SUBARU SPECTROSCOPY OF THE INTERACTING TYPE Ia SUPERNOVA SN 2002ic: EVIDENCE OF A HYDROGEN-RICH, ASYMMETRIC CIRCUMSTELLAR MEDIUM

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ABSTRACT

Optical spectroscopy of the Type Ia supernova SN 2002ic obtained on 2003 June 27.6 UT, i.e., ~222 rest-frame days after explosion, is presented. Strong H emission indicates an interaction between the expanding SN ejecta and an H-rich circumstellar medium (CSM). The spectrum of SN 2002ic resembles those of SNe 1997cy and 1999E.

The three SNe also have similar luminosities, suggesting that they are the same phenomenon and that the CSM is also similar. We propose a new classification, Type Iia SNe, for these events. The observed line profiles and line ratios are measured and discussed within the ejecta-CSM interaction scenario. The emission in H Balmer, [O iii], and He i lines, and in permitted Fe ii blends, resembles the spectra of the Type IIn SN 1987F and of Seyfert 1 galaxies. A high-density, clumpy CSM is inferred. Strong, very broad [Ca ii]/Ca ii and [O i]/O i emissions imply that not all the outer SN ejecta were decelerated in the interaction, suggesting that the CSM is aspherical.

Subject headings: supernovae: general — supernovae: individual (SN 2002ic)

1. INTRODUCTION

Hamuy et al. (2003) reported strong Fe iii, Si ii, and S ii features in the early-time spectra of SN 2002ic and classified it as a Type Ia supernova (SN Ia). However, strong Hα emission was also observed. The detection of Hα is unprecedented in an SN Ia. (For reviews on SN spectra, see Filippenko 1997).

The emission was broad (FWHM > 1000 km s⁻¹), suggesting that it was intrinsic to the SN. Hamuy et al. (2003) suggested that it arose from the interaction between the SN ejecta and a dense, H-rich circumstellar medium (CSM). As in SNe IIn (e.g., Chugai 1991; Chevalier & Fransson 1994). 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 a unique opportunity to explore the CSM within the context of the ejecta-CSM interaction.

In this Letter, we present optical spectroscopy of SN 2002ic obtained more than 200 days after explosion and discuss it within the context of the ejecta-CSM interaction.

2. OBSERVATIONS AND RESULTS

Observations were carried out on 2003 June 27.6 UT with the Faint Object Camera and Spectrograph (Kashikawa et al. 2002) attached to the Cassegrain focus of the 8.2 m Subaru Telescope. For the red observation (5900–10200 Å), we used a 300 groove mm⁻¹ grism (centered at 7500 Å) and an order-cut filter O58. For the blue observation (3800–7000 Å), we used another 300 groove mm⁻¹ grism (centered at 5500 Å) and no filter. A 0′8 width slit was used under moderate seeing conditions (FWHM = 0′6–0′7), resulting in a spectral resolution λ/Δλ ~ 650 (~460 km s⁻¹). The total exposure time was 1680 s for each observation. The flux was calibrated using observations of BD +28°4211 (Massey & Gronwall 1990). A systematic error of ~0.1 mag is caused by the insufficient width of the slit compared with the seeing size. Although all data were taken in polarimetric mode, the signal-to-noise ratio is not high enough for sufficiently accurate polarimetry (~0.2%). Therefore, in the following only the flux data are discussed.

The spectrum is shown in Figure 1, after correction for redshift (z = 0.0666; Hamuy et al. 2003) and Galactic extinction (E_B-V = 0.06; Schlegel, Finkbeiner, & Davis 1998). The epoch is ~222 rest-frame days after explosion, which we assume occurred on 2002 November 3 UT (Hamuy et al. 2003). The spectrum has a brightness of m_v ~ 19.0. In other words, the SN is only ~1.5 mag fainter than at maximum light (Hamuy et al. 2003), while a normal SN Ia at similar epochs would have faded by ~5 mag with respect to maximum light (Fig. 2).

The spectrum is strikingly similar to those of the peculiar SNe 1997cy (Turatto et al. 2000) and 1999E (Rigon et al. 2003), which were classified as Type IIIn. (See also Wang et al. 2004.) SN 2002ic would also have been so classified, had it not been discovered at an early epoch when it appeared to be a genuine SN Ia. Hamuy et al. (2003) also noticed similarities to SN 1997cy in an earlier spectrum (~71 days after explosion).

The UVBYRI light curves (LCs) of the three SNe are also similar (Fig. 2). To construct the LC of SN 2002ic, we first integrated the Subaru spectrum. This yielded L = (5.8 ± 0.6) × 10^{42} ergs s⁻¹, assuming a distance of 307 Mpc. The bolometric correction thus estimated was used to convert m_v at earlier phases in Hamuy et al. (2003) and the late-time MAGNUM telescope (Yoshii 2002) photometry into rough bolometric luminosities.
3. SPECTRAL ANALYSIS

The Hα profile was decomposed using three Gaussians (Fig. 3, top left). (We used Gaussians for mathematical convenience, although real component profiles can be different.) A narrow core (FWHM ∼ 1000 km s⁻¹) is unresolved owing to low instrumental resolution. The intermediate component has FWHM ∼ 4800 km s⁻¹. It may develop from the ∼1800 km s⁻¹ component seen at earlier phases (Hamuy et al. 2003). The broad blue wing centered at ∼6350 Å is likely [O i] λλ6300, 6364 (FWHM ∼ 26,000 km s⁻¹). The integrated fluxes are 4 × 10⁻¹⁵, 1.5 × 10⁻¹⁴, and 3.2 × 10⁻¹⁴ ergs s⁻¹ cm⁻², respectively.

Broad [O i] λλ6300, 6364 is also present in SNe 1997cy and 1999E. [O i] lines seen in a few SNe IIn (e.g., Fransson et al. 2002) are narrower than 4000 km s⁻¹ and much weaker. [O i] λλ5577 is not obvious. Its potential location, marked by an arrow in Figure 1, is well in the smoothly declining part of the ∼5100–5600 Å feature.

The Hβ λ4861–[O iii] λλ5007 complex was decomposed with four Gaussians (Fig. 3, top right). The two Hβ components have FWHM ∼ 1700 and 4000 km s⁻¹ and flux of ∼8 × 10⁻¹⁶ and 9 × 10⁻¹⁶ ergs s⁻¹ cm⁻², respectively. The unresolved [O iii] λλ5007 component (FWHM ∼ 500 km s⁻¹) has a flux of ∼1.4 × 10⁻¹⁶ ergs s⁻¹ cm⁻². The expected intensity of [O iii] λλ4959 is only one-third that of λ5007 (Osterbrock 1989). So the ∼4950 Å feature (FWHM ∼ 6000 km s⁻¹) is mainly due to Fe ii multiplet 42.

Our spectrum shows a possible [O iii] λλ4363 line (Fig. 3, bottom right), as in SNe 1997cy and 1999E. A tentative Gaussian fit gives FWHM ∼ 1200 km s⁻¹ and a flux of ∼1.7 × 10⁻¹⁶ ergs s⁻¹ cm⁻², which are likely overestimates. The feature to the left is also unresolved: it seems not to be Hγ λλ4340; the SN 1999E spectrum (open circles) does not show Hγ.

We decomposed the 7300 Å feature into He i λ7065, [Ca ii] λλ7291, 7324/[O ii] λλ7320, 7330, and O i λλ7774 (Fig. 3, bottom left). The FWHMs are ∼3000, 18,000, and 10,000 km s⁻¹, and the fluxes are ∼6 × 10⁻¹⁶, 1.2 × 10⁻¹⁴, and 2.3 × 10⁻¹⁵ ergs s⁻¹ cm⁻², respectively. He i λ8576 is weak (FWHM ∼ 1400 km s⁻¹, flux ∼ 2 × 10⁻¹⁶ ergs s⁻¹ cm⁻²), as in SN 1997cy.

The strong emission near 8500 Å is a blend of the Ca ii IR triplet and O i λλ8446 (FWHM ∼ 13,000 km s⁻¹ and flux ∼ 4.7 × 10⁻¹⁴ ergs s⁻¹ cm⁻²). A broad feature to the red could be weak O i λ9265. The Ca ii H and K flux is ∼1 × 10⁻¹⁴ ergs s⁻¹ cm⁻².

The lines we have identified can be divided into two groups based on their width. One group, comprising the H Balmer, [O iii], and He i lines, have unresolved cores (FWHM ≤ 1000 km s⁻¹) and, in the case of Hα and Hβ, components of intermediate width (FWHM ∼ 3000–5000 km s⁻¹). The other group includes broad [Ca ii]/Ca ii and [O ii]/O i lines (FWHM > 10,000 km s⁻¹). These lines do not show a narrow component.

We believe the unresolved components are CSM emissions, likely from a progenitor wind, as in SNe IIn (e.g., Fransson et al. 2002). R. Kotak & W. P. S. Meikle (2004, in preparation), using high-resolution spectroscopy, saw a P Cygni line with absorption velocity ∼100 km s⁻¹ atop the Hα core. Rigon et al. (2003) measured a similar P Cygni velocity for Hα (∼200 km s⁻¹) in SN 1999E. The intermediate components of Hα and Hβ may be formed by multiple Thomson scattering of narrow emissions in CSM clouds of n ∼ 10¹⁰ cm⁻³ (Wang et al. 2004). The [O iii] emitting region may have n ∼ 10⁷ cm⁻³ (T ∼ 10⁶ K), near the critical density of the [O iii] 2p²S level, as implied by the comparable flux of the possible [O iii] λλ4363 line (Osterbrock 1989).

The total Hα luminosity, L(Hα) ∼ (2–3) × 10⁴¹ ergs s⁻¹, may imply ∼0.4–3 M⊙ of high-density ionized H (∼10⁶–10⁸ cm⁻³) in the CSM, assuming case B recombination (see also Wang et al. 2004). Our Balmer decrement [L(Hα)/L(Hβ) ∼ 10] is much
steeper than expected for case B. Either collisional processes are important or other Balmer photons are absorbed and cascaded into Hα, or both. In either case, a high density is implied.

We suggest that the broad O/Ca lines are emitted by the SN Ia ejecta. In the W7 model for SNe Ia (Nomoto, Thielemann, & Yokoi 1984), the outer C/O layer has $v > 12,000$ km s$^{-1}$ and a typical density of $\sim 10^3$ cm$^{-3}$ around 200 days, assuming free expansion. This is consistent with the detection of [O i] $\lambda\lambda 6300, 6364$ but not of [O i] $\lambda 5577$, which suggests $n < 10^4$ cm$^{-3}$ if $T \sim 10^4$ K (see Fig. 7 in Leibundgut et al. 1991). The weakness of the [Ca ii] $\sim 7300$ Å line with respect to the IR triplet may suggest that the density is not as low. However, the flux ratio $F_{7300}/F_{8446}$ in SN 1997cy actually decreases with time and density. Perhaps the $\sim 8500$ Å feature is dominated by Ly$\beta$-pumped O i $\lambda 8446$ at later phases.

Parts of the outer ejecta must avoid strong CS interaction to retain high velocities and produce the broad O and Ca emissions (powered by X-ray/UV radiation from the interaction region). The velocity of the shocked region and the preshocked ejecta is too low to explain the width of these lines. According to hydrodynamical simulations (T. Suzuki et al. 2004, in preparation), the preshocked ejecta have velocities less than 7000 km s$^{-1}$ at $\sim 100$ days after explosion and less than 4000 km s$^{-1}$ at $\sim 200$ days, and the shocked ejecta are decelerated to similar velocities. We suggest that the CSM is concentrated near the equator, so that the ejecta near the pole do not strongly interact with it (see also § 5).

We suggest that the features near 4300, 4600, 4950, and 5300 Å (marked by circles and one arrow in Fig. 4) are broad blends of Fe ii multiplets 27; 38 and 37; 42; and 49, 48, and 42, respectively. They strikingly resemble the Fe ii permitted emissions in Seyfert 1 galaxies (Osterbrock 1989; see also Filippenko 1989 for similar conclusions in SN IIn 1987F). They may come from the cool shell in the reverse shocked region or, more likely, from the dense CSM clouds, suggesting a density $\geq 10^9$ cm$^{-3}$.

4. SPECTRAL COMPARISON WITH OTHER TYPES

In Figure 4, we compare the late-time spectra of SNe 2002ic, 2000cx (Ia), 1998bw (Ic), and 1988Z (IIn). Strong [Fe iii]/[Fe ii] blends dominate the normal SNe Ia spectra (e.g., Liu, Jeffery, & Schultz 1997), and this suggests low density and high ionization relative to SN 2002ic where we find permitted Fe ii lines. SNe Ic show very strong Mg i $\lambda\lambda 4571$ (Mazzali et al. 2001). This line could blend with the Fe ii feature near 4400–4700 Å in SN 2002ic, but SNe 1997cy and 1999E disfavor a strong Mg i contribution since in their spectra the central wavelength is $\sim 4640$ Å.

The spectrum of the SN IIn 1988Z also looks different from that of SN 2002ic, although both show strong Hα emission. In SN 1988Z, broad [O i] $\lambda\lambda 6300, 6364$ and [Ca ii] $\lambda\lambda 7291, 7324$ are absent, as in other SNe IIn (Filippenko 1997), while Ca ii IR/O i emission is weak. The broad Fe features near 4600 and 5300 Å are also absent in SN 1988Z.

5. DISCUSSION

The currently preferred model for SNe Ia is the thermonuclear explosion of a C+O white dwarf (WD) in a binary system, reaching the Chandrasekhar limit via either accretion from a normal companion (the SD scenario, which is generally favored) or merging with another WD (the DD scenario). (For recent reviews, see Nomoto et al. 2000; Livio 2000.)

The SD scenario predicts the presence of an H/He-rich CSM. The discovery of strong CSM interaction in SN 2002ic may
prove that this scenario does exist in nature, SNe 1997cy and 1999E may also be CS-interacting SNe Ia. However, such events are rare. Solid observational evidence of CSM has not yet been found in other SNe Ia (Lundqvist et al. 2004).

Our spectral analysis suggests a high-density H i–emitting CSM ($n \sim 10^2$–$10^9$ cm$^{-3}$); so this is probably clumpy. Assuming the CSM was formed in a progenitor wind, we relate the mass-loss rate $\dot{M}$ and the wind velocity $u$ to the H$\alpha$ luminosity, through $L(\text{H}\alpha) \sim (1-5) \times 10^{40} (M/10^{-5} M_\odot \text{ yr}^{-1})^2 (u/100 \text{ km s}^{-1})^{-7/2} r_{\text{eq}} f^{-1}$ ergs s$^{-1}$, where $r_{\text{eq}}$ is the radius of the CSM shock in units of $10^{16}$ cm and $f$ is the CSM filling factor. For $u \sim 100$ km s$^{-1}$ and $f \approx 0.1$, $M$ can be as high as $\sim 10^{-2}$ $M_\odot$ yr$^{-1}$. The case B emissivity used here may underestimate $L(\text{H}\alpha)$ by $\sim 50\%$, considering that most H$\beta$ photons may have cascaded to H$\alpha$.

We have identified high-velocity lines (FWHM $\gtrsim 10^4$ km s$^{-1}$) emitted in the ejecta of SN 2002ic. Based on the hydrodynamical model of T. Suzuki et al. (2004, in preparation), we suggest an equatorially concentrated structure for the CSM to explain the coexistence of these lines with the strong CS interaction. Such a geometry is not unexpected for the mass loss from a binary system or for stars approaching the end of the asymptotic giant branch (AGB). A preexisting clumpy disk was also suggested by Wang et al. (2004), based on spectropolarimetry.

Is $M \sim 10^{-2} M_\odot$ yr$^{-1}$ too high for the SD scenario? The highest $M$ observed in AGB stars is between $10^{-3}$ and $10^{-4}$ $M_\odot$ yr$^{-1}$ (Iben 1995); $M$ in our estimate is scaled as $u$. The bulk of the CSM may be near the equator and at low velocity ($\sim 10$ km s$^{-1}$), which cannot be resolved. The observed H$\alpha$ P Cygni, dominated by the emission component, could be produced by some high-velocity CSM ($\gtrsim 100$ km s$^{-1}$) along the pole, which should be close to our line of sight. Similar wind patterns have been observed in some symbiotic stars (e.g., Solf & Ulrich 1985), which have been suggested as candidates for SN Ia progenitors.

Further observations and modeling are required to understand the nature of the CSM giving rise to this type of event, which may be classified as “Type IIa.” Suggestions include a common envelope (Livio & Riess 2003), WD accretion wind (Hachisu, Kato, & Nomoto 1999), and the superwind from an AGB star exploding as a “type 1.5” event (Hamuy et al. 2003).

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