1. INTRODUCTION

The study of a subclass of hydrogen-deficient supernovae, namely, Type Ib and Type Ic events, has been one of the interesting topics in supernova (SN) research. The observational properties, progenitors, and hence physics of explosions are the least understood for these two subclasses. The recently established connection of bright and energetic Type Ic SN (SN Ic) events with gamma-ray burst sources (e.g., Mazzali et al. 2003) makes their study interesting and exciting. Type Ib and Ic SNe are classified on the basis of their spectra. Both types of SN Ic SNe are classified on the basis of their spectra. Both types of SN Ibc supernovae (SNe Ibc), indicating that the SN possibly ejected $\sim0.31 M_\odot$ of $^{56}$Ni, which is more than the typical amount. The spectra of SN 2005bf around maximum are very similar to those of the Type Ib SNe 1999ex and 1984L about 25–35 days after explosion, displaying prominent He i, Fe ii, and Ca ii H and K, and the near-IR triplet P Cygni lines. Except for the strongest lines, He i absorptions are blueshifted by $\lesssim6500$ km s$^{-1}$, and Fe ii absorptions are blueshifted by $\sim7500$–8000 km s$^{-1}$. No other SNe Ib have been reported to have their Fe ii absorptions blueshifted more than their He i absorptions. Relatively weak H$\alpha$ and very weak H$\beta$ may also exist, blueshifted by $\sim15,000$ km s$^{-1}$. We suggest that SN 2005bf was the explosion of a massive He star, possibly with a trace of a hydrogen envelope.

Subject headings: line: identification — supernovae: general — supernovae: individual (SN 2005bf) — techniques: photometric — techniques: spectroscopic

Online material: color figure

2. THE OPTICAL AND BOLOMETRIC LIGHT CURVES

Photometric observations in the Bessell BVRI bands were made during May 3–28. Landolt standard regions were observed on May 27 to calibrate a sequence of secondary standards in the supernova field. The magnitudes of SN 2005bf and the secondary standards in the field were obtained by point-spread function photometry. The BVRI light curves of SN 2005bf are shown in Figure 1. Also included in the figure with the R magnitudes are the unfiltered CCD magnitudes reported in the IAU Circulars and the estimates made by amateurs. The premaximum evolution of SN 2005bf was quite peculiar and different from that of other SNe Ibc. SN 2005bf had a very slow rise to the maximum, which occurred around 2005 May was reported by Hamuy et al. (2005) to undergo unusual photometric behavior. After an initial brightening from April 7 to 13, the supernova declined until April 21, after which it brightened to magnitudes brighter than the initial maximum (see light curves posted at the Carnegie Supernova Project [CSP] group Web site). Spectra obtained during the rebrightening (Wang & Baade 2005; Modjaz et al. 2005a) indicated that the spectrum had developed conspicuous lines of He i similar to Type Ib supernovae. Also, the SN reached a bright maximum, making it an interesting target.

In this Letter we present optical spectroscopy of SN 2005bf obtained near the maximum and optical photometry during the maximum and subsequent decline. CCD photometric and spectroscopic observations were performed with the 2 m Himalayan Chandra Telescope (HCT) at the Indian Astronomical Observatory (IAO), Hanle, India, using the Himalaya Faint Object Spectrograph Camera (HFOSC).
photometry, corrected for the assumed, into BVRI (HyperLeda database). SN 2005bf declined with rates of 0.07, 0.038, 0.05, and 0.014 mag day$^{-1}$ in B, V, R, and I, respectively, which are similar to the decline rates observed in Type Ib SN 1999ex at similar epochs with respect to maximum.

In this Letter we assume the date of explosion to be 2005 March 30 (JD 2,453,509.5), based on Moore & Li (2005) and the light curve posted by the CSP. A Galactic reddening $E(B-V) = 0.045$ as estimated by Schlegel et al. (1998) in the direction of the host galaxy has been used. As the supernova occurred in one of the spiral arms of the host galaxy, reddening within the host is also expected. However, since no conspicuous Na I D absorption features have been reported, we assume negligible extinction due to the host galaxy. We adopt a distance modulus of $\mu = 34.5$ for the host galaxy using $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Lambda = 0.7$, $\Omega_m = 0.3$, and a redshift of $z = 0.0188$ (HyperLeda database).

The bolometric magnitudes were estimated by converting our BVRI photometry, corrected for the assumed $E(B-V)$, into absolute monochromatic fluxes, adopting the magnitude-to-flux conversion factors compiled by Bessell et al. (1998). The fluxes were then integrated using a fitting spline curve. Around the light maximum, extending the spline fit only to 3600 Å gives bolometric magnitudes about 0.15–0.2 mag fainter than if the fit were extended to 3000 Å, while there is no significant difference around the epochs of our last observations, indicating a significant contribution by the $U$ flux around maximum. Hence, the bolometric magnitudes are estimated with zero-flux terminals of the spline fit chosen as 3000 Å and 2.480 μm in an effort to recover as much as possible the $U$ and near-infrared fluxes that were missed by our photometry. Adding a conservative uncertainty, ±0.2, to the bolometric magnitudes, we estimate the bolometric magnitude at maximum to be $M_{bol} = -18.0 \pm 0.2$ on May 11 (JD 2,453,502.1). We plot in Figure 2 the evolution of the absolute magnitude in $B$ ($M_B$) for SN 2005bf since our assumed date of explosion and compare it with other SNe Ib/c, namely, SN 1999ex (Stritzinger et al. 2002), SN 1994I (Richmond et al. 1996), SN 1984L (Tsvetkov 1987; Schlegel & Kirshner 1989), and SN 1985F (Tsvetkov 1986). The maximum bolometric magnitude (inset in Fig. 2) of SN 2005bf is brighter than the average value for Type Ib/c SNe, even though the time of maximum was significantly later. Furthermore, the $B-V = 0.37$ color at maximum indicates SN 2005bf to be marginally bluer.

The rise time depends on the mass and the explosion energy (e.g., Nomoto et al. 2004). The slow rise suggests a relatively low ratio of explosion energy to ejected mass. A detailed modeling of the light curve and the spectra are beyond the scope of this work and will be reported in a later paper (Tominaga et al. 2005). However, preliminary calculations indicate a tentative value for the explosion energy of $\sim (1.0–1.5) \times 10^{51}$ ergs and an ejected mass of $\sim 6–7 M_\odot$. The brightness of the peak and its late occurrence suggest a relatively large production of $^{56}$Ni ($\sim 0.31 M_\odot$), which points to a rather massive progenitor ($\sim 25–30 M_\odot$; Tominaga et al. 2005).

3. THE SPECTRA

Spectra of SN 2005bf were obtained at a resolution of 8 Å in the wavelength ranges 3600–7200 and 5200–9200 Å on May 4.65, 6.62, and 8.63 (UT) (marked by vertical lines in Fig. 1). All observations were made using a slit of 2.2 width and aligned along the parallactic angle. Spectrophotometric standards HZ 44 and BD +33 2642 observed on 2005 May 4 were used to correct the supernova spectra for the response curves of the instrument and bring them to a flux scale. The spectra in the two different regions were combined, scaled to

![Figure 1: BVRI magnitudes of SN 2005bf.](image1)

![Figure 2: Evolution of $M_B$ of SN 2005bf from the day of explosion compared with other Type Ib/c SNe.](image2)
The spectra show prominent and broad P Cygni lines of Fe II, Fe II, and Ca II. The Fe I λ5876 P Cygni feature is strong, and its identification is supported by the presence of clear Fe I λ6678 and λ7065, although Na I D could also contribute. He I λ7281 may also exist. However, it should be noted that this feature is affected by the telluric H$_2$O absorption, and our spectra are not corrected for the telluric features. The velocities corresponding to the absorption minima of the relatively weak He I λ6678, λ7065, and λ7281 (if real) have average velocities of \( \pm 6500 \text{ km s}^{-1} \), lower than that of He I λ5876, which is \( \sim 7300 \text{ km s}^{-1} \). The very strong P Cygni feature between 3700 and 4100 Å and the very broad one between 8000 and 9000 Å are obviously Ca II H and K and the near-infrared triplet, respectively, with velocities \( \pm 10,000 \text{ km s}^{-1} \), indicating that these lines have large optical depths. Between 4000 and 5500 Å, the spectra are dominated by Fe II multiplets, whose individual identifications are difficult due to the large intrinsic number of Fe II optical transitions and strong line blending in the fast-moving SN atmosphere. Nevertheless, we identify Fe II multiplet 27 (λ4233), 42 (λ4924, λ5018, and λ5169), and 49 (λ5317) with velocities between \( \sim 7500 \) and \( \sim 8000 \text{ km s}^{-1} \). The strong 4570 Å feature is a complex blend of several lines of Fe II multiplets 37 and 38, mainly λ4629, λ4584, λ4549, and λ4520. The absorption velocity, calculated with respect to λ4520, a strong feature in both multiplets, is consistent with other Fe II lines. The identity of the P Cygni line between 6200 and 6500 Å is controversial. This feature, if identified as Hα, corresponds to a velocity as high as \( \sim 15,000 \text{ km s}^{-1} \). If, instead, identified as Si II λ6355, the measured velocity drops to <5500 km s\(^{-1}\), which is significantly lower than all other lines. It may be noted that the uncertainty of our measurements varies from line to line and from spectrum to spectrum and can be as large as \( \pm 500 \text{ km s}^{-1} \), a result of the low signal-to-noise ratio, potential weak lines, and other pollution around the line absorption minima.

To further establish line identifications, we compute synthetic spectra using the fast, parameterized supernova spectrum-synthesis code SYNOW (see Branch et al. 2002 and references therein) and show the fit to the spectrum of May 4 in Figure 4. We assume a -7 power law for the radial dependance of line optical depths. The photospheric velocity, \( V_{\text{ph}} \), is assumed to be traced by the absorption minima of weak lines. We first assume \( V_{\text{ph}} = 8000 \text{ km s}^{-1} \) (lower thick solid line), the value that matches weak Fe II lines. As expected, Fe II and Ca II lines are well
reproduced, while He\text{I} \lambda 6678 and \lambda 7065 absorptions are a bit bluer than the observed. The observed He\text{I} \lambda 6678, \lambda 7065, and \lambda 7281 (if real) are also stronger than in the model. This suggests that nonthermal excitation, which is not included in SYNOW, is important for He\text{I}. The \approx 6240 \, \AA\ absorption minimum is reproduced by introducing a high-velocity H\alpha with a lower cutoff velocity of 15,000 km s\textsuperscript{-1} (see also Wang & Baade 2005). The narrow absorption and flat-topped emission of the synthetic H\alpha profile are consequences of the artificial optical depth discontinuity of a detached line. Identification of this feature with Si\text{II} is actually not included in our spectrum synthesis. With a lower cutoff velocity of 8000 km s\textsuperscript{-1} (Fig. 4, upper thick solid line). This spectrum reproduces the positions of He\text{I} absorption minima, but Fe\text{II} absorptions are too red. As a possible solution, we tentatively introduce a lower cutoff velocity of 8000 km s\textsuperscript{-1} for Fe\text{II}. One can assume that Fe\text{III} dominates over Fe\text{II} below that velocity, although Fe\text{III} is actually not included in our spectrum synthesis. With such a low \textit{V}_\text{ej}, Si\text{II} \lambda 6355 seemingly matches the P Cygni feature between 6200 and 6500 \textit{A} better than the high-\textit{V}_\text{ej} case. Calculations of realistic spatial structures of ionization and excitation above the photosphere are needed to correctly identify this feature and to determine the photospheric velocity, which is beyond the ability of SYNOW and the scope of this Letter.

4. CONCLUSIONS

The \textit{BVRI} light curve and spectra of SN 2005bf around maximum are presented. The light curves indicate that the maximum occurred nearly 40 days after the date of explosion. At maximum, SN 2005bf was brighter and bluer than other SNe Ib/c. The maximum phase was broad, and the decline rates slow, and these may be compared with the core-collapse models of hydrogenless cores. Preliminary calculations suggest a core mass larger than the Type Ib model suggested for SN1984L (Tominaga et al. 2005). The slow rise to the maximum and the brighter peak bolometric luminosity indicate that most of \textit{56Ni} was buried in a relatively low velocity region in the very massive ejecta (Hachisu et al. 1991), although a small part of \textit{56Ni} may be mixed out (Tominaga et al. 2005). The spectra of SN 2005bf around maximum are very similar to those of the Type Ib SNe 1999ex and 1984L about 25–35 days after explosion with prominent He\text{I}, Fe\text{II}, Ca\text{II} H and K, and the near-IR triplet P Cygni lines present. Relatively weak H\alpha and very weak H\beta may also exist, blueshifted by \approx 15,000 km s\textsuperscript{-1}. We suggest that SN 2005bf was the explosion of a massive He star, possibly with a trace of a hydrogen envelope.

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