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SN 2006jc: A WOLF-RAYET STAR EXPLODING IN A DENSE He-RICH CIRCUMSTELLAR MEDIUM

Ryan J. Foley, Nathan Smith, Mohan Ganeshalingam, Weidong Li, Ryan Chornock, and Alexei V. Filippenko
Department of Astronomy, University of California, Berkeley, CA; rfoley@astro.berkeley.edu, nathans@astro.berkeley.edu, mganesh@astro.berkeley.edu, weidong@astro.berkeley.edu, chornock@astro.berkeley.edu, alex@astro.berkeley.edu.
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ABSTRACT

We present optical photometry and spectra of the peculiar Type Ib supernova (SN) 2006jc. Strong and relatively narrow He i emission lines indicate the progenitor star exploded inside a dense circumstellar medium (CSM) rich in He. An exceptionally blue apparent continuum persists from our first spectrum obtained 15 days after discovery through our last spectrum ∼1 month later. Based on the presence of isolated Fe ii emission lines, we interpret the blue "continuum" as blended, perhaps fluorescent, Fe emission. One or two of the reddest He i line profiles in our spectra are double-peaked, suggesting that the CSM has an aspherical geometry. The He i lines that are superposed on the blue continuum show P Cygni profiles, while the redder He i lines do not, implying that the blue continuum also originates from an asymmetric mass distribution. The He-rich CSM, aspherical geometry, and line velocities indicate that the progenitor star was a WNE Wolf-Rayet (W-R) star. A recent (2 years before the SN), coincident, luminous outburst similar to those seen in luminous blue variables (LBVs) is the leading candidate for the dense CSM. Such an eruption associated with a W-R star has not been seen before, indicating that the progenitor star may have recently transitioned from the LBV phase. We also present unpublished spectral and photometric data on SN 2002ao, which, along with SN 1999cq, is very similar to SN 2006jc. We propose that these three objects may represent a new and distinct class of SNe arising from W-R progenitors surrounded by a dense CSM.

Subject headings: stars: winds, outflows — stars: Wolf-Rayet — supernovae: general — supernovae: individual (SN 1999cq, SN2002ao, SN 2006jc)

1. INTRODUCTION

The most massive stars end their lives as core-collapse supernovae (SNe). The broad category of core-collapse SNe is divided spectroscopically based on the presence or absence of H and He, with the sequence from strong H, to He and weak H, to only He, to lacking both H and He being (respectively) Types II, IIb, Ib, and Ic (see Filippenko 1997 for a review). These correspond to progenitor stars with progressively decreasing H and He envelopes, with the mass loss caused by either stellar winds or mass transfer to a companion star. Type IIn SNe (SNe IIn; Schlegel 1990) are objects with narrow H emission lines, which are the result of the SN ejecta interacting with a dense circumstellar medium (CSM; Chugai & Danziger 1994).

Wolf-Rayet (W-R) stars are evolved, core He-burning stars near the end of their lives. They are thought to be the descendants of stars that begin their lives with initial masses $>40\ M_{\odot}$, which have already shed their H envelopes during a luminous blue variable (LBV) stage (Smith & Owocki 2006), exposing their He cores (for a review, see Abbott & Conti 1987). During this stage in stellar evolution, the mass loss from stellar winds is $\sim 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$, about 100 times higher than that of other O and B stars (Crowther 2007). Although the W-R stage lasts only $\sim 5 \times 10^{5}$ yr (Abbott & Conti 1987), a star can lose several solar masses of material during this stage. These facts suggest that W-R stars are possible progenitors of stripped-envelope (Types IIb through Ic) SNe.

Matheson et al. (2000a) showed that SN 1999cq had intermediate width (FWHM $\approx$ 2000 km s^{-1}) He emission lines similar to the hydrogen lines of SNe IIn but that it lacked H lines. They suggested that SN 1999cq was interacting with a CSM of dense He but little or no H. Until now, only one other supernova, SN 2002ao (Martin et al. 2002), has been identified as having intermediate width He emission lines (Filippenko & Chornock 2002).

SN 2006jc was discovered in UGC 4904 by amateur astronomers (Nakano et al. 2006) on 2006 October 9.75 (UT dates are used throughout this Letter). A nondetection was reported on September 22, suggesting that the SN was discovered shortly after explosion. Soon after detection, several groups obtained spectra of SN 2006jc and noted the presence of He i emission lines, but they did not associate it with SN 1999cq (Crotts et al. 2006; Fesen et al. 2006a). Fesen et al. (2006b) later reclassified SN 2006jc as Type Ia, before Benetti et al. (2006) noted its similarity to SNe 1999cq and 2002ao.

In addition to the optical photometry and spectroscopy presented in this Letter, UV and X-ray data were obtained with the *Swift* satellite (Brown et al. 2006), with a positive X-ray detection, probably indicating CS interaction. Further X-ray observations with *Chandra* (Immler et al. 2006) confirm the *Swift* X-ray results.

Detailed study of the well-observed SN 2006jc presents us with an opportunity to examine the progenitor of a rare but important core-collapse SN spanning the gap between SNe IIn and Ib, sampling the environment of a W-R star at the end of its stellar life and helping to clarify what appears to be a new subclass of SNe. Here we present optical photometry and spectroscopy and discuss the implications of those data. We also present observations of SN 2002ao in the interest of completeness, but we leave a detailed analysis of all the data for a future paper.

2. OBSERVATIONS

Once the unusual nature of SN 2006jc was noted, we began a monitoring campaign that consisted of *BVRI* photometry with the Katzman Automatic Imaging Telescope (KAIT; Filippenko et al. 2001) and optical spectroscopy with the Kast spectrograph (Miller & Stone 1993) mounted on the Lick Observatory 3 m Shane telescope, the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) mounted on the Keck I 10 m telescope, and the DEep Imaging Multi-Object Spectrograph (DEIMOS;

Faber et al. 2003) mounted on the Keck II 10 m telescope. The multiband photometry began on October 11, while our first spectrum was obtained on October 24. The photometry in this Letter continues through December 16, while our last spectrum in this Letter was obtained on November 24.

All spectral data were reduced using standard techniques (e.g., Foley et al. 2003). Using our own IDL routines, we fit spectrophotometric standard star spectra to flux-calibrate our data and remove telluric lines (Wade & Horne 1988; Matheson et al. 2000b). Photometric data were obtained with KAIT and the 1 m Nickel telescope at Lick Observatory. Magnitudes were measured in the Kron-Johnson *BVRI* system using the PSF-fitting photometry software (Stetson 1987) in the IRAF[1] DAOPHOT package, as multicolor template images required for galaxy subtraction are not available and as the SN is still visible in KAIT data. Since SN 2006jc is bright and reasonably isolated from its faint host galaxy, galaxy subtraction is not necessary, and simple point-spread function (PSF) fitting provides us with a reasonable approach to reduce the photometry at this early time. The instrumental magnitudes for SN 2006jc derived this way are calibrated with several local standard stars based on a calibration from the photometric night of October 21 with the Nickel telescope.

3. RESULTS

We present our low-resolution spectra of SN 2006jc in Figure 1. In all spectra, we are able to identify intermediate width He I, Hα, O I, Ca II, and Fe II emission lines. There are no photospheric P Cygni profiles, which are typically found in early SN Ib/c spectra (Matheson et al. 2001); the spectra seem to consist of two continuum components (red and blue) and intermediate width (1000 km s$^{-1} < v <$ 4000 km s^{-1}) emission lines. The redder He lines show a intermediate width emission component (FWHM $\approx$ 3000 km s^{-1}) similar to, but slightly wider than, that of SNe IIn (Filippenko 1997). As seen in Figure 2, the bluer He lines show narrow P Cygni profiles, with the absorption minimum blueshifted by roughly -1000 km s^{-1}. The emission components of the lines with P Cygni profiles are narrower (FWHM = 1000 km s^{-1}) than the pure emission components, presumably because their blueshifted emission is self-absorbed. The only discernible characteristic between the groups of lines with the two different types of line profiles is wavelength; in particular, the groups are not distinguished by singlet or triplet state. The line intensity ratios of the He I lines evolve with time, which may be an indication of changing densities or non-LTE effects.

The spectra all show a relatively flat continuum redward of ~5500 Å but a very steep blue continuum shortward of ~5500 Å, with a minimum $B - R$ color of -0.45 mag. We have identified a few isolated Fe II lines in the spectra of SN 2006jc (see Fig. 1), suggesting that there are many other Fe II lines, mostly at short wavelengths. It is likely that most of the apparent blue "continuum" consists of blended Fe lines. Turatto et al. (1993) suggested that Fe II emission lines create the excess blue continuum of SN 1988Z. The blending of the Fe lines makes disentangling the lines difficult, and detailed modeling is necessary to fully interpret our data. However, the amplitudes of the undulations in the blue continuum become larger with time, despite no significant change in the continuum shape. If the apparent continuum is the result of blended Fe lines, the increase of these amplitudes follows the expected result of Fe II lines increasing relative to the continuum (as seen with isolated Fe II lines).

There are still many features that we are unable to identify, most notably the feature centered at 6357 Å, which may be Si II λ6355, with FWHM $\approx$ 6200 km s^{-1}. This feature has some substructure and is wider than other emission lines, and thus is likely a blend of several lines. While most emission lines increase relative to the continuum with time, this feature decreases dramatically relative to the continuum and disappears by our November 23 spectrum, which is likely an excitation effect. Since the Fe II lines increase relative to the continuum with time, it is most likely some other element. The features at 7881 Å (somewhat blended with O I λ7774), 8215 Å, and 9360 Å exhibit the same behavior and width, and may be of the same species.

The slope of the blue continuum of SN 2006jc does not change much with time. The emission components of all He lines increase relative to the continuum with time, while some

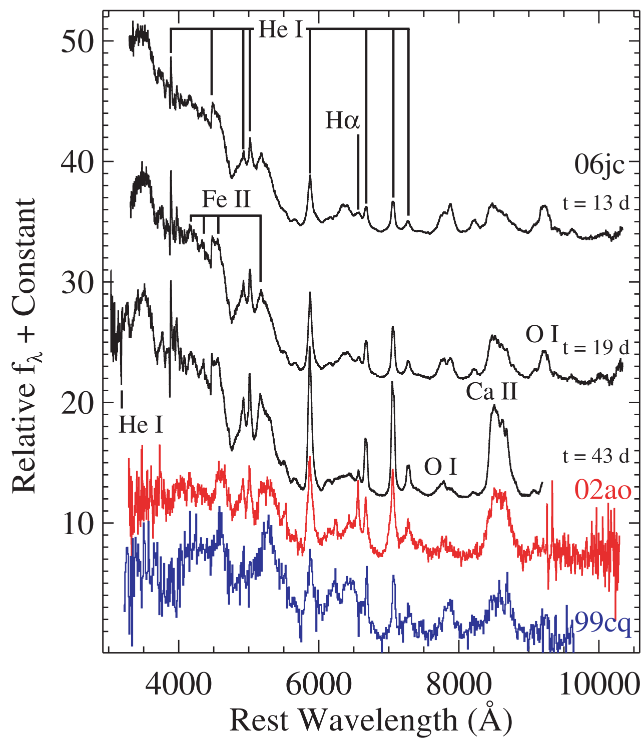

FIG. 1.—Spectra of SN 2006jc with some line identifications. The black curves are SN 2006jc (from top to bottom, the spectra were obtained on 2006 October 24.5, October 30.6, and November 23.6; dates shown are relative to our first photometric observations); the red curve is SN 2002ao obtained on 2002 February 21.5, corresponding to t = 27 days (all dates relative to our first photometric observation, which, as seen in Fig. 3, should be close to maximum brightness) with the Lick 3 m telescope; and the blue curve is SN 1999cq (Matheson et al. 2000a) at t = 20 days. A recession velocity of 1670 km s^{-1} (Nordgren et al. 1997), 1539 km s^{-1} (Koribalski et al. 2004), and 8200 km s^{-1} (Matheson et al. 2000a) has been removed from the spectra of SNe 2006jc, 2002ao, and 1999cq, respectively. The He I, Fe II, and Ca II emission lines of SN 2006jc increase relative to the continuum with time. The blue continuum increases relative to the red continuum with time. SN 2006jc is similar to SNe 2002ao and 1999cq. The main difference is the very blue continuum of SN 2006jc as well as a few lines, most notably the line at ~6355 Å. However, the continuum differences are likely the result of reddening for SNe 2002ao and 1999cq, while the line differences may reflect the observations being obtained at slightly different epochs.

[1] The Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation (NSF).

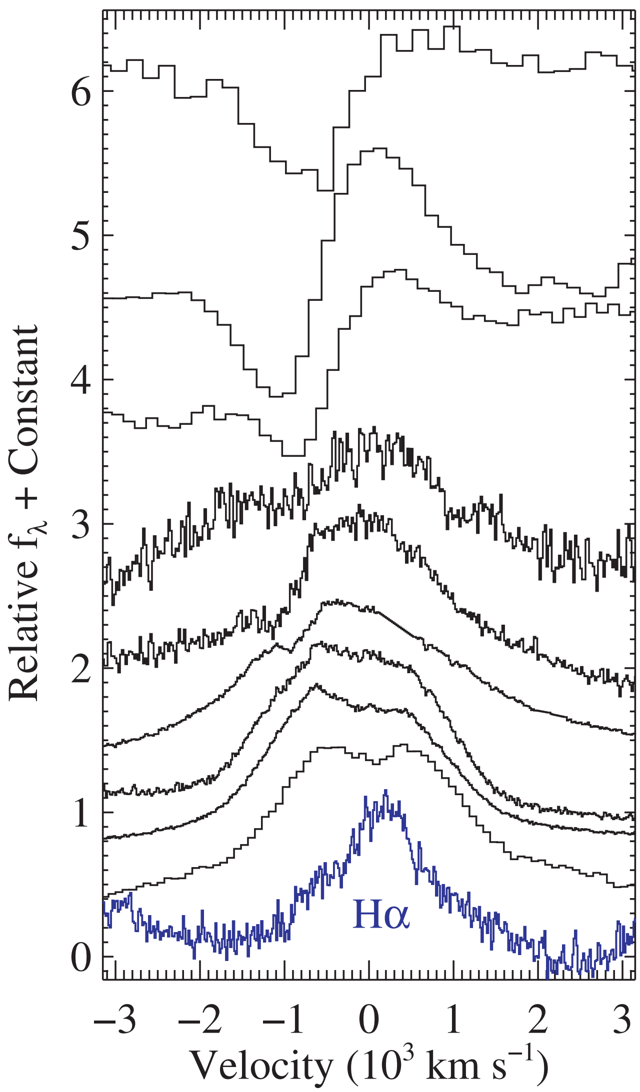

FIG. 2.—He I lines of SN 2006jc from 2006 November 23 (lower resolution) and November 24 (higher resolution). The lines from top to bottom are He I λ3188, λ3889, λ4471, λ4922, λ5016, λ5876, λ6678, λ7065, λ7281, and a line (in blue) we identify as likely Hα. The lines with $\lambda < 4900$ Å exhibit P Cygni profiles. The He I lines with $\lambda > 4900$ Å have broad peaks, with He I λ7281 showing a double-peaked profile. The Hα profile is much narrower than that of the He I lines.

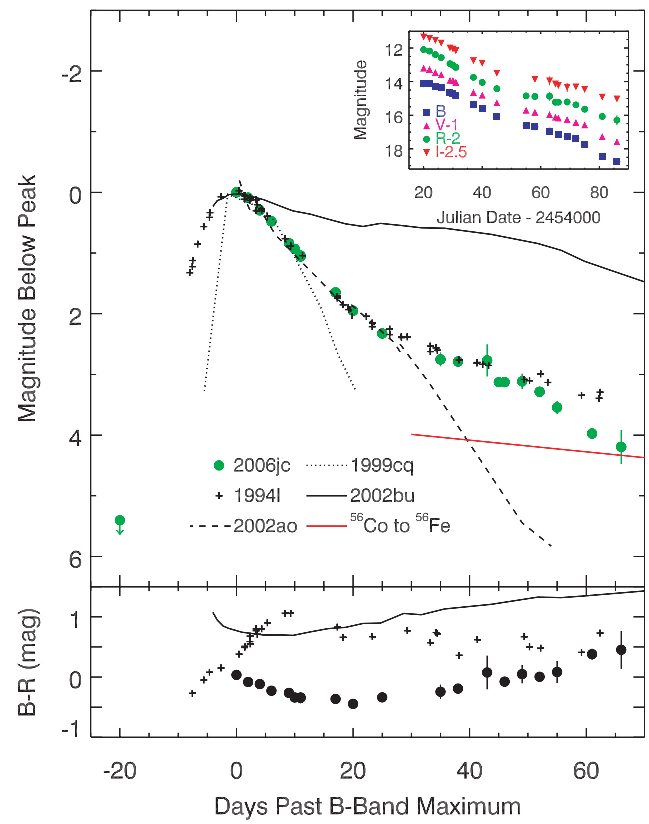

FIG. 3.—*Top large panel*: *R*-band light curve of SN 2006jc with comparison light curves of SNe 1994I (Ic), 1999cq, 2002ao, and 2002bu (IIn). The light curve of SN 2002bu is very different from the others, having a slower rise and decline, and a slight plateau. All other light curves appear similar for ∼10 days past *R* maximum, after which SN 1999cq declines much faster than the other three. At ∼25 days, SNe 2006jc and 1994I slow their decline, while SN 2002ao continues its decline. At ∼55 days, SN 2006jc begins a faster decline, separating from SN 1994I. Arkharov et al. (2006) note a brightening in *JHK* from days ∼30 to 55, corresponding to the plateau in the *R* band. The expected light curve from ^{56}Co decay, corresponding to 0.0098 mag day^{-1}, is plotted as the solid red line. *Inset*: *BVRI* light curves of SN 2006jc. The SN declines rapidly with $\Delta m_{15}(B) = 1.14$. The early (late) decline rates are 0.088 (0.100), 0.087 (0.092), 0.099 (0.066), and 0.092 (0.054) mag day^{-1} for *B*, *V*, *R*, and *I*, respectively. *Bottom panel*: $B - R$ color curve of SN 2006jc with comparison curves of SNe 1994I (Ic) and 2002bu (IIn). SN 2006jc is very blue with $B - R = -0.45$ mag on JD 2,454,040.

other species, including O I, decrease with time. The Ca II IR triplet also increases with time, consistent with other SNe. The evolution of the blue continuum is apparent in Figure 3. The *B*-band light curve declines more slowly than the other bands, which is unusual for a SN light curve. This supports the argument that the blue continuum is the result of a process not typically seen in SNe.

SN 2006jc has maximum absolute magnitudes of −17.8, −17.7, −17.8, and −18.1 for *B*, *V*, *R*, and *I*, respectively, making it as luminous as SN 1994I (Richmond et al. 1996). Assuming that nearly all of its luminosity comes from ^{56}Ni to ^{56}Co to ^{56}Fe decay, the fact that SNe 1994I and 2006jc have similar luminosities suggests they created similar ^{56}Ni masses, ∼0.07 $M_\odot$ (Nomoto et al. 1994).

The early-time decline rates of SNe 2006jc, 2002ao, and 1999cq are much faster than those of normal SNe IIn (see Fig. 3 for a comparison to SN IIn 2002bu). The early light curves of SNe IIn are powered mainly by circumstellar interaction, and their slow declines at early times indicate a massive CSM. Despite showing obvious features of circumstellar interaction in their spectra, SNe 2006jc, 2002ao, and 1999cq all decline very quickly, suggesting an extremely dense but low-mass and clumpy CSM. The late-time decline rates of these objects are also very fast, indicating either a small ^{56}Ni mass or a small ejecta mass.

4. DISCUSSION

4.1. *Wolf-Rayet Progenitor in a Dense,* He-*rich CSM*

The strength of the intermediate width He I emission lines in SN 2006jc relative to other SNe Ib is indicative of a dense CSM rich in He. Similar to the H lines seen in SN IIn spectra, the He lines of SN 2006jc are the result of the SN ejecta interacting with a dense CSM. The He I lines seen only in emission have FWHM ≈ 2000–3000 km s^{-1}, and the absorption minimum of the P Cygni profiles is ∼1000 km s^{-1}, velocities typical of W-R winds (Abbott & Conti 1987). The identification of Hα suggests that the progenitor recently ejected material containing at least some H into its surroundings, perhaps meaning that the progenitor recently evolved from a LBV to a WNE W-R star (Abbott & Conti 1987). Additionally, the smaller width of the Hα line is consistent with a different ejection mechanism from that of the He. LBVs typically have slower expansion speeds than W-R stars, indicating that the H might have been ejected during the LBV stage, while the He was ejected during the W-R stage. Matheson et al. (2000a) did not see any Hα in the spectrum of SN 1999cq, but the low signal-to-noise ratio of the spectrum makes the measurement ambiguous. The spectrum of SN 2002ao does show relatively strong Hα (see Fig. 1), suggesting that its CSM contains more H than that of SN 2006jc.

As noted by Nakano et al. (2006), there was a bright ($M = -14.0$ mag) outburst coincident with the position of SN 2006jc in October of 2004, which was initially thought to be an LBV outburst similar to SN 1961V (Goodrich et al. 1989). Unless it was a mere coincidence, it seems that the progenitor of SN 2006jc suffered an event analogous to the nonterminal eruptions of LBVs shortly before final core collapse, ejecting a He-rich shell with which the SN ejecta are now interacting. The short time between these events may have far-reaching implications for the late evolution of massive stars, beyond what we can discuss here; however, it is worth noting that Chugai et al. (2004) determined that Type IIn SN 1994W had an outburst ~1.5 yr prior to explosion. Equally surprising is that this type of event may have happened in a star inferred to be a WN star; while such outbursts are known to occur in LBVs that still have their H envelopes, no such variability has been documented in WN stars. It may hint that the progenitor of SN 2006jc had just recently transitioned from the LBV to the WN stage, supporting the notion that LBV mass loss facilitates the onset of the W-R phase. This would seem consistent with the presence of H in its CSM.

4.2. *Blue Continuum*

The slow *B*-band decline relative to the *R* band, the steep blue continuum, and the P Cygni profiles for He I all suggest that the emission at wavelengths shorter than ~5500 Å arises from a mechanism that is different from that which produces the red continuum. We identified some isolated Fe II lines, suggesting that many other Fe II lines are present in the spectrum but are blended and appear as a pseudocontinuum because of their large line widths. Since we do not see other high-excitation lines, this emission might be provided by fluorescence and not collisional excitation.

Matheson et al. (2000a) noted that SN 1999cq had a bluer continuum than normal SNe Ic. They also noted that SN 1999cq had $E(B-V) \lesssim 0.45$ mag and argued that $E(B-V) \lesssim 0.25$ mag. Similarly, SN 2002ao may be extinguished. Correcting for reasonably small reddening, the continua of both SNe 1999cq and 2002ao have similar colors to that of SN 2006jc, indicating that these events may also have a strong blue continuum. The main difference between the spectra is the strong Ca II H and K absorption in SN 1999cq.

4.3. *Aspherical Geometry*

The double-peaked nature of some He I lines suggest a complex, asymmetric CSM. Unlike SNe IIn, the light curve of SN 2006jc declined very quickly, suggesting that there is little mass in the CSM. However, the strong emission lines indicate a very dense CSM. These facts are compatible if the CSM is asymmetric or clumpy. Also, the P Cygni profiles seen only for the blue He I lines also indicate asymmetry, because the blue continuum is absorbed by the He gas, whereas the red continuum (presumably from the inner SN debris) is not.

A simple way to explain these observables is supernova ejecta interacting with a bipolar CSM, which causes the double-peaked nature of the He lines. The He-rich CSM, which was likely the result of the recent (2004) outburst, may be asymmetric because of either rapid rotation in the progenitor or strong interaction with a binary companion.

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Facilities: KAIT, Nickel, Shane (Kast Double spectrograph), Keck:I (LRIS), Keck:II (DEIMOS).

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