Circumstellar Interaction of Type Ia Supernova SN 2002ic

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Abstract

SN 2002ic is a unique supernova which shows the typical spectral features of Type Ia supernovae (SNe Ia) near maximum light, but also apparent hydrogen features that have been absent in SNe Ia. We have calculated hydrodynamical models for the interaction between the SN Ia ejecta and the H-rich circumstellar medium (CSM) to reproduce the observed features of SN 2002ic. Based on our modeling, we suggest that CSM is aspherical (or highly clumpy) and contains $\sim 4-5 M_{\odot}$. Possible progenitor systems of SN 2002ic are discussed.

1. Type Ia Supernovae and Circumstellar Medium

Type Ia supernovae (SNe Ia) are characterized by the lack of hydrogen and the prominent Si line in their spectra near maximum light and widely believed to be thermonuclear explosions of mass-accreting white dwarfs in binary systems. SNe Ia have been used as a “standard candle” to determine cosmological parameters thanks to their relatively uniform light curves and spectral evolution. SNe Ia are also the major sources of Fe in the galactic and cosmic chemical evolution. Despite such importance, the immediate progenitor binary systems have not been clearly identified yet (e.g., [10, 13]).

For a model of SN Ia progenitors, Hachisu et al. [5, 6] proposed a single degenerate model in which the white dwarf blows a massive and fast wind (up to $10^{-4} M_{\odot} \text{ yr}^{-1}$ and 2000 km s$^{-1}$) and avoids a formation of common envelope when the mass transfer rate from the normal companion exceeds a critical rate of $\sim 1 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ [11]. Such an evolutionary phase is dubbed “accretion wind evolution” instead of “common envelope evolution.” Such a binary can keep its
separation almost unchanged. The white dwarf can steadily accrete a part of the transferred matter and eventually reach the Chandrasekhar mass.

In the strong wind model, the white winds form a circumstellar envelope around the binary systems prior to the explosion. When the ejecta collide with the circumstellar envelope, X-rays, radio, and Hα lines are expected to be emitted by shock heating. Attempts have been made to detect such emissions, but so far no signature of circumstellar matter has been detected.

The upper limit set by X-ray observations of SN 1992A is $\dot{M}/v_{10} = (2 - 3) \times 10^{-6} \, M_\odot \, yr^{-1}$ \cite{19}. Radio observations of SN 1986G have provided the most stringent upper limit to the circumstellar density as $\dot{M}/v_{10} = 1 \times 10^{-7} M_\odot \, yr^{-1}$, where $v_{10}$ means $v_{10} = v/10 \, \text{km s}^{-1}$. This is still $10 - 100$ times higher than the density predicted for the white dwarf winds, because the white dwarf wind velocity is as fast as $\sim 1000 \, \text{km s}^{-1}$. For Hα emissions, the upper limit of $\dot{M}/v_{10} = 6 \times 10^{-6} \, M_\odot \, yr^{-1}$ has been obtained for SN 1994D.

2. SN 2002ic

SN 2002ic was discovered on 2002 November 13 UT at magnitude 18.5 by the Nearby Supernova Factory search \cite{19}. Hamuy et al. \cite{8} reported strong Fe III features and a Si II λ6355 line in the early-time spectra of SN 2002ic and classified it as a SN Ia.

However, strong Hα emission was also observed. The emission was broad (FWHM $> 1000 \, \text{km s}^{-1}$) suggesting that it was intrinsic not to an H II region of the host galaxy but to the supernova. The detection of Hα is unprecedented in a SN Ia (e.g., \cite{1, 10}).

Hamuy et al. \cite{8} suggested that it arose from the interaction between the SN ejecta and a dense, H-rich circumstellar medium (CSM), as in Type IIn SNe (SNe IIn). If this interpretation is correct, SN 2002ic may be the first SN Ia to show direct evidence of the circumstellar (CS) gas ejected by the progenitor system, presenting us with a unique opportunity to explore the CSM around a SN Ia and the nature of the progenitor system.

2.1. Spectroscopic Features of SN 2002ic

The late-time spectrum of SN 2002ic is strikingly similar to those of Type IIn SNe 1997cy \cite{17} and 1999E \cite{14} as shown in Figure 1. Spectroscopically, SN 2002ic evolve with time significantly, in particular in the Hα line and its complex profile. Hamuy et al. \cite{8} detected in the early-time spectra an unresolved narrow Hα emission on top of a $\sim 2000 \, \text{km/s}$ base, which were superimposed on dominant SN Ia line features. One year after the explosion, however, the Hα line
became much more prominent and consisted of a narrow core and a $\sim 5000$ km/s component. Other strong features identified in Figure 1 include Ca and O lines as broad as $\geq 10,000$ km/s and broad permitted Fe II multiplets [3].

SNe 1997cy and 1999E were initially classified as Type IIn because they showed H$\alpha$ emission. SN 2002ic would also have been so classified, had it not been discovered at an early epoch. SN 1997cy ($z = 0.063$) is among the most luminous SNe discovered so far ($M_V < -20.1$ about maximum light), and SN 1999E is also bright ($M_V < -19.5$). Both SNe 1997cy and 1999E have been suspected to be spatially and temporally related to a GRB [4, 14]. However, both the classification and the associations with a GRB must now be seen as highly questionable in view of the fact that their replica, SN 2002ic, appears to have been a genuine SN Ia at an earlier phase.

2.2. Observed Light Curve of SN 2002ic

The UVOIR bolometric light curve of SN 2002ic has been constructed by Deng et al. [3] from the available BVRI photometry and the spectrophotometry [8, 18] as shown in Figure 2. To construct the light curve of SN 2002ic, we first integrated the Subaru spectrum. This yielded $L = (5.9 \pm 0.6) \times 10^{42}$ ergs s$^{-1}$, corresponding to $M_{bol} \sim -18.2$, assuming a distance of 307 Mpc ($H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$). The bolometric corrections thus estimated was used to convert the early-time photometry in Hamuy et al. [8] and the late-time MAGNUM telescope photometry into bolometric luminosities.
The light curve of SN 2002ic is brighter at maximum and declines much more slowly than typical SNe Ia [8]. The late time light curve of most SNe is powered by the radioactive decay of $^{56}$Co to $^{56}$Fe. The decline of SN 2002ic is much slower than the Co decay rate, which indicates the presence of another source of energy.

In fact the overall light curve of SN 2002ic resembles SNe 1999E [14] and 1997cy [17] (see Figure 2). We use $UBVRI$ bolometric light curves of SNe 1997cy and 1999E for comparison [17, 14]. Assuming $E(B-V) = 0.06$ for the Galactic extinction (NED), SN 2002ic is only a factor of 1.3 dimmer than SN 1997cy, but more than 100 times brighter at late phases than typical SNe Ia. The light curve of SN 1997cy has been modeled in the context of circumstellar interaction [17], which is very likely the same energy source for SN 2002ic.

![Fig. 2. Comparison of the $UBVRI$ bolometric light curves of SN 2002ic (red filled squares) with those of SNe 1997cy (blue open circles) and 1999E (green crosses), and the normal SN Ia 1994D (black dashed line).](image)

### 3. Circumstellar Interaction Models

We calculated the interaction between the expanding ejecta and CSM (details will be seen in Suzuki et al., in preparation). For the supernova ejecta, we used the carbon deflagration model W7 [12]; its kinetic energy is $E = 1.3 \times 10^{51}$ erg. For CSM we assumed the power-law density distribution:

$$\rho = \rho_0 (r/R_0)^{-n} \text{ g cm}^{-3}$$

(1)
where the parameters are the radius ($R_0$) and density ($\rho_0$) of the point where the ejecta and CSM start interacting, and the index ($n$) of the density distribution of CSM. These parameters are constrained from comparison with the observed light curve. The spherical Lagrange hydrodynamical code and input physics are the same as in Suzuki & Nomoto [16].

When the expanding ejecta interacts with CSM, the interaction creates the forward shock which is propagating through the CSM and the reverse shock which is propagating through the ejecta.

Shocked matter is heated to $T \sim 10^7$ K for the reverse shock and $T \sim 10^9$ K for the forward shock. Both shocked regions emit thermal X-rays. For the reverse shock, because of relatively high densities in the ejecta, cooling time scale is shorter than shock propagation so that the shocked ejecta soon forms a dense cool shell [16]. This dense cool shell absorbs the X-ray and re-emits in UV-optical. This re-emitted photons are observed. We assume that a half of the X-rays emitted in the reverse-shocked ejecta is lost into the supernova center, and that the other half is transferred outwardly through the cooling shell. We also assume that a half of the X-rays emitted in the CSM is transferred inwardly to be absorbed by the cooling shell. We take into account the change in time of the column density of the cooling shell to evaluate the X-rays absorbed by the shell and the optical luminosity.

Figure 3 shows the successful model for the light curve of SN 2002ic. Here $R_0 = 2 \times 10^{14}$ cm, $\rho_0 = 4 \times 10^{-13}$ g cm$^{-3}$, and $n = 1.8$ for inner CSM of 4 $M_\odot$. In the early phase, the model with $n = 2.0$ (steady mass loss) declines too fast to
be compatible with the observation. This implies that CSM around the SN was created by unsteady mass loss of the progenitor system.

After day $\sim 350$, the light curve starts declining. To reproduce the declining part of the light curve, we add the outer CSM of $0.7 \, M_\odot$ where the density declines sharply as $n = 6$. This implies that the total mass of CSM is $\sim 4.7 \, M_\odot$.

We note in Figure 4 that the velocity of the ejecta decelerated by the CSM-interaction is $\lesssim 4000 \, \text{km s}^{-1}$ and too low for the value observed in the broad spectral features ($\sim 10,000 \, \text{km s}^{-1}$). On the other hand, in order to produce high enough luminosity to explain the light curve, such a strong interaction between the ejecta and CSM should occur.

To reproduce both the light curve and the observed velocity of SN 2002ic, CSM needs to be aspherical. Suppose the CSM is aspherical consisting of a dense region and a thin region. The expanding ejecta interacting strongly with the dense region can produce high enough luminosity to explain the light curve. On the other hand, the ejecta interacting with the thin region can expand still fast enough to be consistent with the observed velocities (see also Deng et al. [3]). A pre-existing clumpy disk was also suggested by Wang et al. [18], based on spectropolarimetry.

4. Discussion

There are two possible progenitor scenarios for SN 2002ic. One is the explosion of the C+O core of the massive AGB star (SN I+1/2), where the wind from the AGB star formed the CSM. The other is the explosion of the white dwarf in a close binary blowing wind to create the dense CSM (e.g., [9, 2]).
4.1. *Type I+1/2 Supernovae in AGB Stars*

Single star scenario is the explosion of the massive AGB star whose C+O core becomes very close to the Chandrasekhar mass. Before explosion, mass loss (super-wind) from the star creates a dense CSM. The C+O core explodes, which is called Type I+1/2 supernova, and interacts with CSM.

To make this scenario possible, the metallicity of the system should be low because low mass loss rate is necessary for the C+O to grow to reach the Chandrasekhar mass before the envelope is completely lost. Under the solar metallicity, SN I+1/2 have never been observed. Therefore, we can explain the rarity of SN 2002icz-like event assuming that only narrow mass range of AGB stars can explode as SNe in low metal environment.

Aspherical CSM is not unexpected for stars approaching the end of the AGB.

4.2. *White Dwarf Winds*

Binary star scenario is the explosion of the accreting C+O white dwarf (same as typical SNe Ia). However, the companion star is massive and the white dwarf blows large amount of accreting gas as accretion wind to create the dense CSM. In this scenario, the rarity is can be attributed to the fewness of the companion star massive enough to produce the quite massive CSM.

As a progenitor of SN 2002icz, we need a CSM of $\sim 4.7 \, M_\odot$. Such a massive CSM is possible only when the donor is as massive as $6 - 7 \, M_\odot$. For the model consisting of a white dwarf and a main-sequence companion [6], the mass transfer rate from such a massive main-sequence companion reaches $\sim 1 \times 10^{-4} M_\odot \, yr^{-1}$. Then the white dwarf blows a wind of $\sim 1 \times 10^{-4} M_\odot \, yr^{-1}$ and the mass stripping rate becomes several times larger than the white dwarf wind mass loss rate [7].

For the symbiotic model consisting of a white dwarf and a red giant or AGB star, the wind mass loss rate can also reach $\sim 1 \times 10^{-4} M_\odot \, yr^{-1}$. In symbiotic stars, the mass capture efficiency by the white dwarf is observationally estimated to be as small as one or a few percent. Therefore, only when a large part of the red giant wind or AGB super-wind is captured by the white dwarf, the white dwarf can blow a very massive wind of $\sim 1 \times 10^{-5} M_\odot \, yr^{-1}$ or more. Then, the mass stripping rate from the red giant or AGB star also reaches several times $10^{-4} M_\odot \, yr^{-1}$ or more.

Examples of the accretion wind evolution are identified as transient supersoft X-ray sources, i.e., the LMC supersoft X-ray source RX J0513.9–6951 and its Galactic counterpart V Sge [7]. Especially in V Sge, a very massive wind of $\sim 1 \times 10^{-5} M_\odot \, yr^{-1}$ has been observationally suggested by the detection of radio.
Furthermore, the white dwarf wind collides with the companion and strips heavily off its surface matter. This stripping rate reaches a few or several times the wind mass loss rate of the white dwarf, i.e., \( \sim 1 \times 10^{-4} M_\odot \text{ yr}^{-1} \) or more [7]. The matter stripped off has a much lower velocity than the white dwarf wind itself and forms an excretion disk around the binary. Thus the model predict the coexistence of a fast white dwarf wind blowing mainly in the pole direction and a massive disk or a torus around the binary. Deng et al. [3] propose a new classification, Type IIa supernovae, for these events.

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