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SWIFT AND CHANDRA DETECTIONS OF SUPERNOVA 2006jc: EVIDENCE FOR INTERACTION OF THE SUPERNOVA SHOCK WITH A CIRCUMSTELLAR SHELL

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ABSTRACT

The peculiar Type Ib supernova (SN) 2006jc has been observed with the UV/Optical Telescope (UVOT) and X-Ray Telescope (XRT) on board the *Swift* observatory over a period of 19–183 days after the explosion. Signatures of interaction of the outgoing SN shock with dense circumstellar material (CSM) are detected, such as strong X-ray emission ($L_{0.2-10} > 10^{39}$ erg s^{-1}) and the presence of Mg II 2800 Å line emission visible in the UV spectra. In combination with a *Chandra* observation obtained on day 40 after the explosion, the X-ray light curve is constructed, which shows a unique rise of the X-ray emission by a factor of ∼5 over a period of ∼4 months, followed by a rapid decline. We interpret the unique X-ray and UV properties as a result of the SN shock interacting with a shell of material that was deposited by an outburst of the SN progenitor 2 years prior to the explosion. Our results are consistent with the explosion of a Wolf-Rayet star that underwent an episodic mass ejection qualitatively similar to those of luminous blue variable stars prior to its explosion. This led to the formation of a dense (∼10^7 cm^{-3}) shell at a distance of ∼10^{16} cm from the site of the explosion, which expands with the WR wind at a velocity of 1300 ± 300 km s^{-1}.

Subject headings: circumstellar matter — supernovae: individual (SN 2006jc) — X-rays: general —
X-rays: individual (SN 2006jc) — X-rays: ISM — ultraviolet: ISM

Online material: color figures

1. INTRODUCTION

SN 2006jc was discovered on 2006 October 9.75 (all times are UT) with an apparent magnitude of 13.8 in unfiltered CCD exposures (Nakano et al. 2006). No object was visible at the position of the SN on 2006 September 22 (limiting magnitude 19.0). Subsequent observations showed that the SN was around peak at the time of discovery (October 10.33: unfiltered mag-

nitude 13.8 [Nakano et al. 2006]; October 13.67: *Swift V*-band magnitude 14.3 [Brown et al. 2006]). Throughout this Letter we adopt an estimated explosion date around September 25 (±5 days). Approximately 2 years earlier (2005 October) a variable object (∼18 mag) was discovered close to the position of SN 2006jc (≲0.3″ offset; Pastorello et al. 2007) which is thought to be associated with SN 2006jc.

Type Ib/c SNe (see Filippenko 1997 for a review) are the result of the core collapse of a hydrogen-deficient, massive star (e.g., a Wolf-Rayet star); its outer layers were stripped by either mass transfer to a companion or by a strong stellar wind. Spectra of SNe Ib suggest that the progenitors have lost most of the H envelope, while progenitors of SNe Ic have lost the H layer and much of the He layer. The gas lost from the progenitors can be shock heated by the outgoing SN shock, giving rise to nonthermal radio, UV, and thermal X-ray emission.

In this Letter we present and discuss the optical, UV (with emphasis on the UV grism data), and X-ray emission properties of the peculiar Type Ib SN 2006jc as observed by *Swift*, and X-ray emission as observed by *Chandra*. A distance of 24 Mpc is adopted throughout the Letter ($z = 0.00557$; Nordgren et al. 1997). A more detailed discussion of the near-IR/optical/UV light curve of SN 2006jc will be presented in a separate study.

2. OBSERVATIONS

2.1. *Swift UVOT Optical/UV Observations*

The Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005) and X-Ray Telescope (XRT; Burrows et al. 2005) on board the *Swift* observatory (Gehrels et al. 2004) began observing SN 2006jc on 2006 October 13.67. The HEASOFT[17]

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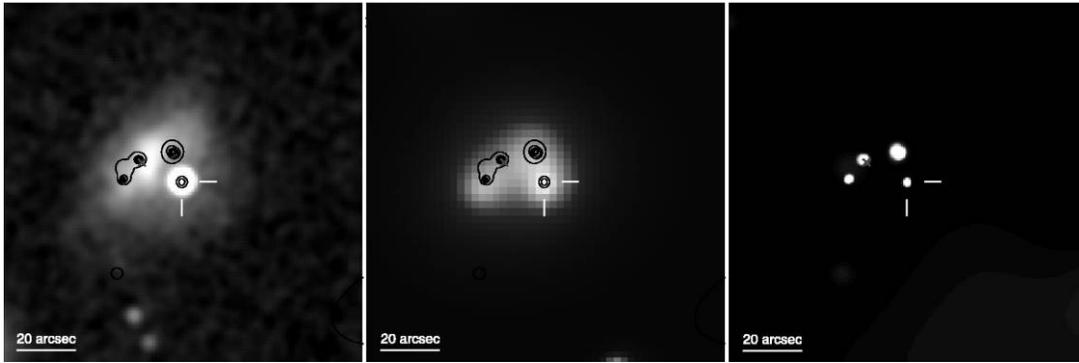[17] See http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/.

FIG. 1.—*Swift* UVOT optical (*left*), XRT X-ray (*middle*), and *Chandra* X-ray (*right*) images of SN 2006jc and its host galaxy UGC 4904. *Left*: The *Swift* optical image was constructed from the UVOT *V* (288 s exposure time; *red*), *B* (357 s; *green*), and *U* (432 s; *blue*) filters obtained on 2006 October 16. The optical position of SN 2006jc (Nakano et al. 2006) is indicated by white tick marks; the nucleus of the host galaxy is marked by a blue cross. The size of the image is $2' \times 2'$. *Middle*: X-ray image (0.2–10 keV band) from the merged 150 ks *Swift* XRT data obtained between 2006 October 13 and 2007 March 3. The image is adaptively smoothed to archive a signal-to-noise ratio (S/N) in the range 2.5–4. *Right*: The 0.2–10 keV X-ray image was constructed from the 10.0 ks *Chandra* ACIS data obtained on 2006 November 4 and is adaptively smoothed to archive a S/N in the range 2.5–4. The contour levels (0.01, 0.1, 1, 10, and 100×10^{-4} counts pixel^{-1}) are overlaid in black on the *Swift* optical and X-ray images. [*See the electronic edition of the Journal for a color version of this figure.*]

(ver. 6.3) and *Swift* Software (ver. 2.7, build 21) tools and latest calibration products were used to analyze the data.

The SN was detected with UVOT at $\alpha = 9^{\mathrm{h}}17^{\mathrm{m}}20.81^{\mathrm{s}}$, $\delta = +41°54'32.9''$ (equinox J2000.0), consistent with the position reported by Nakano et al. (2006), with magnitudes of $V = 14.3$, UVW1 (216–286 nm FWHM) = 13.2, UVM2 (192–242 nm) = 13.5, and UVW2 (170–226 nm) = 13.7. Statistical and systematic errors are 0.1 mag each.

Forty-eight individual exposures were obtained between 2006 October 13.67 and 2007 March 3.28. Assuming an explosion date of 2006 September 25, the observations correspond to days 19–183 after the explosion. A *Swift* *V*-, *B*-, and *U*-filter image of SN 2006jc and its host galaxy UGC 4904 (Hubble type SB; NED) is shown in the left-hand panel of Figure 1.

2.2. *Swift Grism Observations*

The UVOT includes two grisms which operate in the visible and UV bands. The UV grism has a nominal wavelength range of 1800–2900 Å, while the *V* grism has a wavelength range of 2800–5200 Å. We obtained three UV grism and three *V* grism spectra of SN 2006jc. Due to contamination from the
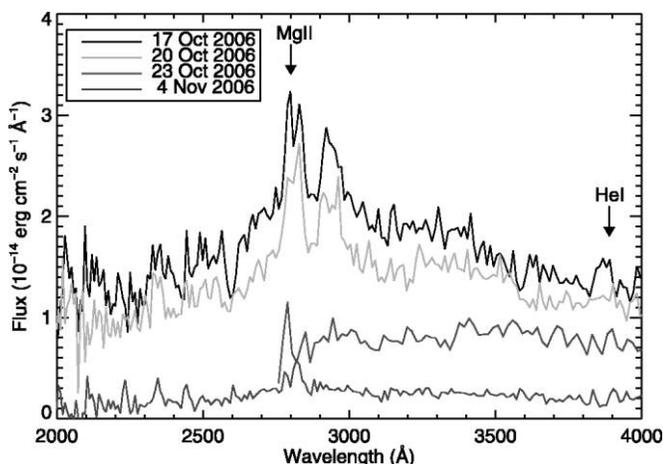

FIG. 2.—*Swift* grism observations of SN 2006jc obtained on 2006 October 17 (UV grism), 20 (UV), 23 (*V*), and November 4 (UV), corresponding to days 21, 25, 28, and 40 after the explosion. [*See the electronic edition of the Journal for a color version of this figure.*]

host galaxy and bright stars in the field we only use three uncontaminated UV (days 21, 25, and 28 after the explosion) and one *V* grism spectrum (day 40) in this study. The wavelength has an uncertainly of up to 20 Å, caused by uncertainties in the dispersed zeroth-order spectrum scale. The UVOT UV grism range is nominally 1800–2900 Å, but extends up to 4900 Å with a lower sensitivity than the *V* grism and the possibility of contamination by the second-order overlap. We therefore selected a wavelength range from 2000 to 4000 Å. The extracted spectra, shown in Figure 2, were smoothed using a running average of 3 points (~8 Å). The synthetic magnitudes, measured by folding the spectra through the UVOT UVW1 filter transmission curve, match the photometric magnitudes within the uncertainties.

2.3. *Swift XRT Observations*

The *Swift* XRT observations were obtained simultaneously with the UVOT observations. X-ray counts were extracted from a circular region with a 3 pixel (7.2″) radius centered on the optical position of the SN. The background was extracted locally from a source-free region of radius 30″ to account for detector and sky background, and for diffuse emission from the host galaxy. The superior resolution *Chandra* image (see below) was smoothed to the larger point-spread function of the *Swift* XRT (15″ half-power diameter), and the XRT count rates were corrected for residual contamination with a nearby (10″) and variable X-ray source. A *Swift* XRT X-ray image of SN 2006jc and its host galaxy is shown in the middle panel of Figure 1.

2.4. *Chandra Observation*

A *Chandra* Advanced CCD Imaging Spectrometer (ACIS) Director's Discretionary Time (DDT) observation was performed on 2006 November 4.33 (PI Immler, sequence 500815), corresponding to day 40 after the explosion. CIAO[18] (ver. 3.4), FTOOLS[19] (ver. 6.3), and the latest *Chandra* calibration products were used to analyze the data. Inspection of the ACIS data for periods with a high particle background showed no contamination of the data, which resulted in a clean exposure time

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[18] See http://cxc.harvard.edu/ciao/.
[19] See http://heasarc.gsfc.nasa.gov/docs/software.html.

TABLE 1
X-Ray Observations of SN 2006jc

$t - t_0$ (1)	Instrument (2)	Exposure (ks) (3)	Rate (10^{-3}) (4)	f_X (10^{-14}) (5)	L_X (10^{39}) (6)	$\langle E \rangle$ (keV) (7)
40	ACIS	10.0	1.0 ± 0.3	0.8 ± 0.3	0.6 ± 0.2	5.0
19–50	XRT	34.6	0.3 ± 0.2	1.2 ± 0.8	0.8 ± 0.5	3.9
53–94	XRT	29.5	0.9 ± 0.2	3.3 ± 0.7	2.3 ± 0.5	3.4
98–126	XRT	31.2	1.5 ± 0.3	5.2 ± 1.0	3.6 ± 0.7	2.8
128–141	XRT	29.3	0.6 ± 0.2	2.0 ± 0.7	1.4 ± 0.5	2.5
143–159	XRT	29.1	0.5 ± 0.2	1.7 ± 0.7	1.2 ± 0.5	2.4
171–183	XRT	35.4	0.5 ± 0.2	1.5 ± 0.6	1.0 ± 0.4	2.3

Notes.—Col. (1): Days after the explosion of SN 2006jc (2006 September 25). Col. (2): Instrument used, *Chandra* ACIS or *Swift* XRT. Col. (3): Exposure time in units of ks. Col. (4): 0.2–10 keV net count rate in units of counts ks^{-1}. Errors are photon statistical 1 σ uncertainties. Col. (5): Unabsorbed (0.2–10 keV) X-ray flux in units of 10^{-14} erg cm^{-2} s^{-1}. Fluxes were converted from count rates using the HEASARC tool PIMMS (ver. 3.9e), a thermal plasma spectrum with a temperature from col. (7), and corrected for the Galactic foreground column density of $N_H = 1.45 \times 10^{20}$ cm^{-2} (Dickey & Lockman 1990). Col. (6): 0.2–10 keV X-ray band luminosity in units of 10^{39} erg s^{-1}. Col. (7): Mean energy of the X-ray photons. The mean energies of the photons in the *Chandra* ACIS and *Swift* XRT cannot be compared directly because of differences in instrument responses and possible contamination of the XRT data by nearby point sources.

of 10.0 ks. The *Chandra* ACIS image of the SN 2006jc field is given in the right-hand panel of Figure 1.

3. RESULTS AND DISCUSSION

3.1. *Optical/UV Emission*

SN 2006jc appears to be a peculiar object in the optical range with features similar to those of both Type IIn and Type Ib SNe (Foley et al. 2007; Pastorello et al. 2007; Smith et al. 2007). The intermediate-width He lines of SN 2006jc are similar to the narrow H lines seen in Type IIn SN spectra (Schlegel 1990; Chugai & Danziger 1994; Filippenko 1997) and can be understood as the result of an interaction between the outgoing SN shock and a dense, H+He-rich CSM. A strong Mg II emission line at 2800 Å and possibly Fe II (between 2900 and 3000 Å) and a He I 3889 Å emission line (seen more clearly in ground-based spectra) are visible in the *Swift* grism data (see Fig. 2). Each of the emission lines become weaker with time. The Mg II emission line might be strong as Mg II is one of the main coolants in the SN 2006jc shell. It is further over-
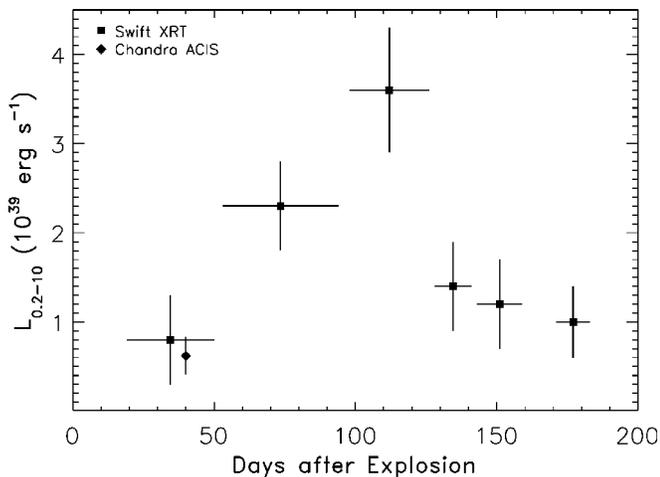

Fig. 3.—X-ray light curve (0.2–10 keV) of SN 2006jc as observed with the *Swift* XRT and *Chandra* ACIS-S instruments. The time is given in days after the outburst. Vertical error bars are statistical 1 σ uncertainties; horizontal error bars indicate the periods covered by the observations (which are not contiguous).

lapped by Mg II absorption from both Galactic and host-galaxy interstellar gas (Panagia et al. 1980). The most likely origin for the Mg II and He I emission lines is a UV-emitting shell consisting of gas originally ejected by the progenitor, likely associated with the luminous outburst found 2 years earlier.

The later *Swift* grism spectra (>25 days) are of lower quality but show how the continuum becomes fainter with time. The UV flux deficiencies of SNe stem from the cooling of the emitting region and from metal line blanketing (e.g., Hillier & Miller 1998).

3.2. *X-Ray Emission*

SN 2006jc is detected in X-rays both with *Swift* XRT and *Chandra* ACIS, at a luminosity of $\sim 10^{39}$ erg s^{-1} at an early epoch (<50 days). In order to study the temporal evolution of the X-ray emission with sufficient photon statistics, we binned the XRT data into six consecutive time intervals with exposure times around 30 ks each (see Table 1 and Fig. 3). An increase of the X-ray flux by a factor of ~ 5 within the first ~ 4 months after the explosion is observed. Such an increase in the X-ray flux is highly unusual for an X-ray-emitting SN.[20] Although the limited photon statistics does not allow a detailed spectral characterization of the emission, we inspected the energy distribution of all X-ray photons that were recorded within a radius of 3 XRT image pixels (7.2″) centered on the optical position of the SN. The mean energy per time bin (listed in col. [7] in Table 1) shows a clear softening of the X-ray emission.

A likely explanation for the brightening and subsequent fading in X-rays can be found in the history of the SN 2006jc progenitor: 2 years before the SN event, a bright outburst ($M = -14.0$ mag) was noted at the position of the SN (Nakano et al. 2006). Foley et al. (2007) and Pastorello et al. (2007) proposed that this outburst could have been the ejection of the outer layers of the progenitor in an outburst qualitatively similar to those experienced by luminous blue variables (LBVs; see Smith & Owocki 2006). The ejected shell would then be shock heated by the outgoing SN shock, giving rise to the observed increase in X-rays as the SN shock passes through the shell, followed by a decline of the X-ray emission as the shock leaves

[20] See http://lheawww.gsfc.nasa.gov/users/immler/supernovae_list.html for a complete list of X-ray SNe and references.

the shell. This scenario is supported by a softening of the X-ray emission over the observed period (see Table 1) as a result of the decreasing absorbing column density as the SN shock passes through the dense shell.

Our X-ray measurements further allow a characterization of the physical properties and geometry of the shell surrounding SN 2006jc (Fig. 4). If the X-rays are produced by the shock-heated shell, the X-ray peak at $t \approx 112$ days after the explosion corresponds to a distance of the shell from the site of the explosion of $r = v_{\text{shock}} \times t = 9 \times 10^{15}$ cm for a shock velocity of $v_{\text{shock}} = 9000$ km s^{-1} (consistent with the FWHM of broad emission lines visible in the optical spectra; Pastorello et al. 2007). The X-ray luminosity of a thermal plasma is the product of the emission measure and the plasma density within the emitting volume, $L_{\text{X}} = \Lambda(T)dVn^2$. For a shell with a thickness of $\Delta R \sim 2 \times 10^{15}$ cm (estimated from the FWHM of the X-ray rise and decline of $\Delta t \sim 60$ days and $\Delta R = \Delta t \times v_{\text{shock}}$), this can be rewritten as $L_{\text{X}} = 4\pi R^3(\Delta R/R)\Lambda(T)n^2$. An effective (0.2–10 keV band) cooling function of $\Lambda = 3 \times 10^{-23}$ erg cm^3 s^{-1} for an optically thin thermal plasma with a temperature in the range 10^6–10^8 K (Raymond et al. 1976) is adopted, which is consistent with the measured energies of the X-ray photons (see col. [7] in Table 1). Solving for the CSM number density of the shocked plasma, $n = \rho_{\text{csm}}/m$, where m is the mean mass per particle (2.2×10^{-24} g for a fully ionized pure He plasma), gives $n_{\text{csm}} \sim 10^7$ cm^{-3} inside the X-ray-emitting shell. This leads to an estimate of the X-ray-emitting mass that was lost by the progenitor system over the 2 years period prior to the explosion of ~ 0.01 $M_\odot$ (which represents a lower limit to the entire mass of the shell).

4. SUMMARY

The *Swift* and *Chandra* observations of the peculiar Type Ib SN 2006jc reveal that the progenitor had a remarkable evolution and environment. The presence of Mg II line emission and the rise of the X-ray emission over a period of ~ 4 months after the explosion, followed by a fast decline, are likely due to the presence of a dense shell of material around the site of the explosion. Our results clearly support the scenario proposed by Foley et al. (2007), Pastorello et al. (2007), and Smith et al. (2007) that SN 2006jc was the explosion of a Wolf-Rayet star in a dense environment which had a giant outburst before its core collapse (also see Pastorello et al. [2007] for a somewhat
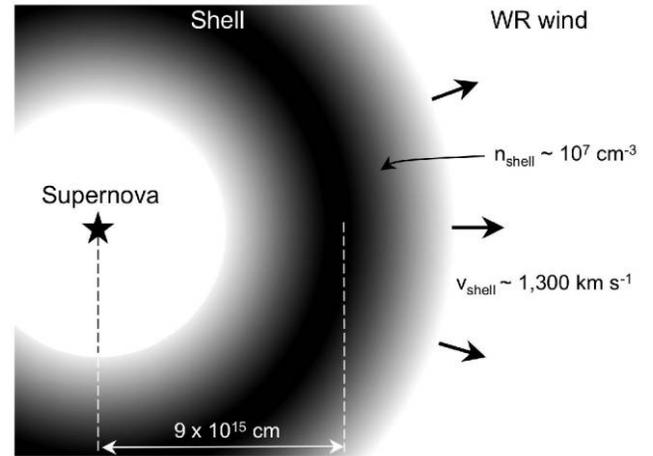

FIG. 4.—Illustration of the environment of SN 2006jc as inferred from the *Swift* and *Chandra* X-ray observations. The ejected shell is expanding at a speed of $v_{\text{shell}} = 1300 \pm 300$ km s^{-1} with the wind blown off by the WR progenitor. At the time of the X-ray peak, around day 112 after the explosion of SN 2006jc, when the SN shock has traveled through the shell, the shell has reached a distance of 9×10^{15} cm from the site of the explosion. The density within the shell is $\sim 10^7$ cm^{-3}.

different interpretation involving a binary system). The *Swift* and *Chandra* observations allow, for the first time, a characterization of the physical properties and geometry of such a LBV-like outburst. During the outburst, a total of >0.01 $M_\odot$ of the outer layers of the star was ejected into space at a speed of 1300 ± 300 km s^{-1}, and heated to UV and X-ray-emitting temperatures as the outgoing shock hit this layer at a distance of $\sim 10^{16}$ cm from the site of the explosion.

The extraordinary properties of SN 2006jc represent considerable theoretical challenges regarding the modeling of Type Ib/c SN photospheres when additional (and perhaps dominating) contributions from CSM interaction, especially cool dense shells between the ejecta and the pre-SN wind, have to be taken into account.

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