On the Progenitor of the Type Ic Supernova 2002ap

Smartt, S.; Vreeswijk, P.M.; Ramirez-Ruiz, E.; Gilmore, G.F; Meikle, W.P.S.; Ferguson, A.M.N.; Knapen, J.H.

Published in:
Astrophysical Journal

DOI:
10.1086/341747

The Astrophysical Journal, 572:L147–L151, 2002 June 20

ON THE PROGENITOR OF THE TYPE Ic SUPERNOVA 2002ap

S. J. Smartt,[1] P. M. Vreeswijk,[2] E. Ramirez-Ruiz,[1] G. F. Gilmore,[1]
W. P. S. Meikle,[3] A. M. N. Ferguson,[4,5] and J. H. Knapen[6,7]
Received 2002 April 18; accepted 2002 May 13; published 2002 May 24

ABSTRACT

This Letter presents wide-field optical and near-IR (*UBVRI*H$\alpha$$K'$) images of the galaxy M74 that were taken between 0.6 and 8.3 yr 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 W-R 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 W-R phase or the core collapse of a massive star in an interacting binary that has had its envelope stripped through mass transfer. Our prediscovery images would be sensitive only to the most luminous ∼30% of W-R stars, hence leaving a substantial fraction of typical W-R stars as viable progenitors. The energetics measured from modeling the initial light curve and spectral evolution of SN 2002ap suggest an explosion of a 5 $M_\odot$ C+O core. While W-R 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 W-R star progenitor. The alternative scenario is that the progenitor was a star of initial mass ∼20–25 $M_\odot$ that 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 that will provide further constraints on the nature of the progenitor star.

Subject headings: binaries: close — galaxies: individual (NGC 628) — gamma rays: bursts — stars: evolution — stars: Wolf-Rayet — supernovae: individual (SN 2002ap)

1. INTRODUCTION

SN 2002ap was discovered by Y. 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 caught at an earlier epoch (e.g., Meikle et al. 2002). Later optical spectra of SN 2002ap indicate that it does appear to be Type Ic, and its optical light curve appears to have peaked at approximately $M_V \simeq -17.5$, some 1.7 mag fainter than SN 1998bw. Unlike SN 1998bw, there has been no detection of a gamma-ray burst (GRB) that 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 ∼(4–10) × 10^{51} ergs, a factor of roughly 10 less than that of SN 1998bw but similar to the hypernova SN 1997ef (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, Karachentsev, & Tikhonov (1996) and Sohn & Davidge (1996) from the magnitudes of the brightest blue and red supergiants. Although this method suffers from significant uncertainties (typically ±0.5 mag in μ_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°202, the precursor to SN 1987A (a B3 Ia supergiant; Walborn et al. 1989). The progenitor of SN 1993J in M81 was identified as a possible K0 Ia 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, SN 1999gi and SN 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^{+3}_{-2} and 12^{+1}_{-1} $M_\odot$, respectively. Type Ic supernovae probably arise in stars that have lost their H and He envelopes, and possible candidates are massive W-R stars or stripped high- or intermediate-mass stars in interacting

[1] Institute of Astronomy, University of Cambridge, Madingley Road, CB3 OHA Cambridge, England, UK.
[2] Astronomical Institute "Anton Pannekoek," University of Amsterdam and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, Netherlands.
[3] Astrophysics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BZ, England, UK.
[4] Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, Netherlands.
[5] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
[6] Isaac Newton Group of Telescopes, Apartado 321, E-38700 Santa Cruz de La Palma, Spain.
[7] Department of Physical Sciences, University of Hertfordshire, Hatfield, Herts AL10 9AB, England, UK.

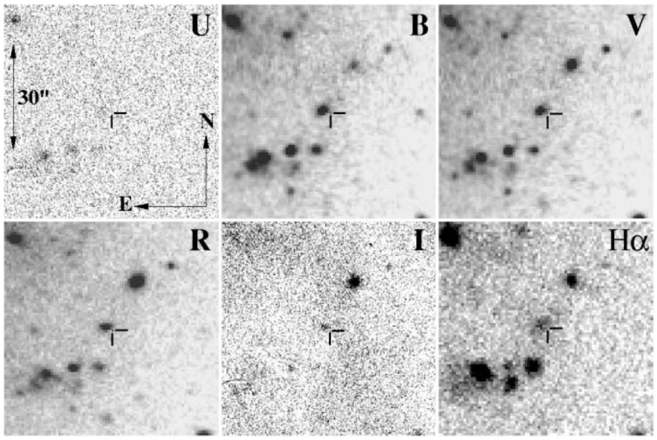

FIG. 1.—Prediscovery optical images, with *BVR*Hα from the KPNO 0.9 m and *UI* from the INT WFC. The location of SN 2002ap is at the center of each frame, indicated by the orthogonal lines. The supernova position is $2''.31 \pm 0''.29$ away from the nearby bright object detected in *BVRI* (and marginally seen in *U*); i.e., it is clearly not coincident with this source.

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 two sets of wide-field optical images of M74 taken before the discovery of 2002ap from different sources. The first set is 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 120 s in each of *BVI* and 180 s in *U*. These were taken at the end of a night during the Wide Field Survey program on Faint Sky Variability (Groot et al. 2002). The WFC comprises four thinned EEV 4k × 2k CCDs, with 13.5 μm ($0''.33$) pixels. Repeat exposures of 120 s in *UVI* were taken on 2002 February 2. The supernova core saturated in these frames, and shorter 2–10 s 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 0.9 m with the Direct Imaging Camera taken on 1993 September 15 and 17. Multiple individual frames of exposure length between 400 and 600 s were stacked together to give total exposure times of 5400 s (in *B*), 3600 s (*V*), 3200 s (*R*), and 6900 s (Hα; presented previously in Ferguson et al. 1998b). This camera has a 2048 × 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 2.3 m telescope of the Steward Observatory on 1999 October 18 with the PISCES camera (McCarthy et al. 2001): a HAWAII array of 1024 × 1024 pixels of $0''.5$ on the sky. These observations were mosaicked to cover the full optical disk of M74, and total on-source exposure time at the position of SN 2002ap was 675 s.

The centroid of SN 2002ap, measured in the 2002 February WFC images, was located on all prediscovery images. Between seven 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 Figure 1. The errors in the supernova 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

TABLE 1
3 σ LIMITING MAGNITUDES

Filter	INT	KPNO 0.9 m	A_λ	Absolute Magnitude
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

NOTE.—Limiting magnitudes were derived from prediscovery images obtained at the Isaac Newton and KPNO 0.9 m telescopes (*UBVRI*) and the Bok 2.3 m telescope (K'). The absolute magnitude limits are calculated assuming a distance of 7.3 Mpc with extinctions as described in § 2. In each band, the value quoted uses the deepest limit available.

*UBVRI*H$\alpha K'$. 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 3 σ 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 (dereddened) absolute magnitudes, the extinction toward 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, $A_V(\text{host}) = 0.025 \pm 0.006$ mag. The Galactic extinction estimates are listed in Table 1 (from Schlegel, Finkbeiner, & Davis 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 mag. 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 Letter. 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 mag 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 from 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 Figure 2.

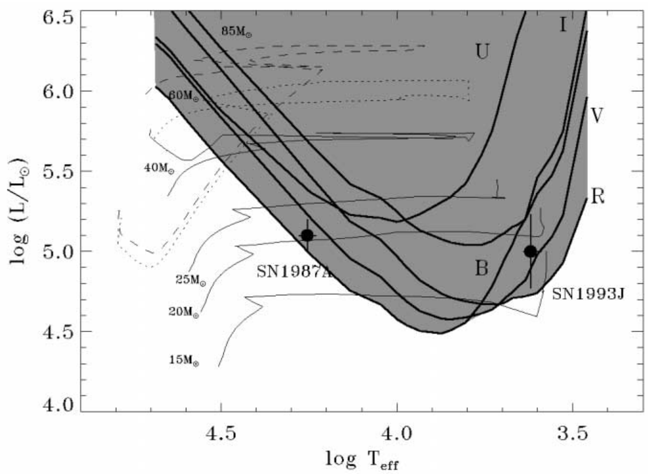

FIG. 2.—Geneva evolutionary tracks (Meynet et al. 1994; Schaller et al. 1992) for 15–85 $M_\odot$ plotted on an H-R diagram. The positions of the progenitors of SN 1987A and SN 1993J are indicated. The luminosity limits as a function of stellar effective temperature are plotted as thick solid lines. The prediscovery images are sensitive to all stars lying in the shaded regions of the H-R diagram.

3. DISCUSSION

SN 2002ap lies at 4′38″ from the center 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 1998a; van Zee et al. 1998). From these four studies, the mean oxygen abundance at a distance of 9.8 kpc is $12 + \log(\mathrm{O/H}) = 8.5 \pm 0.2$ dex, which is a factor of 2 below that of solar neighborhood 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 Figure 2, we plot on an H-R diagram the upper limits on the bolometric luminosities together with the stellar evolutionary tracks for a range of main-sequence 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 ~30 $M_\odot$, which have evolved off the main sequence but not yet reached the Wolf-Rayet stage, such as luminous blue variables (LBVs) 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 η Carinae, P Cygni, and AG Carinae (Humphreys & Davidson 1994).

2. Massive blue supergiants. The *B*-band image should have detected a star like Sk −69°202 (progenitor of SN 1987A) at the 3 σ 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 ~25 $M_\odot$.

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

We cannot dismiss lower mass progenitors (less than approximately 15 $M_\odot$) 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 Type Ic supernovae. The prediscovery images are not sensitive to all typical magnitudes of W-R stars. We stopped the shaded region in Figure 2 at the edge of the O star main sequence (zero-age main sequence mass of 85 $M_\odot$ and $T_{\rm eff} = 48{,}000$ K) to consider the W-R 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 narrowband 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 and −0.75 mag, respectively, for WC stars; i.e., the strongest line WC stars could be 0.55 mag 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 W-R stars. Assuming a BC = −4.5 is appropriate for W-R stars (Crowther et al. 2002; Smith & Maeder 1989), then equation (1) suggests an upper limit to the luminosity of a W-R star progenitor of $\log(L/L_\odot) \lesssim 6.2$. Applying the approximate mass-luminosity relation for W-R stars from Maeder (1983), this corresponds to an initial upper mass limit of ~40 $M_\odot$. These approximate numbers rule out a very high mass W-R progenitor, but about 70% of typical W-R stars (of initial masses less than ~40 $M_\odot$) 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 ~(4–10) × 10^{51} ergs and an ejected heavy-element mass of $M_{\rm ej} \simeq 2.5$–5 $M_\odot$. They suggest that this is most consistent with an explosion of an ~5 $M_\odot$ C+O star, which would have had an initial main-sequence mass of $M_{\rm ms} \sim 20$–25 $M_\odot$. The explosion was less energetic than that of SNe 1998bw or 1997ef (~5 × 10^{52} ergs; Nakamura et al. 2001), although the very broad spectral features indicate that SN 2002ap is of similar nature to these hypernovae. Our nondetection forces us to conclude that an $M_{\rm ms} \sim 20$–25 $M_\odot$ progenitor star either must have been in an evolutionary phase hotter than ~15,000 K (or else we would have detected it on the prediscovery images; see Fig. 2) or did not go through classical single-star evolution. Given that the progenitor must have lost its hydrogen envelope to become a Type Ic, an $M_{\rm ms} \sim 20$–25 $M_\odot$ progenitor in an interacting binary system appears to be the most consistent explanation for the progenitor nondetection 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 W-R stars, and on this basis alone we cannot rule them out. At LMC-type metallicity, W-R stars should have initial masses of ≥30 $M_\odot$ (Massey, Waterhouse, & DeGioia-Eastwood 2000) and final C+O cores of ~10 $M_\odot$. Although

[8] The *ubv* filters often used are typically 100 Å wide and centered near 3650, 4270, and 5160 Å, respectively.

this appears a factor of 2 higher than inferred from the Mazzali et al. (2002) explosion models, the final masses of W-R stars are somewhat uncertain and could be as low as 7 $M_\odot$ (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 W-R formation and a slight lowering of the core mass. Given all of these uncertainties, we cannot distinguish between the single W-R scenario and the progenitor being a 20–25 $M_\odot$ star in an interacting binary system that has had its outer H-rich envelope removed owing 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 H II regions supports the idea that the progenitors of Type Ib and Ic supernovae could be interacting binary stars rather than initially very massive stars that have reached the W-R phase. The results of this Letter together with those of Mazzali et al. (2002) may suggest a similar origin for SN 2002ap. In comparison, hydrodynamic modeling of the light curve and spectra of SN 1998bw suggests the explosion of a 14 $M_\odot$ C+O star that is the core of a star of initial mass 40 $M_\odot$ (Nakamura et al. 2001). This could certainly be a W-R 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 Figure 1, with only a faint sign of the object in the *U* band. At Hα, there is weak, possibly extended emission, although the supernova position is clearly not coincident with any nebular flux. This object has magnitudes (again measured with respect to the calibration of Henden 2002) $B = 21.50$, $B-V = 0.44$, $V-R = 0.19$, and $R-I = 0.37$. 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 colors that would be consistent with it being a very luminous *single* supergiant star of type late A or F with a mass of ~40 $M_\odot$. 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 W-R 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 of Bruzual & Charlot 1993), although its colors are somewhat redder than one would expect from a young cluster of age less than ~100 Myr. 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 star-forming 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* (*HST*). With the Advanced Camera for Surveys, one could resolve the nature of this object and construct an accurate color-magnitude diagram (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 multicolor 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 preexplosion images. These include very high mass ($\gtrsim$40 $M_\odot$) W-R stars, although this still leaves roughly 70% of typical W-R types as viable progenitors. We cannot distinguish between the W-R model and the death of a star with initial mass ~20–25 $M_\odot$ that has had its outer envelope stripped off through mass transfer in a binary system. However, this unexcluded fraction of W-R 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, the Canada-France-Hawaii Telescope, and the William Herschel Telescope; 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 preexplosion site of SN 2002ap.

S. J. S. acknowledges support from PPARC, and E. R.-R. acknowledges CONACYT, SEP, and the ORS foundation. The data were made publicly available through the Isaac Newton Group's Wide Field Camera Survey Program. The Isaac Newton Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos. We acknowledge access to the Wide Field Survey's data products from the Cambridge Astronomical Survey Unit at the Institute of Astronomy. We thank R. de Jong for the K'-band image and P. Crowther and P. Royer for advice on W-R stars.

REFERENCES

Aldering, G., Humphreys, R. M., & Richmond, M. 1994, AJ, 107, 662
Belley, J., & Roy, J.-R. 1992, ApJS, 78, 61
Bruzual A., G., & Charlot, S. 1993, ApJ, 405, 538
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Crowther, P. A., Dessart, L., Hillier, D. J., Abbot, J. B., & Fullerton, A. W. 2002, A&A, submitted
Dray, L., Tout, C. A., Karakas, M., & Lattanzio, J. 2002, MNRAS, submitted
Drilling, J. S., & Landolt, A. U. 2000, in Allen's Astrophysical Quantities, ed. A. N. Cox (4th ed.; New York: AIP), 381
Ferguson, A. M. N., Gallagher, J. S., & Wyse, R. F. G. 1998a, AJ, 116, 673
Ferguson, A. M. N., Wyse, R. F. G., Gallagher, J. S., & Hunter, D. A. 1998b, ApJ, 506, L19
Gal-Yam, A., Ofek, E. O., & Shemmer, O. 2002, MNRAS, in press (astro-ph/0204008)
Groot, P., et al. 2002, MNRAS, submitted
Henden, A. 2002, GCN Circ. 1242 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1242.gcn3)
Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025
Hurley, K., et al. 2002, GCN Circ. 1252 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1252.gcn3)
Iwamoto, K., et al. 2000, ApJ, 534, 660
Klose, S., Guenther, E., & Woitas, J. 2002, GCN Circ. 1248 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1248.gcn3)
Maeder, A. 1983, A&A, 120, 113
Massey, P., Waterhouse, E., & DeGioia-Eastwood, K. 2000, AJ, 119, 2214

Mazzali, P. A., et al. 2002, ApJL, in press (astro-ph/0204007)
McCall, M. L., Rybski, P. M., & Shields, G. A. 1985, ApJS, 57, 1
McCarthy, D. W., Ge, J., Hinz, J. L., Finn, R. A., & de Jong, R. S. 2001, PASP, 113, 353
Meikle, P., Lucy, L., Smartt, S., Leibundgut, B., & Lundqvist, P. 2002, IAU Circ. 7811
Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97
Nakamura, T., Mazzali, P. A., Nomoto, K., & Iwamoto, K. 2001, ApJ, 550, 991
Nakano, S., Kushida, R., Kushida, Y., & Li, W. 2002, IAU Circ. 7810
Nomoto, K., Iwamoto, K., & Suzuki, T. 1995, Phys. Rep., 256, 173
Rozanski, R., & Rowan-Robinson, M. 1994, MNRAS, 271, 530
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sharina, M. E., Karachentsev, I. D., & Tikhonov, N. A. 1996, A&AS, 119, 499
Smartt, S. J., Gilmore, G. F., Tout, C. A., & Hodgkin, S. T. 2002, ApJ, 565, 1089
Smartt, S. J., Gilmore, G. F., Trentham, N., Tout, C. A., & Frayn, C. M. 2001, ApJ, 556, L29
Smith, L. F., & Maeder, A. 1989, A&A, 211, 71
Sohn, Y.-J., & Davidge, T. J. 1996, AJ, 111, 2280
Vacca, W. D., & Torres-Dodgen, A. V. 1990, ApJS, 73, 685
van Dyk, S. D., Hamuy, M., & Filippenko, A. 1996, AJ, 111, 2017
van Zee, L., Salzer, J. J., Haynes, M. P., O'Donoghue, A. A., & Balonek, T. J. 1998, AJ, 116, 2805
Walborn, N., et al. 1989, A&A, 219, 229