SN 2005bf: A POSSIBLE TRANSITION EVENT BETWEEN TYPE Ib/c SUPERNOVAE AND GAMMA-RAY BURSTS

GASTÓN FOLATELL,1 CARLOS CONTRERAS,1 M. M. PHILLIPS,2 S. E. WOOSEY,2 SERGEI BLINNKO,3 NIDIA MORRELL,1,4 NICHOLAS B. SUNTZEFF,5 BRIAN L. LEE,6 MARIO HAMUY,1,7 SERGIO GONZÁLEZ,7 WOJTEK KRZEMINSKI,1 MIGUEL ROTH,4 WEIDONG LI,8 ALEXEI V. FILIPPENKO,9 RYAN J. FOLEY,8 W. L. FREEDMAN,8 BARRY F. MADORE,8,10 S. E. PERSON,1,11 DAVID MURPHY,9 SAMUEL BOISSIER,9 GASPAR GALAZ,11 LUIS GONZÁLEZ,7 P. J. MCCARTHY,8 ANDREW McWILLIAM,1 AND WOJTEK PYCH1,2

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ABSTRACT

We present u′g′r′i′BV photometry and optical spectroscopy of the Type Ib/ic SN 2005bf covering the first ~100 days following discovery. The u′g′BV light curves displayed an unprecedented morphology among Type Ib/ic supernovae, with an initial maximum some 2 weeks after discovery and a second, main maximum about 25 days after that. The bolometric light curve indicates that SN 2005bf was a remarkably luminous event, radiating at least $6.3 \times 10^{42}$ erg s$^{-1}$ at maximum light and a total of $2.1 \times 10^{49}$ ergs during the first 75 days after the explosion. Spectroscopically, SN 2005bf underwent a unique transformation from a Type Ic-like event at early times to a typical Type Ib supernova at later phases. The initial maximum in u′g′BV was accompanied by the presence in the spectrum of high-velocity (>14,000 km s$^{-1}$) absorption lines of Fe ii, Ca ii, and H i. The photospheric velocity derived from spectra at early epochs was below 10,000 km s$^{-1}$, which is unusually low compared with ordinary Type Ib supernovae. We describe one-dimensional computer simulations that attempt to account for these remarkable properties. The most favored model is that of a very energetic ($2 \times 10^{51}$ ergs), asymmetric explosion of a massive ($8.3 M_\odot$) Wolf-Rayet WN star that had lost most of its hydrogen envelope. We speculate that an unobserved relativistic jet was launched producing a two-component explosion consisting of (1) a polar explosion containing a small fraction of the total mass and moving at high velocity and (2) the explosion of the rest of the star. At first, only the polar explosion is observed, producing the initial maximum and the high-velocity absorption-line spectrum resembling a Type Ic event. At late times, this fast-moving component becomes optically thin, revealing the more slowly moving explosion of the rest of the star and transforming the observed spectrum to that of a typical Type Ib supernova. If this scenario is correct, then SN 2005bf is the best example to date of a transition object between normal Type Ib/ic supernovae and γ-ray bursts.

Subject headings: gamma rays: bursts — supernovae: individual (SN 2005bf)
It was likely, therefore, that the explosion occurred between March 15 and 29.

Initial CSP spectroscopy revealed that SN 2005bf was a Type Ib event (Morrell et al. 2005), and optical photometry confirmed that the SN had, indeed, been caught on the rising part of the light curve. An intensive program of follow-up photometric and spectroscopic observations was initiated, which unexpectedly revealed an unusual preliminary rise and fall in the \( u' \), \( g' \), \( B \), and \( V \) light curves preceding by \( \sim 25 \) days the main maxima in these bands (Hamuy et al. 2005). Spectra obtained just before the time of the main maximum also revealed that SN 2005bf had transformed into a Type Ib or transitional Type IIb event with strong \( \text{He} \) lines (Wang & Baade 2005).

In this paper, we present the CSP observations of SN 2005bf and discuss these in the context of possible models of the star that produced this peculiar and, thus far, unique explosion.

2. PHOTOMETRY

Most of our optical photometry was obtained with the Swope 1 m telescope at LCO, using a SITe CCD and a set of Sloan Digital Sky Survey (SDSS) \( u'g'r'i'\) and Johnson \( BV \) filters (Fukugita et al. 1996; Bessell 1990). We read a section of 1200 \( \times \) 1200 pixels from the CCD, which, at a scale of \( 0.435 \) pixel \( ^{-1} \), yielded a field of view of \( 8.7 \times 8.7 \)'. Typical image quality ranged between \( 1'' \) and \( 2'' \) (FWHM). A photometric sequence of comparison stars in the SN field was calibrated with the Swope telescope from observations of standard stars of Landolt (1992) and Smith et al. (2002) during four photometric nights. Figure 1 shows the SN field and the selected comparison stars. Table 1 lists the average \( u'g'r'i'BV \) magnitudes derived for these stars. SN magnitudes in the standard SDSS+Johnson system were obtained differentially relative to the comparison stars using point-spread function (PSF) photometry. On every image, a PSF was fitted to the SN and comparison stars within a radius of \( 3'' \). We refer to Paper I for further details about the instrument and measurements.

Five unfiltered LOSS images obtained with the 0.8 m Katzman Automatic Imaging Telescope (KAIT; Filippenko et al. 2001; Filippenko 2005) were included in our analysis because they allow us to study the very early stages of the SN. After some experimentation we found that the unfiltered instrumental magnitudes of the local standards could be satisfactorily transformed with a simple additive zero point to the \( r' \) standard system with a dispersion \( \leq 0.05 \) mag. The comparison of the resulting LOSS magnitudes of

\[ \text{TABLE 1} \]

| Star ID | \( u' \) | \( g' \) | \( r' \) | \( i' \) | \( B \) | \( V \) |
|---------|----------|----------|----------|----------|--------|--------|
| C1      | 17.251(009) | 15.996(008) | 15.520(008) | 15.353(008) | 16.371(009) | 15.709(007) |
| C14     | 21.969(371) | 20.692(053) | 19.294(017) | 17.730(010) | 21.872(192) | 19.940(029) |
| C13     | 20.418(046) | 18.628(008) | 17.953(008) | 17.691(008) | 19.104(015) | 18.247(008) |
| C11     | 19.416(033) | 18.473(009) | 18.125(008) | 18.022(013) | 18.770(011) | 18.259(008) |
| C10     | 22.883(797) | 20.755(028) | 19.362(018) | 18.302(009) | 19.504(477) | 19.957(024) |
| C9      | 21.254(205) | 18.924(009) | 18.013(008) | 17.676(008) | 19.446(016) | 18.434(008) |
| C8      | 18.328(013) | 17.040(008) | 16.529(008) | 16.328(008) | 17.433(009) | 16.743(007) |
| C7      | 17.105(016) | 15.147(011) | 14.753(011) | 14.603(011) | 15.476(009) | 14.905(010) |
| C6      | 19.988(034) | 17.292(009) | 16.115(008) | 15.624(008) | 17.938(010) | 16.675(007) |
| C5      | 17.105(016) | 15.081(016) | 14.832(009) | 14.589(010) | 16.352(009) | 15.675(010) |
| C4      | 19.203(016) | 16.529(008) | 15.463(008) | 15.067(009) | 17.141(009) | 15.963(008) |
| C3      | 20.418(046) | 18.628(008) | 17.953(008) | 17.691(008) | 19.104(015) | 18.247(008) |
| C2      | 16.360(021) | 15.186(015) | 14.762(015) | 14.630(015) | 15.545(009) | 14.943(010) |
| C1      | 19.203(016) | 16.529(008) | 15.463(008) | 15.067(009) | 17.141(009) | 15.963(008) |

Note.—Uncertainties given in parentheses in thousandths of a magnitude correspond to the rms of the magnitudes obtained on four photometric nights, with a minimum uncertainty of 0.015 mag for an individual measurement.
| JD - 2,453,000 | Epoch* (days) | Telescope | $u'$ | $g'$ | $r'$ | $i'$ | $B$ | $V$ | $T_{eb}$ (K) | $L_{(u'-i')}$ (ergs s$^{-1}$) | $L_{bol}$ (ergs s$^{-1}$) |
|----------------|--------------|-----------|------|------|------|------|-----|-----|-------------|--------------------------|----------------------|
| 444.81         | -54          | KAIT      | ...  | ...  | ...  | ...  | ... | ... | ...          | ...                      | ...                  |
| 459.79         | -39          | Swope     | ...  | ...  | ...  | ...  | ... | ... | ...          | ...                      | ...                  |
| 466.80         | -32          | Swope     | ...  | ...  | ...  | ...  | ... | ... | ...          | ...                      | ...                  |
| 467.65         | -32          | Swope     | 18.69(021) | 17.99(015) | 17.93(015) | 18.04(015) | 18.19(016) | 17.92(015) | 9567 | 42.014 | 42.146 |
| 468.58         | -31          | Swope     | 18.43(016) | 17.89(015) | 17.88(015) | 18.00(017) | 18.06(016) | 17.89(014) | 10082 | 42.061 | 42.183 |
| 472.59         | -27          | Swope     | 17.98(016) | 17.57(015) | 17.57(015) | 17.65(015) | 17.75(016) | 17.58(015) | 10040 | 42.203 | 42.325 |
| 473.61         | -26          | Swope     | 17.90(016) | 17.50(015) | 17.53(015) | 17.58(015) | 17.70(016) | 17.52(015) | 9872 | 42.228 | 42.352 |
| 474.57         | -25          | Swope     | 17.93(016) | 17.47(015) | 17.46(015) | 17.68(016) | 17.46(014) | 9575 | 42.236 | 42.365 |
| 475.64         | -24          | Swope     | 17.99(016) | 17.48(015) | 17.49(015) | 17.68(016) | 17.45(015) | 9214 | 42.237 | 42.373 |
| 475.78         | -24          | KAIT      | ...  | ...  | ...  | ...  | ... | ... | ...          | ...                      | ...                  |
| 476.56         | -23          | Swope     | 18.09(016) | 17.51(015) | 17.46(015) | 17.47(015) | 17.72(016) | 17.46(015) | 8912 | 42.223 | 42.365 |
| 476.73         | -23          | KAIT      | ...  | ...  | ...  | ...  | ... | ... | ...          | ...                      | ...                  |
| 477.56         | -22          | Swope     | 18.24(016) | 17.54(015) | 17.37(015) | 17.41(015) | 17.76(016) | 17.47(015) | 8297 | 42.209 | 42.366 |
| 479.57         | -21          | Swope     | 18.34(017) | 17.55(014) | 17.34(015) | 17.39(015) | 17.80(016) | 17.45(015) | 7974 | 42.200 | 42.366 |
| 479.52         | -20          | Swope     | 18.44(023) | 17.55(015) | 17.29(015) | 17.32(015) | 17.79(016) | 17.39(015) | 7673 | 42.206 | 42.381 |
| 480.54         | -19          | Swope     | 18.55(020) | 17.52(015) | 17.25(015) | 17.29(015) | 17.78(016) | 17.36(015) | 7622 | 42.206 | 42.387 |
| 481.51         | -18          | Swope     | 18.58(026) | 17.49(016) | 17.20(015) | 17.25(015) | 17.77(016) | 17.34(015) | 7462 | 42.215 | 42.400 |
| 482.52         | -17          | Swope     | 18.58(050) | 17.46(030) | 17.14(026) | 17.15(020) | 17.71(025) | 17.28(022) | 7262 | 42.238 | 42.433 |
| 483.54         | -16          | Swope     | 18.53(037) | 17.37(015) | 17.11(015) | 17.14(015) | 17.64(016) | 17.22(015) | 7596 | 42.258 | 42.442 |
| 484.61         | -15          | Swope     | 18.36(040) | 17.31(015) | 17.06(015) | 17.08(015) | 17.61(016) | 17.16(015) | 7485 | 42.285 | 42.469 |
| 489.51         | -10          | Swope     | 17.87(016) | 16.90(015) | 16.74(015) | 16.74(015) | 17.14(016) | 16.80(015) | 8033 | 42.448 | 42.617 |
| 490.50         | -9           | Swope     | 17.68(016) | 16.78(015) | 16.62(015) | 16.68(015) | 17.02(016) | 16.72(015) | 8350 | 42.493 | 42.652 |
| 491.48         | -8           | Swope     | 17.50(016) | 16.69(014) | 16.55(015) | 16.64(015) | 16.93(016) | 16.63(015) | 8675 | 42.534 | 42.683 |
| 493.51         | -6           | Swope     | 17.27(043) | 16.60(033) | ...        | ...        | 16.79(025) | 16.53(025) | 8677 | 42.586 | 42.734 |
| 495.54         | -4           | Swope     | 17.14(016) | 16.52(015) | ...        | ...        | 16.75(016) | 16.47(015) | 8486 | 42.616 | 42.768 |
| 496.54         | -3           | Swope     | 17.15(017) | 16.50(015) | ...        | ...        | 16.72(016) | 16.47(015) | 8449 | 42.624 | 42.778 |
| 497.46         | -2           | Swope     | 17.09(016) | 16.49(015) | ...        | ...        | 16.69(016) | 16.44(015) | 8333 | 42.635 | 42.793 |
| 497.47         | -2           | Clay      | ...  | ...  | ...  | ...  | ... | ... | ...          | ...                      | ...                  |

Note.—Photometric uncertainties given in parentheses in thousandths of a magnitude. A minimum uncertainty of 0.015 mag was set.

* Rest-frame days since $L_{bol}$ maximum (JD 2,453,499.8).

* Synthetic magnitude computed from the spectrum obtained the same night.
The Clarity, the magnitudes in each band have been shifted by an arbitrary constant. For smaller than the symbols. The time axes are given in the observer’s frame. For corresponding light curves. We computed standard magnitudes of bright stars (Paper I). Figure 2 shows the typical scatter in the transformation from instrumental to standard magnitudes of SN 2005bf and their uncertainties are listed in Table 2. A minimum uncertainty of 0.01–0.03 mag was assumed for a single measurement based on the data sampling rates. A star symbol marks a synthetic i’ magnitude obtained from the LDSS-3 spectrum of May 7 (JD 2,453,497). The arrow marks an r’ lower limit from a KAIT image obtained on March 15 (JD 2,453,445). Unless explicitly drawn, the error bars are smaller than the symbols. The time axes are given in the observer’s frame. For clarity, the magnitudes in each band have been shifted by an arbitrary constant.

The SN on April 15 (JD 2,453,475; r’ = 17.419 mag) and 16 (JD 2,453,476; r’ = 17.426 mag) with those obtained with the Swope telescope on the same nights (r’ = 17.409 and 17.406, respectively) confirms that the effective wavelength of the r’ filter is a good match to that of the KAIT unfiltered bandpass. The first LOSS observation obtained on March 15 (JD 2,453,445), in which the SN is not detectable, was used to derive a lower limit to the SN magnitude of r’ > 20.0 mag.

A 17 day gap in the r’ and i’ observations with the Swope telescope was partially filled with an r’ image and a spectrum obtained on May 7 (JD 2,453,497) using the Low Dispersion Survey Spectrograph 3 (LDSS-3) at the Clay 6.5 m telescope at LCO. For this purpose, we used the filter response functions of r’ and i’ given by Smith et al. (2002) to compute a synthetic (r’ – i’) color from the spectrum and thence to derive a synthetic i’ magnitude from the observed r’ magnitude.

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The uncertainty in the light curves. The small scatter seen in the light curves (typically 0.01–0.03 mag) is an indication that the contamination must be very small.

As mentioned in § 1, the u’g’r’i’BV light curves of SN 2005bf show a unique behavior consisting of a first maximum around April 13 (JD 2,453,474), a subsequent decline lasting several days, a second rise that brings the SN to a main maximum around May 8 (JD 2,453,498), and finally a 30 day fast decline phase followed by a slower decline phase. Although the r’i’ light curves do not show this double maximum, they do show a shoulder around the time of the first maximum. The other remarkable feature is the long time (~40 days) in all filters the SN took to reach the main maximum. There is a large range in light-curve width among Type Ib/Ic SNe (Hamuy 2004), with the hypernovae SN 1997ef and SN 1998bw having two of the broadest ones, but even these objects took between 15 and 20 days to reach maximum light (Galama et al. 1998; Iwamoto et al.

![Fig. 2.—Observed u’g’r’i’BV light curves of SN 2005bf from Swope (open and filled circles), KAIT (filled triangles), and Clay (open square). A star symbol marks a synthetic i’ magnitude obtained from the LDSS-3 spectrum of May 7 (~JD 2,453,497). The arrow marks an r’ lower limit from a KAIT image obtained on March 15 (~JD 2,453,445). Unless explicitly drawn, the error bars are smaller than the symbols. The time axes are given in the observer’s frame. For clarity, the magnitudes in each band have been shifted by an arbitrary constant.](image1)

![Fig. 3.—Top: Temperature TBB from the blackbody fits to the B through i’ filters to the B through i’ monochromatic fluxes. Bottom: Observed color evolution for (u’ – g’), (B – V’), (g’ – r’), and (r’ – i’). Circles mark colors computed directly from measurements in both bands, while squares are used when one of the light curves was interpolated in time. Unless explicitly drawn, the error bars are smaller than the symbols. The time axes are given in the observer’s frame. No reddening correction was applied.](image2)

| Filter | JD at Peak | Peak Magnitude |
|--------|------------|----------------|
| u’     | 497.9 ± 0.5 | 17.10 ± 0.01   |
| g’     | 498.1 ± 0.5 | 16.50 ± 0.01   |
| i’     | 500.2 ± 1.0  | 16.32 ± 0.01   |
| r’     | 502.9 ± 1.0  | 16.32 ± 0.02   |

Notes.—Uncertainties in the peak magnitudes were estimated from the rms of the photometric points about a low-order polynomial fit. Uncertainties in the dates of maximum are based on the data sampling rates. * Absolute bolometric magnitude based on Lbol from Table 2 (no host-galaxy correction applied).
Table 4

NEAR-INFRARED PHOTOMETRY OF TWO COMPARISON STARS

| Star ID | Y      | J      | H      | Ks     |
|---------|--------|--------|--------|--------|
| C10     | 17.40(02) | 17.16(02) | 16.87(05) | 16.72(06) |
| C11     | 16.97(02) | 16.58(02) | 16.12(02) | 16.00(03) |

Note.—Uncertainties given in parentheses in hundredths of a magnitude. A minimum uncertainty of 0.02 mag was set.

Table 5

NEAR-INFRARED PHOTOMETRY OF SN 2005bf

| JD  -2,453,000 | Epoch* (days) | Y      | J      | H      | Ks     |
|----------------|---------------|--------|--------|--------|--------|
| 483.51         | -16           | 16.93(03) | 16.75(03) | 16.65(05) | ...    | WIRC   |
| 483.52         | -16           | 16.92(03) | 16.76(03) | 16.64(05) | ...    | WIRC   |
| 511.46         | 11            | 16.19(03) | 15.95(03) | 15.87(05) | 15.80(06) | PANIC  |
| 538.46         | 38            | ...     | 16.91(03) | ...     | 16.43(05) | PANIC  |

Notes.—WIRC data were obtained with two detectors and their magnitudes agree within uncertainties. We use the averages in the present analysis. Uncertainties are given in parentheses in hundredths of a magnitude. A minimum uncertainty of 0.02 mag was set for individual measurements. Uncertainties in the zero points arising from uncertainties in the magnitudes of comparison stars were added in quadrature to the measurement errors.

* Rest-frame days since \( L_{bol} \) maximum (JD 2,453,499.8).
shown at the bottom of Figure 5, the spectra from day +21 and later became almost identical to those of the Type Ib SN 1984L. This transformation was also noticed by Wang & Baade (2005). Interestingly, as shown in the middle of Figure 5, the spectrum from day -20 (and also those from days -2 and +2) was remarkably similar to spectra of the intermediate Type Ib/Ic SN 1999ex obtained around maximum light (Hamuy et al. 2002).

Figure 4 indicates that the He\textsc{i} $\lambda\lambda 5876, 6678, 7065$ lines were present, albeit weakly, in the first spectra of SN 2005bf and grew steadily in strength during the period covered by our observations. The expansion velocities as measured from the absorption minima of these features were nearly constant, at a value of 8000–10,000 km s$^{-1}$, until maximum light and dropped to 6000 km s$^{-1}$ after that.

As a tool for analyzing the premaximum spectral evolution of SN 2005bf, we used the SYNOW code (Fisher 2000) to calculate synthetic spectral fits to our first five spectra. Following the precepts of Branch et al. (2002), we assumed a power-law radial density gradient of index $n = 8$ and a Boltzmann excitation temperature of $T_{\text{exc}} = 7000$ K for all of these fits. In general, only the Fe\textsc{ii}, Ca\textsc{ii}, He\textsc{i}, and H\textsc{i} ions were included in the

| JD -2,453,000 | Epoch$^a$ (days) | Instrument | Wavelength Range (Å) | Resolution$^b$ (Å) | Exposure (s) | (S/N)$^c$ (in 10$^8$) |
|---------------|------------------|------------|----------------------|-------------------|--------------|---------------------|
| 467.57        | -32              | WFCCD      | 3800–9235            | 8                 | 900          | 69                  |
| 472.60        | -27              | WFCCD      | 3800–9235            | 8                 | 900          | 88                  |
| 475.63        | -24              | WFCCD      | 3800–9235            | 8                 | 900          | 74                  |
| 479.51        | -20              | WFCCD      | 3800–9235            | 8                 | 900          | 74                  |
| 497.47        | -2               | LDSS-3     | 3838–10000           | 4$^d$             | 200          | 262                 |
| 501.89        | 2                | LRIS       | 3100–9350            | 4                 | 300/360$^e$ | 343                 |
| 502.48        | 3                | LDSS-3     | 6057–10000           | 5                 | 900          | 200                 |
| 521.50        | 21               | WFCCD      | 3800–8125            | 8$^f$             | 1200         | 64                  |
| 523.49        | 23               | WFCCD      | 3800–8128            | 8                 | 1200         | 42                  |
| 527.54        | 27               | WFCCD      | 3800–8128            | 8                 | 600          | 55                  |

Note.—Some spectra are the combination of multiple observations. In those cases, total exposure times are given.

$^a$ Rest-frame days since $L_{\text{bol}}$ maximum (JD = 2,453,499.8).

$^b$ Average resolution obtained from the FWHM of arc lamp lines.

$^c$ Average S/N in 10 Å bins calculated in the range from 4000 to 9000 Å.

$^d$ Resolution of 2.9 Å in the blue channel (3800 $< \lambda <$ 6000 Å), and 4.7 Å in the red channel (6000 $< \lambda <$ 10000 Å).

$^e$ Different exposure times in blue channel (300 s) and red channel (360 s).

$^f$ A wide slit (8"x5") was used. In this case the resolution was estimated from the FWHM of the spatial profile of the SN.
suggests that the appearance of high-velocity Fe\textsc{ii} absorption. Similarly, a low-velocity Fe\textsc{ii} component, helps to fit the red wing of the H and K absorption. The high-velocity component of Fe\textsc{ii} lines is associated with the initial maximum exhibited by the observed spectra. The epoch is given in rest-frame days relative to the observed maximum.

The addition of other ions would not modify our conclusions. We consider the value of high-velocity H\textalpha\ absorption, like the high-velocity Fe\textsc{ii} and Ca\textsc{ii} lines, was present at early epochs but disappeared by the time of maximum light. A similar feature has been seen in several Type Ib SNe, and its identification is a long-debated issue (e.g., see Wheeler et al. 1994; Branch et al. 2002). We consider the most likely identification to be high-velocity ($\sim 15,000\ km\ s^{-1}$) H\textalpha\ for two basic reasons: (1) the coincidence in expansion velocity with the Fe\textsc{ii} and Ca\textsc{ii} lines, which show a similar association with the peculiar initial maximum in the $u'g'r'i' BV$ light curves, and (2) the presence of a very weak absorption feature in the spectra from days $-24$ and $-20$ (Fig. 4, dotted line), which could be identified as H\beta at the same expansion velocity and with a strength consistent with that predicted by SYNOW spectra. We reject the alternative identification of this feature with Si\textsc{ii} $\lambda 6355$, since it would imply an expansion velocity of $\sim 4800\ km\ s^{-1}$, which is significantly lower than the photospheric velocity estimated at these early epochs. We consider identifications with C\textsc{iii} $\lambda 6580$ or Ne\textsc{ii} $\lambda 6402$ unlikely for the same reasons given by Branch et al. (2002) for ordinary Type Ib SNe. Thus, a small amount of hydrogen appears to be present in the outer ejecta of SN 2005bf.

### 4.2. Bolometric Light Curve

The $u'g'r'i' BV$ photometry was used to compute a quasi-bolometric light curve covering the wavelength range longward of $3000\ \AA$. Our broadband magnitudes were corrected for Galactic extinction using $E(B-V)_{\text{G}} = 0.045$ mag (Schlegel et al. 1998) and the reddening law with $R_V = 3.1$ given by Cardelli et al. (1989). Additional extinction originating in the host galaxy is difficult to estimate. Examination of our spectra from days $-2$ and $+2$, which have the best wavelength resolution and signal-to-noise ratios, reveals the presence of interstellar absorption lines of Na\textsc{i} D1 and D2 and Ca\textsc{ii} H and K at the redshift of the host galaxy, suggesting that some extinction exists. However, the uncertainties in estimating $E(B-V)_{\text{host}}$ from the equivalent widths (EWs) of these lines are large. We measure the total EW of the Na\textsc{i} D1 and D2 lines to be $\sim 1\ \AA$. According to Turatto et al. (2003), two values of the color excess would be favored: $E(B-V)_{\text{host}} = 0.1$ and 0.5 mag, depending on the gas-to-dust ratio of the host galaxy environment. We consider the value $E(B-V)_{\text{host}} = 0.5$ mag to be unrealistic because it would imply color temperatures $\gtrsim 40,000\ K$ during the time of initial maximum (see below). Such high temperatures do not agree with the ion species observed in our spectra. Hence, the lower value of $E(B-V)_{\text{host}} \approx 0.1$ mag seems more likely. Close examination of the day $-2$ spectrum reveals Na\textsc{i} D absorption due to our own Galaxy at an equivalent width of approximately $\sim 0.5\ \AA$. If the interstellar medium in the host galaxy of SN 2005bf is similar to that of the Galaxy, this would also suggest an extinction of $E(B-V)_{\text{host}} \approx 0.1$ mag. Given the uncertainties, we adopt $E(B-V)_{\text{host}} = 0.0$ mag for our analysis but present the case of $E(B-V)_{\text{host}} = 0.1$ mag as an alternative.

The extinction corrected $u'g'r'i' BV$ broadband magnitudes were converted into monochromatic fluxes at the effective wavelengths of 3557, 4825, 6261, 7672, 4448, and 5505 $\AA$, respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.pdf}
\caption{SYNOW fits to the premaximum spectra of SN 2005bf. The SYNOW synthetic spectra, which are described in the text, are overplotted on the observed spectra. The epoch is given in rest-frame days relative to the observed maximum.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.pdf}
\caption{The $u'g'r'i' BV$ light curves. The evolution of the expansion velocities of these components is summarized in the right half of Figure 7.}
\end{figure}

13 According to Wang & Baade (2005), weak absorption consistent with H\beta and H\gamma was also present in a spectrum obtained on April 30 (day $-9$).

14 Nevertheless, we cannot rule out that the absorption is produced by a blend of high-velocity H\alpha with Si\textsc{ii} $\lambda 6355$ at $8000-10,000\ km\ s^{-1}$. 

11 According to Wang & Baade (2005), weak absorption consistent with H\alpha and H\gamma was also present in a spectrum obtained on April 30 (day $-9$). The extinction corrected $u'g'r'i' BV$ broadband magnitudes were converted into monochromatic fluxes at the effective wavelengths of 3557, 4825, 6261, 7672, 4448, and 5505 $\AA$, respectively.
as given by Fukugita et al. (1996; their Tables 2a and 2b). At epochs when a certain filter observation was not available, its magnitude was interpolated in time from the light curve using the surrounding points and a low-order polynomial. The total “UVOIR” flux $F_{\lambda'}^{\prime}$ in the region between the effective wavelengths of the $\lambda'$ and $i'$ filters was integrated using the trapezoidal approximation. On the blue side of 3557 Å the flux $F_{\lambda'}^{\prime}(3557)$ derived from the $\lambda'$ magnitude was extrapolated with a straight line to zero flux at 5000 Å (the blueward limit of the $\lambda'$ filter), and no significant flux was supposed to be emitted at shorter wavelengths, an assumption based on observations of other Type Ib/Ic SNe and of SN 1987A (Panagia 2003). On the infrared side the flux was extrapolated to $\lambda = \infty$ using a BB model obtained by fitting the $g'/i'/B/V$ fluxes with a Planck function (shifted to the rest frame of the SN).\footnote{The $\lambda'$ points were excluded from the BB fits because they clearly departed from the model, especially before maximum light. The $\lambda'$ fluxes generally lay below the fitted BB curves, probably due to strong line blanketing in that part of the spectrum. The effect of including $\lambda'$ would be to lower the derived BB temperature values. For consistency, we kept the same policy for postmaximum epochs, even though there was a better agreement of the $\lambda'$ fluxes with the fitted BB curves.}

The integrated flux under the fitted Planck function between the effective wavelength of the $i'$ filter and $\lambda = \infty$ was taken as the IR correction. This correction remained below 35% of the total flux until a few days after maximum light and increased to 60% thereafter. A by-product of this procedure is the color temperature ($T_{bb}$) obtained from the BB fits. The values of $T_{bb}$ for $E(B-V)_{\text{host}} = 0.0$ mag are given in Table 2 and shown in Figure 3, along with the observed SN colors.\footnote{As a further corroboration, we included the few NIR photometry points in the BB fits. This exercise showed an agreement within 10% between the bolometric flux based on $u'$ through $i'$ and that based on $u'$ through $K_s$ (or $u'$ through $B$ on JD 2,453,483.5). The BB fits showed a systematic increase in temperature of about 500 to 800 K when going from a range of $B$ through $i'$ to $B$ through $K_s$.} The sum of $F_{\lambda'}^{\prime}$ and the UV and IR corrections yielded the bolometric flux $F_{\text{bol}}$.

Both $F_{\lambda'}^{\prime}$ and $F_{\text{bol}}$ were then transformed into UVOIR ($L_{\lambda'}^{\prime}$) and bolometric luminosity ($L_{\text{bol}}$), respectively. We assumed spherical symmetry and used a distance of 83.8 ± 10.2 Mpc based on the Hubble law, a value of the Hubble constant of $H_0 = 72 ± 8$ km s$^{-1}$ Mpc$^{-1}$ (Freedman et al. 2001), and a recession velocity in the cosmic microwave background frame of 6032 ± 300 km s$^{-1}$ (obtained from the heliocentric velocity given by Falco et al. [1999]), and using the velocity transformation tool from the NASA/IPAC Extragalactic Database). The resulting luminosities computed with $E(B-V)_{\text{host}} = 0.0$ mag are listed in Table 2, and the bolometric light curves of SN 2005bf are shown in Figure 8 for both $E(B-V)_{\text{host}} = 0.0$ mag (filled circles) and $E(B-V)_{\text{host}} = 0.1$ mag (dashed line). The UVOIR luminosities are shown with a dotted line. The luminosity corresponding to JD 2,453,565.5 is plotted with an error bar between 4.8 × 10$^{41}$ and 5.4 × 10$^{41}$ ergs s$^{-1}$ owing to the large uncertainties in the $r'i'j'k'$ magnitudes.

Four late-time observations obtained with the Swope 1 m telescope between JD 2,453,538 and 2,453,570 involved only the $BVI$ filters. In those cases, integration of the flux in the optical

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**Figure 7.—** Left: Evolution of the spectral region centered on the Fe $\lambda 4924$, 5018, 5169 lines during the rise to maximum light. The observed spectra are compared with SYNOW synthetic spectral calculations. The three vertical solid lines indicate the approximate wavelengths of this Fe $\lambda$ multiplet in the high-velocity gas that is visible during the peculiar initial maximum in the $u'/y'BV$ light curves. The three vertical dashed lines show the same multiplet at lower expansion velocity. Note that from day $-27$ through day $-20$, both velocity components are clearly present in the spectra. Right: Expansion velocity measurements for SN 2005bf. The expansions of the He $\lambda$ lines are plotted with an asterisk. The time axes are given in the observer’s frame.

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\[ \text{SN 2005bf} \]
1. The relation above was used to derive the colors for the late-time epochs lie in the range from 1.04 to quantities in the range 0.032 for the Type Ib/SN, both its photometric and spectroscopic evolution leading up to maximum light were unusual in many respects, as follows:

2. The initial maximum observed in the u’g’’BV light curves is, to our knowledge, without precedent in Type Ib/Ic light curves. Although it superficially resembles the shock blowouts observed for the Type Ib/Ic SN 1999ex (Stritzinger et al. 2002) and the Type Ib SN 1999J (Richmond et al. 1994), in both of those cases the first rise occurred very quickly (<2 days), whereas the first maximum in SN 2005bf occurred at least 2 weeks following outburst. This much longer rise time argues strongly against it being due to shock breakout.

3. The bolometric light curve did not reach maximum until at least 40 days after outburst. Such a long rise time seems to be unique, although few Type Ib/Ic SNe have been caught early enough for us to be completely sure of this. We are aware of only two other Type Ic events, the hypernovae SN 1997ef and SN 1998bw, which exhibited V light curves of comparable width, although with shorter rise times (Galama et al. 1998; Iwamoto et al. 2000).

4. SN 2005bf was also unusually luminous for a Type Ib/Ic SN, radiating $10^{49}$ ergs in the wavelength range of 3000 Å during the first ~75 days following outburst (assuming spherical symmetry). This is nearly identical to the energy that we derived integrating the bolometric light curve of the hypernova SN 1998bw (Patat et al. 2001).

5. The transformation from a Type Ic SN at early epochs to a Type Ib SN by maximum light is also unprecedented. However, we must point out that few Type Ib/Ic SNe have been observed spectroscopically at such early epochs. It should be noted that if SN 2005bf had not been discovered until maximum light, it would have been classified as a fairly typical Type Ib SN. This serves to emphasize the importance of observing SNe as soon as possible after outburst.

6. The initial maximum in the u’g’’BV light curves was accompanied by the presence in the spectrum of high-velocity absorption lines of Fe ii, Ca ii, and H i. This absorption had disappeared by the time of the principal maximum in the bolometric light curve, which argues for it being physically associated with the mechanism responsible for the initial maximum.

7. The photospheric velocity of 9000–10,000 km s$^{-1}$ observed at the early epochs (~30 days before maximum) was unusually low compared with typical Type Ib SNe (Branch et al. 2002).

The unique properties of SN 2005bf summarized above indicate an unusual event, one having certain features in common with ordinary Type Ib/c SNe (see § 4.1), Type Ib events such as...
SN 1993J (Filippenko et al. 1993) and highly energetic SNe such as those seen in conjunction with GRBs 990425 (Galama et al. 1998) and 030329 (Hjorth et al. 2003; Stanek et al. 2003; Matheson et al. 2003). Both the high luminosity at the main peak and the long rise time argue for a more massive helium core and larger mass of \(^{56}\text{Ni}\) than in ordinary Type Ib/Ic SNe. Assuming a light curve dominated at peak by radioactive decay and complete trapping, to produce a luminosity of \(6 \times 10^{42}\) ergs s\(^{-1}\) 40 days after the explosion requires about 0.6 \(M_\odot\) of \(^{56}\text{Co}\) (made as \(^{56}\text{Ni}\) in the explosion). Such a large mass of \(^{56}\text{Ni}\) is not produced in spherically symmetric explosions unless the explosion energy is very high, much greater than the canonical 10\(^{51}\) ergs, and the density gradient near the iron core is shallow, as in massive stars (\(\geq 25 M_\odot\); Woosley & Weaver 1995).

On the other hand, the comparative faintness of the light curve during its first few days and the fact that the effective temperature was increasing at earlier times, rather than cooling, argue for a compact progenitor, neither a red nor blue supergiant. A red supergiant of any sort would be too bright and too hot initially and would cool monotonically with time. A blue supergiant with a radioactive peak around 40 days would be too faint on day 10 and would also have a declining temperature at early times.

The high-velocity hydrogen (with no low-velocity counterpart) shows that the star had lost most, but not all of its hydrogen envelope. The surface layers are shock accelerated to the highest speeds and a low mass of hydrogen would not mix extensively with the rest of the star. It seems that the progenitor was a Wolf-Rayet star of spectral class WN (Maeder & Meynet 1994) with less than 0.1 \(M_\odot\) of hydrogen in its outer layers.

Within these confines, we explored a variety of models, but found no physically reasonable solutions under the assumption of spherical symmetry and a monotonically decreasing radial abundance of \(^{56}\text{Ni}\). The most successful one-dimensional model was the 2.0 \(\times 10^{51}\) ergs explosion of an 8.29 \(M_\odot\) WN star with a mildly inverted distribution of \(^{56}\text{Ni}\) with mass as shown in Figure 9. This star had a total \(^{56}\text{Ni}\) mass of 0.6 \(M_\odot\), of which about 0.04 \(M_\odot\) was artificially sited in the helium shell. Except for the usual “mixing,” this was essentially the same helium and heavy-element core one obtains by evolving a 25 \(M_\odot\) main-sequence star to its end point. The vast bulk of the hydrogenic envelope was presumably lost to a binary companion quite late in the evolution. We did not conduct a broad survey of progenitor masses because we thought the restriction of doing one-dimensional models did not warrant such an approach. It is possible that an acceptable model might also have been found for a higher mass helium core and larger explosion energy.

Roughly the outer 0.05 \(M_\odot\) of the WN star was composed of hydrogen and helium with mass fractions of 0.34 and 0.66, respectively. Terminal velocities ranged from 13,000 \(\text{km s}^{-1}\) at the base of this “envelope” to over 30,000 \(\text{km s}^{-1}\) in the outer 0.001 \(M_\odot\). The rms velocity in the hydrogen-rich material was 18,000 \(\text{km s}^{-1}\). All calculations of presupernova evolution and explosive hydrodynamics up to the point of shock breakout were done with the KEPLER implicit hydrodynamics package (Weaver et al. 1978; Woosley et al. 2002). The hydrogen envelope was removed at the end of helium burning and the star was in hydrostatic and thermal equilibrium at the time it exploded.

The light curve and multiband photometry of this model were then calculated using the STELLA code of Blinnikov et al. (1998) and Blinnikov & Sorokina (2000). Although no fine-tuning was attempted, Figure 10 shows that this model gave a qualitatively good fit to both the observed bolometric luminosity and individual colors up until the main peak. To achieve reasonable agreement beyond the main peak, however, much greater \(\gamma\)-ray leakage had to be invoked than was calculated by STELLA for the spherically symmetric model. This was achieved by turning down the \(\gamma\)-ray opacity by a factor of 10, while leaving the UVOIR opacities unaltered. During the rise to maximum this alteration had no effect, since the optical depth was very large. After the maximum, however, the decline rate was greatly accelerated. We were unable to find a model with unaltered \(\gamma\)-ray opacity in which the light curve peaked so late and then declined so quickly.

All of these characteristics—the high explosion energy, large \(^{56}\text{Ni}\) mass, inverted distribution of \(^{56}\text{Ni}\), and the need for \(\gamma\)-ray leakage at late times—are suggestive of a grossly asymmetric explosion having many features in common with the supernovae found coincident with GRBs (e.g., Höflich et al. 1999; Mazzali et al. 2001, 2005; Maeda et al. 2003). In fact, SN 2005bf may be the best example so far of a “transition object” between the two classes of phenomena, namely, GRBs and ordinary Type Ib SNe.

A realistic simulation of such an event will only be achievable in a multidimensional simulation that captures the essence of energetic polar jets with milder mass ejection in the equatorial plane. Lacking at present the ability to do such a full multidimensional, relativistic simulation, including the necessary radiation transport, we also considered multicomponent models to reproduce the observed light curves. The scenario we considered was that of a WN progenitor star of about 6 to 15 \(M_\odot\), whose iron core collapses either to a black hole plus an accretion disk (Woosley 1993; MacFadyen & Woosley 1999) or a very rapidly rotating neutron star (Wheeler et al. 2000). A relativistic jet was launched, as in current models for GRBs, but it was not observed, possibly because it was beamed to other angles or because it had too little energy in extremely relativistic ejecta. The jet was accompanied, however, by vigorous \(^{56}\text{Ni}\)-rich outflows extending out to approximately 45° (MacFadyen & Woosley 1999).

The polar regions thus experienced a much more violent explosion than the equator. A small fraction of the star’s mass was ejected with very high velocity at both poles along the star’s rotational axis. This material contained about 0.1 \(M_\odot\) of \(^{56}\text{Ni}\) per pole, and the observer was situated somewhat off axis. The ensuing explosion can be separated into two components: (1) a polar explosion containing a small fraction of the total mass and moving at high velocity and (2) the explosion of the rest of the star. At first only the polar explosion is observed, producing the initial maximum; when that component fades and becomes transparent, the lower velocity ejecta become visible in the rise to the main maximum light.

As a specific example, by no means unique, we consider the same 8.29 \(M_\odot\) WN star as before, but with no mixing of the \(^{56}\text{Ni}\) beyond where it was produced in the one-dimensional model (Fig. 9, dashed line). In addition to this, we represent the higher velocity component by the 2 \(\times 10^{51}\) ergs explosion of a 3.31 \(M_\odot\)
WR star that left behind a 1.52 $M_\odot$ remnant (hence the $2 \times 10^{51}$ ergs is concentrated in 1.79 $M_\odot$ of ejecta). This component contains 0.1 $M_\odot$ of 56Ni (presumably at each pole). The composite light curve and colors are given in Figure 11. At early times ($t < 20$ days), before the rapidly expanding, low-mass component has become optically thin, the more slowly moving explosion is occulted and blocked from view. At late times ($t > 20$ days), the fast component is invisible. The geometry of the slower ejecta, viewed along the equator (side), resembles the number 8. Gamma-rays can diffuse out much more effectively along the polar axis than along the equator. To account for this, the $\gamma$-ray opacity has been reduced by a factor of 10.

6. CONCLUSIONS

The computer simulations presented here, although clearly suffering from being one-dimensional, strongly suggest that the light curve and the two-component spectrum of SN 2005bf can be qualitatively explained by the very energetic explosion of a
massive star that lost almost all of its hydrogen envelope and exploded very asymmetrically. The energy and $^{56}$Ni mass implied are large compared with those of common Type Ib SNe, but the energy is intermediate between ordinary supernovae and so-called hypernovae, suggesting that SN 2005bf might be some sort of transition object between these two classes of phenomena. Given the high energy and the possible detection of polarization (Wang & Baade 2005), it is very likely that the explosion was asymmetric and will ultimately need to be modeled in at least two dimensions. The $^{56}$Ni distribution could have been very aspherical, and this particularly complicates the modeling of the first peak.

Given the previously observed association of GRBs and energetic supernovae, it is quite plausible that SN 2005bf was powered by a central engine like those being discussed for GRBs. To retain the necessary degree of rotation, it is more likely that the envelope of the star was lost to a binary companion rather than in an ordinary standard wind. The longer the star remains a red supergiant, the more its core is braked by torques from the slowly rotating envelope (Heger et al. 2005; Woosley & Heger 2006). Two-dimensional simulations should be conducted to verify the interpretation of this event as a possible “missing link.” Radio observations to limit the amount of relativistic ejecta are also encouraged.

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