On the progenitor of the Type Ic supernova 2002ap

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\textbf{ABSTRACT}

This letter presents wide-field optical and and NIR ($UBVRI\,H\alpha K$) images of the galaxy M74 which were taken between 0.6–8.3 years before the discovery of the Type Ic supernova 2002ap. We have located the position of the supernova on these images with an accuracy of 0.3''. We find no sign of a progenitor object on any of the images. The deepest of these images is the $B$–band exposure which has a sensitivity limit corresponding to an absolute magnitude of $M_B \leq -6.3$. From our observed limits, we rule out as the progenitor all evolved states of single stars with initial masses greater than 20$M_\odot$ unless the WR phase has been entered. Two popular theories for the origin of Type Ic supernovae are the core collapse of massive stars when they are in the WR phase, or the core collapse of a massive star in an interacting binary which has had its envelope stripped through mass transfer. Our prediscovery images would be sensitive only to the most luminous $\sim$30% of WR stars, hence leaving a substantial fraction of typical WR stars as viable progenitors. The energetics measured from modelling

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the initial lightcurve and spectral evolution of SN 2002ap suggest an explosion of a $5\,\text{M}_\odot$ C+O core. While WR stars generally have measured final masses greater than this, the uncertainties associated with the explosion model, stellar evolutionary calculations and mass measurements suggest we cannot definitively rule out a WR star progenitor. The alternative scenario is that the progenitor was a star of initial mass $\sim 20-25\,\text{M}_\odot$ which was part of an interacting binary and stripped of its hydrogen and helium envelope via mass transfer. We discuss future observations of the supernova environment which will provide further constraints on the nature of the progenitor star.

*Subject headings:* binaries: close – stars: evolution – stars: Wolf-Rayet — gamma rays: bursts – supernovae: individual(2002ap) — galaxies: individual(NGC628)
1. Introduction

 Supernova 2002ap was discovered by Yoji Hirose on 2002 January 29.4 UT in the spiral galaxy M74 (Nakano et al. 2002). It was discovered at $V = 14.54$, and at a distance of approximately 7.3 Mpc, may be the closest supernova since SN 1993J in M81 (at 3.6 Mpc). Several observers rapidly obtained spectra, and reported that it appeared similar to the peculiar SN 1998bw and caught at an earlier epoch (e.g. Meikle et al. 2002). Later optical spectra of SN 2002ap indicate that it does appear to be a Type Ic, and its optical lightcurve appears to have peaked at approximately $M_V \simeq -17.5$, some 1.7 magnitudes fainter than SN 1998bw. Unlike SN 1998bw, there has been no detection of a γ-ray burst (GRB) which could in any way be coincident with the position of SN 2002ap (Hurley et al. 2002). However Gal-Yam, Ofek & Shemmer (2002) suggest that their more accurate determination of the date of peak luminosity means the time-frame for which gamma-ray data should be searched needs to be extended, and this has not yet been done systematically. In a preliminary spectral analysis Mazzali et al. (2002) suggest that it had a kinetic energy $\sim 4 - 10 \times 10^{51}$ ergs, a factor of roughly 10 less than that of SN 1998bw, but similar to the hypernova SN1997ef (Iwamoto et al. 2000). The spectral similarity to SN 1998bw, the possible link between very energetic supernovae and GRBs, and the lack of substantive data on rare Type Ic events make this bright supernova a very important object to monitor and study in detail.

 A distance of 7.3 Mpc ($\mu_0 = 29.3$) to the galaxy M74 (= NGC 628) has been determined by Sharina et al. (1996) and Sohn & Davidge (1996) from the magnitudes of the brightest blue and red supergiants. Although this method suffers from significant uncertainties (typically $\pm 0.5$ in $\mu_0$; Rozanski & Rowan-Robinson 1994), M74 is certainly close enough to allow extensive observations of this bright supernova for some time. Supernova Types II, Ib and Ic are thought to originate in the collapse of the iron cores of massive stars at the end of their nuclear burning lifetimes. But the types of stars that cause these, are not well constrained by observations. The only definite detection and determination of the spectral type of a supernova progenitor is that of Sk$–69^\circ$202, the precursor to SN 1987A (a B3Ia supergiant; Walborn et al. 1989). The progenitor of SN 1993J in M81 was identified as a possible K0Ia with some excess $UB$ band flux from either an unresolved OB association or a hot companion (Aldering, Humphreys & Richmond 1994). In two recent papers Smartt et al. (2001, 2002) presented high-resolution prediscovery images of two nearby Type II-P supernovae, SNe 1999gi and 1999em. In neither case was an actual progenitor star detected despite the depth of the exposures, however upper mass limits of the progenitor stars were derived of $9^{+2}_{-1} M_\odot$, and $12^{+1}_{-1} M_\odot$ respectively. TypeIc supernovae probably arise in stars which have lost their H and He envelopes, and possible candidates are massive WR stars, or stripped high- or intermediate-mass stars in interacting binaries. In this Letter we present analysis of optical and near-IR images of M74 taken before the explosion of SN 2002ap, and
ascertain if there is any sign of a massive luminous progenitor star.

2. Observational data and analysis

We have 2 sets of wide-field optical images of M74 taken before discovery of 2002ap from different sources. The first set are from the Wide-Field-Camera (WFC) on the Isaac Newton Telescope (INT), La Palma, taken on 2001 July 24 through filters $UBVI$. The exposures were 120s in each of $BV$ and 180s in $U$. These were taken at the end of a night during the Wide Field Survey programme on Faint Sky Variability (Groot et al. 2002). The WFC comprises 4 thinned EEV 4k×2k CCDs, with 13.5 $\mu$m (0.33″) pixels. Repeat exposures of 120s in $UVI$ were taken on 2002 February 2. The supernova core saturated in these frames, and shorter 2-10s exposures were taken with the telescope guiding continuously between the short and long exposures to determine an accurate position for SN 2002ap. The second set of images is from the KPNO 0.9m with the Direct Imaging Camera taken on 1993 September 15 & 17. Multiple individual frames of exposure length between 400-600s were stacked together to give total exposure times of 5400s (in $B$), 3600s ($V$), 3200s ($R$), and 6900s ($H_\alpha$; presented previously in Ferguson et al. 1998). This camera has a $2048 \times 2048$ TEK CCD with 0.68″ pixels and the seeing in both cases was $\sim 1.5″$. A $K'$–band image of M74 was taken by R.S. de Jong using the Bok 2.3m. telescope of the Steward Observatory on 1999 October 18 with the PISCES camera (McCarthy et al. 2001); a HAWAII HgCdTe array of 1024×1024 pixels of 0.5″ on the sky. These observations were mosaiced to cover the full optical disk of M74 and total on-source exposure time at the position of SN2002ap was 675s.

The centroid of SN 2002ap, measured in the 2002 February WFC images, was located on all prediscovery images. Between 7 and 14 bright stars in each of the images were used to define a transformation with standard techniques within IRAF, using aperture photometry to determine the centroids of the stars. The supernova position is marked in Fig. 1. The errors in the SN position were calculated by taking the quadratic sum of the transformation error and the positional error of the supernova centroid, and are in the range $0.14 - 0.29″$ for $UBVRIH\alpha K'$. There is a nearby bright object clearly detected in $BVRI$ but, at a distance of 2.31″ from the supernova centroid, it is definitely not coincident with the explosion. We have estimated limiting sensitivities for each image based on Poisson statistics and the 3σ limiting magnitudes are listed in Table 1 for each filter. The photometric zero-points for the $UBVRI$ images were calibrated from the photometric sequence in the field of M74 published by Henden (2002). The calibration of the $K'$–band is described in McCarthy et al. (2001).

In order to convert these observational limits to more useful limits on the (de-reddened) absolute magnitudes, the extinction towards the progenitor and distance to the host galaxy
are required. Klose, Guenther & Woitas (2002) have measured the interstellar medium Na I D1 absorption feature due to the gas in M74, and have determined a value of $E(B-V) = 0.008 \pm 0.002$ for the host galaxy. Assuming a ratio of total-to-selective extinction of 3.1, 

$$A_V(\text{host}) = 0.025 \pm 0.006 \text{ magnitudes.}$$

The Galactic extinction estimates are listed in Table 1, (from Schlegel et al. 1998, assuming $R=3.1$, and conversion factors from Cardelli, Clayton & Mathis 1989), and these clearly dominate total extinction (Galactic + host). There is no Cepheid distance determination to M74, and Sharina et al. (1996) point out a discrepancy between two distance modulus measurements of nearly 5 magnitudes. The distance of 7.3 Mpc derived by both Sharina et al. (1996) and Sohn & Davidge (1996) is intermediate between these other two, and we assume this distance in the rest of the paper. We used the distance to M74 itself rather than the mean distance to the M74 group derived by Sharina et al. (1996) which was used by Mazzali et al. (2002). The difference is $0.2^m$, and does not have significant consequences for the conclusions presented below.

The detection limits in each filter can be converted to upper limits on the bolometric luminosity of the progenitor star (as in Smartt et al. 2001, 2002). The simple equation is

$$\log L/L_\odot = (M_{\odot, \text{bol}} - 5 + 5 \log d + A_V - V - \text{BC})/2.5 \quad (1)$$

By applying the bolometric correction (BC) we obtain the upper limit for the bolometric luminosity. However, the spectral type of the progenitor is unknown. To determine $\log L/L_\odot$ for supergiants in the temperature range O5 to M5, the BC for each spectral type is taken from Drilling & Landolt (2000). The other $UBRI$ filters can be used in a similar way (as discussed in Smartt et al. 2002) to provide further constraints on $\log L/L_\odot$. The limiting values of $\log L/L_\odot$ as a function of stellar effective temperature are plotted in Fig. 2.

3. Discussion

SN 2002ap lies at $4'38''$ from the centre of M74. Assuming a distance of 7.3 Mpc, this corresponds to 9.8 kpc, which is outside the main area of current star formation activity. Several authors have studied the radial abundance gradients across this galaxy from H II region analysis (McCall, Rybski & Shields 1985; Belley & Roy 1992; Ferguson, Gallagher & Wyse 1998; Van Zee et al. 1998). From these four studies, the mean oxygen abundance at a distance of 9.8 kpc is $12 + \log O/H = 8.5 \pm 0.2$ dex, which is a factor of 2 below that of solar neighbourhood H II regions and young stars. To compare the evolutionary states of massive evolved stars with the luminosity limits derived, we use the stellar evolutionary tracks of Meynet et al. (1994) which have a metallicity $Z = 0.008$. However, given the scatter in the
abundance measurements, an initial progenitor metallicity close to solar cannot be ruled out.

In Fig. 2 we plot on an HR diagram the upper limits on the bolometric luminosities, together with the stellar evolutionary tracks for a range of MS masses. Hence there are types of massive stars at particular evolutionary states that we can firmly rule out as being the progenitor of this Type Ic supernova. These are as follows

1. Massive stars with initial masses greater than $\sim 30M_\odot$ which have evolved off the main-sequence but not yet reached the Wolf-Rayet stage; such as Luminous Blue Variables (LBV), and yellow hypergiants. These stars still have hydrogen rich envelopes, and so our constraint is in agreement with the lack of hydrogen seen in SN 2002ap and Type Ic SNe in general. We certainly would have detected LBVs similar to Galactic examples such as $\eta$ Carinae, P Cygni, AG Carinae (Humphreys & Davidson 1994).

2. Massive blue supergiants. The $B$–band image should have detected a star like Sk$-69^\circ202$ (progenitor of SN 1987A) at the 3$\sigma$ level. We would certainly have detected more massive counterparts while they were B-type supergiants. We would have detected all B and A-type supergiants with initial masses greater than $\sim 25M_\odot$.

3. Red and yellow supergiants with masses greater than approximately $15M_\odot$. Such progenitors would have been detected in the $VRI$ passbands. This is consistent with the suggestion of Smartt et al. (2002) that normal SN II-P may come from moderate mass progenitors ($M_\lesssim 12M_\odot$) in the red supergiant phase.

We cannot dismiss lower mass progenitors (less than approximately $15M_\odot$) at any stage of their evolutionary lives. However single stars in this mass range are unlikely to lose their hydrogen atmospheres before they reach the end of their lives, and so it is virtually inconceivable that they produce SNe Ic. The prediscovery images are not sensitive to all typical magnitudes of WR stars. We stopped the shaded region in Fig. 2 at the edge of the O-star main-sequence (ZAMS mass of $85M_\odot$ and $T_{\text{eff}}=48000K$), to consider the WR region separately. Wolf-Rayet stars span a large range in absolute magnitudes. For example, in the Galaxy and the LMC they have continuum magnitudes in the range $-8 \lesssim M_b \lesssim -3$ although it is only rarely that they have magnitudes at the brighter end of this range (Vacca & Torres-Dodgen 1990). However these magnitudes are measured with narrow-band filters to sample continuum regions free from the characteristic broad, strong emission lines$^8$. Magnitude differences $b - B$ and $v - V$ can be up to $-0.55^m$ and $-0.75^m$ respectively for WC stars.

$^8$The $ubv$ filters often used are typically 100Å wide and centred near 3650Å, 4270Å and 5160Å respectively
i.e. the strongest line WC stars could be $0.55m$ brighter in $B$ than the Vacca & Torres-Dodgen (1990) $b$ magnitudes. Taking that sample as representative, our sensitivity limit of $M_B = -6.3$ should permit the detection of roughly 30% of WR stars. Assuming a $BC = -4.5$ is appropriate for WR stars (Crowther et al. 2002; Smith & Maeder 1989), then Eqn. 1 suggests an upper limit to the luminosity of a WR star progenitor of $\log L/L_\odot \lesssim 6.2$. Applying the approximate mass-luminosity relation for WR stars from Maeder (1983), this corresponds to an initial upper mass limit of $\sim 40M_\odot$. These approximate numbers rule out a very high mass WR progenitor, but about 70% of typical WR stars (of initial masses less than $\sim 40M_\odot$) would not be detected and so are viable progenitors.

Mazzali et al. (2002) have presented a preliminary model of the early evolution of SN 2002ap, finding a kinetic energy of $\sim 4 - 10 \times 10^{51} \text{ ergs}$ and an ejected heavy element mass of $M_{ej} \simeq 2.5 - 5M_\odot$. They suggest that this is most consistent with an explosion of a $\sim 5M_\odot$ C+O star, which would have had an initial main-sequence mass of $M_{ms} \sim 20 - 25M_\odot$. The explosion was less energetic than that of SNe 1998bw or 1997ef ($\sim 5 \times 10^{52} \text{ ergs}$; Nakamura et al. 2001) although the very broad spectral features indicate that SN 2002ap is of similar nature to these hypernovae. Our non-detection forces us to conclude that a $M_{ms} \sim 20 - 25M_\odot$ progenitor star must either have been in an evolutionary phase hotter than $\sim 15000K$ (or else we would have detected it on the prediscovery images - see Fig. 2), or the star did not go through classical single star evolution. Given that the progenitor must have lost its hydrogen envelope to become a Type Ic, a $M_{ms} \sim 20 - 25M_\odot$ progenitor in an interacting binary system appears to be the most consistent explanation for the progenitor non-detection and the C+O core mass inferred in the Mazzali et al. (2002) analysis. As discussed above, the prediscovery images would not be sensitive to the majority of WR stars, and on this basis alone we cannot rule them out. At LMC type metallicity, WR stars should have initial masses of $\geq 30M_\odot$ (Massey, Waterhouse & DeGioia-Eastwood 2002), and final C+O cores of $\sim 10M_\odot$. Although this appears a factor of two higher than inferred from the the Mazzali et al. (2002) explosion models, the final masses of WR stars are somewhat uncertain, and could be as low as $7M_\odot$ (Dray et al. 2002; Crowther et al. 2002). Also as noted above, the metallicity of the 2002ap region we have adopted is not definitive and could be close to solar, which would result in a lower initial mass for WR formation, and a slight lowering of the core mass. Given all of these uncertainties we cannot distinguish between the single WR scenario and the progenitor being a $20 - 25M_\odot$ star in an interacting binary system which has had its outer H-rich envelope removed due to mass transfer. The latter scenario was first theoretically suggested by Nomoto, Iwamoto & Suzuki (1995) and the observational work of Van Dyk, Hamuy & Filippenko (1996) on the association of Type II, Ib and Ic events with massive HII regions supports the idea that the progenitors of SNe Ib and Ic could be interacting binary stars, rather than initially very massive stars which have reached the WR
phase. The results of this paper together with those of Mazzali et al. (2002) may suggest a similar origin for SN 2002ap. In comparison, hydrodynamic modelling of the lightcurve and spectra of SN 1998bw suggests the explosion of a 14$M_{\odot}$ C+O star which is the core of a star of initial mass 40$M_{\odot}$ (Nakamura et al. 2001). This could certainly be a WR star, although SN 1998bw was too distant to allow constraints on its progenitor from prediscovery images.

The position of SN 2002ap is 2.31″ (or 80 pc) away from the bright object clearly detected in the $BVRI$ images shown in Fig. 1, with only a a faint sign of the object in the $U$−band. At Hα there is weak, possibly extended emission although the SN position is clearly not coincident with any nebular flux. This object has magnitudes (again measured with respect to the calibration of Henden 2002) $B = 21.50$, $B-V = 0.44$, $V-R = 0.19$, $R-I = 0.37$. This source shows some evidence of being more extended than the typical point-spread-function of the image, although the resolution and variable background are such that much higher resolution images are required to determine its exact nature. Assuming a similar extinction to this object as for the supernova, it has $M_B = -7.8$, and colours which would be consistent with it being a very luminous single supergiant star of type late A or F with a mass roughly of $\sim 40M_{\odot}$. Alternatively it could be an unresolved cluster with a diameter similar to, or less than, the seeing disk i.e. roughly 100 pc. It is unlikely that massive stars form individually, and one would expect that if a WR star or 20-25$M_{\odot}$ initial mass binary component was the progenitor then an accompanying population of stars of lower or equivalent mass should be seen. The absolute $B$-magnitude of this object is roughly consistent with a star cluster with a mass $5^{+5}_{-3} \times 10^3 M_{\odot}$ (from the Galaxy Isochrone Synthesis Spectral Evolution Library (GISSEL) of Bruzual & Charlot 1993), although its colours are somewhat redder than one would expect from a young cluster of age less than $\sim 100$ Myrs. The depth of the $K$-band is rather too shallow to constrain individual stellar objects. However the lack of any significant flux shows that there is no large scale starforming region enshrouded in dust, which could be host to an optically hidden large population of massive stars. Once SN 2002ap has faded significantly, it is imperative that deep, high resolution images are taken of its environment. Ideally this should be done with the Hubble Space Telescope. With the Advanced Camera for Surveys one could resolve the nature of this object, and construct an accurate CMD (down to $M_V \sim -2$ in a very modest amount of time) to constrain the star formation history of this region. If it remains a single object then detection of lower mass stars in this region will still produce an extinction map from multi-colour photometry. Furthermore, if the progenitor was part of an interacting binary system, it is likely that the companion is a fairly massive star and may be detectable in deep images several years from now.

In summary, the prediscovery images allow significant constraints to be placed on the nature of the progenitor of the nearest Type Ic supernova (and probable hypernova) to have occurred in modern times. We can rule out various evolutionary states of massive stars
which would be clearly detectable on the pre-explosion images. These include very high
mass (\( \gtrsim 40\text{M}_\odot \)) WR stars, although this still leaves roughly 70\% of typical WR-types as
viable progenitors. We cannot distinguish between the WR model and the death of a star
with initial mass \( \sim 20-25\text{M}_\odot \) which has had its outer envelope stripped off through mass
transfer in a binary system. However, this unexcluded fraction of WR stars may have too
high a final core mass to be consistent with initial models of the supernova energetics. The
galaxy M74 has been imaged by HST, Gemini, CFHT and WHT, however the supernova
position does not fall on any of these images. We have searched all the publicly available
archives for deeper, higher resolution images of M74 but have found no superior images to
those presented here that include the pre-explosion site of SN 2002ap.

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Table 1: The 3σ limiting magnitudes derived from pre-discovery images obtained at the Isaac Newton and KPNO 0.9m telescopes ($UBVRI$), and the Bok 2.3m telescope ($K'$). The absolute magnitude limits are calculated assuming a distance of 7.3 Mpc with extinctions as described in Section 2. In each band the value quoted uses the deepest limit available.

| Filter | INT | KPNO 0.9m | $A_\lambda$ | Abs Mag. |
|--------|-----|-----------|-------------|----------|
| U      | 21.5| ...       | 0.387       | −8.2     |
| B      | 22.7| 23.3      | 0.307       | −6.3     |
| V      | 22.6| 22.9      | 0.236       | −6.6     |
| R      | ... | 22.2      | 0.190       | −7.3     |
| I      | 21.5| ...       | 0.138       | −7.9     |
| K      | 18.1| ...       | 0.026       | −11.2    |
Fig. 1.— The prediscovery optical images, with $BVRH\alpha$ from the KPNO 0.9m and $UI$ from the INT WFC. The location of SN 2002ap is at the centre of each frame, indicated by the orthogonal lines. The SN position is $2.31'' \pm 0.29''$ away from the nearby bright object detected in $BVRI$ (and marginally seen in $U$) i.e. it is clearly not coincident with this source.
Fig. 2.— The Geneva evolutionary tracks (Meynet et al. 1994; Schaller et al. 1992) for $15-85\,M_\odot$ plotted on an HR diagram. The positions of the progenitors of SN 1987A and SN 1993J are indicated. The luminosity limits as a function of stellar effective temperature are plotted as the thick solid lines. The prediscovery images are sensitive to all stars lying in the shaded regions of the HR diagram.