particle distributions. Figure 4 shows the distributions of the tracer particles at times corresponding to panels (b) and (c) in Figure 3. The upper half is color-coded according to the origin of each particle: red for ejecta matter that comes from the primary, and blue for secondary star matter. The lower half is color-coded whether it is bound (light blue) or not (gray). We can see that some of the
particles from the stellar surface are stripped away along the axis, but the mass is very small. If there are any particles that are red in the upper half and light blue in the lower half, it means that ejecta matter has accreted onto the companion. However, most of the light blue particles in the lower half are blue in the upper half, which indicates that the enlargement of the bound region is not due to ejecta matter being accreted to the stellar surface, but is due to the shocked stellar matter expanding because of the heat. A small amount of ejecta matter is mixed into the stellar matter, but their masses are extremely small. The bound region keeps on expanding in a spherical manner, eventually reaching the outer boundary of our simulation. Panel (d) in Figure 3 shows a snapshot at these later stages, where the bound region is almost spherical.

In Figure 5 we show the amount of unbound matter ($M_{ub}$), and the displacement of the center of mass ($\Delta x_{COM}$) as a function of time since the SN. As we can see from the upper panel, hardly any matter was stripped off or accreted onto the star. The absolute values are comparable to the errors arising from the limitation in the numerical resolution. This is consistent with previous works (Marietta et al. 2000; Pan et al. 2010; Hirai et al. 2014) where the unbound mass depends on the orbital separation as $\propto a^{m_{ub}}$, where $a$ is the separation. The exponent $m_{ub}$ depends on the stellar structure, but simulations suggest values $-4.5 \lesssim m_{ub} \lesssim -3$. Since our models

Figure 3. Density plots from the hydrodynamical simulations of the collision of SN ejecta and the companion star. Each snapshot is labeled with the time elapsed since SN. Only the bound matter is colored in the lower half of each panel. The SN ejecta is flowing in from the left side of each panel. The left panels have a radius of $1.3 \times 10^7$ km, and the right panels have a radius of $1.3 \times 10^8$ km.

Figure 4. Distributions of tracer particles at various times. In the upper half of each panel, each particle is colored red or blue if they originate from the ejecta or star, respectively. In the lower half, particles are colored light blue or gray depending on whether they are bound or not. Particles that are red in the upper half and light blue in the lower half are ejecta matter that has mixed into the stellar matter. The radii of the circles are $1.15 \times 10^8$ km.
all have relatively wide separations, it is natural that the amount of stripped mass was so small. The lower panel shows the motion of the center of mass, which reaches a constant velocity in the direction opposite to the exploding star in about a few days. According to simple estimates (Cheng 1974; Wheeler et al. 1975), this so-called “rocket effect” or “kick” velocity should be very small in our present model, due to the wide separation with respect to the stellar radius. In our simulation, the kick velocity reached up to $1.75 \times 10^4$ km hr$^{-1}$, which was $\sim$30% of the orbital velocity. This relatively large kick velocity may help destroy the binary or at least alter the eccentricity of the post-SN system. For model a0.5, the kick velocity was $\sim$5% of the orbital velocity, which is almost negligible. All other models showed qualitatively similar results.

In Table 2 we list the amount of unbound mass and the kick velocity, along with the final temperature and luminosity, which are explained in Section 4.1. It is clear that the unbound mass and kick velocity are negligible in every model. The kick velocity was also negligible compared to the orbital velocities. There seems to be no strong correlation between the binary parameters to the unbound mass or kick velocity. This is because the stellar structure and SN ejecta profiles are different for each model, and the absolute values are all comparable to the numerical resolution.

4. DISCUSSIONS

The dynamical effects of the ejecta hitting the companion star, such as mass stripping and momentum transfer, seem to be limited. But the expansion of the outer layers of the star may become important when we observe the companion after the SN ejecta becomes faint enough. Such expansions have also been found in previous simulations (Hirai et al. 2014; Liu et al. 2013). Here we explore the observable features of the companion star when it became visible.

$^5$ The kick velocity mentioned here is different from the natal kick imparted to the central neutron star in core-collapse SNe.

| Model | $M_{unb}$ ($M_\odot$) | $v_{kick}$ (km hr$^{-1}$) | $v_{orb}$ (km hr$^{-1}$) | log$L_{eff}$ (K) | log$L$ ($L_\odot$) |
|-------|----------------------|---------------------------|--------------------------|-----------------|------------------|
| a1.0  | $2.1 \times 10^{-4}$ | $1.8 \times 10^4$         | $6.1 \times 10^5$        | 3.82            | 5.51             |
| a0.5  | $4.7 \times 10^{-5}$ | $4.3 \times 10^3$         | $7.6 \times 10^4$        | 3.64            | 5.65             |
| b1.0  | $1.1 \times 10^{-4}$ | $5.6 \times 10^3$         | $8.2 \times 10^5$        | 4.01            | 5.85             |
| b0.5  | $3.1 \times 10^{-4}$ | $9.1 \times 10^3$         | $9.3 \times 10^4$        | 3.66            | 5.58             |
| c1.0  | $9.0 \times 10^{-5}$ | $3.3 \times 10^3$         | $6.1 \times 10^4$        | 3.61            | 5.57             |
| c0.5  | $2.2 \times 10^{-4}$ | $5.7 \times 10^3$         | $6.9 \times 10^4$        | 4.22            | 4.98             |

$^a$ The names of the models correspond to those in Table 1.

$^b$ Orbital velocity prior to SN.

$^c$ $T_{eff}$ and $L$ are values estimated three years after SN.
Starting from the companion model at the pre-SN stage of the primary, we artificially input energy into the outer layers as

$$\dot{\varepsilon}_{\text{heat}} (m) = \frac{\Delta E_{\text{heat}}}{t_{\text{heat}} \sqrt{2 \pi \sigma^2}} \exp \left( -\frac{(m - \mu)^2}{2 \sigma^2} \right),$$

(3)

where $$\varepsilon_{\text{heat}}$$ is the artificial specific internal energy injection rate as a function of mass coordinate, $$\Delta E_{\text{heat}}$$ is the total energy input, $$t_{\text{heat}}$$ is the duration of heating, and $$\sigma = (M_f^2 - m(r_{in})) / 6$$, $$\mu = (M_f + m(r_{in}))/2$$. $$r_{in}$$ is the radial coordinate at the inner edge of the heating layer, where the shock could not proceed further inward in the hydrodynamical simulations. Figure 7 illustrates the time evolution of the distribution of specific internal energy along the axis. The black line shows the initial condition, where we can see the ejecta approaching the stellar surface ($$\sim 5.3 \times 10^6$$ km) from the left. The forward and reverse shocks can be seen as a steep wall in the red line, and weaken its strength as it proceeds into the star, which can be seen in the blue line. The forward shock propagates up to $$\sim 3 \times 10^6$$ km from the center at most. We can see from the green line, the internal energy distribution near the end of our simulation, that the stellar matter interior to this point is almost unaffected by the shock. We therefore take $$r_{in} = 3 \times 10^6$$ km as the inner edge of the heating layer. $$\Delta E_{\text{heat}}$$ and $$t_{\text{heat}}$$ are also set to the values taken from the hydrodynamical simulations ($$\Delta E_{\text{heat}} = 1 \times 10^{50}$$ erg, $$t_{\text{heat}} = 100$$ hr). Our strategy of extra energy deposition is similar to Shappee et al. (2013) and Podsiadlowski (2003). The main difference is that we ignore the effects of mass stripping, since the amount of stripped mass in our hydrodynamical simulations was negligible (see Table 2). Due to this assumption, all the energy from the SN ejecta is used to puff up the star, not to ablate away some surface matter.

The shock heating of the outer layers by the SN ejecta modifies the stellar structure, pushing out the outer layers like it did in the hydrodynamical simulations. In Figure 8 we show the evolutionary track of the artificially heated companion star on the HR diagram for 100 years after SN. Focusing on the fiducial model (black line), it can be seen that the temperature decreases almost monotonically. During the heating phase, temperature and luminosity both drop, but the luminosity eventually starts to increase due to the growing expansion speed. As soon as we switch off the artificial heating, the temperature and luminosity show an almost discrete drop because of the disappearance of heat.3 In the following few dynamical times, the radius and luminosity increase to hydrostatic equilibrium. We do not expect these large fluctuations in the early phase to be realistic, since it is highly affected by our methodology. Thus, we only pay attention to the evolution after several dynamical times. After a year, the effective temperature will drop by an order of magnitude, and the luminosity slightly increases. It was roughly estimated in B +14 that three years is the time it takes for the SN light curve to decline below the brightness of the original progenitor. The time it takes for the companion to become visible depends on the declination of the SN light curve and the band used for the observation, but we expect that it is not so far from three years, maybe slightly earlier. At that time, it will be somewhere around the middle star sign in Figure 8, somewhat like a red supergiant. Even after it becomes visible, we expect the star to continue increasing its luminosity for a few decades.

Although we have carefully chosen our parameters $$r_{in}$$, $$\Delta E_{\text{heat}}$$, and $$t_{\text{heat}}$$ to match the hydrodynamical simulations, there are still some uncertainties left. Results for the same simulation with different parameters are also shown in Figure 8. The final temperature strongly depends on $$r_{in}$$, where larger values of $$r_{in}$$ lead to lower temperatures and lower luminosity. This is because if $$r_{in}$$ is larger, the extra energy is injected into a much smaller volume, so it needs to expand more to retain equilibrium. Final states are also sensitive to the value of $$\Delta E_{\text{heat}}$$, which can be seen in Figure 8, where the results for different $$\Delta E_{\text{heat}}$$ are plotted with different colors. Larger values of $$\Delta E_{\text{heat}}$$ give lower temperatures and higher luminosities. We have also conducted the same simulation with different $$t_{\text{heat}}$$ (black dotted line in Figure 8), but the differences were limited. As explained earlier, the early evolution is largely affected by our methodology, particularly on $$t_{\text{heat}}$$, but the differences become indistinguishable within a few dynamical times after the heating phase. We are therefore sure that the long term evolution will not depend on our choice of $$t_{\text{heat}}$$, and any earlier

\footnote{The artificial heat is applied all the way up to the surface, contributing to the surface temperature.}
evolution (which is not observable anyway) should be studied by hydrodynamical simulations since it is highly unspherical. Regardless of the uncertainties in our assumptions, the secondary star will appear as a red star when it becomes visible, with temperatures lower by a factor of $\sim 2$–10 off the main sequence. The parameter dependence of the luminosity is weak, just slightly increasing in some cases by less than a factor of $\sim 2$.

Estimates of the final temperature and luminosity for all models are listed in Table 2. All other models have considerably lower temperatures compared to their original states. The expansion depends strongly on the stellar structure so it may be possible to distinguish among models from observations.

4.2. Other Consequences

The expansion of the star exceeded the original binary separation in some of our models, which means that it may engulf the newly born neutron star. For such cases, the pulsar wind emitted by the neutron star may heat or strip the loosely bound envelope and distort the shape. If the neutron star becomes embedded in the expanded envelope, it might initiate a common envelope phase, possibly leading to much tighter orbits or the formation of Thorne–Żytkow objects (Thorne and Żytkow 1977). It will be difficult to confirm whether the system has entered a common envelope phase by observations, but if the red supergiant-like companion is found and no neutron star is detected for the following couple of years, it may be the first evidence of an ongoing common envelope phase.

5. CONCLUSION

iPTF 13bvn is a candidate for the first case in which the progenitor for an SN Ib is confirmed to be a binary. There are several possible evolutionary paths that can both reproduce the SN light curve and the pre-SN photometry of iPTF 13bvn, all containing a compact ($\lesssim 5 M_\odot$) He star primary and an overluminous OB secondary star. We have studied the effects of SN ejecta colliding with this secondary OB star and have found that the surface of the star may swell up with the heat, becoming more red and luminous when it becomes visible in the SN remnant. The change in temperature and luminosity strongly depends on the parameters $\Delta P_{\text{heat}}$ and $r_{\text{in}}$ that we used in the post-SN evolution calculations. But in any case, the secondary will be found off the main sequence, with lower effective temperatures and a slight increase in luminosity, which also depends on the time we detect it. The effects of mass stripping and kicks are limited and will not affect the further evolution of the binary.

The radius of the secondary star becomes so large that it may engulf the primary-produced neutron star. In that case we might be able to observe the first ever ongoing common envelope phase as an absence of the neutron star in the vicinity.

We note that other evolutionary paths are possible if we include stellar rotation, common envelope phases, or eccentric orbits. Theories that can deal with all of these cases have not been established yet, so such cases are beyond the scope of this paper (see Ivanova et al. 2013, for a review on common envelopes). If we do address these possibilities, there is a much wider range of possible progenitors, so further studies are certainly warranted.

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