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# ON THE HYDROGEN EMISSION FROM THE TYPE Ia SUPERNOVA SN 2002ic[1]

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## ABSTRACT

The discovery of SN 2002ic and subsequent spectroscopic studies have led to the surprising finding that SN 2002ic is a Type Ia supernova with strong ejecta-circumstellar interaction. Here we show that nearly 1 year after the explosion the supernova has become fainter overall, but the H$\alpha$ emission has brightened and broadened dramatically compared to earlier observations. We have obtained spectropolarimetry data that show that the hydrogen-rich matter is highly aspherically distributed. These observations suggest that the supernova exploded inside a dense, clumpy, disklike circumstellar environment.

*Subject headings:* planetary nebulae: general — polarization — stars: AGB and post-AGB — supernovae: individual (SN 2002ic)

*On-line material:* color figures

## 1. INTRODUCTION

SN 2002ic (Hamuy et al. 2003; Wood-Vasey et al. 2002; W. M. Wood-Vasey et al. 2004, in preparation) is an important supernova (SN). Spectroscopy shows that it is a Type Ia SN with strong hydrogen emission arising from the ejecta-circumstellar interaction. Hamuy et al. (2003) point out that SN 2002ic bears a strong spectroscopic similarity to SN 1997cy, previously identified as a Type IIn (Germany et al. 2000; Turatto et al. 2000).

We present in this Letter spectropolarimetry observations of SN 2002ic obtained nearly a year after the explosion. This is the latest epoch for which spectropolarimetry has been obtained for any SN. We discuss the nature of the polarization and the structure of the circumstellar environment surrounding SN 2002ic.

## 2. OBSERVATIONS

We observed SN 2002ic on 2003 July 8.4 (UT), July 29.4 (UT), July 31.3 (UT), and September 29 (UT) using the Very Large Telescope of the European Southern Observatory (ESO) with the FORS1 instrument in spectropolarimetry mode. The conditions during the July 8.4 observations were photometric, and the seeing was around $0''.7$. The slit width used in these observation was $1''$. Four separate exposures each of 30 minutes were obtained with the retarder wave plate at position angles of 0°, 45°, $22^\circ.5$, and $67^\circ.5$. The July 8.4 (UT) data provide both reliable spectropolarimetry and spectrophotometry. The conditions for July 29.4 (UT) and 31.3 (UT) were less ideal. Only exposures at wave plate position angles of 0°, 45°, and $22^\circ.5$ were obtained on July 29.4 (UT), but all four position angles were again observed on July 31.3 (UT). The July 29.4 (UT) and July 31.3 (UT) data were combined to produce the spectropolarimetric results. The flux calibrations of the July 29.4 (UT), July 31.3 (UT), and September 28 (UT) data are less reliable but not by more than 10% as found from the scatter of the final reduced data set of each individual exposure. The spectral profiles show little evolution during these observations. Figure 1 shows the spectroscopic data derived from the July 8.4 (UT) observations together with the spectra of SN 1997cy (Turatto et al. 2000) and SN 1999E (Rigon el al. 2003) at comparable dates. The most prominent spectral line is the broad sharply peaked H$\alpha$ emission that is typical of a Type IIn SN. SN 2002ic remains strikingly similar to SN 1997cy and SN 1999E at later epochs (Hamuy et al. 2003).

### 2.1. *Time Evolution and Comparisons to Other Type IIn Supernovae*

The H$\alpha$ line in our observations is broader than measured in earlier observations (Hamuy et al. 2003). The FWZI can be traced to about 20,000 km s$^{-1}$ compared to an earlier value of about 4000 km s$^{-1}$. The H$\alpha$ line profile shows a strong central peak and is significantly different from that of the broad Mg I] 457.1 nm line. Several lines from neutral helium and doubly ionized oxygen were also detected. The FWZI of these lines is typically around 5,000 km s$^{-1}$. The profiles of these lines are actually very similar to the central peak of the H$\alpha$ line. The broad wings, if present, may not be detectable because of line blending and the faintness of these lines.

The flux of the H$\alpha$ line increased by a factor of more than 6 compared to that of 2002 November 11 to 2003 January 9. The light curve of the H$\alpha$ line is shown in Figure 2, together with those of SN 1997cy (Turatto et al. 2000) and SN 1999E (Rigon el al. 2003) for comparison. The H$\alpha$ fluxes derived from our spectra are 2.2, 1.9, 1.8, and 1.7 in units of $\times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ for observations of July 8.4 (UT), July 29.4 (UT), July 31.3 (UT), and September 28 (UT), respectively. The brightening of the H$\alpha$ line after optical maximum is not unique to SN 2002ic but is also observed for similar events such as SN 1988Z (Turatto et al. 1993), SN 1997cy (Turatto et al. 2000), and SN 1999E (Rigon el al. 2003). The spectroscopic data show no remarkable evolution during these observations.

### 2.2. *Spectropolarimetry*

To investigate the details of the polarization spectral variation, it is necessary to identify the dominant axis of asymmetry in the plot of Stokes parameters, $Q$ versus $U$, and to decompose

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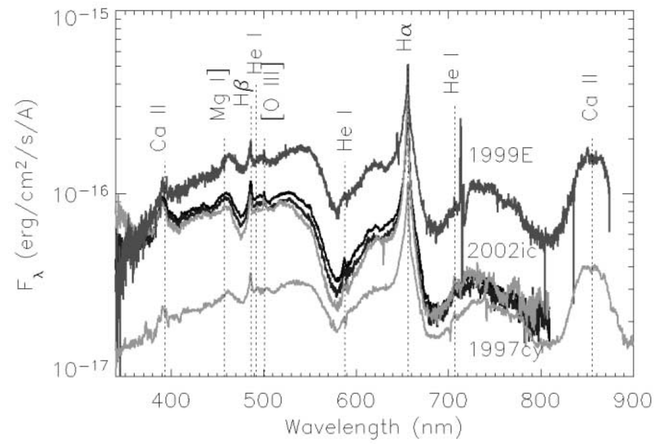


FIG. 1.—Spectra of SN 2002ic are compared with those of SN 1997cy and SN 1999E. *From top to bottom*: SN 1999E, SN 2002ic on 2003 July 8, July 31, and September 28 (UT), and SN 1997cy. The SN 1997cy and SN 1999E spectra are at epochs where the H$\alpha$ line is close to maximum (see Fig. 2). [*See the electronic edition of the Journal for a color version of this figure.*]

the data into components along the dominant axis (hereafter $P_d$) and the axis orthogonal to the dominant axis, or the secondary axis (hereafter $P_o$; Wang et al. 2001, 2003). The advantage of identifying the dominant axis is that the spectral features of $P_d$ will not be sensitive to the uncertainties of interstellar polarization (ISP) if the majority of the polarization is produced by a global asphericity of the emitting region. A weighted $\chi^2$ fit of the data points on the *Q*-*U* plot binned to 10 nm shows that the dominant axis is at a position angle of $-10° \pm 2$.

The polarization due to Galactic dust particles in the field of SN 2002ic should be less than 0.15% (Heiles 2000) and cannot be the cause of the polarization. Dust scattering in the host galaxy may contribute. To determine the amount of host interstellar dust polarization, we assume that the observed polarization of the central portion of the H$\alpha$ line (from 6553 to 6573 Å) is due completely to interstellar dust. This assumption is justified because line photons seen in the H-peak are produced by recombination and, thus, are intrinsically unpolarized (in the absence of large magnetic fields). In addition, the narrow-line photons, unlike the broad-line photons, are not polarized by Thomson scattering in the circumstellar disk because the narrow-line photons emerge predominantly from regions with negligible electron scattering (the thermal velocity of electrons is sufficiently high that the scattered photons are shifted to the broad wings of the H$\alpha$ profile). We thus take the ISP to be that corresponding to the central 20 Å of the H$\alpha$ emission peak. This gives an estimate of the ISP of about 1.6% with components $Q = 0.9\%$ and $U = -1.3\%$. With this ISP we determine the net polarization to be about 1% for wavelength regions outside the narrow H$\alpha$ emission peak. The dominant and secondary polarization components after correcting for ISP are shown in Figure 3. It can be seen that across the

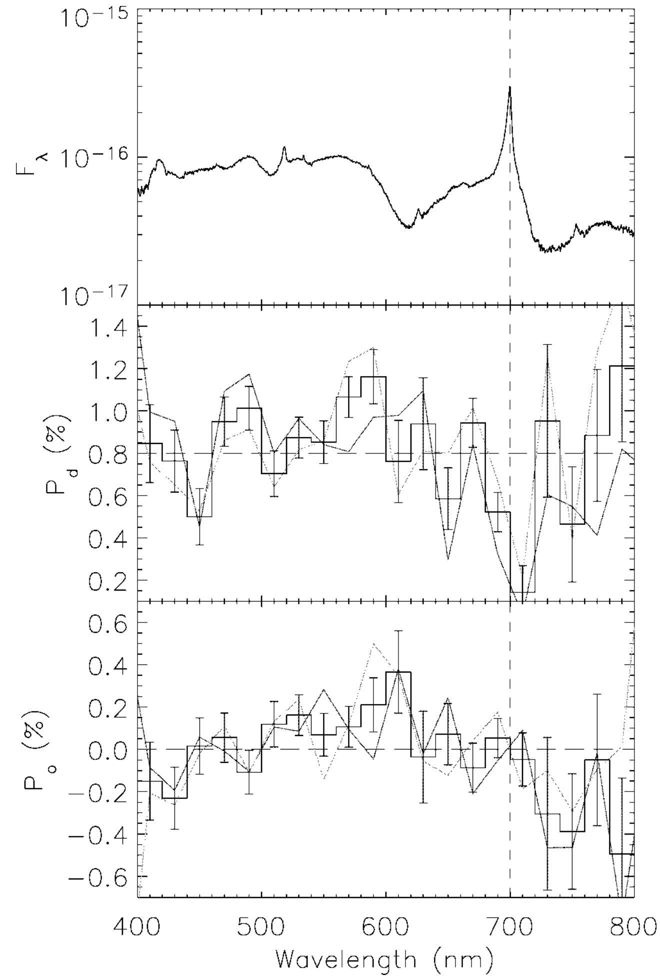


FIG. 3.—Polarization vectors (*middle and bottom panel*) of SN 2002ic are shown together with the flux spectrum (*top panel*). The Stokes parameters are projected onto the dominant axis ($P_d$) and the axis orthogonal to the dominant axis ($P_o$). The thick solid line shows the combined data of all observations, and the thin lines show the July 8.4 (UT) and 31.4 (UT) observations, respectively. The dominant axis is constructed by a weighted linear fit of the data points on the *Q*-*U* plot, and the position angle of the dominant axis was found to be $10° \pm 0.2°$. In constructing $P_d$ and $P_o$, we have also assumed that the central peak of the H$\alpha$ line is unpolarized to deduce the ISP component. The ISP used in calculating $P_d$ and $P_o$ is $Q = 0.9\%$ and $U = -1.3\%$. The long dashed lines illustrate the mean values of the polarization vectors, and the short dashed line shows the location of the H$\alpha$ line. The H$\alpha$ line clearly shows a different degree of polarization when compared to the overall polarization of the wavelength region from 300 to 600 nm. [*See the electronic edition of the Journal for a color version of this figure.*]

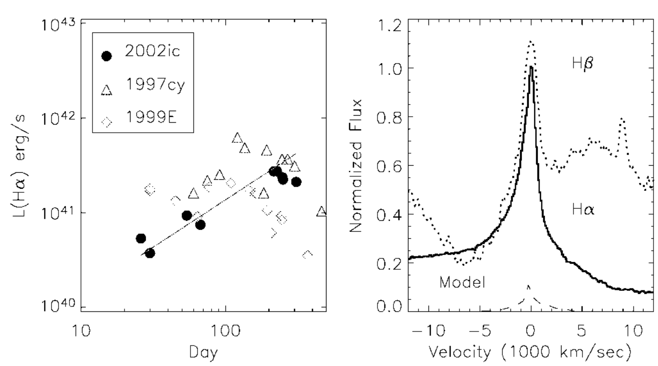


FIG. 2.—*Left*: H$\alpha$ luminosity of SN 2002ic compared with those of SN 1997cy and SN 1999E. The solid line illustrates a linear increase with time of the line flux. SN 2002ic shows comparable H$\alpha$ emission to SN 1997cy and SN 1999E. The dates of explosion for SN 1997cy and SN 1999E are uncertain, and the data points can shift by more than 20 days on the horizontal axis. *Right*: H$\alpha$ line profile (*solid line*) of SN 2002ic is compared with the H$\beta$ profile (*dotted line*). Also shown is a line profile calculated for a spherical H II region with electron temperature of 30,000 K and Thomson scattering optical depth of 4 (*dashed line*). The overall agreement of the line profile suggests that electron scattering plays a major role in forming the line profiles. [*See the electronic edition of the Journal for a color version of this figure.*]

H$\alpha$ line center the dominant component $P_d$ is indeed different than that of other wavelength regions.

The polarization is different from what was found in other Type Ia supernovae (SNe Ia) such as SN 2001el (Wang et al. 2003), which shows a strong feature at 615 nm corresponding to the strong line of Si II. The polarization in SN 2002ic is likely to be related to the circumstellar medium (CSM) rather than to the explosion process itself.

## 3. THE CIRCUMSTELLAR MATTER DISK

### 3.1. *Constraints from* H$\alpha$ *Emission Line*

At the dates of these observations, SN 2002ic is powered by the high-energy photons from the ejecta-CSM shock (Chugai & Yungelson 2004; Fransson, Lundqvist, & Chevalier 1996). The velocity of the ejecta-CSM shock is found to be around 11,500 km $s^{-1}$ from the width of the emission lines associated with the ejecta, such as the Mg I] 457.1 nm line and the Ca II IR triplet. As noted above, the H$\alpha$ line has a remarkably different profile than the Mg I] line, suggesting different origins of these emission lines. Also, the He I and the [O III] lines are typically narrower than the Mg I] line with profiles similar to the central peak of the H$\alpha$. This is important evidence that the narrow component of the H$\alpha$ and the He I lines is produced in the CSM and that the composition of the SN ejecta, as reflected in the Mg and Ca lines, is consistent with that of a typical Type Ia.

If the CSM is due to a stellar wind, the luminosity of the H$\alpha$ from the unshocked wind is $\sim 4.4 \times 10^{39} r_{\rm sh,\,16}^{-1} \dot{M}_{-3}^{2} u_1^{-2}$ ergs $s^{-1}$, where $r_{\rm sh,\,16}$ is the radius of the shock in units of $10^{16}$ cm and we have taken the emissivity for case B recombination at a temperature of ∼10,000 K. The emissivity is a weak function of temperature and changes slightly with H$\alpha$ opacity (Xu et al. 1992). This is a decreasing function of time and cannot explain the rise of the H$\alpha$ flux. If the CSM were dense enough, the shocked CSM may become radiative and produce enough H$\alpha$ emission to account for the observed flux; however, the line profile from a thin shell of material moving at the shock speed of 11,500 km $s^{-1}$ would be flat-topped and hence inconsistent with the observed H$\alpha$ line profile. The mass of hydrogen required to produce the observed H$\alpha$ luminosity is $\sim 6\ M_\odot (n_e/10^8\ {\rm cm}^{-3})$. This amount of mass is consistent with those derived by Chugai & Yungelson (2004). More realistic modeling of H$\alpha$ emission may alter this estimate but is unlikely to change the qualitative conclusion that a few solar masses of dense hydrogen-rich matter are required to explain the H$\alpha$ luminosity.

### 3.2. *Constraints of the Spectropolarimetry*

The configuration that we encounter here is different from those for normal SNe Ia where the polarization is produced by electron scattering from an aspherical photosphere (Höflich 1991). Mass loss from asymptotic giant branch (AGB) stars is known to be highly asymmetric and predominantly on the equatorial plane. The polarization is due to scattering by the dense CSM of photons that originate from the SN at the center. Such systems have been studied in great detail in models of polarizations of Be stars. In these models the opening angle of the scattering CSM has the shape of a disk with opening angles typically of the order of a few degrees in order to reproduce an observed polarization of the order of 0.5%–1% (McDavid 2001; Melgarejo el al. 2001). Such a geometry is in good agreement with the required several solar masses of hydrogen with densities above $10^8$ cm$^{-3}$ that contributes to the H$\alpha$ emission. The dense CSM must have a small volume filling factor.

## 4. EJECTA-CSM INTERACTION AND THE H$\alpha$ LINE PROFILE

If the mass loss during the AGB phase were predominantly in the equatorial plane, we would expect the shock of the ejecta-CSM interaction to be hourglass shaped. The disk of unshocked CSM could be ionized by the hard photons from the ejecta-CSM interaction and give rise to the central peak of the H$\alpha$ emission whereas the shocked CSM could be radiative and give rise to the broad H$\alpha$ wings. Detailed calculations are needed to see if this scenario can account for the observed line profile and the increase of H$\alpha$ luminosity while the overall luminosity decreases.

Another possibility is that broad wings of H$\alpha$ are formed by scattering, rather than emission from shocked matter. If the CSM is optically thick to electron scattering, electron scattering can effectively broaden the H$\alpha$ line and produce a center-peaked profile (Chugai 2001). An example of such a profile is shown in Figure 2. For this simple model, spherical symmetry and a temperature of 30,000 K, presumably produced by the flash ionization of the CSM, are assumed. Note that this model can produce the smooth line profile with both the narrow peak and the broad wings whereas such an agreement would require careful tuning of a model where the broad wings were shock-accelerated material and the narrow core was from nearly stationary CSM. In this model, photons that remain within the core have not been scattered and are thus unpolarized.

It is likely that the flattened CSM is not uniform but clumpy, so that the H$\alpha$ line is dominated by emission from the densest clumps. The clumps may have densities of about $10^8$–$10^9$ cm$^{-3}$ with sizes of about $5 \times 10^{16}$ cm, at which point they would be marginally optically thick to Thomson scattering and hence provide the sort of line profiles illustrated by the simple model in Figure 2. As noted above, about 1 $M_\odot$ of matter is needed in the clumps/disk to reproduce the observed H$\alpha$ luminosity.

If the disk and dense clumps extend to ∼200 lt-days, $\sim 3 \times 10^{17}$ cm, the rising flux of H$\alpha$ could be the result of the time delay effect. At early times, only a small fraction of the dense clumps would be visible, and only at around day 200 when these observations were made would the majority of the CSM clumps be observed, therefore giving rise to the increased H$\alpha$ luminosity. In the mean time, the emission from the ejecta-CSM interaction should show a constant decrease of luminosity after reaching maximum a few weeks past explosion, as observed.

## 5. CONCLUSIONS

The strong growth in the H$\alpha$ luminosity, the H$\alpha$ line profile, and the polarization that we observe for SN 2002ic is consistent with several solar masses of clumpy material arrayed to distances of $\sim 3 \times 10^{17}$ cm in a manner that is globally asymmetric. The CSM may be related to the dense disks or rings observed in some proto–planetary nebulae (Zijlstra et al. 2001; Slijkhuis, de Jong, & Hu 1991; Su et al. 1998). The mass loss was found to be highly asymmetric at this stage. For example, IRAS 16342−3814 (Zijlstra et al. 2001) shows a dense torus with mass 0.1 $M_\odot$ and density of $10^8$ cm$^{-3}$. Alternatively, a similar configuration may be produced during the binary evolution leading to the thermonuclear explosion. During a phase of rapid expansion of the donor star very high mass loss may be channeled through the outer Langrange points. Wind interaction (Kwok 1993) can create dense shells or rings that may naturally explain the observed structure (Kwok 1993; Young et al. 2003).

The star that exploded as SN 2002ic could be either the dying post-AGB star (Swartz et al. 1991) or a preexisting white dwarf companion around it. The large radial extent of the disk seems to be incompatible with a model in which the hydrogen represents an expelled common envelope at a distance of $\sim 10^{15}$ cm (Livio & Riess 2003). The proto–planetary nebula phase lasts only for a few hundred years. This may account for the rarity of events such as SN 2002ic but raises questions of how the SN is timed to precisely this phase. Alternatively, a structure with similar properties may be produced during the binary evolution leading to the explosion, although questions of the phasing remain. In any case, events such as SN 2002ic suggest that SNe Ia can occur in a wide range of CSM environments.

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