

ON THE PROGENITOR AND EARLY EVOLUTION OF THE TYPE II SUPERNOVA 2009kr

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ABSTRACT

We identify a source coincident with SN 2009kr in *Hubble Space Telescope* pre-explosion images. The object appears to be a single point source with an intrinsic color $V - I = 1.1 \pm 0.25$ and $M_V = -7.6 \pm 0.6$. If this is a single star, it would be a yellow supergiant of $\log L/L_\odot \sim 5.1$ and a mass of $15^{+5}_{-4} M_\odot$. The spatial resolution does not allow us yet to definitively determine if the progenitor object is a single star, a binary system, or a compact cluster. We show that the early light curve is similar to a Type IIL SN, but the prominent H α P-Cygni profiles and the signature of the end of a recombination phase are reminiscent of a Type IIP. The evolution of the expanding ejecta will play an important role in understanding the progenitor object.

Key words: galaxies: individual (NGC 1832) – stars: evolution – supernovae: general – supernovae: individual (SN 2009kr)

Online-only material: color figures

1. INTRODUCTION

In recent years, the hypothesis that red supergiants (RSGs) explode as Type II Plateau (IIP) supernovae (SNe) has been confirmed by several direct detections of progenitors in pre-explosion images (for a review, see Smartt 2009). Two progenitor candidates which show luminous blue variable (LBV) characteristics, either in quiescence or outburst, have been found for SNe with clear signatures of circumstellar interaction, the Ibn 2006jc (Pastorello et al. 2007, 2008; Foley et al. 2007; Immler et al. 2008) and IIn 2005gl (Gal-Yam 2007; Gal-Yam & Leonard 2009). Despite these successes, the total number of SNe for which we have definite progenitor identifications is still low. SN 2009kr was found in the spiral galaxy NGC 1832 on 2009 November 6 by K. Itagaki (Nakano 2009), at coordinates ($5^{\text{h}}12^{\text{m}}33.3, -15^{\circ}41'52''.1$) and with an unfiltered magnitude of 16.0. Tendulkar et al. (2009) obtained a spectrum on November 8, and suggested that SN 2009kr showed the features of a IIn SN, with narrow hydrogen Balmer emission lines. A second spectrum was obtained by Steele et al. (2009) on November 9, which showed weak P-Cygni absorption in the hydrogen lines. Based on this, and indications that the narrow Balmer lines seen by Tendulkar et al. were in fact produced by a nearby H II region, Steele et al. claimed SN 2009kr to be a young Type II.

In this Letter, we have taken the host galaxy of SN 2009kr to be at a distance of 26.2 ± 1.8 Mpc (from the recessional velocity, correcting for Virgo-centric infall; with values taken from NED.¹²), which corresponds to a distance modulus ($m - M$)

of 32.09 ± 0.15 mag. Estimates from the Tully–Fisher (T–F) relation, however, give a higher value of $(m - M) = 32.61 \pm 0.43$ mag (Willick et al. 1997). This value may be unreliable as NGC 1832 has a faint absolute magnitude, where the T–F relation has a larger scatter. Terry et al. (2002) give a low value of $(m - M) = 30.76 \pm 0.41$ mag from the method of “sosie” galaxies. These two methods bracket our recessional velocity distance; in the absence of any indication of which method is the most reliable in this case, we used the recessional velocity based distance as a compromise, with a conservative error of ± 0.5 mag. We have used the standard Schlegel et al. (1998) relation for Galactic extinction, giving $A_V = 0.242$ and $A_I = 0.142$ mag (values taken from NED). Host extinction is assumed to be negligible, as our spectra of the SN appear blue and lack prominent Na I D lines. We have used the calibrations of Pilyugin et al. (2004) and Boissier & Prantzos (2009) to estimate a metallicity of $12 + \log(\text{O}/\text{H}) = 8.06 \pm 0.24$ dex at the SN location.

2. OBSERVATIONS AND DATA ANALYSIS

The host galaxy of SN 2009kr was observed on 2008 January 11 (~660 days before explosion) with the Wide Field and Planetary Camera 2 (WFPC2) on board the *Hubble Space Telescope* (HST) as part of HST Program 10877. Data were reduced and calibrated by the on-the-fly calibration pipeline, and downloaded from the MAST archive at STScI.¹³ Pre-explosion images consisted of two 230 s exposures in the F555W filter, and two 350 s exposures in the F814W filter. Each pair of images was

¹² <http://nedwww.ipac.caltech.edu/>

¹³ <http://archive.stsci.edu/>

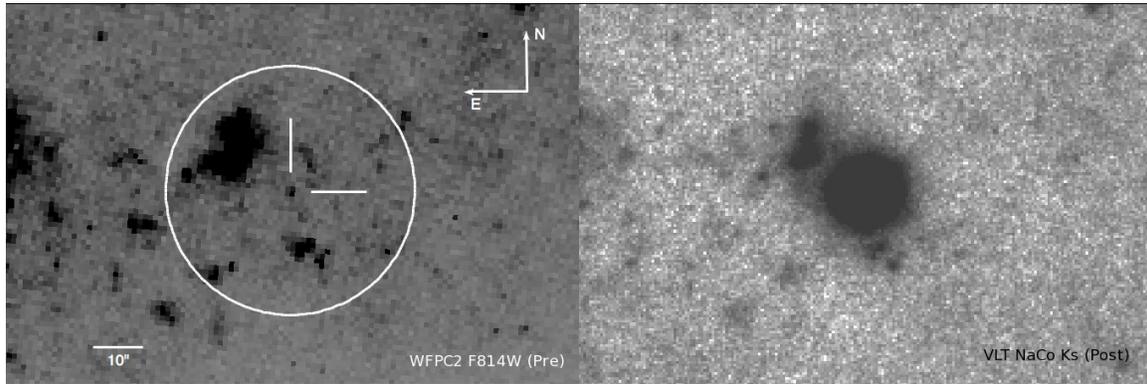


Figure 1. Pre- and post-explosion images of the site of SN 2009kr, registered as per the text. Cross marks indicate the progenitor location, circle shows location of sources in Figure 2. Progenitor candidate is located at WFPC2 pixel coordinates (432.8, 149.6).

combined with the CRREJ routine within IRAF¹⁴ to remove cosmic rays. The site of SN 2009kr fell on the WF3 chip, which has a pixel scale of $0''.1 \text{ pixel}^{-1}$. A 2340 s on-source integration in the *Ks* filter of SN 2009kr was obtained with Naos–Conica (NaCo) on the Very Large Telescope (VLT) on 2009 November 21.¹⁵ The S54 camera was used (pixel scale of $0''.054$) across a $56'' \times 56''$ field of view and the SN itself ($m_V \sim 15$ mag) was used as a natural guide star to provide adaptive optics correction for the image. Data were reduced using standard IRAF routines. The pre-explosion WFPC2 image and post-explosion NaCo images are shown in Figure 1.

To determine the position of SN 2009kr in the pre-explosion images, 18 sources common to both frames were identified. Their centroids were measured with aperture photometry and the resulting list of matched coordinates was used to determine a geometrical transformation between the pre- and post-explosion images with IRAF GEOMAP. Translations and independent rotation and scaling in x and y were allowed for. Six outliers lying more than 1 pixel outside the fit were rejected and the fit recalculated. The final rms error in the transformation (as taken from the output of GEOMAP) was 34 mas. The position of the SN was measured using the three different centering algorithms within PHOT (Gaussian, centroid, and ofilter) with the mean of the three results being taken as the position and the standard deviation of the results as the uncertainty (3 mas). The same procedure was used to determine the position and uncertainty (39 mas) in the progenitor candidate. The position of the SN as measured in the post-explosion NaCo image was then transformed into WFPC2 coordinate system using the GEOXYTRAN task and the transformation determined previously. The uncertainties in the progenitor candidate and SN positions were added in quadrature together with the uncertainty in the transformation to give the total uncertainty in the procedure. The separation between the progenitor candidate and the SN was found to be 6 mas, which is well within the total uncertainty of 52 mas. We thus conclude that the source indicated in Figure 1 is coincident with SN 2009kr. Li et al. (2009) identified the same progenitor in the archival WFPC2 images, using an alignment to a post-explosion image obtained with the Canada–France–Hawaii Telescope and Mega-Cam.

To characterize the progenitor, we carried out point-spread function (PSF)-fitting photometry with the HSTPHOT package

(Dolphin 2000, 2009). The coincident source was clearly detected in both the F814W and F555W images by HSTPHOT at the 10σ level in F555W and 14σ in F814W. We ran HSTPHOT twice, first measuring the sky at each pixel from the mean of its neighboring pixels, and secondly recalculating the local sky at the location of the progenitor using the pixels immediately outside the photometric aperture. Measured magnitudes were $V = 24.53 \pm 0.11$ and $I = 23.47 \pm 0.08$ for the first run, and $V = 24.71 \pm 0.14$ and $I = 23.48 \pm 0.10$ for the second. I is unchanged within the uncertainties, however, there is a 0.2 mag difference in V . We have taken the magnitudes from the second run as more reliable, as the recalculated sky value is likely more appropriate for backgrounds that vary rapidly over short distances, such as in this case. To give a more reliable uncertainty estimate for our photometry, we have added the error in the output of HSTPHOT in quadrature with the difference between the magnitudes given by the first and second runs. This gives a final progenitor magnitude of $m_V = 24.71 \pm 0.23$ and $m_I = 23.48 \pm 0.10$ from HSTPHOT. With the distance modulus (and its uncertainty) and extinction from Section 1, this corresponds to an absolute magnitude of $M_V = -7.62 \pm 0.55$, $M_I = -8.75 \pm 0.51$, and $V - I = 1.13 \pm 0.25$.

As an independent check of the output of HSTPHOT, aperture photometry was performed. We applied the same CTE corrections as HSTPHOT; aperture corrections were determined from bright isolated sources. The magnitudes obtained from aperture photometry are 0.2 mag brighter than those given by HSTPHOT; we attribute this as likely due to extra flux from nearby sources which the PSF-fitting of HSTPHOT can better remove. We obtain $V - I = 1.03$, which agrees with HSTPHOT within the uncertainties.

The χ^2 and sharpness statistics in the output of HSTPHOT suggest the source is a single star-like PSF; we note, however, that at the distance of NGC 1832 a single WF chip pixel corresponds to ~ 13 pc. Unfortunately, the progenitor candidate did not have a high enough signal-to-noise ratio for us to use ISHAPE (Larsen 1999) to characterize the best PSF fit to the progenitor source.

Bastian et al. (2005) suggest that sources with $M_V < -8.6$ are likely to be clusters. While the source detected is ~ 1 mag fainter than this, a greater distance to the host galaxy would increase the true absolute magnitude of the progenitor candidate. In Figure 2, we plot a color–magnitude diagram (CMD) of 21 sources detected at least 5σ above the noise level in both filter pre-explosion images. We used the fitting statistics in the output of HSTPHOT to try to identify extended sources. While HSTPHOT should return $\chi^2 < 1.5$ and $-0.3 < \text{sharpness} < 0.3$ for single,

¹⁴ <http://iraf.noao.edu>

¹⁵ Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere, Chile, Programs 083.D-0131 and 184.D-1140.

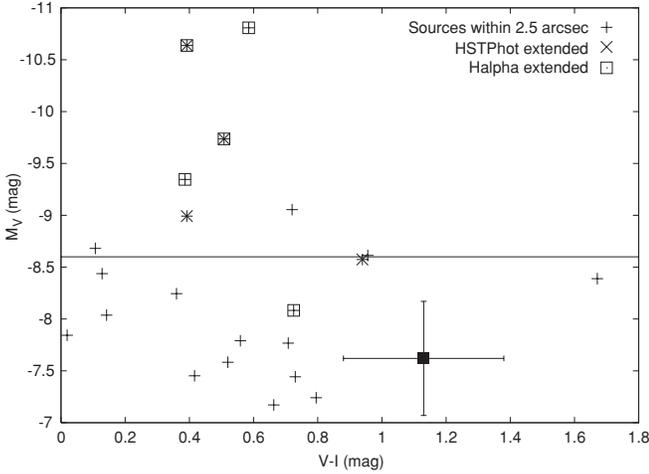


Figure 2. CMD of all WFPC2 sources detected above the 5σ level in both filters, within an arbitrary radius of $2.5''$ centered on the progenitor location. Sources which have indications that they may be extended from either $H\alpha$ or the output of HSTPHOT have been marked with a square or cross, respectively. The line at $M_V = -8.6$ is an indication of the magnitude threshold above which all brighter sources are likely clusters (Bastian et al. 2005, see Section 3). Progenitor is marked with a filled square.

uncrowded sources, values of $\chi^2 < 2.5$ and $-0.5 < \text{sharpness} < 0.5$ are reasonable. While all sources within $2.5''$ were within the sharpness limits, four sources were found to have $1.5 < \chi^2 < 2.5$, and have been classed as possibly extended on this basis, this is also supported by visual inspection of the images. We also inspected pre-explosion R -band and $H\alpha$ images taken with the Wide Field Camera (WFC) on the 2.5 m Isaac Newton Telescope on 2005 March 20. The continuum subtracted $H\alpha$ image was aligned to the pre-explosion WFPC2 image, and although the pixel scale of WFC (0.33 pixel^{-1}) is poor compared to WFPC2, identifiable sources of $H\alpha$ emission are visible. Four of the five brightest V -band sources are associated with $H\alpha$ emission, indicating they are young stellar clusters. There is no obvious strong $H\alpha$ emission at the position of SN 2009kr in these images.

3. DISCUSSION

The $V-I$ color of our progenitor after correcting for foreground extinction is $1.13 \pm 0.25 \text{ mag}$. Taking the intrinsic colors of supergiants from Drilling & Landolt (2000), this corresponds to a spectral type of G6, with an effective temperature of 4850 K, although the uncertainty in color means it could be as early as G1 or as late as K2. For a G6 star, we take a V -band bolometric correction of $-0.36 \pm 0.2 \text{ mag}$ from Drilling & Landolt, with the uncertainty corresponding to the variation in bolometric corrections across the range of possible spectral type. Applying the bolometric correction to the absolute magnitude of the progenitor, we find the bolometric magnitude to be -8.0 ± 0.6 . Using the standard relation between bolometric magnitude and luminosity

$$\log \frac{L(T_{\text{eff}})}{L_{\odot}} = \frac{M_{\text{bol}} - 4.74}{-2.5}, \quad (1)$$

we find a progenitor luminosity of $\log L/L_{\odot} = 5.10 \pm 0.24$. We show this luminosity and temperature on a Hertzsprung–Russell (H–R) diagram in Figure 3, together with the STARS evolutionary tracks of Eldridge & Tout (2004a, 2004b). We have plotted tracks for two different metallicities, $Z = 0.004$ and $Z = 0.008$ (comparable to the Small Magellanic Cloud (SMC) and Large

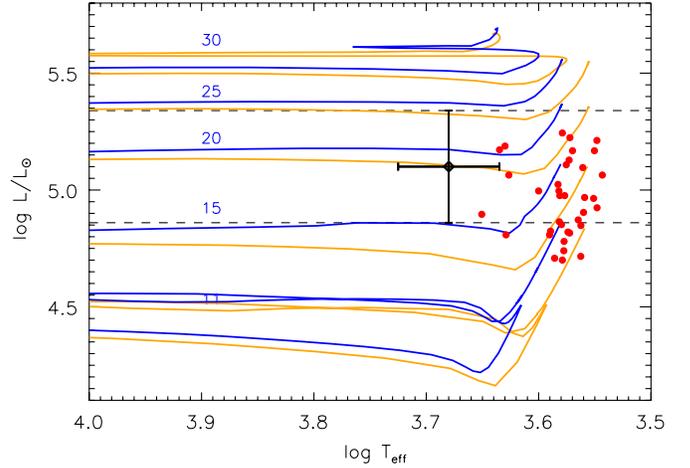


Figure 3. H–R diagram showing evolutionary tracks and the progenitor of SN 2009kr. Orange tracks are for $Z = 0.008$, blue tracks for $Z = 0.004$. Red dots are observed LMC RSGs.

(A color version of this figure is available in the online journal.)

Magellanic Cloud (LMC), respectively), we note however that the final luminosity of each pair of metallicities is extremely close, indicating that the precise progenitor metallicity is not a significant source of error in determining the progenitor mass. While the progenitor lies closest to the $20 M_{\odot}$ track, it is important to remember that a $20 M_{\odot}$ model will explode when it has an Fe core, and hence its luminosity will be higher by about 0.25 dex. It is more appropriate to compare the progenitor luminosity to the luminosity reached by the models at their end point, which corresponds to the helium core luminosity at the end of core carbon burning, i.e., the initial mass–final luminosity diagram as discussed in Smartt et al. (2009). We hence find a progenitor mass of $15_{-4}^{+5} M_{\odot}$.

Elias-Rosa et al. (2009b) identify the same progenitor for SN 2009kr as found in this work, but find a higher mass of $18\text{--}24 M_{\odot}$ for the progenitor. The authors do not, however, compare the measured luminosity of the progenitor to the luminosity of models at the end of core helium burning, but rather to the closest track at the observed progenitor color. Smartt et al. (2009) have argued that this type of comparison is inappropriate, as the models are not sufficiently evolved to explode until the end of the tracks.

From Figure 2, the suggestion that sources brighter than $M_V \sim -8.6$ (marked with a line) are clusters seems reasonable. It is important to remember, however, that this does not mean that all objects fainter than this magnitude are single sources. It is possible that the population of blue sources contains several early-type supergiants, and that the progenitor of SN 2009kr was originally one of these objects, which was transitioning between a blue and an RSG when it exploded. A further intriguing possibility is that, despite the apparent color, the progenitor of this SN was in fact an LBV. Smith et al. (2004) have suggested that the bi-stability jump observed at a temperature of $\sim 21,000 \text{ K}$, where the stellar wind properties change from a fast wind, with a low \dot{M} to a slow wind with a high \dot{M} , may also lead to the formation of a pseudo-photosphere. If this occurs, then an early B star could appear to be a yellow supergiant from its position on the H–R diagram. In Smith et al.’s models, the effect is stronger for slightly lower masses ($10 M_{\odot}$) than that which we find for our progenitor ($15 M_{\odot}$). Furthermore, the models used by these authors are for higher luminosities, $\log L/L_{\odot} = 5.7$, than that of our progenitor. We also fail to

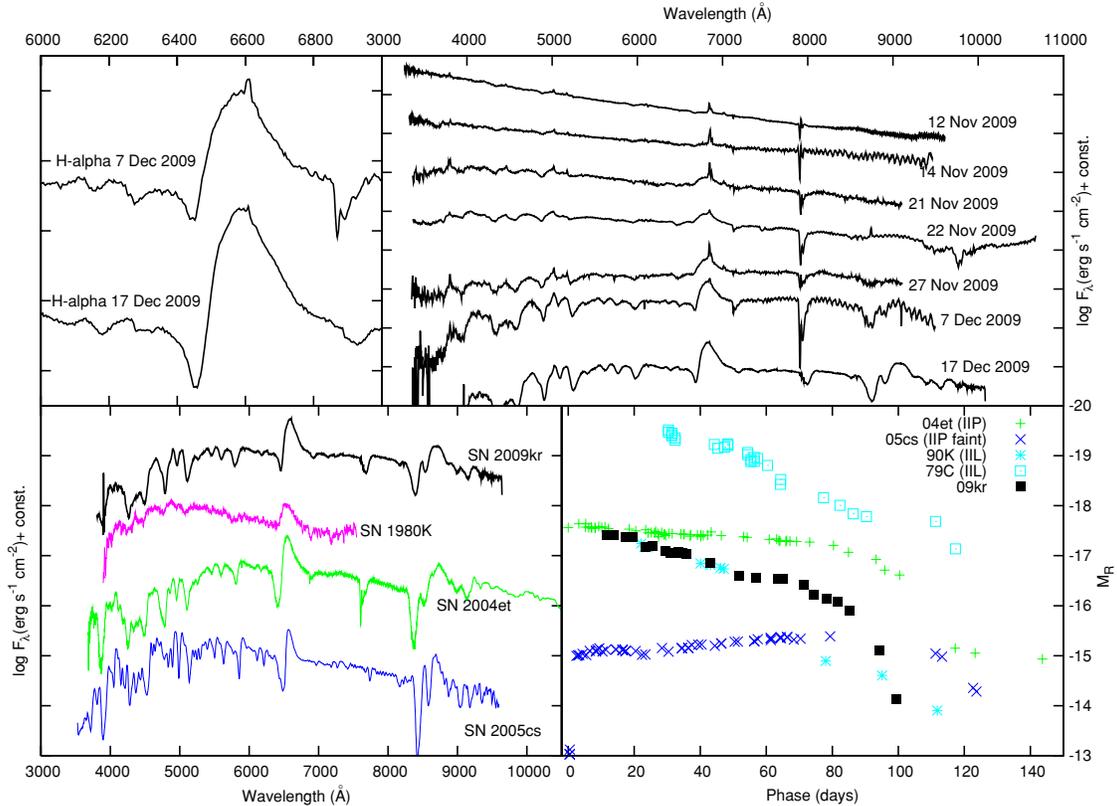


Figure 4. Top panels: time series of spectra of SN 2009kr from Telescopio Nazionale Galileo+Dolores, Nordic Optical Telescope+ALFOSC, Calar Alto 2.2 m telescope+CAFOS, New Technology Telescope+EFOSC2, and VLT+FOR2, showing the evolution of the SNe, and in particular the development of the H α P-Cygni profile. Narrow components are believed to be from a nearby H II region. Bottom panels: R -band (r' images from RatCam have been calibrated to Bessell R) light curve of SN 2009kr based on photometry obtained with Liverpool Telescope+RatCam, CAHA, NTT, NOT, WISE; and spectrum of the SN at ~ 30 days compared to other SNe at similar epochs. SN 1990K (Cappellaro et al. 1995), SN 2004et (Maguire et al. 2010; Sahu et al. 2006), SN 2005cs (Pastorello et al. 2009), SN 1979C (Balinskaya et al. 1980), and SN 1980K (Barbieri et al. 1982). Phase is relative to discovery epoch (November 6).

(A color version of this figure is available in the online journal.)

see the indications of strong circumstellar interaction in the SN spectrum, which we would expect to see for an object which has undergone significant episodes of recent mass loss, such as an LBV.

Smartt et al. (2009) have suggested that there may be a missing progenitor population of RSGs compared to what one expects from a typical initial mass function and Local Group RSG populations. There have been no detections of RSG SN progenitors above $\log L/L_{\odot} \simeq 5.1$, and one possibility is that stars above this traverse back to the blue and become Wolf-Rayet stars. As the progenitor of SN 2009kr was of this luminosity, it is possible that it was in this blueward moving phase (as was suggested for SN 2008cn by Elias-Rosa et al. 2009a). However, this scenario does not sit comfortably with the low metallicity estimate of around 8.1 dex for the SN environment. Some authors have suggested that the classical LBV stage could even stretch down to luminosities as low as 5.1 dex (Smith et al. 2010). Hence, the apparently hotter photosphere than for an RSG could be due to a post-RSG LBV stage during which the core collapses much earlier than most theoretical models predict (Vink 2009).

The progenitor appears to be a single source, although a cluster cannot be ruled out, except by observing the disappearance of the progenitor several years hence (e.g., Gal-Yam & Leonard 2009; Maund & Smartt 2009). The progenitor of SN 2004et was originally proposed to be a yellow supergiant (Li et al. 2005) of similar luminosity to the progenitor detected here. However, Crockett et al. (2009) show that this object was not a single star,

but a blend of three sources. The spatial resolution of the NGC 6946 images (the galaxy in which SN 2004et exploded, $0'.8$ at 5.9 Mpc) of 23 pc is similar to the resolution of the WFPC2 images. Hence, the progenitor object could be a similar blend of multiple sources. When the SN fades, future ACS or WF3 images will determine the nature of the source.

A sequence of spectra spanning a period of about 1 month is shown in Figure 4 (top panel). Early-time spectra show a very blue continuum and weak lines of H and He I. Later, with the H envelope recombination onset, the continuum becomes redder and metal lines (especially, Fe II and Sc II) become prominent. In the bottom left panel, a ~ 30 days spectrum of SN 2009kr is compared with spectra of SNe 1987A, 2005cs and 2004et at a similar phase. The spectrum of SN 2009kr shows a relatively red continuum and the classical Fe II lines that are usually visible in Type II SNe during recombination. However, the two-component absorption profile of H α is puzzling. It can be explained with a very prominent high velocity ($\sim 15,000$ km s $^{-1}$) H component in addition to the canonical moderate-velocity (~ 7300 km s $^{-1}$) absorption. Alternatively, the bluer shoulder can be interpreted as due to line blending (e.g., with N II). Similar profiles have been already observed in SNe IIP (e.g., SN 1999em, see Baron et al. 2000; Dessart & Hillier 2006), but always with the redder component dominating over the bluer. The dominance of emission over absorption in H α at early phases is reminiscent of Type II Linear SNe, and would support the stripped (to some extent) envelope progenitor, although P-Cygni profiles become prominent at later stages.

The *R*-band absolute light curve of SN 2009kr spanning a period of ~ 100 days after the core-collapse is shown in Figure 4 (bottom right panel), and is compared with the light curves of two Type II SNe with progenitor information: SN 2005cs (Pastorello et al. 2006, 2009) and SN 2004et (Maguire et al. 2010), together with examples of the IIL subtype. The 0–80 day period of the light curve suggests the most appropriate classification would be a Type IIL, as suggested by Elias-Rosa et al. (2009b). But we see a sharp increase in the rate of decline at ~ 100 days which is typical of Type IIP SNe.

Type IIP SNe show a plateau because they are initially powered by H recombination, while IILs do not (their light curve is powered by escaping photons from a cooling photosphere). A clear signature for the former would be either long flat plateau, or, if there is a decline in magnitude, a sudden drop when the H recombination has ceased. SN 2009kr does not satisfy the first criterion, but may satisfy the second, suggesting that SN 2009kr is a transitional event between the two types. Further observations of the evolution of SN 2009kr, together with late time imaging to confirm the disappearance of the progenitor will greatly enhance our understanding of this unusual SN.

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REFERENCES

- Balinskaya, I. S., et al. 1980, *A&A*, **85**, L19
 Barieri, C., Bonoli, C., & Cristiani, S. 1982, *A&A*, **114**, 216
 Baron, E., et al. 2000, *ApJ*, **545**, 444
 Bastian, N., Gieles, M., Efremov, Y. N., & Lamers, H. J. G. L. M. 2005, *A&A*, **443**, 79
 Boissier, S., & Prantzos, N. 2009, *A&A*, **503**, 137
 Cappellaro, E., Danziger, I. J., della Valle, M., Gouiffes, C., & Turratto, M. 1995, *A&A*, **293**, 723
 Crockett, R. M., Smartt, S. J., Pastorello, A., Stephens, A. W., Maund, J. R., & Mattila, S. 2009, *MNRAS*, submitted (arXiv:0912.3302)
 Dessart, L., & Hillier, D. J. 2006, *A&A*, **447**, 691
 Dolphin, A. E. 2000, *PASP*, **112**, 1183
 Dolphin, A. E. 2009, arXiv:0906.3557
 Drilling, J. S., & Landolt, A. U. 2000, in *Allen’s Astrophysical Quantities*, ed. A. N. Cox (4th ed.; New York: AIP Press)
 Eldridge, J. J., & Tout, C. A. 2004a, *MNRAS*, **348**, 201
 Eldridge, J. J., & Tout, C. A. 2004b, *MNRAS*, **353**, 87
 Elias-Rosa, N., et al. 2009a, *ApJ*, **706**, 1174
 Elias-Rosa, N., et al. 2009b, arXiv:0912.2880
 Foley, R., et al. 2007, *ApJ*, **657**, L105
 Gal-Yam, A., & Leonard, D. C. 2009, *Nature*, **458**, 865
 Gal-Yam, et al. 2007, *ApJ*, **656**, 372
 Immler, et al. 2008, *ApJ*, **674**, L85
 Larsen, S. S. 1999, *A&AS*, **139**, 393
 Li, W., Filippenko, A. V., & Miller, A. A. 2009, *ATel*, **2312**, 1
 Li, W., Van Dyk, S. D., Filippenko, A. V., & Cuillandre, J.-C. 2005, *PASP*, **117**, 121
 Maguire, K., et al. 2010, *MNRAS*, in press (arXiv:0912.3111v1)
 Maund, J. R., & Smartt, S. J. 2009, *Science*, **324**, 486
 Nakano, S., Yusa, T., & Kadota, K. 2009, *CBET*, **2006**, 1
 Pastorello, A., et al. 2006, *MNRAS*, **370**, 1752
 Pastorello, A., et al. 2007, *Nature*, **447**, 829
 Pastorello, A., et al. 2008, *MNRAS*, **389**, 113
 Pastorello, A., et al. 2009, *MNRAS*, **394**, 2266
 Pilyugin, L. S., Vílchez, J. M., & Contini, T. 2004, *A&A*, **425**, 849
 Sahu, D. K., Anupama, G. C., Srividya, S., & Muneer, S. 2006, *MNRAS*, **372**, 1315
 Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, **500**, 525
 Smartt, S. J. 2009, *ARA&A*, **47**, 63
 Smartt, S. J., Eldridge, J. J., Crockett, R. M., & Maund, J. R. 2009, *MNRAS*, **395**, 1409
 Smith, N., Vink, J. S., & de Koeter, A. 2004, *ApJ*, **615**, 475
 Smith, et al. 2010, *AJ*, **139**, 1451
 Steele, T. N., Cobb, B., & Filippenko, A. V. 2009, *CBET*, **2011**, 1
 Tendulkar, S. P., Kasliwal, M. M., Quimby, R., & Kulkarni, S. R. 2009, *ATel*, **2291**, 1
 Terry, J. N., Patreul, G., & Ekholm, T. 2002, *A&A*, **393**, 57
 Vink, J. S. 2009, in *Eta Carinae and the Supernova Impostors*, ed. R. Humphreys & K. Davidson (Berlin: Springer), arXiv:0905.3338
 Willick, J. A., Courteau, S., Faber, S. M., Burstein, D., Dekel, A., & Strauss, M. A. 1997, *ApJS*, **109**, 333