SN 2009ip: CONSTRAINING THE LATEST EXPLOSION PROPERTIES BY ITS LATE-PHASE LIGHT CURVE

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ABSTRACT

We constrain the explosion and circumstellar properties at the 2012b event of SN 2009ip based on its recently reported late-phase bolometric light curve. The explosion energy and ejected mass at the 2012b event are estimated as $0.01 M_\odot$ and $2 \times 10^{49}$ erg, respectively. The circumstellar medium is assumed to have two components: an inner shell and an outer wind. The inner shell, which is likely created at the 2012a event, has a mass of $0.2 M_\odot$. The outer wind is created by the wind mass loss before the 2012a mass ejection, and the progenitor is estimated to have had a mass-loss rate of about $0.1 M_\odot$ yr$^{-1}$ with a wind velocity of $550$ km s$^{-1}$ before the 2012a event. The estimated explosion energy and ejected mass indicate that the 2012b event is not caused by a regular SN.

Key words: stars: massive – stars: mass-loss – supernovae: individual (SN 2009ip)

1. INTRODUCTION

It is widely believed that the efficient conversion of kinetic energy to radiation results in luminous transients. Type IIn supernovae (SNe IIn), which sometimes even become super-luminous (e.g., Gal-Yam 2012), are largely powered by the interaction between SN ejecta and the circumstellar medium (CSM; e.g., Moriya et al. 2014). Bright transients called “SN impostors” also exist; these objects are likely brightened by the collision of the material ejected intermittently from the progenitor (e.g., Van Dyk et al. 2000). SN impostors are not caused by the final SN explosions of their progenitors, but they sometimes become as bright as SNe. SNe IIn and SN impostors are related to the unsolved problems in stellar mass loss, and it is important to understand their origins (e.g., Langer 2012; Smith 2014). They also have been suggested to be important high-energy cosmic-ray producers (Murase et al. 2011, 2014). In addition, they can play a role as a distance ladder (e.g., Cooke et al. 2009; Tanaka et al. 2012).

SN 2009ip is one of the most studied transients powered by the interaction due to its activeess which has kept us surprised since 2009. The progenitor of SN 2009ip grew bright and was assigned an SN name in 2009 August (Maza et al. 2009). However, subsequent observations revealed that it was not a genuine SN and that the progenitor remained there at the location (Smith et al. 2010; Foley et al. 2011). The progenitor mass is estimated to be above $\sim 60 M_\odot$, and the observed brightening is considered to be an SN impostor from a luminous blue variable star (Smith et al. 2010; Foley et al. 2011). The progenitor has experienced several rebrightenings since 2009 (Pastorello et al. 2013).

SN 2009ip showed drastic changes in 2012 (Figure 1). In 2012 August, SN 2009ip started to become bright again and faded temporarily after about 40 days (the 2012a event; see Figure 1). Then, it became bright again and reached a peak luminosity of $8 \times 10^{42}$ erg s$^{-1}$ (Pastorello et al. 2013), which is comparable to those observed in SNe (the 2012b event; Figure 1). Observations during and after the 2012 events of SN 2009ip have been reported by many authors (Fraser et al. 2013, 2015; Mauerhan et al. 2013, 2014; Ofek et al. 2013a; Pastorello et al. 2013; Prieto et al. 2013; Smith et al. 2013, 2014; Graham et al. 2014; Levesque et al. 2014; Margutti et al. 2014; Fox et al. 2015; Martin et al. 2015).

2. LC MODEL

2.1. Assumptions

We assume that a progenitor system schematically shown in Figure 2 led to the 2012b and later event of SN 2009ip. The events are assumed to be caused by an ejection of the mass $M_{\text{ej}}$ with the kinetic energy $E_{\text{kin}}$ in a dense CSM. The dense CSM is assumed to have two components: an inner shell and an outer regular wind. The inner shell is presumed to be created by the mass ejection during the 2012a event with a mass-loss rate of $\dot{M}_{\text{ej}}$, and it is assumed to have a mass of $M_{\text{sh}}$. We note that this kind of shell may also be formed by the confinement of the stellar wind (Mackey et al. 2014). The outer wind structure is assumed to be created with wind mass loss with a mass-loss rate of $\dot{M}_{\text{w}}$ and a velocity of $v_{\text{w}}$. Although the observed...
luminosity fluctuations before the 2012a event indicate that the CSM may not be smooth, we assume that the overall density structure is approximately proportional to $r^{-2}$. Based on the observations of SN 2009ig in 2009, we assume that $v_w = 550 \text{ km s}^{-1}$ (Smith et al. 2010; Foley et al. 2011). The inner and outer components are separated at $R_{sh}$.

We assume that the inner shell is responsible for the rise and decline observed until $\sim$100 days after the 2012b event (“early phase”; Section 2.2). Then, a shock containing both $M_{ex}$ and $M_{sh}$ is assumed to propagate in the outer wind. The shock is assumed to be thin due to the efficient radiative cooling. The continuous interaction between the shock and the outer wind is assumed to be responsible for the efficient radiative cooling. The total energy during the 2012b event is estimated to be $E_{\text{rad}} \approx 2 \times 10^{49} \text{ erg}$ (Fraser et al. 2013; Margutti et al. 2014).

2.2. Early Phase (Diffusion Phase)

We assume that the early phase is caused by diffusion in the inner shell (see also Ofek et al. 2013a; Margutti et al. 2014). If we assume that the shell has an average density $\rho$, the diffusion time $t_{\text{diff}}$ in the shell, which corresponds to the rise time of the LC, is expressed as

$$t_{\text{diff}} \approx \frac{\kappa \rho R_{sh}^2}{c},$$

where $\kappa$ is the opacity and $c$ is the speed of light. We assume $\kappa = 0.34 \text{ cm}^2 \text{ g}^{-1}$ in this study. Using the diffusion time, $M_{sh}$ can be estimated as

$$M_{sh} \approx \frac{4}{3} \pi \rho R_{sh}^3 = \frac{4\kappa c t_{\text{diff}} R_{sh}}{3\kappa}.$$  

As the rise time and the $\epsilon$-folding time of the later luminosity decline are both about 14 days (e.g., Pastorello et al. 2013; Moriya et al. 2014), a shock breakout likely occurred in the shell (Ofek et al. 2013a; Margutti et al. 2014). This indicates that the entire shell was shocked at the LC peak. Thus, we presume that the blackbody radius at the LC peak of the 2012b event corresponds to $R_{sh}$ and we set $R_{sh} \approx 10^{15} \text{ cm}$ (Margutti et al. 2014). Assuming $t_{\text{diff}} \approx 14$ days and $R_{sh} \approx 10^{15} \text{ cm}$, we obtain $M_{sh} \approx 0.22 M_{\odot}$. The estimated mass is consistent with those obtained in previous studies ($\sim 0.1 M_{\odot}$, e.g., Fraser et al. 2013; Margutti et al. 2014). If the shell is ejected during the 2012a event which lasted for $\sim$40 days, the mass-loss rate during the 2012a event becomes $\dot{M}_{sh} \approx 2 M_{\odot} \text{ yr}^{-1}$.

The explosion properties ($E_{ex}$ and $M_{ex}$) can be related to the total radiation energy emitted during the 2012b event. The conservation of momentum and energy results in (e.g., Moriya et al. 2013a)

$$E_{\text{rad}} = \frac{M_{sh}}{M_{ex} + M_{sh}} E_{ex}.$$  

The total energy during the 2012b event is estimated to be $E_{\text{rad}} \approx 2 \times 10^{49} \text{ erg}$ (Fraser et al. 2013; Margutti et al. 2014).

2.3. Late Phase (Momentum-driven Phase)

Fraser et al. (2015) recently reported late-phase LCs until about 750 days after the 2012b event and constructed a bolometric LC (Figure 1). The late bolometric LC is shown to evolve with a power law $L = L_0 t^{-\alpha}$, where $t$ is time since the explosion. Fraser et al. (2015) fitted the power-law function by setting $t = 0$ at the beginning of the 2012a event and obtained $\alpha = 1.74$ as the best fit parameter. However, we here assume that the inner explosion causing the 2012b event occurred after the 2012a event. If we set $t = 0$ at MJD = 56193 when the 2012b event began, we obtain $\alpha = 1.44$ as the best fit parameter.

What is surprising is that $\alpha$ is near 1.5 and it is significantly larger than 1.0. If the interaction between SN ejecta and the dense wind is still ongoing, $\alpha$ is expected to be significantly below 1.0 when the wind is almost steady because of the continuous momentum injection from the SN ejecta (e.g., Moriya et al. 2013b; Ofek et al. 2014). For example, in the case of SN IIn 2010jl, the bolometric LC follows a power law with...
\( \alpha < 1 \) even at around 600 days after the explosion (e.g., Maeda et al. 2013), although some arguments exist for the LC interpretation (Fransson et al. 2014).

The large \( \alpha \) near 1.5 in the LC after about 200 days since the 2012b explosion indicates that the shock proceeding in the wind is already in the momentum-driven phase at about 200 days. The momentum-driven phase (also called the “snowplow phase”) is the phase when the momentum injection to the shock has already terminated and the shock moves only with the momentum previously injected into it (see, e.g., Svirski et al. 2012; Moriya 2014b; Ofek et al. 2014). Moriya et al. (2013b) obtained the luminosity evolution during the momentum-driven phase in the steady wind as

\[
L = \frac{\epsilon}{2} M_c \left( \frac{2 E_m}{M_m} \right)^{3/2} \left[ 1 + 2 \frac{M_c}{v_w} \left( \frac{2 E_m}{M_m^3} \right)^{1/2} t \right]^{3/2},
\]

where \( \epsilon \) is the conversion efficiency from the kinetic energy to radiation, and \( E_m \) and \( M_m \) are the energy and mass released inside the wind, respectively. In the system in which we are interested (Figure 2), the shock propagates in the outer wind component after it has passed through the inner shell. Thus, we can set

\[
M_m = M_{ex} + M_{sh},
\]

from the conservation of mass, and

\[
M_m E_m = M_{ex} E_{ex},
\]

from the conservation of momentum.

The luminosity evolution in the momentum-driven phase (Equation (4)) can be separated into two parts. At first, when \( 2(M_{sh}/v_w)(2E_m/M_m^3)^{1/2} t \leq 1 \), the luminosity is constant. This is because the wind mass swept by the shock is much smaller than the initial injected mass \( (M_m) \) and the shock freely expands with a constant velocity. Then, when

\[
2 \frac{M_{sh}}{v_w} \left( \frac{2 E_m}{M_m^3} \right)^{1/2} t \gtrsim 1,
\]

starts to hold after the shock has swept a large amount of the wind (see Moriya 2014b for detailed discussion on this condition), the luminosity evolves as \( L = L_1 t^{-1.5} \), where

\[
L_1 = 2^{-7/2} \epsilon \left( \frac{M_{sh}}{v_w} \right) E_m^{3/4} M_m^{1/4}.
\]

Using Equation (8), condition (7) can be used to constrain \( M_m \), i.e.,

\[
M_m \lesssim 2^{3/2} \epsilon^{-1/2} \frac{1}{3} L_1^{1/2} \left( \frac{M_{sh}}{v_w} \right)^{3/2} t^{1/2}.
\]

The late-phase bolometric LC of SN 2009ip indicates that the condition (9) is satisfied at least about 200 days after the explosion.

In Figure 1, we show the results of fitting of the function \( L = L_1 (t + t_0)^{-1.5} \) to the bolometric LC after 150 days since the beginning of the 2012b event with several different explosion times \( (t_0) \) relative to the beginning of the 2012b event

\begin{table}[h]
\centering
\caption{Estimated Explosion and Circumstellar Properties at the 2012b Event}
\begin{tabular}{cccccc}
\hline
\( M_{ex} \) & \( E_{ex} \) & \( M_{sh} \) & \( E_{sh} \) & \( E_{ex}, \) & \( V_{ex} \) \\
\hline
10^{-1} & 2.1 & 1.1 \times 10^3 & 0.22 & 10 & 0.98 \\
10^{-2} & 2.02 & 2.5 \times 10^3 & 0.22 & 2.2 & 2.0 \\
10^{-3} & 2.005 & 5.3 \times 10^4 & 0.22 & 0.48 & 4.3 \\
\hline
\end{tabular}
\end{table}

(MJD = 56193). Although \( \alpha = 1.5 \) is fixed in the fitting, decent fits to the bolometric LC are obtained. The best \( L_1 \) is found as \( 1.15 \times 10^{51} \) \( (t_0 = 0 \) days), \( 1.18 \times 10^{51} \) \( (t_0 = 5 \) days), \( 1.22 \times 10^{51} \) \( (t_0 = 10 \) days), \( 1.29 \times 10^{51} \) \( (t_0 = 20 \) days), and \( 1.42 \times 10^{51} \) \( (t_0 = 40 \) days) in the cgs unit. Since \( L_1 \) does not depend strongly on \( t_0 \), we use \( L_1 = 1.15 \times 10^{51} \) cgs \( (t_0 = 0 \) days) as a representative value in the following discussion.

Finally, the mass ejected at the inner explosion \( (M_{ex}) \) can be expressed as

\[
M_{ex} = -\frac{M_{sh}}{2} + \frac{1}{2} \left[ M_{sh}^2 + 2^{13/2} \epsilon^{-4} L_1^{1/2} \left( \frac{M_{sh}}{v_w} \right)^{1/2} E_{rad} \right]^{1/2},
\]

using Equations (3), (5), (6), and (8).

3. EXPLOSION AND CIRCUMSTELLAR PROPERTIES

AT THE 2012B EVENT OF SN 2009ip

We now look into the explosion and circumstellar properties of the final explosive event observed in SN 2009ip so far. We have already constrained the inner shell mass in the previous section \( (M_{sh} \simeq 0.22 M_{\odot}) \). The wind velocity is fixed to \( v_w = 550 \) km s\(^{-1}\). We also set \( \epsilon = 0.3 \), which is typically found in SN IIn studies (e.g., van Marle et al. 2010; Fransson et al. 2014). The conversion efficiency is related to the physical properties of radiative shocks, and it is not likely to be altered by the origins of the explosions inside. Thus, we use a typical value found in SN studies here. The conversion efficiency can be reduced by, e.g., multi-dimensional motions and asphericity (e.g., Moriya et al. 2013a). The observational information we have is \( E_{rad} \simeq 2 \times 10^{49} \) erg and \( L_1 \simeq 1.15 \times 10^{51} \) cgs. We first assume several mass-loss rates for the outer wind \( (M_{ex} = 10^{-1}, 10^{-2}, 10^{-3} M_{\odot} \) yr\(^{-1}\) \) and give constraints on the other parameters for the assumed mass-loss rates.

The explosion properties at the 2012b event can be easily constrained with the formulae derived in Section 2. First, the ejected mass \( M_{ex} \) can be constrained with Equation (10). Then, the explosion energy \( E_{ex} \) can be estimated with Equation (3) assuming the obtained \( M_{ex} \) and \( M_{sh} \). Finally, we need to check if condition (9) holds for the estimated parameters for consistency.

Table 1 summarizes the estimated parameters for SN 2009ip. We can first find that \( M_{ex} \) is much smaller than \( M_{sh} \). This means that most of the kinetic energy released at the 2012b event is converted to radiation energy (Equation (3)). In other words, Equation (3) indicates that \( E_{rad} \simeq E_{ex} \), and only a small amount of the released kinetic energy is available for the late phase. The remaining kinetic energy \( (E_{sh}) \) is only below 10% of \( E_{ex} \) (Table 1). The total amount of energy radiated after 100 days is obtained by assuming \( L = L_1 t^{-1.5} \) is 7.8 \times 10\(^{47}\) erg, and only the \( 10^{-1} M_{\odot} \) yr\(^{-1}\) model is consistent with the total radiated energy.
The fact that the late-phase bolometric LC roughly follows $\propto r^{-1.5}$ gives constraint (9). Assuming $t \approx 200$ days in Equation (9), we obtain the following constraint:

$$M_{\text{ex}} + M_{\text{sh}} \lesssim \begin{cases} 0.2 M_\odot & (M_e = 10^{-1} M_\odot \, \text{yr}^{-1}), \\ 0.04 M_\odot & (M_e = 10^{-2} M_\odot \, \text{yr}^{-1}), \\ 0.009 M_\odot & (M_e = 10^{-3} M_\odot \, \text{yr}^{-1}). \end{cases} \quad (11)$$

Because $M_{\text{sh}}$ is estimated to be $0.22 M_\odot$ and $M_{\text{sh}} \gg M_{\text{ex}}$, this constraint also indicates that $M_e$ is around $10^{-1} M_\odot \, \text{yr}^{-1}$. The estimated mass-loss rate is consistent with those estimated by the H$\alpha$ luminosity (Fraser et al. 2013; Ofek et al. 2013a), while it is lower than that estimated by Ofek et al. (2013a) based on multi-wavelength observations. Combining all of the above, we suggest $M_{\text{ex}} \approx 0.011 M_\odot$ and $E_{\text{ex}} \approx 2.1 \times 10^{59}$ erg as the explosion properties at the 2012b event.

The estimated $E_{\text{ex}}$ and $M_{\text{ex}}$ with $M_e = 10^{-1} M_\odot \, \text{yr}^{-1}$ are also consistent with the interpretation that the shock breakout occurred in the inner shell at the 2012b event (Section 2.2). The explosion velocity $v_{\text{ex}} \equiv \sqrt{2E_{\text{ex}}/M_{\text{ex}}}$ is shown in Table 1. The explosion velocity indicates that the shock breakout occurs where the optical depth is $\sim c v_{\text{ex}} \approx 30$ (e.g., Weaver 1976). If we use $\tau \approx 10^{-13} \, \text{g cm}^{-2}$ estimated by Equation (1), the shock breakout occurs at $\sim 2 \times 10^{14} \, \text{cm}$. This radius is near $4-5 \times 10^{14} \, \text{cm}$, which is the smallest photospheric radius observed at the beginning of the 2012b event (Margutti et al. 2014).

The estimated average ejecta velocity of $v_{\text{ex}} \approx 10^4 \, \text{km s}^{-1}$ is also consistent with the broad spectra observed in the 2012b event of SN 2009ip indicating an ejecta velocity of $\sim 10^4 \, \text{km s}^{-1}$ (e.g., Fraser et al. 2013). Pastorello et al. (2013) reported similarly broad spectral lines in SN 2009ip before the 2012 events, and these kinds of broad lines are known to be associated with non-SN events.

The estimated explosion energy and mass at the 2012b event are not those of regular SNe, which typically have $\sim 10^{51}$ erg and $\sim 1-10 M_\odot$. In particular, the progenitor of SN 2009ip is likely heavier than $60 M_\odot$ (Smith et al. 2010; Foley et al. 2011), and the estimated small ejecta mass is inconsistent with its successful SN explosion. Even if the ejecta has $\sim 10^{51}$ erg and only the ejecta within a certain direction interacted with the dense CSM to emit only 1% of the kinetic energy ($\sim 10^{49}$ erg, e.g., Smith et al. 2014), the estimated ejecta mass is much smaller than 1% of the progenitor mass. Thus, the explosion that occurred inside during the 2012b event is not likely related to a regular SN. However, some SNe may have properties similar to those estimated here, and we cannot conclude for sure if the core collapse of the progenitor occurred or not. For example, an SN with large fallback can have a small amount of ejecta with small kinetic energy (e.g., Moriya et al. 2010). Low energy and small mass ejection are also predicted to be caused by failed SNe (Nadezhin 1980; Lovegrove & Woosley 2013). Massive star mergers may also have a similar fast mass ejection (e.g., Soker & Kashi 2013).

4. CONCLUSIONS

We have estimated the explosion and circumstellar properties at the 2012b event of SN 2009ip based on the late-phase bolometric LC recently reported by Fraser et al. (2015). The bolometric LC roughly follows $L \propto t^{-1.5}$ at least from about 200 days after the 2012b event (Figure 1), and it indicates that the shock is already at the momentum-driven phase without any momentum injection from inside at that time. Thus, we use an analytic bolometric LC model for the momentum-driven phase to estimate the explosion and circumstellar properties. We assume that an explosion occurred inside the circumstellar medium with two components: an inner shell and an outer wind (Figure 2). The inner shell is presumed to have been created during the 2012a event of SN 2009ip, while the outer wind was made by the wind mass loss of the progenitor prior to the 2012a event.

Combining all the bolometric LC information available after the 2012b event, we suggest that an explosion with energy $2.1 \times 10^{59}$ erg and a mass $0.011 M_\odot$ occurred at the 2012b event of SN 2009ip. The ejecta first collided with the inner shell whose mass is estimated to be $0.22 M_\odot$. The collision between the ejecta and the inner shell is responsible for the early LC during the 2012b event which is dominated by photon diffusion after the shock breakout in the shell. The thin shock made by the efficient cooling, which contains the mass of both the ejecta and the inner shell, continues to travel in the outer wind, powering the late-phase LC of SN 2009ip. The total radiated energy and the fact that the bolometric LC is already at the momentum-driven phase with $L \propto t^{-1.5}$ at about 200 days after the explosion indicate that the mass-loss rate of the progenitor prior to the 2012a event is about $0.1 M_\odot \, \text{yr}^{-1}$ with a wind velocity of $550 \, \text{km s}^{-1}$.

The estimated explosion properties are not those of regular SNe. Thus, the explosion at the 2012b event is not related to a regular SN. It is likely to be a non-SN explosive event or a peculiar SN like those accompanied by large fallback or caused by failed SN explosions.

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