On the nature of the circumstellar medium of the remarkable type Ia/IIn supernova, SN 2002ic

R. Kotak, W.P.S. Meikle, A. Adamson, S.K. Leggett

1 Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London, SW7 2BZ, U.K.
2 Joint Astronomy Centre, 660 N. A’ohoku Place, University Park, Hilo HI 96720, USA

ABSTRACT

We present results from the first high resolution, high S/N, spectrum of SN 2002ic. The resolved Hα line has a P Cygni-type profile, clearly demonstrating the presence of a dense, slow-moving (∼100 km s^{-1}) outflow. We have additionally found a huge near-IR excess, hitherto unseen in type Ia SNe. We argue that this is due to an IR light-echo arising from the pre-existing dusty circumstellar medium. We deduce a CSM mass probably exceeding 0.3M⊙ produced by a mass loss rate greater than several times 10^{-4} M⊙ yr^{-1}. For the progenitor, we favour a single degenerate system where the companion is a post-AGB star. As a by-product of our optical data, we are able to provide a firm identification of the host galaxy of SN 2002ic.

Key words: circumstellar matter – supernovae: general – supernovae: individual: SN 2002ic stars: winds, outflows – dust

1 INTRODUCTION

The lack of a convincing detection of hydrogen in the spectrum of any type Ia supernova has been difficult to reconcile in the single-degenerate scenario where the non-degenerate companion, in most candidate progenitor channels, is hydrogen-rich. However, Hamuy et al. (2003) recently announced the discovery of Hα emission associated with the type Ia supernova, SN 2002ic. Over a time-span of about +7 to +48 d from maximum light (t=max = JD 2452601 = 2002 November 22; Hamuy et al. 2003, Fig. 4), the optical spectra of SN 2002ic exhibited similar but weaker features to those of ‘normal’ type Ia SNe. However, strong Hα emission was also apparent: the Hα feature consisted of a narrow component (unresolved at 300 km s^{-1}) atop a broad component (FWHM ∼1800 km s^{-1}). While the narrow component could have been due to an underlying HII region (but see below), Hamuy et al. (2003) argued that the broad component arose from ejecta/circumstellar medium (CSM) interaction, and that this interaction also provided the continuum source required to dilute the spectral features of SN 2002ic. By day +48, they found that the spectrum could be equally well-matched by either a suitably ‘diluted’ coeval spectrum of the type Ia supernova, SN 1990N, or an unmodified, roughly coeval spectrum of the type IIn SN 1997cy. Type IIn supernovae (SNe IIn) are so called because of the presence at early times of narrow lines in the spectra originating in a relatively undisturbed circumstellar medium (CSM) (Schlegel 1990). Their progenitors must therefore have undergone one or more mass-loss phases before explosion.

In order to investigate the origin of the hydrogen emission and hence the nature of SN 2002ic and its circumstellar environment, we have acquired high resolution optical spectroscopy at +256 days, and HK-band IR photometry at +278 and 380 days. The first results of this study are presented here.

2 OBSERVATIONS

2.1 Optical Spectroscopy

We obtained optical spectra of SN 2002ic and its purported host galaxy on 2003 August 05 (=+256 d) with the ESO Very Large Telescope (VLT) Unit 2 (Kueyen) and Ultra-Violet Echelle Spectrograph (UVES). We used a 3′′ (PA=90°) slit which yielded a resolution of ∼9 km s^{-1}. The seeing was ∼0.9. The exposure times for SN 2002ic and the galaxy were 2200 s and 1100 s respectively. The data were reduced in the Figaro 4 environment. Wavelength calibration was by means of a ThAr arc taken at the end of the exposure of each of the targets. Flux calibration was carried out with respect to the spectrophotometric standard Feige 110.

A portion of the UVES spectrum obtained on day 256 is shown in Fig. 2.1. The spectrum is dominated by a strong Hα feature. In addition, a weak broad feature around 9000 Å is present which is the blend of O I 8446Å and the Ca II IR
triplet (Wang et al. 2004). In Fig. 2.1b we show the Hα profile in more detail: it comprises a narrow, but resolved, P Cygni-like profile atop a broad emission feature. There may also be a very broad feature present, but owing to the blue limit of the spectrum, we are unable to give a complete description of this feature. The Deng et al. (2004) +217 d spectrum extends further to the blue, and they attribute the very broad feature to [O I] 6300,6364Å. We do not give further consideration to this component. However, we note that as a consequence of the presence of the very broad feature, some authors refer to the "broad emission feature" mentioned above and shown in Fig. 2.1 as the "intermediate component". We shall continue to refer to this as the "broad" feature. It is about 5800 km s$^{-1}$ across the base (FWHM~1550km s$^{-1}$). In order to extract more detailed information about the narrow feature, we generated a model P Cygni profile using a homologously expanding CSM above a photosphere, with a rest frame wavelength equal to that of the narrow peak and an exponentially-declining density profile. The P Cygni profile parameters were adjusted by eye to match the absorption component, yielding a velocity of 100 km s$^{-1}$ at the photosphere, and an e-folding velocity of 30 km s$^{-1}$. The maximum detectable extent of the blue wing of the absorption is ~250 km s$^{-1}$. The P Cygni model also demonstrated that the narrow component includes additional emission not taken into account by the absorption. Both the narrow emission component and the P Cygni profile suggest a CSM velocity of 80–100 km s$^{-1}$. In addition, there is a small but significant shift between the narrow emission component and the 1500 km s$^{-1}$ component in the sense that the narrow component peak is 111 ± 7 km s$^{-1}$ further to the red. The Hα profile parameters are summarised in Table 1.

In Fig. 2.1c we show the evolution of the Hα profile from +7 to +256 d. Our +256 d UVES spectrum provides a good match to the +217 d profile, showing that the narrow absorption feature which we detected would not have been apparent in the Deng et al. (2004) spectrum. In contrast, however, our +256 d UVES spectrum binned to the Hamuy et al. (2003) resolution still shows evidence of the narrow absorption feature, whereas no such feature is evident up to +48 d. Indeed, there is little evidence of an asymmetry in the profile at early times. This suggests that the photosphere is located in a thin, opaque, cool dense shell (CDS) formed by the reverse shock propagating into the extended stellar envelope (e.g. Chevalier & Fransson 1994).

### Table 1. Parameters for the Hα profile of SN 2002ic at +256 d.

<table>
<thead>
<tr>
<th></th>
<th>Narrow</th>
<th>Broad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak wavelength (Å)</td>
<td>6998.10±0.05</td>
<td>6995.5±0.15</td>
</tr>
<tr>
<td>Width (FWHM Å)</td>
<td>1.83±0.04</td>
<td>36±0.5</td>
</tr>
<tr>
<td>Width (FWHM km/s)</td>
<td>78.4±1.7</td>
<td>1500±20</td>
</tr>
<tr>
<td>Intensity ($10^{-16}$ erg cm$^{-2}$ s$^{-1}$)</td>
<td>4.9±0.1</td>
<td>50.7±0.5</td>
</tr>
</tbody>
</table>

### 2.2 Near-infrared photometry

We obtained a K-band image of SN 2002ic at UKIRT on 2003 August 27 (= +278 d) using UIST; subsequent H and K-band images were obtained on 2003 December 7 (= +380 d) using UFTI. The data were reduced using standard procedures implemented in the pipeline software. The 278 d K-band image is shown in Fig. 3. The supernova is clearly visible ~5′′ west of galaxy A.

Magnitudes were measured using aperture photometry within the Starlink package GAIA. The sky background was measured using a concentric annular aperture. An aperture radius of 0′.72 was selected, equivalent to 6 and 8 pixels for UIST and UFTI respectively. The sky annulus was chosen to have inner and outer radii, respectively, ×1.5 and ×2.5 that of the aperture. Magnitudes were determined by comparison
with the UKIRT standard star FS 105. We assess the overall uncertainty in the photometry to be about \pm 5\%. The $HK$ magnitudes are listed in Table 2.

### Table 2. Infrared magnitudes of SN 2002ic

<table>
<thead>
<tr>
<th>Date</th>
<th>day</th>
<th>$H$</th>
<th>$K$</th>
<th>$H-K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20030827</td>
<td>+278</td>
<td>\cdots</td>
<td>+18.01\pm0.03</td>
<td>\cdots</td>
</tr>
<tr>
<td>20031207</td>
<td>+380</td>
<td>+18.98\pm0.02</td>
<td>+17.76\pm0.03</td>
<td>+1.22\pm0.04</td>
</tr>
</tbody>
</table>

Notes. The errors shown are statistical only.

Figure 2. Decomposition of the Hα profile of SN 2002ic at +256 d. The thick line shows the combination of the three Gaussians and the P Cygni model (dashed-dotted line).

3 REDSHIFT OF SN 2002IC AND HOST GALAXY IDENTITY

We determined the redshift of SN 2002ic from the narrow emission component of the P Cygni profile and found it to be $z = 0.0663$. This is consistent with the measurement of Hamuy et al. (2003). Our redshift implies a distance of \sim 280 Mpc ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$). According to Hamuy et al. (2003), the redshift of the galaxy \sim 5'' E of SN 2002ic (marked A in Fig. 3) is 0.22 thereby ruling out association with the supernova. The only other nearby galaxy is the one marked B in Fig. 3, lying \sim 10'' S of the supernova; Hamuy et al. (2003) suggested an association but do not report a redshift for this galaxy. However, our UVES spectrum of galaxy B indicates $z = 0.0784$, i.e. it is unlikely to be the host galaxy. Fortuitously, during our UVES observation of the supernova, the extreme eastern end of the slit intercepted the nuclear region of galaxy A. We noticed an emission feature at the corresponding spatial position (along the slit) in the spectra, and in the same order as the Hα feature of SN 2002ic, shifted only slightly in wavelength. Assuming the feature was also due to Hα emission (but from Galaxy A), we derive $z = 0.0667$. This indicates that Galaxy A must be the host of SN 2002ic. Hamuy (priv. comm.) confirms that, owing to a target acquisition error, the redshift given for the host galaxy in Hamuy et al. (2003) is incorrect.

4 DISCUSSION

4.1 Constraints from the Hα profile

The narrow component of the Hα feature suggests an origin in a wind flowing at $v_w \sim 100$ km s$^{-1}$. The presence and velocity of the P Cygni-like absorption immediately rules out an origin in a line-of-sight H II region i.e. the narrow emission/absorption feature is intrinsic to the supernova or its immediate environment. The similarity of the early-time, low-resolution spectra of SN 2002ic to that of the type II SN 1997cy has been noted by several authors. We find that the similarity also holds at high resolution; the late-time Hα profile of SN 2002ic is compared to those of type II supernovae observed at comparable epochs in Fig. 4. Narrow emission/absorption profiles superimposed on broad emission features have been observed in the type II events SN 1997ab at 425 d and SN 1997eg at +202 d (Salamanca et al. 1998, 2002). For SN 1997ab the narrow absorption blue wing limit yields a velocity of 90 km s$^{-1}$, superimposed on an emission feature of \sim 1800 km s$^{-1}$ FWHM, with wings extending to \sim 4000 km s$^{-1}$. For SN 1997eg, the corresponding figures are 160 km s$^{-1}$, 3800 km s$^{-1}$ and \sim 11000 km s$^{-1}$. In both cases the narrow feature is displaced redward of the peak of the broad component by \sim 600 km s$^{-1}$. Salamanca et al. (1998) attribute the apparent relative shifts to self-absorption in the intermediate component which preferentially attenuates the red wing. As indicated above, the SN 2002ic narrow component also exhibits a ‘redshift’ relative to the broad peak, but at 111 km s$^{-1}$ the shift is much smaller, suggesting that self-absorption is less important. The luminosity of the narrow and intermediate Hα features of SN 2002ic are, respectively, \5 \times 10^{49}$ erg s$^{-1}$ and \5 \times 10^{48}$ erg s$^{-1}$.

The 1500 km s$^{-1}$ component is probably produced by
the supernova ejecta/wind interaction, as suggested by Hamuy et al. (2003). We note that the width of the broad component declined from 1800 km s$^{-1}$ to 1500 km s$^{-1}$ between days +47 and +256. This gives additional weight to the ejecta/wind interaction scenario.

The high late-time luminosity of SN 2002ic allows us to rule out radioactive decay of $^{56}$Ni as the dominant energy source. The $UBVRI$ light curve Deng et al. (2004) gives a luminosity of $5 \times 10^{42}$ erg s$^{-1}$ at 250 d, whereas the total radioactive luminosity of $0.7 M_\odot^{56}$Ni at this epoch is only $1 \times 10^{42}$ erg s$^{-1}$. Moreover, by +250, only about $\sim$10% of the decay gamma-rays would be deposited in the ejecta of the presumed type Ia SN ejecta (e.g. Axelrod 1980). Therefore, the dominant source of energy for the broad component luminosity, $L_{\text{Broad}}^{H_\alpha}$, must be due to the ejecta/CSM interaction. In this scenario, $L_{\text{Broad}}^{H_\alpha}$ is proportional to the kinetic energy dissipation rate across the shock front. We can use this luminosity to estimate the mass-loss rate, $\dot{M}$, (Salamanca et al. 1998):

$$L_{H_\alpha}^{\text{Broad}} = \frac{1}{4} \epsilon_{H_\alpha} \frac{\dot{M}}{v_\infty} v_\infty^3$$  \hspace{1cm} (1)$$

where $\epsilon_{H_\alpha}$ is an efficiency factor which peaks at $\sim$0.1. $v_\infty$ is the shock velocity, and $v_\infty$ is the velocity of the unshocked wind, assumed to be freely-expanding. From the broad $H_\alpha$ line, $v_\infty = 2000$ km s$^{-1}$, while the narrow feature gives $v_\infty = 100$ km s$^{-1}$. Substituting into the above equation, and using the broad component luminosity, we obtain a mass-loss rate of $\dot{M} \sim 1.2 \times 10^{-2}/(\epsilon_{H_\alpha}/0.1) M_\odot$ yr$^{-1}$.

Salamanca et al. (1998) also show that by using the luminosities of both the broad and narrow emission components, the CSM density and mass can be estimated. Using the component luminosities given above, we find that the number density at the CSM inner limit on day 256 is $n_1 = 1.35 \times 10^7$ cm$^{-3}$. Assuming that the CSM was created by a steady wind ($\rho \propto r^{-2}$) and that the inner limit of the CSM on day 256 corresponds to the radius reached by the 2900 km s$^{-1}$ shock, we find a total CSM mass of $0.037 R_2/ R_i M_\odot$, where $R_i$ and $R_2$ are, respectively, the inner and outer limits of the CSM, and $R_2 >> R_i$. $R_i$ can be identified with the shock radius.

### 4.2 Constraints from NIR photometry

We now consider the IR emission. On day +380, $H-K = 1.22 \pm 0.04$. Such a colour corresponds to a $1430 \pm 40$ K blackbody. We therefore propose that the late-time IR emission is due to thermal emission from hot dust associated with SN 2002ic or its progenitor. However, it is possible that the IR flux contains a component due to hot ($T \sim 10000$ K) residual photospheric emission such as might be produced by the shock/CSM interaction. We therefore measured the continuum level in the vicinity of 0.94$\mu$m on day +256 and extrapolated to day +380 assuming an exponential decline timescale of 170 d (Deng et al. 2004). We then extrapolated to the $H$ and $K$ bands assuming a Rayleigh-Jeans law. From this we conclude that $\sim$30% and $\sim$8.5% of the $H$ and $K$ band fluxes respectively was due to contamination by the hot photosphere. After subtracting the photospheric component and correcting for a Galactic extinction of A$\nu = 0.198$ (NED), we find that the net IR flux on day 380 can be reproduced by a T=1220 K blackbody and a luminosity of $1 \times 10^{42}$ erg s$^{-1}$. The corresponding figure for +278 d (assuming the same temperature) is $0.7 \times 10^{42}$ erg s$^{-1}$. We note that if the IR emission were due to dust condensation in the ejecta, for the corresponding 1220 K blackbody to attain these luminosities it would need to have expanded at 8000–9000 km s$^{-1}$ since the supernova exploded.

We now consider the location and origin of the hot dust. We first note that as with the $UBVRI$ emission, contemporary radioactive decay can have made only a minor contribution to the late-time IR luminosity of SN 2002ic. We also note that dust is not expected to condense in type Ia explosions. This is consistent with the fact that to produce the observed IR luminosity, the 1220 K blackbody surface would have to be located as far out as the $\sim$8500 km s$^{-1}$ region of the ejecta. Dust condensation in such circumstances seems unlikely. We conclude that the IR luminosity arises from a pre-existing dusty CSM. Heating of this dust can be via (a) local heating by the ongoing ejecta/CSM shock interaction, or (b) photon emission from the supernova yielding an IR echo in the unshocked CSM. Deng et al. (2004) find velocities exceeding 10000 km s$^{-1}$ in C, O, and Ca, which they attribute to the supernova ejecta. Thus, local heating of a dusty CSM by the ejecta/CSM shock might seem to be a possibility. However, the the initial flash from the supernova would have evaporated any CSM dust to at least $\sim$3500 AU for carbon-rich grains ($T_{\text{evap}} = 1500$ K) and 16,500 AU for oxygen-rich grains ($T_{\text{evap}} = 1500$ K) (Dwek 1983, 1985). Yet a 10000 km s$^{-1}$ shock would have reached only 1600 AU by +278 d. We therefore rule out local heating of the dust by the ejecta/CSM shock.

We now test the possibility that the IR emission arose from the heating of CSM dust by photons from the supernova i.e. the IR-echo scenario. We use the bolometric light curve of Deng et al. (2004) which can be approximately described as having a peak ($t=0$) luminosity of $L_0 = 3 \times 10^{43}$ erg s$^{-1}$ and an exponential decline timescale of 170 d. We attribute this slow decline to the energy released in the interaction of the shock with the CSM. The bolometric light curve is based on $UBVRI$ photometry, and so does not in-

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**Figure 4.** Comparison of the $H_\alpha$ profile of SN 2002ic with high-resolution spectra of two type IIn supernovae at roughly comparable epochs. The data for SN 1997ab and SN 1997eg are taken from Salamanca et al. (1998, 2002) and have been corrected for their respective redshifts.
clude possible additional energy from an X-ray precursor. However, given the much higher opacity of dust grains to UV-optical light, it is likely that the X-ray contribution to grain heating will be small.

Dwek (1983) showed that the IR-echo light curve comprises an initial plateau phase, followed by a decline. The transition from plateau to decline corresponds to the passing of the ellipsoid vertex from the dust-free cavity into the region of unevaporated dust. Thus, the radius of the dust-free cavity \( R_1 = c t / 2 \). We noted that the IR flux from SN 2002 ic barely changed between days 278 and 380. From this we conclude that the vertex was still within the dust-free cavity on day 380, implying a cavity radius of \( \lambda \) dust IR emissivity proportional to \( \lambda^{-1} \) for wavelengths down to 0.2 \( \mu m \), a mean UV-vis-sional absorption efficiency of 1, and an initial dust temperature at the cavity boundary assumed 

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\text{Eq. 17 in Dwek (1983) to estimate the optical depth of dust required to yield the observed IR flux from SN 2002 ic. The parameters adopted were: } R_1 = 32800 \text{ AU, } d = 280 \text{ Mpc, dust IR emissivity proportional to } \lambda^{-1} \text{ for wavelengths down to } 0.2 \mu m, \text{ a mean UV-vis-sional absorption efficiency of 1, and an initial dust temperature at the cavity boundary assumed to be about equal to an evaporation temperature of 1500 K. The CSM was assumed to have been produced by a steady wind so that the density is proportional to } r^{-2}. \text{ We find that the IR flux at both epochs is reproduced with a dust optical depth of } \tau_0 \sim 0.01. \text{ For a gas-to-dust mass ratio of } 160, \text{ a grain material density of } 3 \text{ gcm}^{-3} \text{ and a grain radius of } 0.1 \mu m, \text{ this translates (from Dwek 1983) into a total CSM mass (including the dust-free cavity) of } \sim 0.3 R_2 / R_1 M_\odot, \text{ where } R_2 \text{ is the outer limit of the CSM and } R_2 >> R_1. \text{ Thus the CSM mass exceeds 0.3 } M_\odot. \text{ The corresponding mass loss rate (again for } R_2 >> R_1), \text{ assuming a wind velocity of } 100 \text{ km s}^{-1} \text{ is } 1.9 \times 10^{-4} M_\odot \text{yr}^{-1} \text{ (Dwek 1983, Eq. 19). It is about } \times 5 \text{ the value which Dwek (1983) derived for the type III SN 1979 C.}

Compared with the derivations from the H\alpha line, the IR analysis produces a lower mass-loss rate (\sim 1%). This discrepancy could, in part, be due to an underestimate of the shock velocity leading to an overestimate of the mass-loss rate derived from the broad H\alpha line. Nevertheless, both analyses indicate a CSM mass probably exceeding 0.3 \( M_\odot \) produced by a mass loss rate greater than several times \( 10^{-4} M_\odot \text{yr}^{-1} \). The mass-loss rate inferred from this work and that of others is higher than expected from traditional mass loss mechanisms. We remark that the high values of \( M \) are \sim at least partly \sim a consequence of simplifying assumptions e.g. clumped winds would mimic a high mass-loss rate.

The close similarity between SN 2002 ic and type II SNes, has raised doubts as to whether SN 2002 ic is a bona fide Ia event and whether other type II (i.e. core-collapse) SNe, only discovered at late epochs, may have been SN 2002 ic-like events. We suggest that the type II phenomenon is predominantly related to the amount of CSM around the progenitor system rather than the type of explosion.

A type 1.5 scenario i.e. the explosion of a single, massive AGB star has been invoked as a possible progenitor of SN 2002 ic (e.g. Hamuy et al. 2003). We point out that an extremely low metallicity would be required to inhibit mass-loss so as to allow the degenerate core to grow to \( M_c \odot \), e.g., a \( 4 M_\odot \) star would need to have \( \log Z/Z_\odot \leq -3 \) (Zijlstra 2003). Also, a low mass-loss rate is at odds with the large amount of CSM inferred for this event, although we cannot rule out the possibility that the CSM is due to a binary companion. Furthermore, SN 2002 ic exhibited an exceptionally high maximum V-band luminosity and a much slower post-\sim+25 days decline rate in BV I than is seen in normal SNe Ia. The opposite effect would be expected for type 1.5 events i.e. the photometric and spectral evolution should be similar to II events at early times and dominated by the decay of radioactive Ni and Co at late times as for type I and IIP events (Iben & Renzini 1983).

Any progenitor scenario must satisfy all the observational constraints \( m_3 \): the type Ia-like behaviour at early-times and the type II behaviour at late-times (Hamuy et al. 2003); broad profiles of Ca and O (Deng et al. 2004); an aspherical CSM (Wang et al. 2004); a slow-moving outflow at \sim 100 km s\(^{-1}\) and a dusty CSM. It must also explain the apparent rarity of SN 2002 ic-like events. Taking these observational constraints at face-value, we currently favour a system involving a post-AGB star. There are several known examples of post-AGB stars that have high inferred mass-loss rates and dusty discs CSM (e.g. IRAS 08544-4431, Maas et al. 2003). These objects have typical outflow velocities of the order of 100 km s\(^{-1}\). Furthermore, the post-AGB phase can be relatively short, \sim 10^3 - 10^4 yrs. (van der Veen et al. 1994). Further planned observations will no doubt provide more clues as to the previous evolution of SN 2002 ic.

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