

SN 2006bp: PROBING THE SHOCK BREAKOUT OF A TYPE II-P SUPERNOVA¹

ROBERT M. QUIMBY,² J. CRAIG WHEELER,² PETER HÖFLICH,^{3,4} CARL W. AKERLOF,⁴
PETER J. BROWN,⁵ AND ELI S. RYKOFF⁴

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ABSTRACT

HET optical spectroscopy and unfiltered ROTSE-III photometry spanning the first 11 months since explosion of the Type II-P SN 2006bp are presented. The data suggest that the supernova was first detected just hours after shock breakout. Optical spectra obtained about 2 days after breakout exhibit narrow emission lines corresponding to He II $\lambda 4200$, He II $\lambda 4686$, and C IV $\lambda 5805$ in the rest frame. These emission features persist in a second observation obtained 5 hr later but are not detected the following night or in subsequent observations. These lines probably emanate from material close to the explosion site, possibly in the outer layers of the progenitor that have been ionized by the high-energy photons released at shock breakout. A P Cygni profile is observed around 4450 Å in the +2 and +3 day spectra. We propose that this line is due to He II $\lambda 4687$ rather than high-velocity H β , as previously suggested. Further HET spectra cover the evolution across the photometric plateau up to 73 days after breakout and during the nebular phase around day +340. Expansion velocities are derived for key features. The measured decay slope for the unfiltered light curve is 0.0073 ± 0.0004 mag day⁻¹ between days +121 and +335, which is significantly slower than the decay of rate ⁵⁶Co. We present a quasi-bolometric light curve through day +60. We see a slow cooling over the first 25 days but no sign of an early sharp peak; any such feature from the shock breakout must have lasted less than ~ 1 day.

Subject heading: supernovae: individual (SN 2006bp)

Online material: color figures

1. INTRODUCTION

Type II supernovae (SNe II) are explosions marking the deaths of massive stars with significant amounts of hydrogen still intact. They do not typically obtain the high peak luminosities or the uniformity exhibited therein by their thermonuclear cousins, the Type Ia events; however, what SNe II lack as intrinsic standard candles is compensated for by their relative limpidity: SNe II are easier to model, as the explosions do not involve steep chemical gradients, and the progenitors of a few events have been identified (see Li et al. 2007 for a recent example). SNe II hold the promise of serving as independent and perhaps absolute distance indicators (Kirshner & Kwan 1974; Shaviv et al. 1985; Höflich 1991; Schmidt et al. 1994; Hamuy & Pinto 2002; Baron et al. 2004; Nugent et al. 2006). In recent years several Type II-P supernovae (SNe II-P; where the “P” indicates a plateau phase in the light curve) discovered at early times have been observed and modeled in detail (SN 1999em: Baron et al. 2000, 2004; Hamuy et al. 2001; Leonard et al. 2002a; Elmhamdi et al. 2003; Baklanov et al. 2005; Dessart & Hillier 2006; SN 1999gi: Schlegel 2001; Leonard et al. 2002b; SN 2005cs: Pastorello et al. 2006; Tsvetkov et al. 2006; Brown et al. 2006; Baron et al. 2007). Polarization observations of SNe II-P have shown the outer, hydrogen-rich envelope to be rather spherical and that the polarization increases at late times, which can be understood in terms of asymmetric

excitation (Leonard et al. 2003; Höflich et al. 2001; Wang et al. 2001).

SNe II-P are thought to result from stars massive enough to ignite carbon ($>7-8 M_{\odot}$; Eldridge & Tout 2004) but light enough to avoid envelope-stripping winds ($<25 M_{\odot}$; Heger et al. 2003). These explosions begin after the energy release from nuclear activity in the core ceases to provide sufficient pressure to support the stellar interior and the core collapses under its own weight, most likely forming a neutron star. The processes by which the energy released in the collapse subsequently unbinds the envelope are still a matter of debate (Khokhlov et al. 1999), but neutrino interactions (Janka et al. 2006), shock instabilities (Blondin & Mezzacappa 2006), acoustic instabilities (Burrows et al. 2006), and magnetorotational effects (Akiyama et al. 2003) may each play a role.

Gravitational waves are emitted during the bounce-back phase and neutrinos escape moments later, but the electromagnetic signal is initially swallowed by the envelope. An outside observer would not detect any change in the light output by the star until the hydrodynamic front or the light front reached the photosphere, which could be up to 3 days after the explosion, depending on the extent of the progenitor’s envelope. The ensuing phase is known as the shock breakout and is manifest by a sudden, rapid increase in the radiated luminosity. The emergent spectrum will have its peak energy in the X-ray to UV bands, and this hard emission may ionize any circumstellar material or recent wind. The bolometric light curve will peak hours to days after breakout, before decreasing in an adiabatic free expansion phase to the plateau stage. During the plateau a cooling recombination wave recedes (in the mass frame) through the ejecta layers, and the balance of a slowly increasing photospheric radius with an effective temperature tied closely to the recombination temperature works to maintain the nearly constant plateau luminosity. After the photosphere has swept through the bulk of the envelope a nebular phase ensues, and the light curve fades exponentially, now powered predominantly by the decay of ⁵⁶Co.

¹ Based on observations obtained with the Hobby-Eberly Telescope, which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen.

² Department of Astronomy, University of Texas, Austin, TX 78712.

³ Department of Physics, Florida State University, Tallahassee, FL 32312.

⁴ Randall Laboratory of Physics, University of Michigan, Ann Arbor, MI 48104.

⁵ Astronomy and Astrophysics Department, Pennsylvania State University, University Park, PA 16802.

The generic observational consequences of a shock breakout were laid out by Falk & Arnett (1977). Thus far the only observations acquired during the breakout phase were for SN 1987A (a peculiar Type II), SN 1993J (a peculiar Type II/Ib hybrid), and SN 2006aj (a peculiar Type Ic related to GRB 060218; Campana et al. 2006), and the bulk of light-curve modeling in the past two decades has been focused on SN 1987A or models without extended photospheres or winds (Litvinova & Nadezhin 1985; Arnett 1989; Woosley 1988; Höflich 1991; Ensmann & Burrows 1992; Eastman et al. 1994; Blinnikov et al. 2000). While there is now good agreement found for the observations and models of the shock breaking out of SN 1987A's compact progenitor, little progress has been made in modeling the breakout through an extended envelope, which is the scenario expected for common SNe II-P. In particular, detailed, high-resolution calculations of the shock breakout, including the hydrodynamical, ionization, and light fronts expected in red supergiant atmospheres, are still lacking (Mair et al. 1992; Chieffi et al. 2003). Polarization observations indicate that differential runtime effects within the extended progenitor envelope are likely to be small (i.e., the shock front reaches the photosphere at a uniform time; Leonard et al. 2003; Höflich et al. 2001). As illustrated by Falk & Arnett (1977), the properties of the breakout peak depend on the envelope mass and especially the density structure of the outer layers. We may therefore gain a better understanding of the envelope structure of massive stars in their final years by studying the early-time light curves and spectra of SNe II-P.

An astute amateur astronomer, Koichi Itagaki of Yamagata, Japan, first identified SN 2006bp on unfiltered images of NGC 3953 taken with an 0.60 m f/5.7 reflector around April 9.60 UT (Itagaki et al. 2006). Itagaki observed the SN to brighten rapidly (about 0.9 mag in 4 hr), and he quickly made the discovery public (Nakano & Itagaki 2006). The host galaxy was observed frequently in the days prior to discovery by our Texas Supernova Search (Quimby 2006), resulting in prediscovery detections and stringent observational limits. Observations by the *Swift* satellite beginning April 10.54 revealed a fading X-ray source coincident with the explosion site, while observations by the Very Large Array (VLA) put an upper limit to the 22.46 GHz flux of <0.4 mJy on April 11.97 (Immler & Brown 2006; Kelley et al. 2006; Immler et al. 2007). We obtained an optical spectrum with the Hobby-Eberly Telescope (HET) on April 11.11, which showed SN 2006bp to be an early Type II event (Quimby et al. 2006).

In this paper we present photometric and spectroscopic observations and analysis of SN 2006bp. We begin with a description of the unfiltered optical ROTSE-III (Robotic Optical Transient Search Experiment) observations in § 2, including flux upper limits in the days leading up to shock breakout. The complete light curve is presented and analyzed in § 2.1, leading to an estimate of the shock breakout date. The spectral observations from the HET are detailed in section 3. Data from the first two nights are discussed in § 3.1, and the full spectral evolution is considered in § 3.2. We give an approximate reconstruction of the early-time quasi-bolometric light curve in § 4. Discussion and conclusions are presented in § 5.

2. PHOTOMETRY

We detected SN 2006bp as part of the Texas Supernova Search's nightly monitoring of the Ursa Major galaxy cluster (Quimby 2006) with the 0.45 m f/1.9 ROTSE-IIIb telescope (Akerlof et al. 2003) at the McDonald Observatory. The ROTSE-III telescopes gather unfiltered optical light; the approximate spectral

TABLE 1
ROTSE-III SENSITIVITY

Wavelength (Å)	Efficiency
3000.....	0.00
3500.....	0.09
4000.....	0.45
4500.....	0.67
5000.....	0.83
5500.....	0.84
6000.....	0.84
6500.....	0.82
7000.....	0.78
7500.....	0.71
8000.....	0.57
8500.....	0.40
9000.....	0.28
9500.....	0.16
10000.....	0.07

NOTES.—Approximate spectral response for ROTSE-III not including atmospheric losses. The values have not been empirically measured, but were instead calculated based on the typical CCD and optical element efficiencies. Additional losses due to degradation of the optical elements over time are not taken into account.

response is given in Table 1. The SN is located in the overlap of three of our search fields, and typically two of these fields were covered in the nights leading up to the discovery. On April 9.15, the SN was formally detected by the image subtraction pipeline at the 4.8σ level in both of the fields covered that night, but these detections were still below the 5σ threshold adopted for the automatic candidate-filtering procedure used to limit spurious events, and so the SN was not identified as a possible supernova until the following night. Beginning on April 11, we obtained additional unfiltered images centered on SN 2006bp with both ROTSE-IIIb and ROTSE-IIIc, the latter located at the Turkish National Observatory in Bakiritepe, Turkey. All images were flat-fielded and dark-subtracted using the standard ROTSE-III image processing pipeline (Rykoff 2005). The ROTSE-III instruments have a $1.85^\circ \times 1.85^\circ$ field of view; however, the point-spread function (PSF) varies significantly across the frame, as can the instrumental zero point under nonphotometric conditions. We therefore selected $30' \times 30'$ subframes centered on the SN for the final photometry.

Although we have a number of reference images taken prior to the explosion of SN 2006bp in each of the three search fields, in each case the location of the SN appears near the edge of the field, where the image quality is at its worst, and there is very little overlap between the fields. Lacking a quality reference image, we decided to construct a reference template using the best post-explosion images available following the general procedure of Li et al. (2003). Briefly, we co-added 44 ROTSE-IIIb images acquired at various phases of the explosion, empirically measured the PSF, and then subtracted the scaled PSF to remove the SN light. We were able to test the resulting template by subtracting it from the images taken prior to the SN explosion. No significant positive or negative residual was found on these subtracted frames, which validates the template (referred to hereafter as “REF”). Because the PSF on the REF is superior (much sharper) than is obtained from the preexplosion images, this greatly improves our ability to convolve the template to match the delivered PSF on a given night, and we are able to use the same template for all of the available images. This procedure allows for better and more

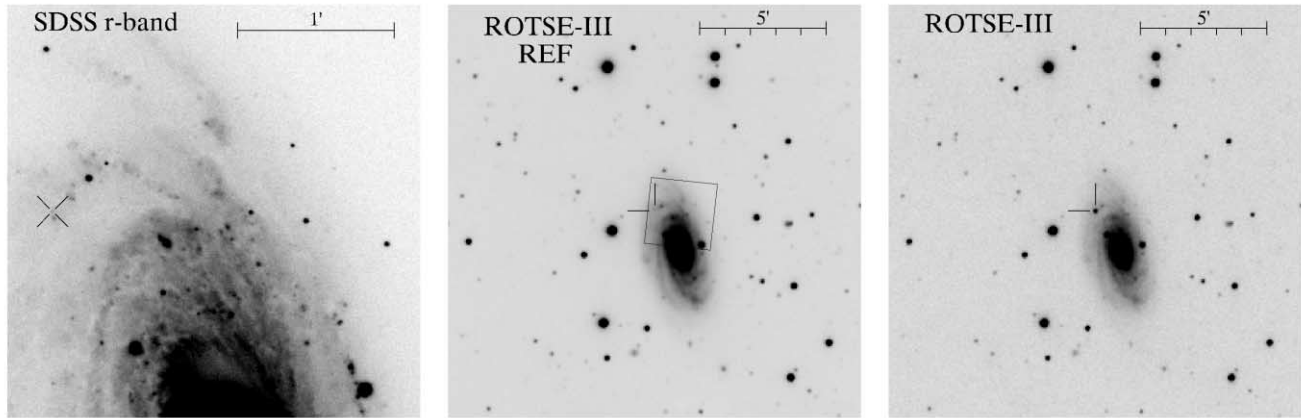


FIG. 1.—Finding chart for SN 2006bp. The middle image shows the ROTSE-III reference template, which was constructed from postexplosion data, as explained in the text. The box marks the overlap with the detail of the SDSS r -band data shown in the left image. The location of the SN is marked with a cross. The image on the right shows the SN as it appeared in ROTSE-IIIb data from May 23 (near the middle of the plateau). North is up and east is to the left in each image.

consistent measurements of the SN flux on the template subtracted frames. The template is shown in Figure 1.

To determine the flux evolution of SN 2006bp, we first made separate co-additions for each unique night/field/telescope combination. In doing so, we only used the best images available, defined to be those images with detections for at least 80% of all the objects found on the deepest frame in that set. We median-filtered the individual images and masked bad pixels to create the co-added image (hereafter NEW). If any of the pixels within 1 FWHM of the SN position was masked, the image was removed from the NEW.

We performed PSF-matched image subtraction of the REF from the NEWs using a modified version of the Supernova Cosmology Project code. A selection of isolated, pointlike objects was chosen to serve as field standards (REFSTARS). The local PSF was first measured empirically on the REF and on each NEW using the REFSTARS, and this template was then fit to each REFSTAR to determine the PSF-fit flux and later the scaling between the REF and the NEWs. The local sky bias was found in annuli of 2–6 times the FWHM and removed prior to PSF fitting with the DAOPHOT routines (Stetson 1987; ported to IDL by Landsman 1989). We calibrated the magnitude scale on the REF, and thereby all the data, via the USNO-B1.0 R2 magnitudes for the REFSTARS. The convolved REF was subtracted from the scaled NEWs to generate subtracted frames (SUBs), and the PSF template measured on the NEWs was then fit on the SUBs to find the SN flux. Although we only considered a $30' \times 30'$ region centered on the SN, some variation in the PSF was noted across the subframes, and we decided to use a spatially varying kernel, as described by Alard (2000), which did render improved results. Limiting magnitudes were calculated for a 1 FWHM radius aperture from the noise measured in the sky annuli. The photometric observations and calculated magnitudes are detailed in Table 2.

As we first registered the individual images in the NEWs to the REF, after the image subtraction we obtained multiple, semi-independent measurements of the SN position on the REF. To determine the equatorial position of the SN, we matched the REFSTARS to the USNO-B1.0 and solved for the transformation coefficients. SN 2006bp is located at $\alpha = 11^{\text{h}}53^{\text{m}}55.74^{\text{s}}$, $\delta = +52^{\circ}21'09.7''$ (J2000.0), with an estimated error of $0.2''$ in each coordinate. We found the location of the SN on a preexplosion SDSS r -band frame by directly matching it to the REF and then transforming the SN position to the SDSS frame. As shown

in Figure 1, the SN was found coincident with a red knot in an outer spiral arm of NGC 3953, and just to the north of a possible H II region.

2.1. ROTSE-III Light Curve

The unfiltered light curve of SN 2006bp is shown in Figure 2. ROTSE-III data are plotted as filled circles, and open squares are used to mark the discovery photometry from Nakano & Itagaki 2006. Because this object is located in the overlap of three of our search fields, we typically have at least two observations per night covering the position of SN 2006bp in the weeks leading up to its discovery. We can therefore rule out any bright optical emission prior to our first detection, as might be expected from the ejecta colliding with a dense stellar wind, energy released from the shock breakout, or a thermal wave precursor (see Nadyozhin 2003 and references therein).

The PSF-fit flux and 4σ upper limits of SN 2006bp between 2006 March 20 and April 29 are shown relative to the peak flux in Figure 3. Given the initial rapid increase in flux, it is safe to assume that SN 2006bp was detected soon after the explosion shock emerged from the progenitor envelope; however, detailed modeling tuned to the observations is required to accurately pinpoint the moment of core collapse and the subsequent shock breakout. Here we estimate the date of shock breakout from the early ROTSE-III flux upper limits and the detections on the first two nights. We modeled the early light curve as

$$F(t) = \begin{cases} 0 & \text{for } t \leq t_0, \\ A(t - t_0)^2 & \text{otherwise} \end{cases} \quad (1)$$

and performed a least-squares fit to determine the date of shock breakout, t_0 . The fit is plotted as the curve in Figure 3 (note that we fit the model to the flux measured in 1 FWHM circular apertures instead of the PSF-fit fluxes, which are not statistically accurate for low-significance or nondetections, although the PSF-fit detections are shown in the figure). Under the simplistic assumption of a quadratic rise, the best-fit date for the shock breakout is 2006 April 8.7. The figure shows an inflection point in the data around April 10, and extending the fitting range beyond this date results in an unacceptably large χ^2 , which indicates the model assumptions are not valid over longer periods. Lacking the true functional form for the shock breakout light curve in our unfiltered band pass, we have chosen to reference all phases in this work

TABLE 2
ROTSE-III OBSERVATIONS OF SN 2006bp

Instrument ^a	Phase ^b	Date	Exposure (s)	C_R	σ_{C_R}	Limit ^c
3b.....	-18.8	2006 Mar 21.152	3 × 20	...	...	18.37
3b.....	-18.8	2006 Mar 21.154	4 × 20	...	...	18.54
3b.....	-17.9	2006 Mar 22.148	3 × 20	...	...	17.75
3b.....	-15.6	2006 Mar 24.396	4 × 20	...	...	16.06
3b.....	-14.9	2006 Mar 25.135	4 × 20	...	...	18.37
3b.....	-14.9	2006 Mar 25.142	4 × 20	...	...	18.44
3b.....	-13.9	2006 Mar 26.134	4 × 20	...	...	17.72
3b.....	-9.9	2006 Mar 30.132	3 × 20	...	...	18.03
3b.....	-9.9	2006 Mar 30.137	2 × 20	...	...	17.60
3b.....	-8.7	2006 Mar 31.295	4 × 20	...	...	18.44
3b.....	-2.6	2006 Apr 6.373	4 × 20	...	...	16.80
3b.....	-2.6	2006 Apr 6.382	2 × 20	...	...	17.08
3b.....	-1.6	2006 Apr 7.370	1 × 20	...	...	17.43
3b.....	-1.6	2006 Apr 7.379	4 × 20	...	...	18.10
3b.....	-0.8	2006 Apr 8.176	1 × 20	...	...	16.49
3b.....	-0.8	2006 Apr 8.177	2 × 20	...	...	17.19
3b.....	0.1	2006 Apr 9.147	4 × 20	17.75	0.19	17.97
3b.....	0.2	2006 Apr 9.151	4 × 20	17.50	0.18	17.69
3b.....	1.1	2006 Apr 10.149	4 × 20	15.44	0.03	17.65
3b.....	1.2	2006 Apr 10.152	4 × 20	15.44	0.05	17.47
3d.....	2.1	2006 Apr 11.058	5 × 20	15.29	0.07	17.43
3b.....	2.1	2006 Apr 11.115	3 × 20	15.14	0.04	17.72
3b.....	2.1	2006 Apr 11.134	4 × 20	15.14	0.05	17.40
3d.....	2.8	2006 Apr 11.751	4 × 20	15.11	0.06	16.97
3b.....	4.1	2006 Apr 13.116	3 × 20	14.88	0.03	17.65
3b.....	6.1	2006 Apr 15.139	6 × 20	14.75	0.03	18.24
3b.....	7.2	2006 Apr 16.202	3 × 20	14.73	0.02	17.71
3d.....	7.8	2006 Apr 16.808	4 × 60	14.74	0.02	18.50
3d.....	8.8	2006 Apr 17.798	3 × 60	14.76	0.03	17.47
3b.....	9.1	2006 Apr 18.120	3 × 20	14.69	0.03	18.34
3d.....	11.8	2006 Apr 20.822	8 × 60	14.82	0.03	19.14
3d.....	12.8	2006 Apr 21.792	5 × 60	14.87	0.02	18.80
3d.....	14.1	2006 Apr 23.103	7 × 60	14.85	0.04	18.14
3b.....	16.1	2006 Apr 25.124	3 × 20	14.73	0.03	18.51
3d.....	17.8	2006 Apr 26.785	8 × 60	14.82	0.02	18.67
3b.....	21.2	2006 Apr 30.190	9 × 20	14.77	0.02	19.12
3b.....	22.2	2006 May 1.231	6 × 20	14.78	0.02	18.89
3d.....	23.1	2006 May 2.074	5 × 60	14.81	0.04	18.74
3d.....	26.0	2006 May 4.994	6 × 60	14.82	0.02	18.67
3b.....	26.2	2006 May 5.152	6 × 20	14.79	0.03	18.59
3b.....	27.2	2006 May 6.153	6 × 20	14.80	0.02	18.46
3d.....	27.9	2006 May 6.905	1 × 60	14.92	0.07	16.44
3b.....	28.3	2006 May 7.253	3 × 20	14.75	0.03	17.77
3b.....	29.2	2006 May 8.181	3 × 20	14.78	0.03	17.20
3b.....	30.2	2006 May 9.170	6 × 20	14.85	0.04	18.29
3d.....	30.8	2006 May 9.837	8 × 20	14.86	0.03	17.85
3b.....	31.2	2006 May 10.150	5 × 20	14.79	0.03	17.85
3b.....	32.2	2006 May 11.176	5 × 20	14.79	0.03	17.65
3b.....	33.1	2006 May 12.135	3 × 20	14.81	0.03	17.65
3b.....	34.2	2006 May 13.238	3 × 20	14.85	0.04	17.53
3d.....	34.9	2006 May 13.874	8 × 20	14.91	0.04	17.92
3b.....	35.2	2006 May 14.195	2 × 20	14.77	0.05	16.66
3d.....	35.8	2006 May 14.833	12 × 20	14.88	0.03	18.30
3d.....	36.8	2006 May 15.793	4 × 60	14.96	0.03	18.78
3b.....	38.2	2006 May 17.160	6 × 20	14.91	0.03	18.87
3d.....	38.9	2006 May 17.869	8 × 60	14.92	0.02	18.79
3b.....	39.2	2006 May 18.160	6 × 20	14.93	0.03	19.07
3d.....	40.0	2006 May 18.950	4 × 60	14.98	0.04	18.28
3b.....	40.1	2006 May 19.140	3 × 20	14.99	0.02	18.48
3d.....	40.8	2006 May 19.823	11 × 60	14.94	0.03	18.96
3b.....	41.2	2006 May 20.162	6 × 20	14.99	0.04	18.98
3d.....	41.8	2006 May 20.827	12 × 60	14.95	0.02	18.85
3b.....	42.2	2006 May 21.184	3 × 20	14.98	0.04	18.74
3d.....	42.9	2006 May 21.921	7 × 60	14.97	0.02	18.91

TABLE 2—Continued

Instrument ^a	Phase ^b	Date	Exposure (s)	C_R	σ_{C_R}	Limit ^c
3b.....	43.2	2006 May 22.152	4 × 20	14.94	0.04	18.56
3d.....	43.9	2006 May 22.852	7 × 60	14.94	0.02	18.82
3b.....	44.2	2006 May 23.194	5 × 20	14.97	0.02	18.73
3d.....	44.9	2006 May 23.927	8 × 60	14.92	0.02	18.62
3b.....	45.2	2006 May 24.174	5 × 20	14.97	0.03	18.85
3d.....	45.8	2006 May 24.830	12 × 60	14.97	0.02	19.02
3b.....	46.2	2006 May 25.185	3 × 20	15.01	0.03	18.61
3d.....	46.8	2006 May 25.845	9 × 60	14.99	0.03	18.84
3b.....	48.2	2006 May 27.209	2 × 20	14.99	0.09	16.19
3b.....	49.1	2006 May 28.145	3 × 20	14.99	0.04	18.25
3d.....	49.9	2006 May 28.920	12 × 60	15.01	0.03	19.17
3b.....	50.2	2006 May 29.229	5 × 20	14.96	0.04	18.61
3d.....	50.8	2006 May 29.835	12 × 60	15.01	0.03	19.02
3b.....	51.2	2006 May 30.178	4 × 20	14.95	0.03	18.42
3d.....	51.8	2006 May 30.836	11 × 60	15.04	0.04	19.00
3b.....	52.2	2006 May 31.168	4 × 20	15.01	0.04	18.56
3d.....	52.8	2006 May 31.836	12 × 60	15.07	0.02	19.04
3b.....	53.2	2006 Jun 1.247	3 × 20	14.99	0.03	18.15
3d.....	53.9	2006 Jun 1.890	6 × 60	15.03	0.02	18.64
3b.....	54.2	2006 Jun 2.169	6 × 20	15.03	0.04	18.60
3d.....	54.8	2006 Jun 2.841	11 × 60	15.05	0.05	18.74
3b.....	55.2	2006 Jun 3.188	6 × 20	15.03	0.03	18.57
3b.....	56.2	2006 Jun 4.178	4 × 20	15.07	0.03	18.40
3b.....	57.2	2006 Jun 5.170	6 × 20	15.08	0.03	18.46
3b.....	58.2	2006 Jun 6.170	6 × 20	15.07	0.02	18.38
3d.....	58.9	2006 Jun 6.852	9 × 20	15.00	0.03	18.14
3d.....	59.8	2006 Jun 7.847	10 × 20	15.04	0.03	18.06
3b.....	60.2	2006 Jun 8.170	4 × 20	15.02	0.03	17.96
3d.....	60.8	2006 Jun 8.831	10 × 20	15.05	0.03	17.88
3b.....	61.2	2006 Jun 9.166	5 × 20	15.05	0.04	18.05
3b.....	63.2	2006 Jun 11.171	3 × 20	15.06	0.04	17.56
3d.....	63.9	2006 Jun 11.886	8 × 20	15.03	0.04	17.22
3b.....	64.2	2006 Jun 12.152	2 × 20	15.13	0.03	17.66
3d.....	64.8	2006 Jun 12.841	12 × 20	15.09	0.05	18.04
3b.....	65.2	2006 Jun 13.163	4 × 20	15.10	0.02	18.26
3b.....	66.2	2006 Jun 14.152	3 × 20	15.09	0.04	18.45
3d.....	66.8	2006 Jun 14.843	4 × 60	15.14	0.03	18.26
3b.....	67.2	2006 Jun 15.178	5 × 20	15.15	0.03	18.63
3b.....	68.2	2006 Jun 16.174	6 × 20	15.14	0.04	18.79
3d.....	68.8	2006 Jun 16.831	5 × 60	15.15	0.02	18.45
3b.....	69.2	2006 Jun 17.165	4 × 20	15.11	0.02	18.27
3d.....	69.9	2006 Jun 17.902	4 × 60	15.15	0.04	18.28
3b.....	70.2	2006 Jun 18.165	4 × 20	15.19	0.03	18.61
3d.....	70.8	2006 Jun 18.818	5 × 60	15.15	0.02	18.40
3b.....	71.2	2006 Jun 19.175	6 × 20	15.22	0.03	18.66
3d.....	71.8	2006 Jun 19.850	8 × 60	15.16	0.03	18.68
3b.....	72.2	2006 Jun 20.182	3 × 20	15.22	0.03	18.54
3d.....	72.8	2006 Jun 20.844	12 × 60	15.26	0.04	19.01
3b.....	73.2	2006 Jun 21.176	6 × 20	15.20	0.03	18.83
3d.....	73.8	2006 Jun 21.841	11 × 60	15.22	0.03	18.85
3d.....	74.9	2006 Jun 22.873	8 × 60	15.23	0.03	18.61
3d.....	75.9	2006 Jun 23.893	4 × 60	15.25	0.03	18.23
3d.....	76.9	2006 Jun 24.858	8 × 60	15.29	0.04	18.64
3d.....	79.8	2006 Jun 27.802	4 × 60	15.26	0.04	18.26
3b.....	82.2	2006 Jun 30.230	3 × 20	15.34	0.05	18.31
3b.....	83.2	2006 Jul 1.198	3 × 20	15.45	0.04	17.92
3d.....	83.8	2006 Jul 1.802	4 × 60	15.70	0.07	16.93
3b.....	84.2	2006 Jul 2.181	6 × 20	15.52	0.05	18.46
3d.....	84.8	2006 Jul 2.836	4 × 60	15.52	0.05	17.41
3b.....	85.2	2006 Jul 3.176	6 × 20	15.50	0.04	18.32
3d.....	85.8	2006 Jul 3.823	8 × 60	15.46	0.04	18.18
3b.....	86.2	2006 Jul 4.176	6 × 20	15.64	0.06	18.31
3b.....	87.2	2006 Jul 5.165	4 × 20	15.62	0.03	18.00
3b.....	90.2	2006 Jul 8.197	3 × 20	15.79	0.09	16.97
3b.....	91.2	2006 Jul 9.170	5 × 20	15.78	0.12	16.85

TABLE 2—Continued

Instrument ^a	Phase ^b	Date	Exposure (s)	C_R	σ_{C_R}	Limit ^c
3d.....	92.8	2006 Jul 10.820	8 × 20	15.75	0.08	17.41
3d.....	93.8	2006 Jul 11.816	7 × 20	15.90	0.08	17.28
3d.....	94.8	2006 Jul 12.819	8 × 20	16.02	0.07	17.29
3d.....	95.8	2006 Jul 13.798	4 × 60	16.02	0.06	18.20
3d.....	97.8	2006 Jul 15.833	4 × 60	16.14	0.05	18.10
3b.....	98.2	2006 Jul 16.171	3 × 20	16.19	0.05	17.40
3b.....	101.1	2006 Jul 19.146	3 × 20	16.58	0.06	18.15
3b.....	102.2	2006 Jul 20.155	12 × 20	16.68	0.07	18.94
3d.....	102.8	2006 Jul 20.808	3 × 60	16.86	0.05	18.05
3b.....	103.2	2006 Jul 21.155	12 × 20	16.75	0.05	18.92
3d.....	103.8	2006 Jul 21.793	4 × 60	16.76	0.08	18.09
3b.....	104.2	2006 Jul 22.161	8 × 20	16.88	0.09	18.45
3d.....	104.8	2006 Jul 22.792	3 × 60	17.06	0.17	18.07
3b.....	105.1	2006 Jul 23.147	6 × 20	16.69	0.09	17.47
3b.....	106.2	2006 Jul 24.153	12 × 20	16.95	0.06	18.74
3d.....	106.8	2006 Jul 24.791	3 × 60	16.69	0.10	17.72
3b.....	107.2	2006 Jul 25.165	3 × 20	16.95	0.08	18.16
3b.....	108.2	2006 Jul 26.152	12 × 20	17.04	0.06	18.86
3b.....	109.1	2006 Jul 27.150	9 × 20	17.00	0.06	18.79
3d.....	109.8	2006 Jul 27.788	3 × 60	17.32	0.19	17.92
3d.....	110.8	2006 Jul 28.787	4 × 60	17.21	0.13	18.42
3b.....	112.1	2006 Jul 30.146	2 × 20	...	...	16.94
3d.....	117.8	2006 Aug 4.780	2 × 60	...	...	17.07
3b.....	120.2	2006 Aug 7.156	2 × 20	...	...	16.98
3d.....	120.8	2006 Aug 7.816	10 × 20	16.86	0.17	17.43
3b.....	121.1	2006 Aug 8.119	16 × 20	17.32	0.16	17.96
3b.....	122.1	2006 Aug 9.118	10 × 20	17.47	0.18	17.64
3b.....	123.1	2006 Aug 10.117	17 × 20	17.49	0.16	18.12
3b.....	124.1	2006 Aug 11.114	11 × 20	17.15	0.14	18.19
3b.....	126.1	2006 Aug 13.111	12 × 20	17.11	0.16	17.65
3b.....	187.5	2006 Oct 13.505	12 × 20	17.32	0.24	17.33
3b.....	194.5	2006 Oct 20.493	33 × 20	17.94	0.16	19.12
3b.....	195.5	2006 Oct 21.485	9 × 20	...	...	17.78
3b.....	197.5	2006 Oct 23.504	1 × 20	...	...	17.02
3b.....	200.5	2006 Oct 26.482	32 × 20	17.95	0.15	19.21
3b.....	201.5	2006 Oct 27.480	7 × 20	17.77	0.13	18.29
3b.....	202.5	2006 Oct 28.477	32 × 20	17.96	0.19	19.22
3b.....	203.5	2006 Oct 29.471	24 × 20	17.77	0.08	19.25
3d.....	204.1	2006 Oct 30.108	4 × 60	17.74	0.19	18.10
3b.....	204.5	2006 Oct 30.472	16 × 20	17.77	0.18	19.09
3b.....	205.5	2006 Oct 31.478	24 × 20	17.94	0.18	19.12
3b.....	206.5	2006 Nov 1.476	24 × 20	17.87	0.18	19.07
3b.....	210.5	2006 Nov 5.464	23 × 20	17.66	0.18	18.39
3b.....	211.5	2006 Nov 6.460	23 × 20	18.12	0.21	18.52
3b.....	212.5	2006 Nov 7.458	24 × 20	18.15	0.24	18.65
3b.....	213.5	2006 Nov 8.469	2 × 20	...	...	17.45
3b.....	214.5	2006 Nov 9.455	7 × 20	...	...	17.76
3d.....	215.1	2006 Nov 10.072	4 × 20	...	...	17.11
3b.....	215.5	2006 Nov 10.501	7 × 20	17.32	0.11	17.97
3d.....	216.1	2006 Nov 11.084	4 × 60	...	...	17.74
3b.....	216.5	2006 Nov 11.453	18 × 20	17.81	0.12	18.51
3d.....	217.1	2006 Nov 12.066	1 × 60	...	...	17.01
3b.....	218.4	2006 Nov 13.442	23 × 20	17.91	0.13	18.98
3b.....	219.4	2006 Nov 14.427	7 × 20	17.72	0.13	18.29
3b.....	220.5	2006 Nov 15.457	4 × 20	17.73	0.14	18.08
3b.....	221.4	2006 Nov 16.433	24 × 20	18.04	0.21	19.13
3b.....	222.4	2006 Nov 17.428	9 × 20	17.91	0.15	18.34
3d.....	223.1	2006 Nov 18.078	8 × 60	17.95	0.24	18.61
3b.....	223.4	2006 Nov 18.430	24 × 20	17.91	0.15	18.95
3d.....	224.1	2006 Nov 19.097	4 × 60	17.78	0.12	18.38
3b.....	224.4	2006 Nov 19.428	24 × 20	18.18	0.15	19.08
3d.....	225.1	2006 Nov 20.051	4 × 60	17.91	0.17	18.28
3d.....	226.1	2006 Nov 21.076	4 × 60	17.78	0.14	18.25
3b.....	226.4	2006 Nov 21.414	15 × 20	18.23	0.10	18.83
3b.....	227.4	2006 Nov 22.420	24 × 20	18.11	0.17	19.18

TABLE 2—Continued

Instrument ^a	Phase ^b	Date	Exposure (s)	C_R	σ_{C_R}	Limit ^c
3b.....	228.4	2006 Nov 23.417	24 × 20	17.96	0.15	19.04
3b.....	229.4	2006 Nov 24.413	24 × 20	18.09	0.14	19.15
3d.....	230.1	2006 Nov 25.063	12 × 60	18.11	0.22	18.78
3b.....	230.4	2006 Nov 25.411	21 × 20	18.11	0.13	19.09
3d.....	231.1	2006 Nov 26.056	8 × 60	18.01	0.23	18.65
3d.....	232.0	2006 Nov 27.031	4 × 60	...	...	17.33
3b.....	232.4	2006 Nov 27.404	23 × 20	18.30	0.22	19.12
3d.....	233.1	2006 Nov 28.090	8 × 60	17.96	0.14	18.53
3b.....	233.4	2006 Nov 28.401	15 × 20	18.03	0.09	18.95
3d.....	234.0	2006 Nov 29.049	8 × 60	17.94	0.23	18.65
3b.....	234.4	2006 Nov 29.399	22 × 20	18.01	0.12	19.04
3d.....	235.0	2006 Nov 30.046	8 × 60	18.05	0.18	18.67
3d.....	236.1	2006 Dec 1.064	3 × 60	...	...	18.05
3b.....	236.4	2006 Dec 1.402	5 × 20	17.87	0.20	17.93
3d.....	237.1	2006 Dec 2.081	3 × 60	17.67	0.19	17.94
3b.....	237.4	2006 Dec 2.389	24 × 20	18.40	0.25	18.69
3d.....	238.0	2006 Dec 3.034	8 × 20	17.81	0.27	17.83
3b.....	239.4	2006 Dec 4.397	3 × 20	...	...	16.23
3b.....	240.4	2006 Dec 5.422	2 × 20	...	...	17.00
3b.....	245.4	2006 Dec 10.378	8 × 60	18.29	0.20	18.61
3b.....	246.4	2006 Dec 11.375	8 × 60	18.18	0.19	18.77
3b.....	247.4	2006 Dec 12.367	7 × 60	18.07	0.17	18.49
3d.....	248.1	2006 Dec 13.065	8 × 60	18.35	0.27	18.48
3b.....	248.4	2006 Dec 13.379	6 × 60	18.54	0.19	18.70
3d.....	249.0	2006 Dec 14.014	6 × 60	...	...	17.74
3b.....	249.4	2006 Dec 14.358	3 × 60	18.15	0.22	18.37
3d.....	250.0	2006 Dec 15.025	4 × 60	...	...	18.13
3b.....	250.3	2006 Dec 15.344	3 × 60	...	...	16.66
3d.....	251.0	2006 Dec 15.988	3 × 60	...	...	17.70
3b.....	251.4	2006 Dec 16.363	6 × 60	18.25	0.11	18.88
3d.....	252.0	2006 Dec 16.979	4 × 60	17.95	0.19	18.37
3b.....	252.3	2006 Dec 17.328	2 × 60	...	...	17.97
3b.....	253.4	2006 Dec 18.378	5 × 60	18.27	0.26	18.82
3b.....	256.5	2006 Dec 21.505	6 × 60	18.29	0.10	19.30
3d.....	257.0	2006 Dec 21.963	4 × 60	...	...	17.46
3b.....	257.4	2006 Dec 22.413	4 × 60	18.02	0.12	18.79
3b.....	258.3	2006 Dec 23.313	1 × 60	...	...	17.68
3d.....	259.0	2006 Dec 23.980	8 × 60	...	...	18.57
3d.....	261.0	2006 Dec 25.974	8 × 60	18.33	0.25	18.46
3b.....	261.4	2006 Dec 26.393	2 × 60	...	...	17.07
3b.....	262.3	2006 Dec 27.334	7 × 60	18.27	0.08	19.31
3d.....	263.1	2006 Dec 28.086	3 × 60	...	...	17.37
3b.....	263.3	2006 Dec 28.342	1 × 60	17.93	0.20	18.16
3d.....	265.0	2006 Dec 29.961	8 × 20	...	...	17.89
3d.....	272.9	2007 Jan 6.939	8 × 20	...	...	17.33
3d.....	274.0	2007 Jan 7.990	9 × 20	...	...	17.50
3d.....	274.9	2007 Jan 8.934	8 × 20	...	...	17.69
3b.....	275.3	2007 Jan 9.295	8 × 20	...	...	18.00
3d.....	275.9	2007 Jan 9.933	8 × 60	...	...	18.26
3b.....	276.3	2007 Jan 10.291	6 × 60	18.34	0.20	18.44
3d.....	276.9	2007 Jan 10.942	10 × 60	...	...	18.55
3b.....	277.3	2007 Jan 11.330	2 × 60	...	...	18.15
3d.....	277.9	2007 Jan 11.939	5 × 60	...	...	18.29
3b.....	278.4	2007 Jan 12.416	2 × 60	...	...	16.57
3b.....	279.5	2007 Jan 13.455	4 × 60	18.40	0.20	18.53
3b.....	280.3	2007 Jan 14.273	2 × 60	...	...	18.15
3d.....	280.9	2007 Jan 14.920	8 × 60	18.43	0.18	18.64
3b.....	281.4	2007 Jan 15.360	2 × 60	...	...	18.37
3d.....	282.1	2007 Jan 16.148	1 × 60	...	...	16.55
3d.....	283.9	2007 Jan 17.916	5 × 60	...	...	18.01
3d.....	287.9	2007 Jan 21.899	8 × 60	18.31	0.14	18.67
3d.....	289.1	2007 Jan 23.077	8 × 60	18.38	0.16	18.75
3b.....	293.3	2007 Jan 27.346	1 × 60	...	...	17.56
3b.....	294.3	2007 Jan 28.312	8 × 20	...	...	18.49
3b.....	295.2	2007 Jan 29.240	4 × 20	...	...	16.68

TABLE 2—Continued

Instrument ^a	Phase ^b	Date	Exposure (s)	C_R	σ_{C_R}	Limit ^c
3b.....	296.3	2007 Jan 30.269	1 × 20	...	...	16.67
3d.....	297.9	2007 Jan 31.927	7 × 20	...	...	16.93
3b.....	302.2	2007 Feb 5.222	8 × 20	...	...	18.14
3b.....	303.2	2007 Feb 6.219	8 × 20	...	...	18.29
3b.....	304.2	2007 Feb 7.185	2 × 60	18.47	0.27	18.48
3b.....	305.2	2007 Feb 8.215	4 × 40	...	...	18.48
3b.....	306.2	2007 Feb 9.216	5 × 60	18.41	0.19	19.06
3d.....	307.0	2007 Feb 10.041	3 × 60	...	...	18.14
3b.....	307.2	2007 Feb 10.211	8 × 60	18.53	0.17	19.18
3d.....	307.8	2007 Feb 10.848	7 × 60	...	...	18.09
3b.....	308.2	2007 Feb 11.209	7 × 60	18.51	0.21	19.16
3b.....	309.2	2007 Feb 12.215	2 × 60	...	...	18.20
3b.....	310.2	2007 Feb 13.203	4 × 60	...	...	18.30
3b.....	312.3	2007 Feb 15.265	4 × 60	18.68	0.23	18.81
3b.....	313.2	2007 Feb 16.195	8 × 60	18.55	0.22	19.12
3b.....	314.2	2007 Feb 17.159	2 × 60	...	...	18.22
3b.....	315.2	2007 Feb 18.188	8 × 60	18.69	0.16	19.31
3b.....	316.5	2007 Feb 19.454	7 × 60	18.94	0.19	19.25
3d.....	316.8	2007 Feb 19.824	4 × 60	...	...	17.41
3b.....	317.4	2007 Feb 20.422	5 × 60	18.39	0.15	19.00
3b.....	318.2	2007 Feb 21.197	4 × 60	...	...	17.94
3d.....	318.9	2007 Feb 21.936	4 × 60	...	...	18.42
3b.....	319.2	2007 Feb 22.179	8 × 60	18.88	0.23	19.19
3d.....	319.8	2007 Feb 22.791	4 × 60	...	...	17.43
3b.....	320.5	2007 Feb 23.453	6 × 60	18.64	0.22	19.16
3d.....	320.9	2007 Feb 23.935	3 × 60	...	...	18.02
3b.....	321.2	2007 Feb 24.211	4 × 60	18.55	0.15	18.66
3b.....	324.2	2007 Feb 27.162	8 × 20	...	...	18.34
3b.....	325.2	2007 Feb 28.164	7 × 20	...	...	17.92
3b.....	326.3	2007 Mar 1.326	1 × 20	...	...	16.04
3b.....	327.1	2007 Mar 2.139	5 × 20	...	...	16.65
3b.....	328.1	2007 Mar 3.134	3 × 20	...	...	16.52
3b.....	329.1	2007 Mar 4.138	6 × 20	...	...	17.32
3b.....	330.1	2007 Mar 5.145	8 × 20	...	...	17.86
3d.....	332.1	2007 Mar 7.101	8 × 20	...	...	17.47
3b.....	332.1	2007 Mar 7.131	4 × 60	...	...	18.79
3d.....	332.8	2007 Mar 7.786	7 × 60	...	...	18.31
3b.....	333.2	2007 Mar 8.165	3 × 60	...	...	18.66
3d.....	333.9	2007 Mar 8.911	8 × 20	...	...	17.95
3b.....	334.2	2007 Mar 9.163	6 × 60	18.83	0.26	19.13
3d.....	334.8	2007 Mar 9.804	5 × 60	...	...	17.99
3b.....	335.1	2007 Mar 10.134	8 × 60	18.98	0.21	19.24
3d.....	335.8	2007 Mar 10.771	4 × 60	...	...	17.79
3b.....	336.2	2007 Mar 11.208	2 × 60	...	...	17.40
3d.....	336.9	2007 Mar 11.854	8 × 60	...	...	18.75
3d.....	337.8	2007 Mar 12.762	8 × 60	...	...	18.38

^a Instrument responsible for the observation, abbreviated “3b” for ROTSE-IIIb in west Texas and “3d” for ROTSE-IIIId in Turkey.

^b Relative to 2006 April 9.0.

^c This is the 4σ limiting magnitude.

relative to 2006 April 9.0 for convenience. It is important also to note that the actual core collapse can occur 1–3 days before the shock breakout, depending on the progenitor radius.

The ROTSE-III light curve of SN 2006bp rises 3.0 mag from the first detection on April 9.1 to reach a peak unfiltered magnitude of 14.7 mag on April 16.5 (day +7.5; estimated from a third-order polynomial fit to the data). The light curve then fades by about 0.2 mag before possibly rising to a second maximum on April 25 (day +16), although the coverage flanking this point is incomplete. There is otherwise little (<0.1 mag) evolution between days +12 and +33, after which there is a slight decline of $0.016 \text{ mag day}^{-1}$ until day +42. The average decay rate from

day +38 to day +61 is $0.006 \text{ mag day}^{-1}$, and this rate then increases to $0.013 \text{ mag day}^{-1}$ through day +82. The plateau phase finally comes to an end around day +80, and SN 2006bp fades by about 2 mag before entering an exponential decay phase on day +110.

Rejecting a single outlier, the late-time ROTSE-III light curve shows an average linear decline of $0.0073 \pm 0.0004 \text{ mag day}^{-1}$ between days +121 and +335, which is significantly slower than the $0.0098 \text{ mag day}^{-1}$ decline expected from the decay of ^{56}Co into ^{56}Fe (e -folding time $\tau_{\text{Co}} = 111$ days). The late-time quasi-bolometric and V -band light curves of most core-collapse SNe have been shown to follow the decay of ^{56}Co , although the U - and B -band flux drops more slowly, and the R - and I -band light curves show departures as well (see Hamuy & Suntzeff 1990 for an example). The ROTSE-III data are unfiltered, but the peak response is in the V and R bands (see Table 1). The higher energy bands contribute little to the measured signal, as shown by the low flux observed at early times when the spectral peak lies in the UV (see § 4). It is unclear how the low level U - and B -band fluxes at late times (see § 3 for the spectra) could dictate the light-curve behavior.⁶ It is possible that our reference template, which was constructed by removing the SN light from postexplosion data, may not accurately reflect the background signal around the SN; however, in such a case we would expect the light curve to flatten out or drop quickly once the discrepancy is larger than the SN flux, while the data show a smooth linear decline. It is therefore worth considering the possibility that an additional source of energy production is sustaining the luminosity, such as an ejecta-wind interaction, as proposed by Chugai (1991) to explain the slower than expected decline in the $H\alpha$ line flux for three SNe II at late times.

3. SPECTROSCOPY

We observed SN 2006bp with the Low Resolution Spectrograph (LRS; Hill et al. 1998) on the Hobby-Eberly Telescope (HET; Ramsey et al. 1998), located at the McDonald Observatory, on 13 nights between 2006 April 11 and June 21 and again on 2007 March 14 and 16. The HET can rotate freely in the azimuthal plane, but it is fixed at 55° in elevation (air mass ~ 1.22), and it uses an Arecibo-type tracker to follow targets as they rise through the observable altitude window in the east or set through it in the west. The HET has an effective aperture of 9.2 m, although the pupil can vary along a given track (e.g., the effective mirror size drops toward the track limits). We used the g1 grism on LRS, which covers 4050 to 11000 Å, with a resolving power of $R \sim 300$ in a $2.0''$ slit. To avoid order overlap, we observed SN 2006bp each night with both the GG385 and the OG590 order-sorting filters. The spectroscopic observing log is detailed in Table 3.

Dome flats and arc lamp calibration data were obtained on all nights with each observing setup; however, standard stars were only observed on 7 of the first 13 nights. Drawing on past experience with the LRS, which shows the instrument to be quite stable from night to night, we decided to combine all the available calibration data and use them to uniformly process the target spectra from each night. We constructed master flats from all the data available and compared these to the nightly flats to verify the stability. For the GG385 data, which we trim to 4100–9200 Å, the flats vary by less than 1% from night to night. We noticed significant variation in the OG590 setup near the cutoff frequency, however, which seems to correlate with the ambient (filter)

⁶ For comparison, the Type II-P SN 2004et faded by $0.0064 \text{ mag day}^{-1}$ in the B -band in the nebular phase, while the VRI rates were all $>0.01 \text{ mag day}^{-1}$ (Sahu et al. 2006).

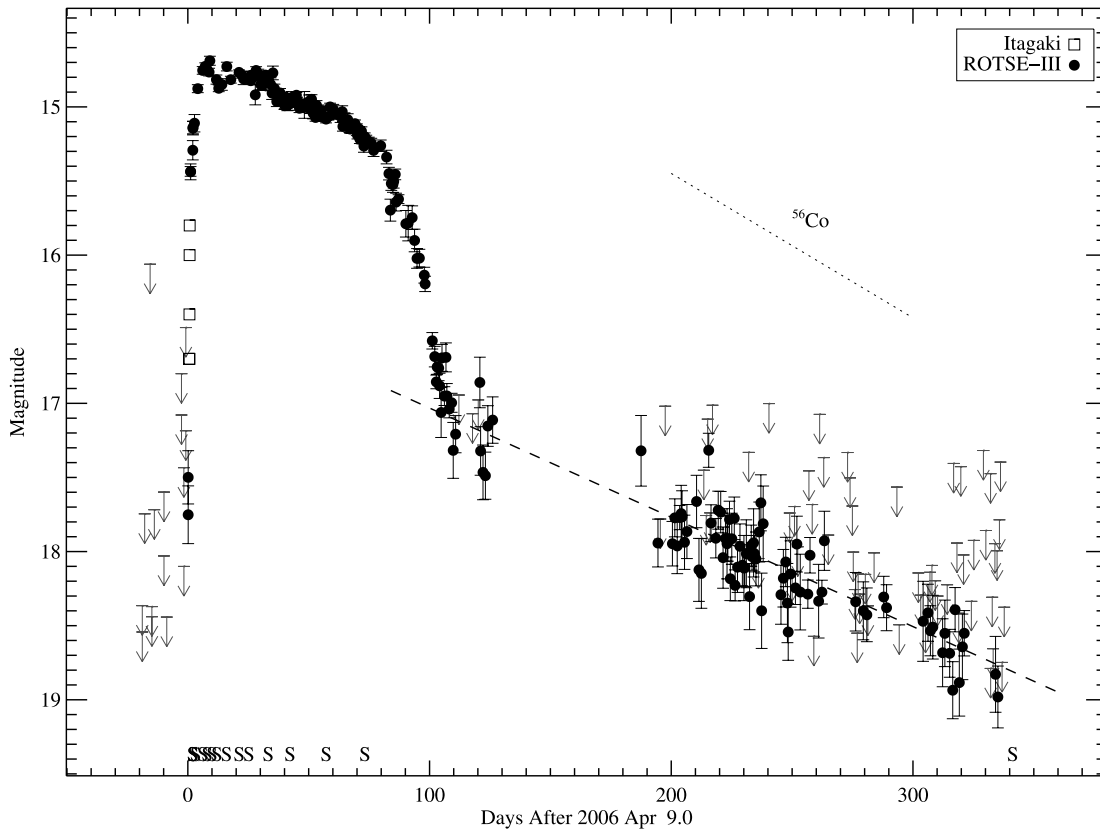


FIG. 2.—ROTSE-III unfiltered light curve of SN 2006bp. Detections are plotted with filled circles, and arrows mark the 4σ upper limits (for clarity, only limits fainter than 17 are shown after day 150). Open squares mark the observations of Itagaki et al. 2006. The dashed line shows the best-fit linear decay of $0.0073 \pm 0.0004 \text{ mag day}^{-1}$ between days +121 and +335, and the dotted line shows the decay rate for an arbitrary mass of ^{56}Co . The S's along the abscissa mark the spectral observation epochs.

temperature. We trimmed the OG590 data to the 6270–10820 Å range, which keeps the nightly variations below 1%.

The target spectra were trimmed, bias-subtracted, and flat-corrected in the usual manner with IRAF scripts.⁷ We used the routine LACOSMIC (van Dokkum 2001) to remove particle events and then combined the frames from each night in each filter prior to extraction with `apa11`. We used spectral observations of the standard stars BD+17 4708, BD+26 2606, and Wolf 1346 to derive a relative spectrophotometric correction for the data. After grayshifting, the different standards taken on different nights agree out to 10000 Å to typically better than 0.05 mag.

We removed strong telluric absorption features using the averaged BD+26 2606 spectrum as reference. The atmospheric conditions varied significantly over the course of observations, and the relative strengths of different telluric features changed from night to night, so we separately removed features predominantly caused by O I before correcting for the H₂O lines. We note the H₂O line profiles change somewhat as the individual transitions move in and out of saturation, and removal of the strong H₂O absorption band between 8900 and 9800 Å is imperfect.

From the H I maps of Verheijen & Sancisi (2001) we find a recession velocity of 1280 km s⁻¹ at the location of SN 2006bp, which we adopt as the rest-frame velocity. To combine the two channels, we first scaled the OG590 data by a constant and re-sampled it to match the GG385 spectra in the overlap region. The nightly data are deredshifted into the heliocentric rest frame and combined with a weighted average to produce the final spectra.

To ensure a smooth transition, the weights drop exponentially toward the end of each component spectrum in the overlap region. For example, the weight of the GG385 spectra drops from 50% at 7700 Å to zero at 9200 Å. On the first night of observations we obtained spectra in both the east and west tracks. We

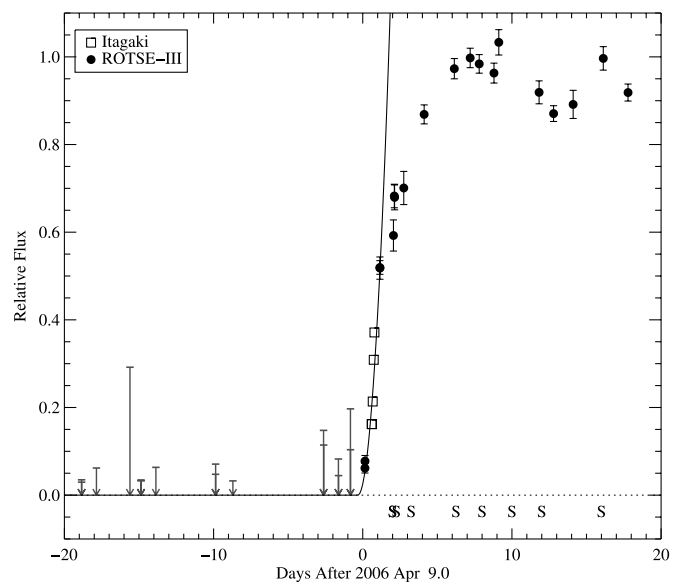


FIG. 3.—Early-time light curve of SN 2006bp in flux space relative to the 2006 April 16.5 maximum. Arrows mark the 4σ flux limits for the null detections (see text). The curve shows the simplistic $F \propto (t - t_0)^2$ model fit, where $t_0 = \text{April } 8.7$.

⁷ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

TABLE 3
OBSERVING LOG FOR HET SPECTRA OF SN 2006bp

Date (UT)	JD -2,400,000.5	Phase ^a (day)	Exposure (s)	Filter	Notes ^b
2006 Apr 11.11.....	53,836.11	2	2 × 300	GG385	S
2006 Apr 11.12.....	53,836.12	2	1 × 500	OG590	S, cloudy
2006 Apr 11.31.....	53,836.31	2	3 × 360	GG385	N, cloudy
2006 Apr 11.33.....	53,836.33	2	2 × 550	OG590	N, cloudy
2006 Apr 12.35.....	53,837.35	3	1 × 600	GG385	N, cloudy
2006 Apr 12.36.....	53,837.36	3	1 × 900	OG590	S, cloudy
2006 Apr 15.30.....	53,840.30	6	1 × 600	GG385	N, cloudy
2006 Apr 15.31.....	53,840.31	6	572, 900	OG590	N, cloudy
2006 Apr 17.10.....	53,842.10	8	2 × 200	GG385	S
2006 Apr 17.11.....	53,842.11	8	2 × 450	OG590	S
2006 Apr 19.10.....	53,844.10	10	2 × 200	GG385	S
2006 Apr 19.11.....	53,844.11	10	2 × 450	OG590	S
2006 Apr 21.12.....	53,846.12	12	2 × 200	GG385	P
2006 Apr 21.13.....	53,846.13	12	400, 500	OG590	P
2006 Apr 25.10.....	53,850.10	16	2 × 400	GG385	N, cloudy
2006 Apr 25.11.....	53,850.11	16	540, 421	OG590	S
2006 Apr 30.28.....	53,855.28	21	2 × 200	GG385	S
2006 Apr 30.29.....	53,855.29	21	2 × 450	OG590	S
2006 May 4.26.....	53,859.26	25	2 × 200	GG385	P
2006 May 4.27.....	53,859.27	25	2 × 450	OG590	P
2006 May 12.26.....	53,867.26	33	2 × 200	GG385	S
2006 May 12.27.....	53,867.27	33	500, 550	OG590	S
2006 May 21.21.....	53,876.21	42	2 × 400	GG385	S
2006 May 21.23.....	53,876.23	42	2 × 600	OG590	S
2006 Jun 5.19.....	53,891.19	57	2 × 200	GG385	S
2006 Jun 5.20.....	53,891.20	57	2 × 450	OG590	S
2006 Jun 21.14.....	53,907.14	73	2 × 200	GG385	P
2006 Jun 21.14.....	53,907.14	73	2 × 450	OG590	P
2007 Mar 14.21.....	54,173.21	339	2 × 900, 875	OG590	S
2007 Mar 16.17.....	54,175.17	341	650, 2 × 600	GG385	P

NOTE.—All observations were taken through a 2'' slit oriented along the parallactic angle.

^a Relative to 2006 April 9.0 and rounded off to the nearest day.

^b Sky conditions at the time of observation (P=photometric, S=spectroscopic, N=nonspectroscopic).

separately analyze each spectrum as well as the combined spectrum. The fully processed spectra are plotted in Figures 4 and 5. Figures 6–9 show the spectral evolution on expanded scales to emphasize the evolution of individual spectral lines.

3.1. Early Spectra

The HET data from 2006 April 11 and 12 (about 2 and 3 days after shock breakout) not only rank among the earliest of supernova observations, but to our knowledge they represent the earliest spectra of any normal supernova to date (i.e., excluding the peculiar SN 1987A). On top of the largely featureless +2 day spectra are narrow emission lines corresponding to rest-frame He II $\lambda 4200$, He II $\lambda 4686$, H β , C IV $\lambda \lambda 5805$, and H α that are each detected in both the east and west tracks. Table 4 gives the measured equivalent widths and line fluxes for the combined day +2 data. Note that the He II $\lambda 4200$ line appears broader than the $\lambda 4686$ line, which may indicate a blend. Other intermediate lines from the Pickering series are not detected. In the day +3 spectra, H α is clearly detected, although the broad H α P Cygni emission has increased such that the line is less pronounced, and the H β line is similarly lost in the broad H β P Cygni emission, while the He II and C IV lines have disappeared despite little change or even a decrease in the local continua. The narrow H α emission is further detected at later phases, but the high-ionization lines are not. One possible explanation for this behavior is that all the narrow lines originate from circumstellar gas or within a wind blown off the

progenitor, although given the location of the SN in a spiral arm and the proximity to several possible H II regions, it is likely that the narrow H α emission originates in a physically distinct region. The narrow He II and C IV emission lines, however, require high temperatures or an ionizing flux, which implies that they are local to the SN explosion. Their disappearance by day +3 suggests either rapid recombination at densities larger than $\approx 10^9$ particles cm⁻³, which is characteristic of extended red supergiant atmospheres, or that the material has been swept up by the shock (the low velocities exclude the SN ejecta as a source for these narrow lines).

In addition to the narrow emission lines, the day +2 and +3 spectra also exhibit a limited number of broad absorption features. Figure 10 shows these early spectra plotted in velocity space relative to H α . A P Cygni profile is seen in each case extending out to beyond 20,000 km s⁻¹, and the absorption and emission components both strengthen in the latter spectra. Near the broad emission peak, there are apparent absorption or emission features in addition to the narrow rest-frame H α line. Most prominent among these is a notch extending from 4000 to 6500 km s⁻¹. Heeding the cautionary tale of Matheson et al. (2000), we checked the high-resolution atmospheric transmission atlas from Hinkle et al. (2003) and found that uncorrected telluric lines are likely responsible.

Perhaps the most distinct feature in the day +2 spectra is a P Cygni profile around 4450 Å (Figs. 4 and 6). The feature is also present in the day +3 spectra, which are similar to a spectrum of

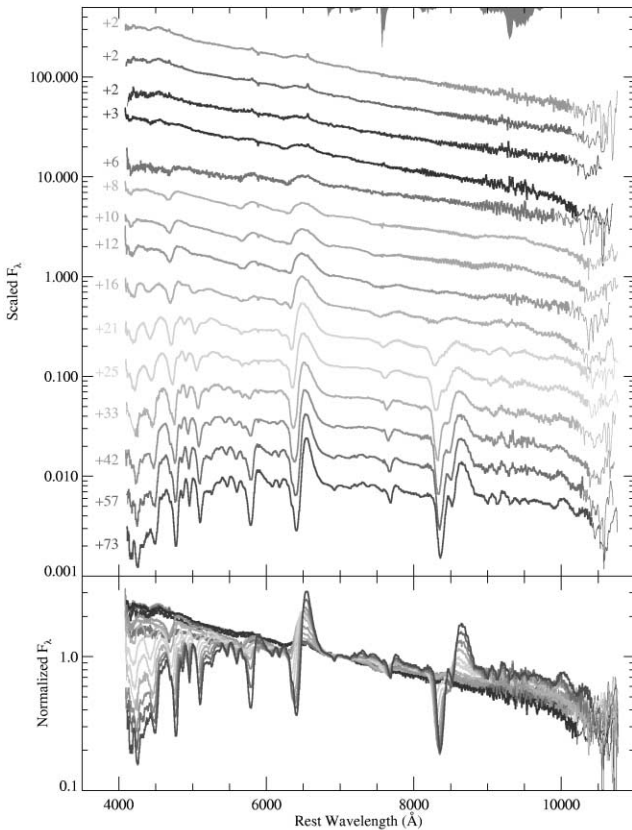


FIG. 4.—Spectral evolution of SN 2006bp through day +73. The top portion of the figure shows each spectrum scaled by an arbitrary factor for clarity and arranged with the earliest spectra on top and the latest on the bottom. Portions of the spectra suffering from low S/N have been smoothed for display purposes (*thin lines*). Phases relative to 2006 April 9.0, a convenient epoch close to our estimated date of shock breakout and rounded to the nearest day, are given to the left of each spectrum. For the observations on the first night (day +2), the spectra from both the east and west tracks are plotted and the combined data are shown in between. Note that the +6 day spectra were obtained under nonspectroscopic conditions, which may explain the abrupt departure in the continuum slope as compared to days +3 and +8. The bottom of the figure shows each spectrum normalized around 7000 Å to emphasize the evolution of the line features and the general reddening with time. [See the electronic edition of the *Journal* for a color version of this figure.]

SN 1999gi taken one day after discovery (Leonard et al. 2002b). Leonard et al. (2002b) tentatively associate this feature to high-velocity H β , although they caution that no corresponding high-velocity H α profile is observed. In our early spectra of SN 2006bp we similarly do not identify P Cygni profiles from any other species in the same velocity range (see Fig. 10). If this feature does in fact arise from H β , then the absorption wing extends out to about 35,000 km s $^{-1}$. This P Cygni profile, taken together with the narrow He II λ 4686 emission line, is rather evocative of the H α P Cygni profile and the narrow H α emission line (Fig. 10). Noting this similarity, we suggest that the 4450 Å P Cygni profile may alternatively arise from He II λ 4686. This would require high ionization in the outer ejecta layers, which is plausible given the recent passage of the breakout shock. Following the modeling of SN 1999em by Baron et al. (2000), Leonard et al. (2002b) also identify a broad absorption trough around 5450 Å from high-velocity He I λ 5876 in their early spectra of SN 1999gi. While this absorption also appears in our +3 day spectra of SN 2006bp, it is absent in the +2 day data (Fig. 7, *top*; around 24,000 km s $^{-1}$ relative to He I λ 5876 in Fig. 10). If the 5450 Å absorption trough is caused by He I λ 5876, then its appearance on day +3, in concert

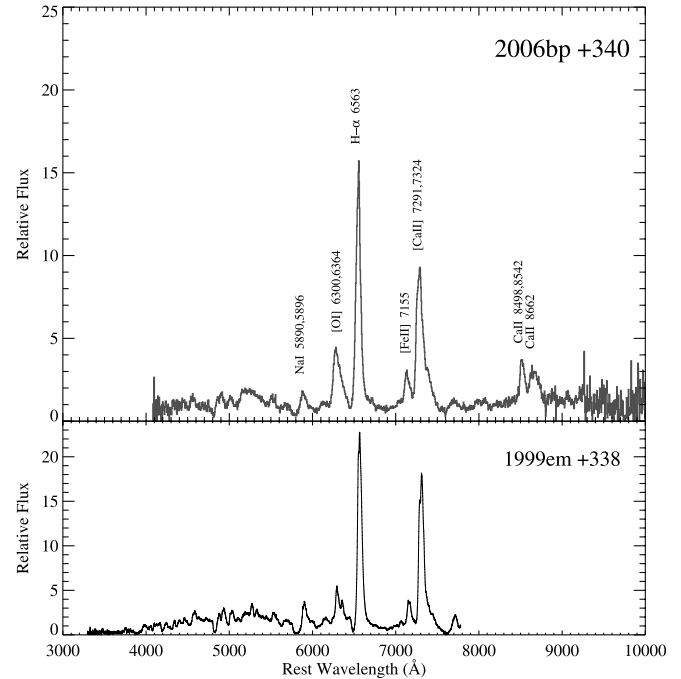


FIG. 5.—HET/LRS spectra of SN 2006bp in the nebular phase (*top*). Plotted is the combined spectrum from the 2007 March 14 (OG590) and March 16 (GG385) data. For reference, a spectrum of SN 1999em taken around 333 days after discovery (\sim 338 days after shock breakout; Leonard et al. 2002a) is shown below, and a few of the strongest emission lines are labeled.

with the fading of the proposed He II λ 4686 P Cygni line, would be consistent with recombination of helium. Dessart & Hillier (2005) suggest that photospheric N II lines can simultaneously fit the features blueward of both He I λ 5876 and H β in spectra of SN 1999em taken around 5 days after shock breakout (see also Baron et al. 2000). Detailed modeling is encouraged to accurately identify these features.

3.2. Line Evolution

We compared the HET spectra of SN 2006bp to a spectral atlas of the Type II-P SN 1999em to identify the line features (Leonard et al. 2002a; their Fig. 10 and Table 4). For this work we have chosen to focus on the strongest features, as well as to select lines useful for EPM (expanding photosphere method) studies. To determine the wavelength of maximum absorption for each feature, we first smoothed the spectra with a Fourier transform (FT) and divided by the local continuum estimated from a linear extrapolation to the neighboring peaks. We then interpolated the data into 0.01 Å bins with a spline function and selected the flux minima. These wavelengths are then converted into expansion velocities using the rest wavelength (or *gf*-weighted rest wavelength for blends) and the relativistic Doppler transformation. Derived values for the 20 lines chosen are reported in Table 5 and plotted in Figure 11.

Figure 6 shows a detail of the spectral evolution between 4100 and 5300 Å. The top portion shows the +2 day to +8 day spectra on an expanded scale, and the +8 to +73 day spectra are plotted below. Only the combined (east and west tracks) spectrum is shown for day +2. The FT-smoothed minima of key line features are circled and labeled. We identify the absorption around 4450 Å in the +2 day data as a signature of He II λ 4686 P Cygni as described above. By day +8 this feature is almost completely lost in the continuum, which indicates why it may not have been

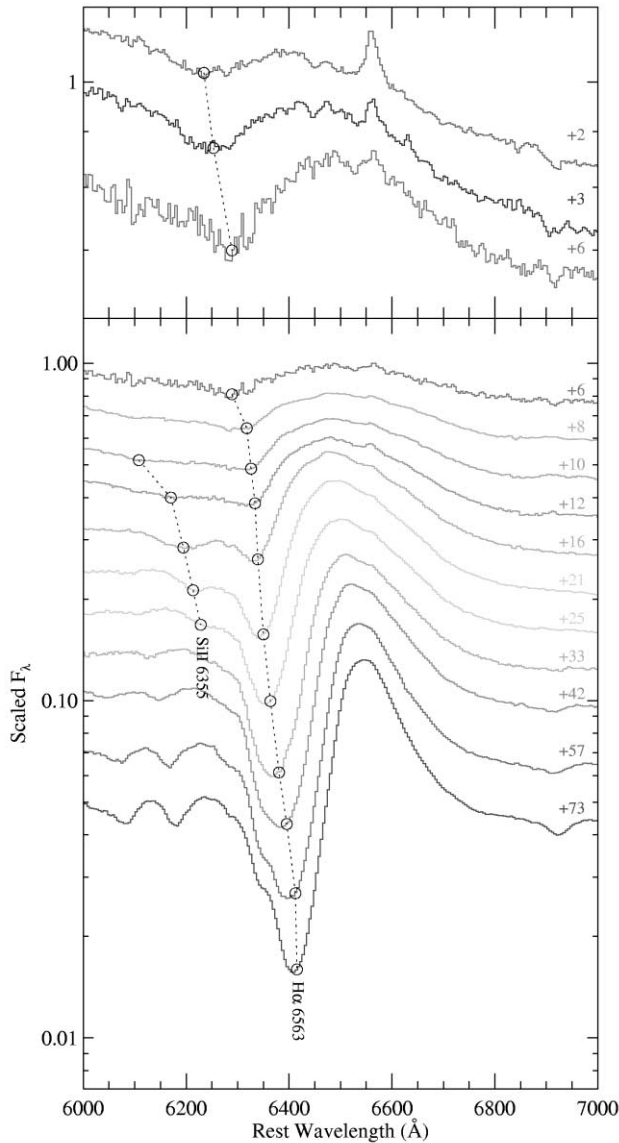


FIG. 8.—Same as Fig. 7, but covering the 6000 to 7000 Å range. Note the narrow H α emission line seen clearly in the +2 day spectrum, which persists atop the broad H α P Cygni emission peak into the later phases. The absorption notch at 6450 Å seen in days +2 and +3 is likely due to uncorrected telluric absorption. [See the electronic edition of the Journal for a color version of this figure.]

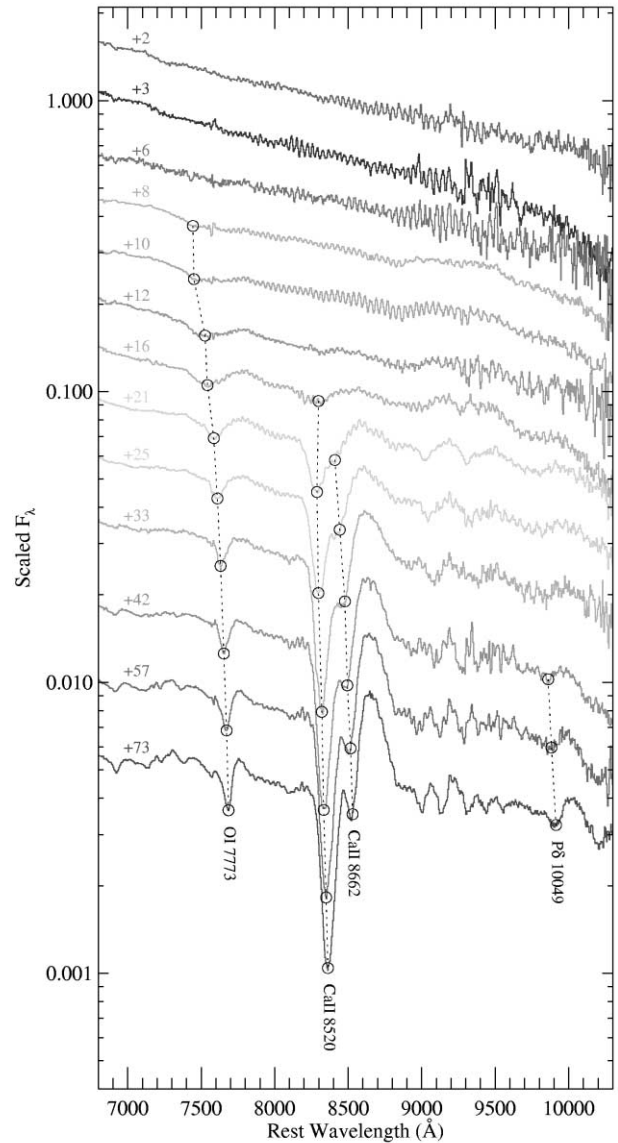


FIG. 9.—Same as Fig. 6, but for the 6800 to 10300 Å range and with all spectra plotted on the same scale (see Fig. 4 for coverage above 10300 Å). P Cygni profiles from P δ λ 10049 can be seen clearly in day +73 spectra and earlier. [See the electronic edition of the Journal for a color version of this figure.]

The redder component then strengthens on day +25, clearly becomes the stronger of the two starting on day +33, and subsequently develops into the Na I D P Cygni feature that dominates this wavelength range in the latter phases. We have labeled this red component as Na I λ 5892 from day +12 through day +73, although this feature is likely blended with He I λ 5876 throughout and He I λ 5876 may even be the stronger component prior to day +21. We further labeled the minimum around 5700 Å as He I λ 5876, although this designation requires velocities much higher than the other photospheric lines. Interestingly, this line does drift to the red with time, but it does so considerably more slowly than the neighboring Sc II λ 5533 and Fe II λ 5666 lines. We note that the absorption around 5700 Å is much stronger for SN 2006bp than was seen for SN 1999em—and which Leonard et al. (2002a) identify as high-velocity Na I. Detailed modeling is required to accurately determine the source of the 5700 Å absorption, be it

TABLE 4
NARROW EMISSION LINES ON DAY +2

Line	EW (Å)	Flux ^a (10^{-15} ergs cm ⁻² s ⁻¹)
He II λ 4200	2.6 \pm 0.8	6.8 \pm 2.0
He II λ 4686	1.2 \pm 0.1	3.0 \pm 0.3
H β λ 4861	0.7 \pm 0.2	1.6 \pm 0.4
C IV λ 5805	2.3 \pm 0.2	3.8 \pm 0.3
H α λ 6563	3.1 \pm 0.1	4.3 \pm 0.1

NOTES.—Equivalent widths and line fluxes measured via Gaussian fits to the continuum-subtracted HET spectra on day +2 (combined east and west tracks). Error estimates do not include systematics.

^a The flux scale was calibrated using the *Swift* V-band photometry.

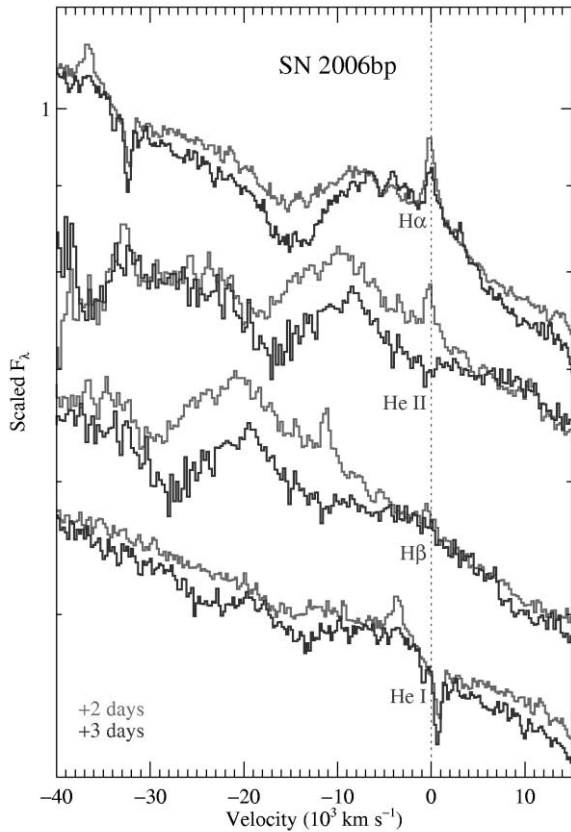


FIG. 10.—Day +2 (combined) and day +3 spectra of SN 2006bp plotted in velocity space for (top to bottom) $H\alpha\lambda 6563$, $He\ II\ \lambda 4686$, $H\beta\lambda 4861$, and $He\ I\ \lambda 5876$ in the adopted 1280 km s^{-1} rest frame. Note that the narrow emission features appear biased to the blue, and it is ambiguous whether this shift is caused by an incorrect rest-frame velocity for the SN or whether these lines emanate from gas moving relative to the SN. The narrow absorption line seen to the red of rest-frame $He\ I\ \lambda 5876$ is $Na\ I\ D$ in the NGC 3953 rest frame. The narrow emission feature in the day +2 spectrum blueshifted by $\sim 3500\text{ km s}^{-1}$ relative to $He\ I\ \lambda 5876$ is $C\ IV\ \lambda\lambda 5805$. [See the electronic edition of the *Journal* for a color version of this figure.]

high-velocity $He\ I\ \lambda 5876$ or $Na\ I\ \lambda 5892$, $N\ II\ \lambda 5679$, a combination of these, or something else. The unmarked absorption features around 6100 and 6200 \AA are due to $Fe\ II$, $Sc\ II$, and $Ba\ II$ blends.

Figure 8 shows the spectral evolution of SN 2006bp between 6000 and 7000 \AA , including the $H\alpha$ P Cygni profile. The day +2 to day +6 spectra are shown on an expanded scale at the top of the figure. $H\alpha$ is detected over all epochs. There is a kink along the blue wing of the absorption around 6350 \AA that clearly becomes visible in the last three epochs. There is also a notch around 6280 \AA in the +57 and +73 day spectra that may be traced back to day +16. Leonard et al. (2002a) identify a similar feature in SN 1999em as high-velocity $H\alpha$, and Chugai et al. (2007) argue that such absorption features observed in the spectra of SNe 1999em and 2004dj result from ejecta-wind interactions. $Si\ II\ \lambda 6533$ absorption is detected between days +12 and +25, and there is formally a minimum found near this line in the +10 day spectra. Given the large jump in velocities between the +10 and +12 day minima, however, the identification with $Si\ II$ is dubious (see, however, § 5).

Fringing becomes a problem in the HET spectra to the red of about 8000 \AA , as shown in Figure 9. No lines are detected in the 6800 to 10300 \AA range until day +8. Likely due to their limited wavelength coverage, the only feature listed by Leonard et al.

(2002a) to the red of $H\alpha$ is the $Ca\ II$ IR triplet. This feature is weakly detected in the +16 day spectra, and it quickly grows in strength to dominate this wavelength range. In the later phases shown in the figure there is a distinct double minimum as the two bluer lines blend into $Ca\ II\ \lambda 8520$, while the redder component, $Ca\ II\ \lambda 8662$, remains distinct. This complicated blend and pronounced emission make for a difficult continuum estimation, and the $Ca\ II\ \lambda 8662$ line is particularly impacted. The components are not clearly split in the +16 day spectrum, and we have associated the absorption only with $Ca\ II\ \lambda 8520$ in the figure, although the 8662 \AA line is likely blended in as well and pulls the minimum to the red as a result. We identify the P Cygni feature that becomes clearly visible around 7700 \AA in the later phases in our HET spectra of SN 2006bp as the $O\ I\ 7773\text{ \AA}$ triplet. An alternative identification is a blend of $Fe\ II$ lines at 7690 , 7705 , and 7732 \AA (Branch et al. 2004). With either identification or a combination of both, this feature can be seen as early as day +8. Note in the +10 day spectrum the absorption profile is asymmetric with the red wing extending much further from the minimum than the blue wing. On day +21, there is an extended blue wing next to the deepening absorption core. A P Cygni profile from $Pa\delta$ also becomes apparent in the latter spectra. Several notches are seen in the +73 day spectra, and these may also be present in the +42 and +57 day spectra, although fringing and night-sky line subtraction errors distort these features. Fassia et al. (1998) identify three of these lines in the Type II-P SN 1995V at a similar phase as $C\ I\ \lambda 9088$, $Sc\ II\ \lambda 9236$, and $C\ I\ \lambda 9405$. A possibly distinct set of P Cygni features is seen between +21 and +33 days.

As shown in Figure 4, the HET spectra extend to almost 10800 \AA in the rest frame, although the signal-to-noise ratio (S/N) per pixel can be low beyond $\sim 10300\text{ \AA}$. There is, however, a clear absorption dip seen in the +8 and +10 day spectra, with a minimum at about 10400 \AA . Infrared spectra of SN 1999em also show such a dip at a similar phase, and Hamuy et al. (2001) identify this feature as $He\ I\ \lambda 10830$. At later phases (about 25 and 35 days after breakout), Hamuy et al. (2001) find multiple absorption and emission features in the 10000 to 11000 \AA range, with possible contributions from $Sr\ II\ \lambda 10327$, $Fe\ II\ \lambda 10547$, and $C\ I\ \lambda 10695$ (see also Fassia et al. 1998). Another possible contributor to the absorption in this range is high-velocity $He\ I\ \lambda 10830$ (Chugai et al. 2007).

4. BOLOMETRIC LIGHT-CURVE APPROXIMATION

Our ROTSE-III photometry is invaluable in determining the shock breakout date, but at early times the unfiltered optical response is insensitive to the bulk of the flux, which is emitted at higher frequencies. In this section we attempt to reconstruct the quasi-bolometric light curve of SN 2006bp using the X-ray, ultraviolet, and optical observations of Immler et al. (2007) and our HET spectroscopy.

We begin by interpolating the *Swift* UVOT measurements in the UVW2, UVM2, UVW1, *U*, *B*, and *V* filters presented by Immler et al. (2007) onto a grid spaced regularly in time. We fit fourth-order polynomials to the light curves over the first 2–5 weeks and first- to second-order fits to the data after days +10 to +20, as the coverage allows, and smoothly average the fits in the overlap. We then convert the measured magnitudes into flux densities using the conversion factors available from the *Swift* calibration database.⁸ We calibrated our HET spectra by normalizing the flux densities to the *Swift* *V*-band measurements. We then proceeded to interpolate the flux densities in each wavelength

⁸ At <http://swift.gsfc.nasa.gov/docs/heasarc/caldb/swift/docs/uvot>.

TABLE 5
MEASURED LINE MINIMA VELOCITIES

LINE	PHASE (days)												
	2.1	3.4	6.3	8.1	10.1	12.1	16.1	21.3	25.3	33.3	42.2	57.2	73.1
H γ λ 4340	...	13.91	12.19	12.19	12.46	11.28	9.36	9.89	8.57	7.41	7.39	6.29	6.27
Fe II λ 4629	4.58	3.91	3.27
Sc II λ 4670	3.89	3.43
He II λ 4686	18.33	16.71	13.53	12.59	...	...	...	...	...	...	...	...	...
H β λ 4861	...	13.12	11.16	11.66	10.76	10.61	10.21	9.42	8.17	6.50	6.04	5.61	5.28
Fe II λ 4924	7.95	6.61	5.59	4.78	4.04	3.40
Fe II λ 5018	10.23	7.80	6.83	5.94	4.89	4.19	3.62
Fe II λ 5169	12.20	11.13	9.77	8.04	6.86	5.60	5.00	4.40	3.95
Fe II λ 5276	3.70	3.36
Fe II λ 5318	8.13	6.74	5.57	4.62	3.94	3.20
Sc II λ 5533	7.75	6.84	6.02	4.96	4.00	3.43
Fe II λ 5666	7.22	6.80	5.68	4.94	3.94	3.55
He I λ 5876	15.77	13.93	11.41	11.63	10.53	12.15	11.34	10.91	10.46	10.20	10.07	9.91	9.81
Na I λ 5892	9.36	8.15	6.67	6.57	5.90	5.25	4.98	5.11
Si II λ 6355	11.89	8.85	7.67	6.76	6.04	...	...	...	...
H α λ 6563	15.38	14.48	12.77	11.40	11.01	10.65	10.38	9.87	9.23	8.45	7.74	6.95	6.82
O I λ 7773	13.00	12.71	9.69	9.04	7.32	6.35	5.51	4.64	3.90	3.40
Ca II λ 8520	7.91	8.30	7.93	7.09	6.65	6.05	5.61
Ca II λ 8662	8.87	7.69	6.45	5.87	5.10	4.61
P δ λ 10049	5.69	5.01	4.06

NOTES.—Velocities measured from the FT-smoothed minima of selected absorption features in units of 10^3 km s^{-1} . Phases are relative to 2006 April 9.0.

bin to the same regular time grid using a similar method of smoothly connected polynomial fits across the early (third-order) and late (second-order) phases. The HET spectra obtained under nonspectroscopic conditions on day +6 were excluded from the fits. For the *Swift* XRT and *XMM* data (Immler et al. 2007), we simply perform a linear fit to the three epochs of declining flux.

To approximate the bolometric light curve, we then integrate the 1600–5500 Å flux densities from the *Swift* photometry and our HET flux densities between 5500 and 10000 Å, and then add in the X-ray flux for each time bin. The results are plotted in Figure 12.

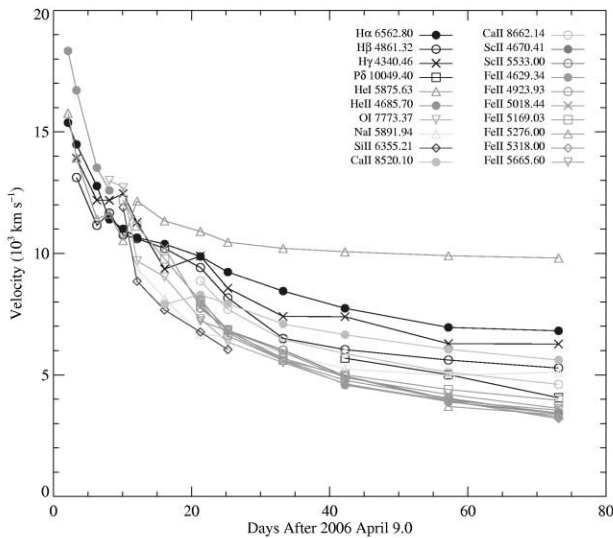


FIG. 11.—Velocities derived from the FT-smoothed minima of selected line features. Symbols mark the measurements, and the lines are intended only to guide the eye. [See the electronic edition of the Journal for a color version of this figure.]

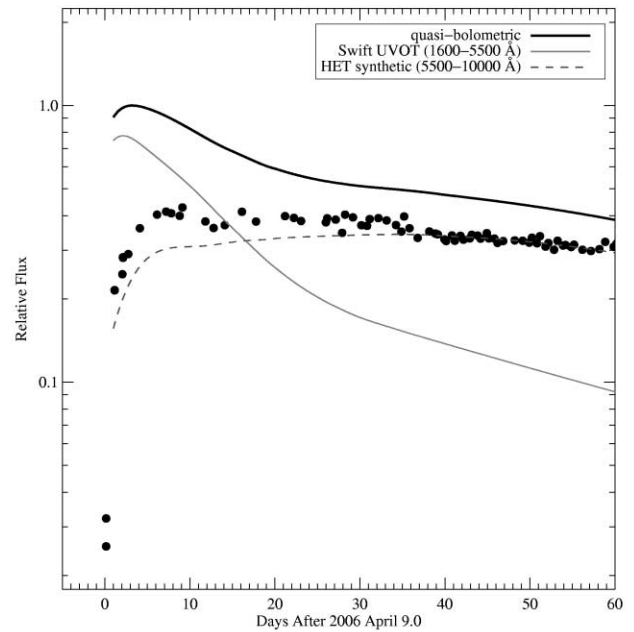


FIG. 12.—Approximate quasi-bolometric light curve (thick black line) constructed from the X-ray, UV, and optical observations of Immler et al. (2007) and our HET spectra, as described in the text. The 0.2–10 keV X-ray contribution included is negligible, and the light curve falls below the plotted range. Note the gap in coverage between the X-ray and UV bands; at early times the SED peaks in this range, but we have not attempted to interpolate the flux densities over this gap, so the early bolometric flux is likely underestimated. The dots mark the ROTSE-III observations arbitrarily scaled to match the synthetic HET flux after day +40. [See the electronic edition of the Journal for a color version of this figure.]

As shown by Immler et al. (2007), the spectral energy distribution (SED) at early times rises from the optical to the UV (their Fig. 5). Because the 0.2–10 keV X-ray flux is much lower, we can deduce that the peak lies between the X-ray and UVW2 bands on day 1, but, lacking constraint on the SED in this range, we have not attempted to interpolate the flux densities over the coverage gap. The early-time bolometric fluxes are therefore somewhat underestimated. As constructed, the bolometric light curve reaches its peak about 3 days after shock breakout and slowly declines up to day +25 before leveling off on the plateau.

5. DISCUSSION AND CONCLUSIONS

We have presented the ROTSE-III unfiltered light-curve and HET optical spectroscopy for the Type II-P SN 2006bp. Because of our frequent coverage of the explosion site in the days leading up to shock breakout, and with the rapid increase in flux observed on 2006 April 9 and 10, we can set the most stringent observational limits ever for the shock breakout date of a SN II-P. A simple quadratic fit to the early limits and the detections on the first two nights gives an estimate of 2006 April 8.7 as the date of shock breakout, which is just 11 hr prior to our first detection, although proper modeling of the light curve with a realistic density structure of the outer layers is required to accurately determine the breakout epoch. The flux does increase rapidly between the first two epochs, but the rate of brightening decreases over the next few nights before reaching a maximum of 14.7 mag around April 16.5. No distinct breakout peak is seen in ROTSE-III's unfiltered band pass, and our limits rule out any such bright optical emission in the 3 days before our first detection.

Swift began observations of SN 2006bp on 2006 April 10.54 in the optical, UV, and X-ray bands (Immler et al. 2007). Over the first few nights, the *U*-, *B*-, and *V*-band curves all rise slightly, and no breakout peak or rapid decay from these is seen, consistent with the ROTSE-III data. This behavior excludes the models from Falk & Arnett (1977) with extended, low-density shells exterior to the progenitor envelope (i.e., their models B, E, and F), as such a configuration leads to a pronounced, 10–15 day peak in visible wavelengths. Furthermore, the UVW2, UVM2, and UVW1 light curves decline slowly and do not show any signs of a distinct, 1–2 day breakout peak, as expected for models A and D from Falk & Arnett (1977). The bolometric light curve approximated in § 4 shows a 3 day rise followed by a 22 day decline to a plateau phase. Although the early peak flux may be somewhat underestimated, this asymmetric peak rises just a factor of ~ 2 above the plateau. Any sharp jump in luminosity associated with the arrival of the shock at the progenitor's photosphere must have lasted less than one day.

The HET spectra are unprecedented not only for the early response, but also for the broad (4100–10800 Å), uniform coverage across all epochs. We employed the same instrument and setups for all observations from early through late times, in contrast to the hodgepodge of observations typically collected. The spectra obtained on April 11, just 2 days after the derived date of shock breakout, represent the earliest spectroscopic observations of a Type II-P, took place at a similar phase to the first observations of SN 1993J (Lewis et al. 1994), and are the earliest of any supernova other than SN 1987A. The most intriguing features in these early spectra are narrow emission lines corresponding to the high-ionization species He II $\lambda 4686$, C IV $\lambda \lambda 5805$, and possibly He II $\lambda 4200$ as well. These features all appear in our first two epochs of data separated by ~ 5 hr, but they have vanished by the following night. The coincidence of these narrow lines in both space and time with SN 2006bp, their rapid evolution, and the high temperatures or bright ionizing flux required to produce them all suggest

that the emitting region is located close to the explosion site, although their low velocities and narrow profiles imply that this region is positioned beyond the hydrodynamic front 2 days after breakout. The sudden disappearance of the narrow He II and C IV emission lines by day +3 requires either rapid recombination or disruption of the emission region through direct interaction with the SN ejecta. Given the lack of narrow emission lines from lower ionization species on subsequent nights (e.g., He I or C III), we favor the latter interpretation. On that basis, we can then determine the distance from the progenitor's photosphere at the moment of shock breakout to the emitting region using the observed velocities from H α P Cygni in the day +2 spectra (15,000 km s $^{-1}$ measured from the absorption minimum or 21,000 km s $^{-1}$ as measured from the blue limit of the absorption). The material responsible for the narrow emission lines in the day +2 data must lie beyond 3×10^{14} cm, but within 5×10^{14} cm of the progenitor's surface. If this material was cast off the progenitor during a stellar eruption and traveled at 10 km s $^{-1}$, then this occurred just 10–20 yr prior to the explosion.

After the narrow emission lines, the most pronounced feature in the April 11 spectra is the P Cygni profile at around 4450 Å. Other studies of SNe II-P with early spectra have noted absorption in this range and associated it with high-velocity H β , but our earlier data clearly show that such an interpretation requires significant material at velocities up to 35,000 km s $^{-1}$. A mechanism to suppress H α at similar velocities, while allowing an H α P Cygni profile to form at slower velocities, would further be required. We find the identification of this P Cygni profile with He II $\lambda 4686$ to be more compelling, and modeling to directly test this possibility is encouraged. Only weak He I $\lambda 5876$ absorption at velocities consistent with the H α P Cygni absorption is found in the day +2 spectra, but by day +3 a distinct absorption profile appears to the blue of He I $\lambda 5876$ as well. We hypothesize that this second minimum may form as He II in the outer ejecta recombines to He I, although much of the corresponding velocity range for the presumed high-velocity He I $\lambda 5876$ absorption is higher than the He II $\lambda 4686$ velocity limit observed in the day +2 spectrum, so that the observed absorption regions cannot map directly from one line to the other. This scenario then predicts He II $\lambda 4686$ absorption at earlier phases in the appropriate velocity range. Contributions from photospheric metal lines such as N II should be considered as well (Baron et al. 2000, 2007; Dessart & Hillier 2005).

In the later phases enhanced absorption appears in the blue wings of the H β (by at least day +33) and Na I $\lambda 5892$ (day +12) P Cygni absorption troughs, and in the case of H α there are two such notches (day +16 and day +42). A possible explanation for these features is unidentified metal blends, although for the absorption to the blue of the H α minimum and for the absorption blueward of Na I $\lambda 5892$ (labeled “He I $\lambda 5876$ ” in Fig. 7), the weak absorption minima do not shift to longer wavelengths with time in a manner consistent with the photospheric evolution. A second possibility is that these lines originate in higher velocity layers above the photosphere. We find anecdotal evidence for such a line-forming region when considering (1) the three of these features that appear at about 10,000 km s $^{-1}$ relative to H β , He I $\lambda 5876$, and H α and (2) the Fe II $\lambda 5018$, Fe II $\lambda 5169$, Si II $\lambda 6533$, and O I $\lambda 7773$ lines that all initially appear at substantially higher velocities than would be predicted from backward extrapolation of later phase measurements (see Fig. 11). More intriguing still, the velocities of these lines upon entrance (days +8 to +10) match the egress velocity of the proposed He II $\lambda 4686$ line (day +8). SN 2006bp may very well have had a line-forming region exterior to the photosphere, perhaps formed from the interaction of

the progenitor wind, as suggested by Chugai et al. (2007). The initial emergence of certain species in these high-velocity layers could then imply that this region cools faster than the photospheric layers, perhaps signaling a source of heating such as outward mixing of ^{56}Ni in the lower line-forming region (Fassia et al. 1998). In this rough picture the ongoing ejecta-wind interaction could supply additional energy at late times and thus help explain the slow, $0.0073 \pm 0.0004 \text{ mag day}^{-1}$ decline derived from the ROTSE-III photometry in the nebular phase.

Finally, we would like to comment on the confusion of the terms “shock breakout” and “explosion,” which appears to occur quite frequently in the literature. For Type II supernovae, the explosion date should be referenced to the moment at which the core reverses its collapse. The shock breakout, on the other hand, is the first electromagnetic signal of the explosion and should be referenced to the moment at which the stellar flux begins its rapid ascent to super-Eddington luminosities and beyond. This epoch will be delayed relative to the core collapse, as the signal must first reach the surface of the progenitor. Depending on the extent of the envelope, this delay may be hours (e.g., SN 1987A) or up to a few days for super red giant envelopes ($\sim 5000 R_{\odot}$). Of particular importance are dates derived from the expanding photosphere method, in which an equation analogous to

$$R = R_0 + v(t - t_0) \quad (2)$$

is solved via least-squares fits to give t_0 and the radius of the emitting photosphere, R . The initial radius, R_0 , is typically assumed to be negligible, and in that same vein, t_0 is often referred to as the explosion date; however, it is clear from equation (2) that t_0 is actually the epoch at which the photospheric radius begins to grow and properly refers to the shock breakout date. As electromagnetic studies push toward earlier and earlier epochs, and with gravitational wave detectors soon to join the neutrino experiments as complimentary probes into the deaths of stars, it is important that we exercise diligence in our use of these separate terms.

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