The Unique Type Ib Supernova 2005bf: A WN Star Explosion Model for Peculiar Light Curves and Spectra

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ABSTRACT

Photometric and spectroscopic observations of supernova (SN) 2005bf and theoretical modeling of the light curve and the spectra are reported. This SN showed unique features: the bolometric light curve had two maxima and declined rapidly after the second maximum, the velocity of the helium lines increased with time. The double-peaked light curve can be reproduced by a double-peaked $^{56}$Ni distribution, with a large amount of $^{56}$Ni at low-velocity and a small amount at high-velocity. The rapid post maximum decline requires that a large fraction of the $\gamma$-rays can escape from the $^{56}$Ni-dominated region possibly because of the presence of many low-density "holes". Enhanced $\gamma$-ray escape from the $^{56}$Ni-dominated region yields rapidly increasing $\gamma$-ray deposition in the He layer, which may explain the increasing He line velocity. Balmer lines were actually present in the earlier spectrum, so the SN did not transform from Ib to Ic. The SN has rather massive ejecta ($\sim 6 - 7 M_\odot$), a normal kinetic energy ($\sim 1.0 - 1.5 \times 10^{51}$ ergs), and a large amount of $^{56}$Ni ($\sim 0.31 M_\odot$). These properties, and the presence of a small amount of hydrogen suggest that the progenitor was a massive star, with initial mass $\sim 25 - 30 M_\odot$, that lost most of its H envelope, possibly a WN star. The double-peaked $^{56}$Ni distribution suggests that the explosion may have formed jets that did not reach the He layer. The properties of SN 2005bf resemble those of the explosion of Cassiopeia A.

Subject headings: supernovae: general — supernovae: individual (SN 2005bf) — stars: Wolf-Rayet — ISM: individual (Cassiopeia A)
1. INTRODUCTION

As the sample of well-studied supernovae (SN) grows, it is not surprising that rare types are observed. At first, these may seem strange and unique; in time they may become well-understood subtypes. We believe that SN 2005bf is one of these new types: it has unique photometric and spectroscopic behavior. However, based on a successful effort to model our light curve and spectra, we believe that SN 2005bf fits into the scheme suggested by Nomoto et al. (1995) which places core-collapse SN in a sequence (IIP-IIL-IIb-Ib-Ic) representing different degrees of envelope stripping.

Discovered by Monard (2005) and Moore & Li (2005) in the outer spiral arms of the nucleus of the SBb galaxy MCG +00-27-5, SN 2005bf was initially classified as a Type Ic SN (SN Ic) (Morell et al. 2005; Modjaz et al. 2005a). The later development of He lines suggested an unprecedented transition to Type Ib (Wang & Baade 2005; Modjaz et al. 2005b). Even more puzzlingly, the light curve was very different from those of known SN Ib (Hamuy et al. 2005): a fairly rapid rise to a first peak was followed by a period of stalling or slow decline, and by a new rise to a later, brighter peak (Ampama et al. 2005) at ~ 40 days after explosion (computed to be ~ 2005 March 30 UT, see §2). The brightness ($M_{bol} = -18$) and the late epoch of the second peak suggest the this SN ejected a large amount of $^{56}$Ni. SN 2005bf does not show the broad lines seen in hypernovae (e.g., SN 2003dh, Deng et al. 2005). These properties make SN 2005bf a very interesting SN.

We report the results of our observations and theoretical modeling of SN 2005bf. Photometry was obtained in $UBVr'i'j'$ bands at Fred Lawrence Whipple Observatory (FLWO; Modjaz et al. 2005c), $BVRI$ bands at the Himalayan Chandra Telescope (HCT; Anupama et al. 2005), and $BVIJHK$ bands at the MAGNUM Telescope (Yoshii et al. 2003; Inada et al. 2005). Spectroscopic observations were made at FLWO, HCT and the SUBARU Telescope (Kawabata et al. 2002, 2005). We modeled the light curve and spectra and constrained the properties of the SN and consequently those of the progenitor star.

2. LIGHT CURVE MODELS

The bolometric light curve (LC) was constructed as in Yoshii et al. (2003) (see Figure 1). Synthetic bolometric LCs were computed with an LTE radiation hydrodynamics code and a gray $\gamma$-ray transfer code (Iwamoto et al. 2000). Electrons-scattering and line opacity are considered for radiation transport. The former was computed with the Saha equation. For the latter the approximate formula used in Mazzali et al. (2001) was adopted, with modifications to account for the C, O, and He-rich layers. We assumed a galactic reddening $E(B-V) = 0.045$ and a distance modulus $\mu = 34.5$ (Anupama et al. 2005).

The LC is powered by the radioactive decay of $^{56}$Ni to $^{56}$Co and $^{56}$Fe. The theoretical LC width near maximum depends on the ejected mass $M_{ej}$ and the explosion kinetic energy $E$ as $M_{ej}E^{-3}$ (Arnett 1982; Nomoto et al. 2004). The mass and distribution of $^{56}$Ni can be constrained from the LC brightness and shape, but different combinations of ($M_{ej}, E$) can fit the data. Spectra break this degeneracy and help establish the abundance distribution in the ejecta.

The density structure used for the LC calculation was based on the C+O star model $CO138E50$ used for SN 1998bw (Nakamura et al. 2001) but rescaled as $M_{ej}$ and $E$ are rescaled as $M_{ej} \propto r^3$ and $E \propto r^2 \rho^2 r^3$, respectively. The He distribution is constrained by observational evidence and spectral fitting, as discussed in §3.

The He absorption lines first appeared at a velocity of ~ 6,000 km s$^{-1}$. This then increased slowly with time, reaching ~ 7,000 km s$^{-1}$ (Fig. 2), an unusual behavior for SN Ib (see, e.g., Branch et al. 2002). On the contrary, the velocities of the Fe lines decline with time. $H\alpha$, and possibly $H\beta$ and $H\gamma$, were detected (Wang et al. 2005; Ampama et al. 2005; see Deng et al. 2000 and Branch et al. 2002 for possible H detections in other SN Ib). Their weakness suggests a small H mass (see §3), so we can assume that H did not affect the LC. Seeing traces of hydrogen suggests that the helium layer was reasonably intact before the explosion, so we included it in our LC computation. We assumed that He is mainly above $v \gtrsim 6,000$ km s$^{-1}$, as suggested by the observed He line velocity. The light curve for a model with...
$M_{ej} = 7M_\odot$ and $E_{51} = E/10^{51}$ ergs = 2.4 is shown as a dashed line in Figure 1.

In order to reproduce the double-peaked LC, we assumed the following $^{56}$Ni distribution: $(X(^{56}$Ni), $M(^{56}$Ni)/$M_\odot$) = (0.46, 0.17) at $v \lesssim 2,000$ km s$^{-1}$, (0.012, 0.05) at $v \sim 2,000 - 5,000$ km s$^{-1}$, (0.025, 0.04) at $v \sim 5,000 - 8,000$ km s$^{-1}$, and no $^{56}$Ni at $v \gtrsim 8,000$ km s$^{-1}$. Here $X$ denotes the mass fraction. The total $^{56}$Ni mass is $M(^{56}$Ni) = 0.26$M_\odot$. The first peak of the LC is powered by a small amount of high-velocity $^{56}$Ni at $v \gtrsim 5,900$ km s$^{-1}$. The second peak of the LC is powered by $^{56}$Ni in the low velocity central region. The outer extent of the inner $^{56}$Ni ($v \sim 2,000$ km s$^{-1}$) is determined strictly from the time of the second peak, but the outer distribution of $^{56}$Ni is rather arbitrary.

The large amount of $^{56}$Ni (~ 0.26$M_\odot$) should lead to a bright $^{56}$Co tail, as shown by the dashed line in Figure 1 (computed with a $\gamma$-ray opacity $\kappa_\gamma = 0.027$ cm$^2$ g$^{-1}$; e.g., Shigeyama & Nomoto 1990). However, the observed LC continued to decline rapidly, suggesting that the escape of $\gamma$-rays is favoured with respect to the typical case. We used a reduced $\gamma$-ray opacity to simulate this situation.

We used $\kappa_\gamma = 0.001$ cm$^2$ g$^{-1}$ at $v < 5,900$ km s$^{-1}$, keeping $\kappa_\gamma = 0.027$ cm$^2$ g$^{-1}$ at $v > 5,900$ km s$^{-1}$, and obtained a sequence of models with $(M_{ej}/M_\odot, E_{51}) = (5, 0.6), (6, 1.0), (7, 1.3), (8, 1.7), (9, 2.3), (10, 2.8), and (11, 3.3)$, that reproduce the light curve. The models with $M_{ej} = 6 - 7M_\odot$ give the best fits to the spectra (§3). The solid line in Figure 1 shows the LC with $M_{ej} = 7M_\odot$, $E_{51} = 1.3$, and total $^{56}$Ni mass of $M(^{56}$Ni) = 0.31$M_\odot$. The $^{56}$Ni distribution is as follows: $(X(^{56}$Ni), $M(^{56}$Ni)/$M_\odot$) = (0.2, 0.23) at $v \lesssim 2,200$ km s$^{-1}$, (0.006, 0.02) at $v \sim 2,200 - 3,900$ km s$^{-1}$, (0.028, 0.06) at $v \sim 3,900 - 5,900$ km s$^{-1}$, and no $^{56}$Ni at $v \gtrsim 5,900$ km s$^{-1}$. Because of the smaller $\kappa_\gamma$ in the $^{56}$Ni region and the enhanced escape of $\gamma$-rays compared with the model with normal $\kappa_\gamma$, lower velocity $^{56}$Ni (i.e., $v \lesssim 5,900$ km s$^{-1}$) can reproduce the first peak of the LC, and a larger amount of $^{56}$Ni is necessary to power the LC. In other words, $^{56}$Ni is mixed out but does not reach the He layer at $v \gtrsim 6,000$ km s$^{-1}$. Such a double peaked distribution of $^{56}$Ni might also be produced by jets which did not reach the He layer.

3. SPECTROSCOPIC MODELS

We computed synthetic spectra from the explosion models that give the best fit to the light curve. The comparison with the observed spectra is necessary to distinguish among the models. We used the Monte-Carlo spectrum synthesis code described in Mazzali & Lucy (1993), Lucy (1999), and Mazzali (2000). Since the code does not take into account non-thermal processes, which are essential for the He lines (Lucy 1991), we introduced a “non-thermal factor” (Harkness et al. 1987) to reproduce the He lines. This parameterized factor, denoted as $f$, represents the degree of departure from the level populations computed using a modified nebular approximation, and is used to multiply all He I line opacities.

Our synthetic spectra are compared to the observed ones in Figure 3. The model with $(M_{ej}/M_\odot, E_{51}) = (7, 1.3)$ provides satisfactory fits for all spectra. Also, the photospheric velocities obtained from this model agree with those that give the best fit to the spectra.

At the time of the first peak (UT April 13, 14 days after explosion, Modjaz et al. 2005c) SN 2005bf exhibited SN Ic features, but at a closer look both He and H can be distinguished. The feature around 5700$\AA$ may be attributed to HeI 5876$\AA$. We could obtain a good fit for this spectrum with a luminosity $L = 2.01 \times 10^{42}$ erg s$^{-1}$ and a photospheric velocity $v_{ph} = 6,600$ km s$^{-1}$. The non-thermal factor was set to 1. The model with $M_{ej} = 7M_\odot$ is slightly better than that with $M_{ej} = 6M_\odot$. The feature at 6300$\AA$ is reproduced as a blend of H$\alpha$ and SiII 6355$\AA$ (Fig.3, inset). The core of the line cannot be due to SiII because this would require a Si velocity of ~ 5,000 km s$^{-1}$, which is smaller than the photospheric velocity. It can, however, be reproduced as H$\alpha$ if $\sim 0.02M_\odot$ of H is present above $v \gtrsim 13,000$ km s$^{-1}$.

Near maximum brightness (UT May 4, 35 days after explosion) He lines become conspicuous. The model has $L = 5.04 \times 10^{42}$ erg s$^{-1}$, $v_{ph} = 4,600$ km s$^{-1}$, and $f = 1.0 \times 10^{3}$ (only at $v \gtrsim 6,500$ km s$^{-1}$). Most features, including CaII, FeII and MgII are also well reproduced. The line near 6300$\AA$ is explained by SiII (6355$\AA$) at this epoch: the photospheric velocity is low enough and the H layer is too far above the photosphere to produce an absorption. For a spectrum on UT May 16th
(47 days, Kawabata et al. 2005), we also obtain a reasonable fit with parameters \( L = 3.83 \times 10^{42} \text{erg s}^{-1} \), \( v_{\text{ph}} = 3,800 \text{km s}^{-1} \) and \( f = 2 \times 10^6 \) (at \( v \gtrsim 7,200 \text{ km s}^{-1} \)).

These values of the “non-thermal factor” compare well with the results of detailed calculations (Lucy 1991), although the value at the last epoch appears too large. To mimic the increasing velocity of He I λ 5876, we have introduced the non-thermal factor in regions of increasingly high velocity at more advanced epochs. A realistic solution must include the following diffusion of the γ-rays. Enhanced γ-ray escape from the \(^{56}\text{Ni}\)-dominated region can yields rapidly increasing γ-ray deposition in the He layer and higher He excitation. As the optical depth of the He lines increases, the region where they become optically thick (therefore where the non-thermal factor is applied) may move to higher velocity.

4. CONCLUSIONS & DISCUSSION

We have studied the properties of SN 2005bf by computing the light curve and the spectra. Our best fit model has \( M_{\text{ej}} \sim 7M_\odot \) and \( E_{51} \sim 1.3 \). The ejecta model consist of \(^{56}\text{Ni} \sim 0.31M_\odot\), He \( \sim 0.4M_\odot\), intermediate mass elements (mainly O, Si, S), and possibly a small amount of H \( \sim 0.02M_\odot\). This indicates that the progenitor had lost its H envelope, but had retained most of the He-rich layer, thus being a WN star. The double peaked light curve is reproduce by the double peaked distribution of \(^{56}\text{Ni}\); such a distribution may be formed by jets that did not reach the He layer.

Our model requires the production of unusually large amount of \(^{56}\text{Ni}\) with normal explosion energy. To examine if this is possible, we have performed hydrodynamical computations of explosive nucleosynthesis for the model with \( M_{\text{MS}} = 25M_\odot \) and \( E_{51} = 1.3 \). In order to produce \( \sim 0.31M_\odot \) \(^{56}\text{Ni}\), the mass-cut that separates the ejecta and the compact remnant should be as deep as \( M_{\text{cut}} \sim 1.4M_\odot \). In the spherical model no fallback occurs. This small mass-cut suggests that the remnant was a neutron star rather than a black-hole. The mass range around \( M_{\text{MS}} \sim 25M_\odot \) corresponds to the transition from neutron star (SN 2005bf) to black hole formation (SN 2002ap, Mazzali et al. 2002), the exact boundary depending on rotation and mass loss.

In total, the He core mass at explosion was \( M_{\text{He}} = M_{\text{ej}} + M_{\text{cut}} \sim 7.5 - 8.5M_\odot \). Then the progenitor was a WN star whose main-sequence mass was \( M_{\text{MS}} \sim 25 - 30M_\odot \) (Nomoto & Hashimoto 1988; Umeda & Nomoto 2005). The formation of a WN star from a star of \( \sim 25M_\odot \) (which is small for a WN star) suggests that the effect of rotation may be important (Hirschi, Meynet & Maeder 2005), although maybe less than in hypernovae.

Interestingly, the progenitor of Cassiopeia A (Cas A) supernova remnant (SNR) was also probably a WN star, and its nucleosynthesis features are consistent with a \( \sim 25M_\odot \) star (e.g., Fesen et al. 2005 and references therein). The compact remnant of Cas A could be a magnetar, a neutron star with strong magnetic fields (Krause et al. 2005). The Cas A SNR is extremely clumpy, with many knots; Fesen et al. (2005) showed that the fastest Fe-rich ’jet’ moves with \( v \sim 6,000 \text{ km s}^{-1} \) and is not mixed with N-He or O-rich layers. These properties resemble our model for SN 2005bf. We might speculate that SN 2005bf was similar to the explosion of Cas A and that magnetorotational effects on core-collapse and a magnetar activity produced jets that created extremely clumpy ejecta with many holes in the \(^{56}\text{Ni}\)-rich layer. These jets were not energetic enough to reach the He layer.

Our best-fit model with enhanced γ-ray escape predicts that as SN 2005bf emerges from behind the Sun in the fall 2005, its bolometric magnitude will be \( \sim 20.8 \) (Figure 1, inset). Without the enhanced γ-ray escape, the value would be \( \sim 19.2 \) mag. Polarization observations (e.g. Kawabata et al. 2002, 2005) could be extremely useful to reveal the detailed distribution of the elements in the ejecta and the orientation of the possible jet, as would nebular spectra (Maeda et al. 2002, Mazzali et al., 2005).

This work was supported in part by the Grant-in-Aid for Scientific Research (16540229, 17030005, 17033002) and the 21st Century COE Program (QUEST) from the MEXT of Japan. Research on supernovae at Harvard University is supported by NSF Grant AST-0205808.
REFERENCES

Anupama, G. C., Sahu, D. K., Deng, J., Nomoto, K., Tominaga, N., Tanaka, M., Mazzali, P. A., & Prabhu, T. P. 2005, ApJL, 631, in press

Arnett, W. D. 1982, ApJ, 253, 785

Branch, D., et al., 2002, ApJ, 566, 1005

Deng, J.S., Qiu, Y.L., Hu, J.Y., Hatano, K., & Branch, D. 2000, ApJ, 540, 452

Deng, J., Tominaga, N., Mazzali, P.A., Maeda, K., & Nomoto, K. 2005, ApJ, 624, 898

Fesen, R.A., et al. 2005, ApJ, in press (astro-ph/0509067)

Hamuy, M., Contreras, C., Gonzalez, S., Krzeminski, W. 2005, IAU Circ. 8520

Harkness, R.P., et al. 1987, ApJ, 317, 355

Hirschi, R., Meynet, G., & Maeder, A. 2005, A&A, 433, 1013

Inada, N., et al. 2005, in preparation

Iwamoto, K., et al. 2000, ApJ, 534, 660

Kawabata, K., et al. 2002, ApJ, 580, L39

Kawabata, K., et al. 2005, in preparation

Krause, O., et al. 2005, Science, 308, 1604

Lucy, L. B. 1991, ApJ, 383, 308

Lucy, L. B. 1999, A&A, 345, 211

Maeda, K., Nakamura, T., Nomoto, K., Mazzali, P.A., Patat, F., & Hachisu, I. 2002, ApJ, 565, 405

Mazzali, P. A. & Lucy, L. B. 1993, A&A, 279, 447

Mazzali, P. A. 2000, A&A, 363, 705

Mazzali, P. A., Nomoto, K., Cappellaro, E., Nakamura, T., Umeda, H., & Iwamoto, K. 2001, ApJ, 547, 988

Mazzali, P. A., et al. 2002, ApJ, 572, L61

Mazzali, P. A., et al. 2005, Science, 308, 1284

Moldjaz, M., Kirshner, R., Challis, P., Matheson, T., & Landt, H., 2005a, IAU Circ. 8509

Modjaz, M., Kirshner, R., & Challis, P. 2005b, IAU Circ. 8522

Modjaz, M., et al. 2005c, in preparation

Monard, L. A. G. 2005, IAU Circ. 8507

Morrell, N., Hamuy, M., Folatelli, G., Contreras, C. 2005 IAU Circ. 8509

Nakamura, T., Mazzali, P. A., Nomoto, K., Iwamoto, K. 2001, ApJ, 550, 991

Nomoto, K., & Hashimoto, M. 1988, Phys. Rep., 163, 13

Nomoto, K., Iwamoto, K., & Suzuki, T. 1995 Phys. Rep., 256, 173

Nomoto, K., Maeda, K., Mazzali, P.A., Umeda, H., Deng, J., & Iwamoto, K. 2004, in Stellar Collapse, ed. C. L. Fryer (Kluwer: Dordrecht), 277 (astro-ph/0308136)

Shigeyama, T. & Nomoto, K. 1990, ApJ, 360, 242

Umeda, H., & Nomoto, K. 2005, ApJ, 619, 427

Wang, L., & Baade, D. 2005, IAU Circ. 8521

Yoshii, Y. et al. 2003, ApJ, 592, 467

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Fig. 1.— The bolometric light curve (LC) constructed from the photometric observations with Fred Lawrence Whipple Observatory (filled squares; Modjaz et al. 2005c), Himalayan Chandra Telescope (filled circles; Anupama et al. 2005), and MAGNUM Telescope (triangles; Yoshii et al. 2003; Inada et al. 2005). For the MAGNUM points, the bolometric luminosity with/without JHK bands (triangle/inverted triangle) indicates that the contribution of Near IR fluxes is important. Calculated model light curves are shown for normal (dashed) and reduced (solid) $\gamma$-ray opacities (see text). The inset shows the predicted LC of each model when SN 2005bf emerges from behind the Sun in the fall 2005. See §2 for details.
Fig. 2.— The time evolution of the He line velocity derived from the absorption minimum of \HeI{} \lambda{} 5876 (Modjaz et al. 2005c).
Fig. 3.— Spectra of SN 2005bf (thick lines: 2005 April 13 - Fred Lawrence Whipple Observatory, Modjaz et al. 2005c; May 4 - Himalayan Chandra Telescope, Anupama et al. 2005; May 16 - Subaru Telescope, Kawabata et al. 2005) compared to the synthetic spectra (dashed lines) computed with the model \((M_\odot/E_{51}) = (7, 1.3)\). The positions of He lines are shown by verticals. The absorptions around 4900 and 5100 Å are blended with FeII lines. The inset shows the absorption feature around 6300 Å in a spectrum on April 13th. The model with H at \(v \gtrsim 13,000\) km s\(^{-1}\) (dashed line) provides the best fit. The thin and dotted lines show the results of models with H in the whole ejecta and no H, respectively. See §3 for details.