Letter to the Editor

Revealing the binary origin of Type Ic superluminous supernovae through nebular hydrogen emission

Takashi J. Moriya¹, Zheng-Wei Liu¹, Jonathan Mackey², Ting-Wan Chen¹, and Norbert Langer¹

¹ Argelander Institute for Astronomy, University of Bonn, Auf dem Hügel 71, 53121 Bonn, Germany  
² I. Physikalisches Institut, Universität zu Köln, Zülpicher Straße 77, 50937 Köln, Germany

e-mail: moriyatk@astro.uni-bonn.de

Received 06 October 2015 / Accepted 26 October 2015

ABSTRACT

We propose that nebular Hα emission as detected in the Type Ic superluminous supernova iPTF13ehe stems from matter which is stripped from a companion star when the supernova ejecta collide with it. The temporal evolution, the line broadening, and the overall blueshift of the emission are consistent with this interpretation. We scale the nebular Hα luminosity predicted for Type Ia supernovae in single-degenerate systems to derive the stripped mass required to explain the Hα luminosity of iPTF13ehe. We find a stripped mass of 0.1–0.9 solar masses, assuming that the supernova luminosity is powered by radioactivity or magnetar spin down. Because a central heating source is required to excite the Hα emission, an interaction-powered model is not favored for iPTF13ehe if the Hα emission is from stripped matter. We derive a companion mass of more than 20 solar masses and a binary separation of less than 20 companion radii based on the stripping efficiency during the collision, indicating that the supernova progenitor and the companion formed a massive close binary system. If Type Ic superluminous supernovae generally occur in massive close binary systems, the early brightening observed previously in several Type Ic superluminous supernovae may also be due to the collision with a close companion. Observations of nebular hydrogen emission in future Type Ic superluminous supernovae will enable us to test this interpretation.

Key words. supernovae: general – supernovae: individual (iPTF13ehe)

1. Introduction

Superluminous supernovae (SLSNe) are a newly discovered class of supernovae (SNe) (see Gal-Yam 2012 for a review), and their origin is still a mystery. In particular, the origin of Type Ic SLSNe which do not show hydrogen features in the early phases (e.g., Quimby et al. 2011) has been actively discussed. Several scenarios to make Type Ic SLSNe bright are proposed, e.g., magnetar spin-down (e.g., Kasen & Bildsten 2010; Dessart et al. 2012; Inserra et al. 2013; Chen et al. 2013; Metzger et al. 2013), large production of 56Ni (e.g., Gal-Yam et al. 2009; Moriya et al. 2010; Kasen, Woosley, & Heger 2011; Dessart et al. 2013; Kozyreva et al. 2014, Whalen et al. 2014), and the interaction between SN ejecta and hydrogen-free dense circumstellar media (e.g., Chevalier & Irwin 2011; Moriya & Maeda 2012; Ginzburg & Balberg 2012; Chatzopoulos & Wheeler 2012; Baklanov, Sorokina, & Blinnikov 2015; Sorokina et al. 2015). Revealing the progenitors and the power source of Type Ic SLSNe is essential for a better understanding of massive star evolution (Langer 2012), as well as for the possible use of Type Ic SLSNe as a standardizable candle (Quimby et al. 2013; Inserra & Smartt 2014).

Type Ic SLSNe were thought to be hydrogen-free. However, Yan et al. (2015) suggest that nebular Hα emission is observed in late phases. Y15 estimate that about 10% of Type Ic SLSNe may have nebular Hα emission as is observed in iPTF13ehe.

Y15 suggest that the nebular Hα emission in iPTF13ehe results from the interaction between the SN ejecta and a hydrogen-rich circumstellar shell. If the shell is located far from the progenitor, it takes time for the SN ejecta to reach the hydrogen-rich shell. Thus, the Hα emission is observed in late phases. Y15 propose that the hydrogen-rich shell is formed by the pulsational pair instability (e.g., Woosley, Blinnikov, & Heger 2007) of the progenitor and that the subsequent explosion may have resulted in iPTF13ehe. The confinement of stellar wind by external photoionization may also result in the formation of a massive circumstellar shell (Mackey et al. 2014, Wang et al. 2015) invoke the necessity to simultaneously consider three suggested luminosity sources in iPTF13ehe, i.e., 56Ni, magnetars, and interaction.

In this Letter, we present an alternative view to interpret the nebular Hα emission. We suggest that the hydrogen observed in iPTF13ehe originates from the matter stripped from the companion star contaminating the inner low-velocity layers of the SN ejecta. The photosphere is in the outer high-velocity layers soon after explosion and we do not observe emission from the inner layers in the early phase. In the nebular phase when the inner layers are transparent, emission from the contaminated inner layers becomes observable. It has been argued that nebular Hα emission from the stripped matter should be detectable in Type Ia SNe that originate from single-degenerate progenitor systems, although this has not yet been observed (Mattila et al. 2005; Leonard 2007; Shappee et al. 2013; Lundqvist et al. 2013).
The stripped mass in Type Ia SNe is estimated to be less than $\sim 10^{-3} M_\odot$. We apply the same idea to the case of iPTF13ehe and argue that iPTF13ehe may be the first SN for which the emission of stripped matter from a companion star is detected.

2. Stripped mass from the companion

In this section, we estimate the mass required to be stripped from the companion star during the collision in order to explain the hydrogen emission observed in iPTF13ehe.

2.1. Scaling relation

Mattila et al. (2005) perform nebular spectral modeling of Type Ia SNe assuming that the inner layers of the ejecta of the W7 model (Nomoto, Thielemann, & Yokoi 1984) are contaminated by solar-metallicity matter stripped from the companion. They predict that the nebular H$\alpha$ luminosity from the stripped matter is $\sim 5 \times 10^{36}$ erg s$^{-1}$ at 380 days after the explosion for a stripped mass of $M_{\text{st}} = 0.05 M_\odot$. We scale this result to estimate the stripped mass in iPTF13ehe.

We assume that the H$\alpha$ emission is mainly due to the non-thermal excitation of hydrogen due to y-rays from the nuclear decay of $^{56}$Co $\rightarrow ^{56}$Fe in the nebular phase (e.g., Mattila et al. 2005). The inner layers of the W7 model at 380 days are optically thin to y-rays. Thus, the H$\alpha$ luminosity ($L_{\text{H}\alpha}$) is proportional to $\tau_{\gamma,\alpha} L_\alpha$, where $\tau_{\gamma,\alpha}$ is the y-ray optical depth in the ejecta and $L_\alpha$ is the y-ray luminosity (cf. Kozma & Fransson 1992). The y-ray optical depth $\tau_{\gamma,\alpha}$ is proportional to $\rho_\alpha r_\alpha$ where $\rho_\alpha$ is the ejecta density and $r_\alpha = (2E_{\text{ej}}/M_{\text{ej}})^{1/2}$ is the characteristic length scale in the ejecta. Because the inner layers of SN ejecta have an almost-constant density profile (e.g., Kases 2010), we assume $\rho_\alpha \propto M_{\text{ej}}^{5/2} E_{\text{ej}}^{-3/2} r^{-2}$. Then, we obtain $\tau_{\gamma,\alpha} \propto \rho_\alpha r_\alpha \propto M_{\text{ej}}^{5/2} E_{\text{ej}}^{-1} r^{-2}$. The late-phase y-ray luminosity is $L_\alpha \propto M_{56} \exp(-t/\tau_{\gamma,\alpha})$ where $M_{56}$ is the initial $^{56}$Ni mass and $\tau_{\gamma,\alpha} = 111$ days is the $^{56}$Co decay timescale. Finally, the H$\alpha$ luminosity is proportional to the stripped mass $M_{\text{st}}$. Thus, we expect that the H$\alpha$ luminosity scales as $L_{\text{H}\alpha} \propto M_{\text{ej}}^{5/2} E_{\text{ej}}^{-1} M_{56}^{1/2} \exp(-t/\tau_{\gamma,\alpha})$.

Using the W7 parameters ($M_{\text{ej}} = 1.4 M_\odot$, $E_{\text{ej}} = 1.3$ B, and $M_{56} = 0.6 M_\odot$) and $L_{\text{H}\alpha} \approx 5 \times 10^{36}$ erg s$^{-1}$ at $t = 380$ days with $M_{\text{ej}} = 0.05 M_\odot$ (Mattila et al. 2005), we obtain the scaling relation

$$L_{\text{H}\alpha} \approx 5 \times 10^{44} \frac{M_{\text{ej}}}{M_\odot} \frac{M_{\text{ej}}^{5/2}}{M_\odot} \frac{E_{\text{ej}}}{B} \frac{M_{56}^{1/2}}{M_\odot} \frac{t}{\text{day}}^{-2} \exp\left(-\frac{t}{111 \text{days}}\right) \text{ erg s}^{-1}. \quad (1)$$

We apply this formula to iPTF13ehe in the next section. Its validity and uncertainties for this application are discussed in Section 2.3.

2.2. The stripped mass in iPTF13ehe

iPTF13ehe is observed to have $L_{\text{H}\alpha} \approx 2 \times 10^{41}$ erg s$^{-1}$ at $\sim 250$ days after the LC peak (Y15). The rise time is uncertain, so we adopt $\sim 110$ days based on the polynomial fit to the LC (Y15). Given the redshift of iPTF13ehe (0.3434, Y15), we estimate that the above H$\alpha$ luminosity is observed at about 270 days after the explosion in the rest frame. Y15 find that the H$\alpha$ luminosity decreases by roughly 20% from 270 days to 290 days in the rest frame. Our interpretation that the stripped matter provides the H$\alpha$ luminosity predicts about 28% luminosity reduction during this period (Eq. 1). This is consistent with the observation.

If iPTF13ehe is powered by $^{56}$Ni, the required $^{56}$Ni mass to obtain the peak luminosity is about 15 $M_\odot$ (Y15). If we assume that iPTF13ehe is a pair-instability SN, the expected ejecta mass and explosion energy are roughly 110 $M_\odot$ and 60 B, respectively (e.g., Heger & Woosley 2002). Substituting these properties for Eq. 1, we obtain $M_{\text{ej}} \approx 0.1 M_\odot$. If the large $^{56}$Ni production is due to a core-collapse SN (e.g., Umeda & Nomoto 2008), the ejecta mass can be smaller than what we expect from the pair-instability SN (e.g., Moriya et al. 2010). A large explosion energy is still required to have the large $^{56}$Ni production. If we adopt $M_{\text{ej}} = 70 M_\odot$ and $E_{\text{ej}} = 60$ B, we obtain $M_{\text{st}} = 0.3 M_\odot$.

Even if iPTF13ehe is powered by a magnetar, a y-ray deposition from the magnetar similar to that in the $^{56}$Ni-powered model is required to explain its slowly-declining LC. Thus, we estimate the stripped mass by assuming $M_{56} = 15 M_\odot$ in Eq. (1) even in the magnetar model. The main difference between the magnetar-powered and $^{56}$Ni-powered models is in the SN ejecta mass and energy. If we take typical ejecta mass ($5 M_\odot$) and energy (1 B) estimated for magnetar-driven SLSNe (e.g., Inserra et al. 2013, Nicholl et al. 2015a), we obtain $M_{\text{ej}} \approx 0.9 M_\odot$. However, the magnetar model for iPTF13ehe by Wang et al. (2015) requires $M_{\text{ej}} = 35 M_\odot$ and $E_{\text{ej}} = 40$ B. In this case, the stripped mass is $M_{\text{st}} = 0.7 M_\odot$.

If the interaction between the SN ejecta and a hydrogen-free dense circumstellar medium is the major luminosity source of iPTF13ehe, the SN explosion itself can be normal. For instance, the Type Ic: SLSN 2010gx had a spectrum that is similar to those observed in broad-line Type Ic SNe (Pastorello et al. 2011). If we adopt typical broad-line Type Ic SN properties ($E_{\text{ej}} = 10$ B, $M_{\text{ej}} = 5 M_\odot$, and $M_{56} = 1 M_\odot$, e.g., Taddia et al. 2015), we obtain $M_{\text{ej}} \approx 140 M_\odot$ which is unrealistically high. If we assume a higher ejecta mass, for example $M_{\text{ej}} = 20 M_\odot$, we obtain a lower stripped mass, $8 M_\odot$. A significant central heating source is necessary to excite hydrogen to explain the nebular H$\alpha$ emission from the stripped mass. We note that a reverse shock created by the interaction, which could propagate into the inner layers to excite hydrogen, does not move rapidly inwards because the interaction forms a radiative, dense, cool shell (e.g., Sorokina et al. 2015). Table 1 summarizes the stripped masses estimated in this section.

| model                      | $M_{\text{ej}}/M_\odot$ | $E_{\text{ej}}/B$ | $M_{56}/M_\odot$ | $M_{\text{st}}/M_\odot$ |
|----------------------------|--------------------------|-------------------|------------------|-------------------------|
| PISN                       | 110                      | 60                | 15               | 0.1                     |
| core-collapse SN           | 70                       | 60                | 15               | 0.3                     |
| magnetar                   | 5                        | 1                 | (15)             | 0.9                     |
| Wang et al. (2015)         | 35                       | 40                | (15)             | 0.7                     |
| interaction                | 5                        | 10                | 1                | 140                     |

Table 1. Estimated stripped mass $M_{\text{st}}$ for different progenitor models. Values in parentheses for $M_{56}$ denote an energy input consistent with that provided by this mass of $^{56}$Ni, even though this energy may be injected by a central engine.
2.3. Consistency check and uncertainties

In Eq. (1), it is assumed that the inner layers of the SN ejecta are optically thin to $\gamma$-rays as in the Type Ia SN model of Mattila et al. (2005) at $t = 380$ days. Assuming a $\gamma$-ray opacity of $0.03 \text{ cm}^2 \text{ g}^{-1}$ (Axelrod 1980), the Type Ia SN model has $\tau_{\gamma,\gamma} \sim 10^{-2}$. For the models at 270 days in the previous section, we obtain $\tau_{\gamma,\gamma} \sim 1$. Thus, the scaling relation is still able to provide a rough estimate for the stripped mass. Because the optical depth is around unity, the scaling relation may slightly underestimate the stripped mass.

Y15 estimate a $^{56}$Ni mass of 2.5 $M_\odot$ in iPTF13ehe based on their nebular spectral modeling. This $^{56}$Ni mass is too small to explain the peak luminosity of iPTF13ehe, leading to the suggestion that two or more luminosity sources power iPTF13ehe (Y15 and Wang et al. 2015). However, this $^{56}$Ni mass estimate assumes that $^{56}$Ni is irrelevant to the $\text{H}_\alpha$ emission. Because the $\text{H}_\alpha$ emission is powered by radioactive decay, the mass estimate of $^{56}$Ni increases. The estimated $^{56}$Ni mass is also uncertain because of the uncertainties in the spectral modeling itself (Y15).

Thus, the $^{56}$Ni-powered model with 15 $M_\odot$ of $^{56}$Ni is not ruled out if the $\text{H}_\alpha$ emission is emitted by the stripped matter.

3. Constraint on the progenitor binary system

Liu et al. (2015) have recently studied the collision between SN ejecta and its companion star in core-collapse SNe with different separations, companion masses, ejecta masses, and explosion energies (see also Hirai, Sawai, & Yamada 2014). They investigate how the stripping fraction $f \equiv M_{\text{st}}/M_2$ (where $M_2$ is the companion mass before the collision) is affected by these parameters. Liu et al. (2015) only investigate the collision with the companion stars of 0.9 and 3.5 $M_\odot$. To constrain the massive progenitor system of iPTF13ehe, we perform numerical simulations of the collision between the SN ejecta ($110 M_\odot$ and 60 B) and a massive main-sequence star ($50 M_\odot$ with 10 $R_\odot$) by adopting the same method as in Liu et al. (2015). The three-dimensional smoothed-particle hydrodynamics code Stellar GADGET (Pakmor et al. 2012) is used for the simulations. We run simulations for two separations, 5 $R_\odot$ and 10 $R_\odot$, where $R_2$ is the companion radius. The Roche-lobe radii for the mass ratios of 0.5 and 1 are 3.1 $R_2$ and 2.6 $R_2$, respectively (Eggleton 1983).

The numerical simulations reveal stripped masses of 0.3 $M_\odot$ ($f \sim 6 \times 10^{-3}$) and 0.05 $M_\odot$ ($f \sim 10^{-2}$) for the separations of 5 $R_2$ and 10 $R_2$, respectively. The stripped mass therefore reaches more than 0.1 $M_\odot$, as required from our estimate, and the binary system with the 50 $M_\odot$ main-sequence companion is consistent with the $\text{H}_\alpha$ luminosity observed in iPTF13ehe. Assuming $f = (6-1) \times 10^{-3}$, the companion mass needs to be 20 – 100 $M_\odot$ if $M_{\text{st}} = 0.1 M_\odot$. Because the ejecta mass does not strongly affect the stripping fraction (Liu et al. 2015), the companion mass is expected to be 50 – 300 $M_\odot$ if the ejecta mass is 70 $M_\odot$ ($M_{\text{st}} = 0.3 M_\odot$).

The stripping fraction is proportional to $E_{\gamma}$ (Liu et al. 2015). The magnetar model in Wang et al. (2015) has a high explosion energy (40 B) and the companion mass needs to be more than about 80 $M_\odot$ to have $M_{\text{st}} \approx 0.7 M_\odot$. If $E_{\gamma} \approx 1$ B as estimated from the typical magnetar model, the stripping fraction is likely to be $f \sim 10^{-4}$ or less. Then, the companion mass needs to be larger than $\sim 10^2 M_\odot$ ($M_{\text{st}} = 0.9 M_\odot$), which is extremely high.

The stripped mass strongly depends on the separation. As the separation becomes larger, the angular size of the companion star from the SN ejecta becomes smaller. Thus, less energy is ejected in the direction of the companion and the mass stripping becomes less efficient. The above stripping fraction is estimated for separations between 5 and 10 $R_2$. As is indicated in Liu et al. (2015), the stripping fraction drops significantly as the separation doubles (see also Hirai, Sawai, & Yamada 2014). If the separation is more than about 20 $R_2$, the required companion mass is likely to become more than $10^3 M_\odot$ in most of the models.

4. Discussion

4.1. $\text{H}_\alpha$ emission features

So far, we have focused on the observed $\text{H}_\alpha$ luminosity of iPTF13ehe. Here we discuss other $\text{H}_\alpha$ features of iPTF13ehe in the context of our stripping scenario.

The $\text{H}_\alpha$ emission in iPTF13ehe is observed to have a line broadening of $\sim 4000$ km s$^{-1}$ and an overall line shift of several 100 km s$^{-1}$ (Y15). Because the stripped matter remains within the inner layers of the SN ejecta, it is expected to emit at relatively low velocities ($\lesssim 1000$ km s$^{-1}$ in the case of Type Ia SNe, e.g., Liu et al. 2012). If the explosion energy is higher, stripped matter can end up with higher velocities and we expect to observe broader emission lines, as seen in iPTF13ehe. In Fig. 1 we show the velocity distribution of the stripped matter in our impact simulation with a separation 5 $R_2$. The typical velocity of the stripped matter is around 3000 km s$^{-1}$, while the typical velocity of the ejecta is around 8000 km s$^{-1}$. The velocities of the stripped matter are actually slower than the typical ejecta velocity and they are close to the line broadening observed in iPTF13ehe.

If the companion star is located between the progenitor and the observer at the time of the explosion, the collision occurs in the ejecta moving toward the observer. Thus, we expect that the stripped matter has an overall velocity toward the observer and an observer measures blueshifted $\text{H}_\alpha$ emission. If the companion is in the opposite direction, the emission is likely to have an overall redshift. Thus, for emission from the stripped matter, we expect to eventually observe an overall redshift in other Type Ic SLSNe. Detailed modeling of the nebular spectra based on impact simulations similar to Liu et al. (2015) is required to further investigate the expected emission properties.
4.2. Early brightening observed in Type Ic SLSNe

Some Type Ic SLSNe are known to have an early brightening before the main LC rise (Nicholl et al. 2015a; Leloudas et al. 2012). This early brightening has been related to, e.g., circumstellar interaction (Moriya & Maeda 2012) and magnetar spin-down (Kasen, Metzger, & Bildsten 2015). However, if Type Ic SLSNe originate from binary systems, this early emission may be related to the collision between the SN ejecta and the companion (Kasen 2014). We expect an early luminosity of \( \sim (1 - 5) \times 10^{43} \) erg s\(^{-1}\) within 10 days after the explosion from the analytic formula of Kasen (2010), assuming \( M_0 = 110 \, M_\odot \), an ejecta velocity of 13000 km s\(^{-1}\) (Y15), and a separation of 10\( \times 10^3 \) cm. This is consistent with the early luminosity observed in Type Ic SLSNe (Leloudas et al. 2012; Nicholl et al. 2015b).

The luminosity estimate is not sensitive to \( M_0 \) and we expect similar luminosity in the magnetar model (Kasen 2010). Because the general likelihood to observe an early brightening by the companion star in Type Ic SNe is estimated to be low (Moriya, Liu, & Stancliffe 2013), the frequent observations of an early brightening in Type Ic SLSNe may also imply that they preferentially occur in close binary systems. Early brightening by impact onto a companion star strongly depends on the viewing direction to the observer, while H\( \alpha \) emission from stripped matter can be observed from all directions (e.g., Kasen 2010; Liu, Moriya, & Stancliffe 2015). Thus, H\( \alpha \) emission may be observed more frequently. For example, if we assume a companion viewing angle of about 10 degrees as is nearly the case for 5\( R_2 \), about 10% of randomly oriented observers are in a preferred direction to find the early brightening (Kasen 2010).

4.3. The progenitor of iPTF13ehe and its binary evolution

Binary evolution has been suggested to be important for SLSN progenitors (e.g., Justham, Podsiadlowski, & Vink 2014). The fact that we find a possible signature of the companion star in Type Ic SLSN iPTF13ehe suggests that binary evolution can indeed play a key role in their progenitors. For example, binary can help progenitors to have a large angular momentum through tidal interactions (e.g., de Mink et al. 2009; Song et al. 2015) and mass transfer (e.g., de Mink et al. 2013). Rotationally-induced mixing may reduce the initial mass needed to obtain PISNe (e.g., Yoon, Diers, & Langer 2012; Chatzopoulos & Wheeler 2012; Yusof et al. 2013). Rapid rotation is also essential in the magnetar-powered model as its energy source is rotation.

Y15 estimate that about 10% of Type Ic SLSNe may have nebular H\( \alpha \) emission. This may indicate that insufficient mass to have detectable nebular H\( \alpha \) emission is stripped from the companion in about 90% of Type Ic SLSNe currently observed. For example, if the typical separation is larger than about 20 \( R_2 \), we do not expect sufficient stripping to observe the emission, as discussed. Alternatively, many progenitors may be effectively single stars. This does not mean that they are single stars from the beginning. A stellar merger leads to an apparent single star (cf. Justham, Podsiadlowski, & Vink 2014) and to the increase of its rotational velocity (cf. de Mink et al. 2013).

5. Conclusions

We suggest that the H\( \alpha \) emission observed during the nebular phases of Type Ic SLSN iPTF13ehe originates from matter which is stripped off a hydrogen-rich companion star of the SN progenitor. Matter near the surface of the companion star is stripped when the SN ejecta collide with the companion and the hydrogen-rich stripped matter contaminates the inner low-velocity layers of the SN ejecta. Emission from the contaminated ejecta can only be observed during the nebular phases when the inner layers are transparent. The temporal evolution, the line broadening, and the overall blueshift of the observed H\( \alpha \) emission in iPTF13ehe are consistent with emission from stripped matter. By scaling the predicted H\( \alpha \) luminosity based on the W7 model of Type Ia SNe, we estimate a stripped mass in iPTF13ehe between 0.1 and 0.9 \( M_\odot \) (Table 1). We do not expect nebular H\( \alpha \) emission from the stripped matter if iPTF13ehe is powered by the interaction between the SN ejecta and a dense circumstellar medium because a central heating source is required to excite hydrogen located at the inner low-velocity layers of the SN ejecta.

We perform numerical simulations of the mass stripping using the same technique as in Liu et al. (2015). We assume \( M_0 = 110 \, M_\odot \) and \( E_{\text{diss}} = 60 \, B \) and put a main-sequence companion star with \( 50 \, M_\odot \) and \( 10 \, R_\odot \) at a separation of 5\( R_2 \) and 10\( R_2 \). Our mass stripping efficiency implies that the companion mass is larger than about 20 \( M_\odot \) (\( ^{56}\text{Ni}-\text{powered models} \)) or more than about 80 \( M_\odot \) (magnetar spin-down models). Our results imply that the progenitor evolved in a massive binary system and that stellar binary may play a critical role in the evolution of Type Ic SLSN progenitors. If Type Ic SLSN progenitors are typically in close binary systems, the early brightening sometimes observed in them may also be related to the collision.

If our interpretation of the origin of the H\( \alpha \) emission is correct, we expect some diversity in the H\( \alpha \) emission feature. Especially, the overall line shift, which is a blue shift in the case of iPTF13ehe, is likely affected by the viewing angle. If the companion star is located behind the SN progenitor at the time of explosion, an overall redshift of the H\( \alpha \) emission may be observed. It will be also interesting to obtain the H\( \alpha \) detection rate separately in slowly-declining and fast-declining Type Ic SLSNe in future SLSN studies. A large number of observations of late-phase emission from Type Ic SLSNe can test our interpretation and reveal the origin and nature of mysterious Type Ic SLSNe.

Acknowledgements. TJM is supported by Japan Society for the Promotion of Science Postdoctoral Fellowships for Research Abroad (26-51). JM acknowledges support from the Deutsche Forschungsgemeinschaft priority program 1573, Physics of the Interstellar Medium.

References

Axelrod T. S., 1980, Ph.D. thesis, University of California, Santa Cruz
Baklanov P. V., Sorokina E. I., Blinnikov S. I., 2015, AstL, 41, 95
Chatzopoulos E., Wheeler J. C., 2012a, ApJ, 760, 154
Chatzopoulos E., Wheeler J. C., 2012b, ApJ, 757, 44
Chen T.-W., et al., 2015, MNRAS, 452, 1567
Chevalier R. A., Irwin C. M., 2011, ApJ, 729, L6
de Mink S. E., Cantiello M., Langer N., Pols O. R., Brott I., Yoon S.-C., 2009, A&A, 497, 243
de Mink S. E., Langer N., Izzard R. G., Sana H., de Koter A., 2013, ApJ, 764, 166
Dessart L., Hillier D. J., Waldman R., Livne E., Blondin S., 2012, MNRAS, 426, L76
Dessart L., Waldman R., Livne E., Hillier D. J., Blondin S., 2013, MNRAS, 428, 3227
Eggleton P. P., 1983, ApJ, 268, 368
Gal-Yam A., 2012, Science, 337, 927
Gal-Yam A., et al., 2009, Nature, 462, 624
Ginzburg S., Balberg S., 2012, ApJ, 757, 178
Heger A., Woosley S. E., 2002, ApJ, 567, 532
Hirai R., Sawai H., Yamada S., 2014, ApJ, 792, 66
Inserro C., Smartt S. J., 2014, ApJ, 796, 87
Inserro C., et al., 2013, ApJ, 770, 128
Justham S., Podsiadlowski P., Vink J. S., 2014, ApJ, 796, 121
