THE ASTRONOMICAL JOURNAL, 117:736–743, 1999 February

THE STUDY OF A TYPE IIb SUPERNOVA: SN 1996cb

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Received 1998 July 31; accepted 1998 October 26

ABSTRACT

We present spectroscopic and photometric results of SN 1996cb. The supernova was independently discovered in NGC 3510 by M. Aoki, T. Cho, & K. Toyama of Japan and Qiao et al. of Beijing Astronomical Observatory on 1996 December 15 and 18, respectively. The results cover about 6 months following the discovery. The first few spectra showed strong Balmer lines with obvious P Cygni profiles, offering evidence of a Type II supernova. The emergence of He I lines could be inferred in these spectra. That the He I lines became quite prominent in the spectra near optical maximum confirmed that SN 1996cb was definitely a Type IIb supernova, like SN 1987K and SN 1993J.

The photometric results showed that the $B-I$ color evolution was very similar to that of SN 1993J. Comparing two color curves, we were able to estimate that the explosion of SN 1996cb occurred on UT 1996 December 12. Although the overall light curves resembled that of SN 1993J, they showed some differences, especially for the B band. SN 1996cb had a broad peak in the light curves, and it declined somewhat slowly and, compared with SN 1993J, exhibited a plateau-like shape between 20 and 50 days after the maximum for the B and V bands. This indicates that there was relatively more hydrogen in the outer envelope of the progenitor of SN 1996cb.

The spectral evolution of SN 1996cb displayed further differences from SN 1993J. In the case of SN 1996cb, the Balmer lines showed strong P Cygni profiles at a very early time, resembling the early spectra of SN 1987A, a supernova resulting from a compact blue supergiant star. The dramatic changes of expansion velocities at early times indicated that the photosphere of SN 1996cb receded more quickly than it did in SN 1993J. The He I lines emerged much earlier and evolved more dramatically, causing SN 1996cb to display the features of a Type Ib supernova before maximum. This might be the result of a dramatic recession of the photosphere at an early time; the He I lines and [O I] lines showed conspicuous blueshifts when they emerged, resembling the blueshifts of the [O I] lines that appeared in the late spectra of SN 1993J. This is probably observational evidence of Rayleigh-Taylor instabilities occurring at the interfaces between the H and He and the He and O + C layers, respectively; Hα emission and absorption components, especially the latter, were conspicuous 100 days after the explosion. We also conclude that the outer envelope of SN 1996cb had relatively more hydrogen than was the case for SN 1993J, even though the amount remained much less than is typical of other Type II supernovae. This finding is consistent with the results of the photometry. The [O I] and O lines emerged very late and exhibited weak emission, indicating that the He-rich layer was relatively thick. Combining the analyses of photometric and spectroscopic evolution, we conclude that the progenitor of SN 1996cb, like that of SN 1993J, was a stripped massive star exhibiting some special features: it was probably a more compact star with a thick helium layer and a relatively more massive hydrogen envelope.

Key words: supernovae: individual (SN 1996cb)

1. INTRODUCTION

Supernova SN 1996cb, in the spiral galaxy NGC 3510, was first discovered by M. Aoki, T. Cho, & K. Toyama of Japan (Nakano 1996) on 1996 December 15. Independent discovery was made by the Supernova Survey Group of the Beijing Astronomical Observatory (BAO) during a routine supernova survey with a 0.6 m telescope on 1996 December 18 (Qiao et al. 1996). The supernova was not present on a BAO CCD image obtained on 1996 November 29, and a visual supernova patrol undertaken by Evans (1997) on 1996 December 10 showed no star at the position of the supernova. The explosion was estimated to have taken place on 1996 December 12 (see § 3.1) by comparing the $B-V$ color curve of SN 1996cb with that of SN 1993J.

SN 1996cb was first spectroscopically confirmed by Garnavich & Kirshner (see Nakano 1996) with the 1.5 m telescope at the Harvard-Smithsonian Center for Astrophysics on 1996 December 17. Independent confirmation was made by Qiao et al. (1996) on 1996 December 19 with the BAO 2.16 m telescope. Both spectroscopic observations showed broad P Cygni profiles of the H Balmer lines dominating the spectra, implying that SN 1996cb was a Type II supernova.

Soon after the discovery, on 1996 December 21, radio observation of SN 1996cb was conducted by Van Dyk & Sramek (1996) with the Very Large Array. They detected radio emissions at several wavelengths, 3.6, 2.0, and 1.3 cm, implying the presence of substantial circumstellar matter around the supernova. From analyzing the spectrum on 1997 January 2, which showed strong emissions of He I λ6678, λ7065, and λ5876, Garnavich & Kirshner concluded that SN 1996cb was a Type IIb supernova (see Evans 1997). They also considered the findings of radio detection by Van Dyk et al. as additional evidence supporting the classification.

Type IIb comprises a subclass of Type II supernovae (Wheeler & Filippenko 1996). Type IIb supernovae are usually thought to show features of a typical Type II supernova at early times (e.g., strong Balmer lines), but as they evolve they exhibit some features of Type Ib supernovae (e.g., prominent He I lines at 5876 and 6678 Å). As discussed by Filippenko (1997), this type of supernova can be considered a transitional type, from SN II to SN Ib. The characteristics of Type IIb supernovae imply that the explosions of Type Ib, and probably Type Ic, supernovae result from the collapse of massive stars. Since this type of supernova plays an important role in the study of mechanisms of supernovae, intensive observations of this type of supernova at all phases are valuable. SN 1996cb is the third supernova known as Type IIb; the first two of this class are SN 1987K and SN 1993J. SN 1987K metamorphosed while it was behind the Sun, so no observation was done during that time. Because of its brightness and circumpolar position, SN 1993J was intensively observed not only at optical wavelengths but also at X-ray, ultraviolet, infrared, and radio wavelengths, and theoretical analyses were made by many authors. Since SN 1996cb was positioned far from the Sun when it was discovered, it was possible for it to be observed continually for at least 6 months. This circumstance provided us another excellent opportunity to study this class of supernova.

After the discovery of SN 1996cb, a program was quickly organized at BAO to obtain photometric and spectroscopic observations with, respectively, a 0.6 m and a 2.16 m reflector. Fortunately, SN 1996cb occurred during BAO's best observational season. Photometric and spectroscopic data spanning about 3 and 6 months were obtained. In addition, since SN 1996cb was located far from the nucleus of the host galaxy, it was easy to conduct photometric measurements with high precision.

In this paper, we present and analyze the photometric and spectroscopic results obtained by BAO from 1996 December to 1997 June. In § 2, the observations and reductions are described. In § 3, the photometric and spectral evolution is discussed and compared with that of SN 1993J. Section 4 discusses the special features of SN 1996cb, e.g., the blueshifts of lines of He I and [O I]. Finally, the discussion is summarized in § 5.

2. OBSERVATIONS

2.1. *Photometry*

The photometric data of SN 1996cb were obtained on a total of 47 nights between 1996 December 20 and 1997 May 23 with a 0.6 m telescope at Xinglong Station of the BAO. The CCD camera attached at the prime focus is a Texas Instruments TI-215, which has 1024 × 1024 pixels and a field of view of 16.′8 × 16.′8. The broadband filters used for the photometry of SN 1996cb are Johnson's B and V (Johnson 1955) and Cousins's R_C (Cousins 1976a, 1976b, 1978). Since there is no guider on the 0.6 m telescope, the exposure time could not exceed 300 s. We primarily used exposures of 120 s when the supernova was around maximum and 300 s when it dimmed. The FWHM of the stars was about 3″–4″, as a result of strong winds in the winter and spring seasons.

The data were reduced using the IRAF package. Even though SN 1996cb was located far from the nucleus of the host galaxy (offsets: 20.″9 west, 65.″7 north; Nakano 1996), the background still had an effect on photometric precision, especially when the supernova dimmed. Since the brightness of the background around SN 1996cb in the host galaxy was not homogeneous, we used a linear approximation to fit the background along one spiral arm of the galaxy. APPHOT in the IRAF package was used to measure the instrumental magnitudes for each night. We used a fixed aperture (6″) during the entire reduction process. On two photometric nights, 1997 January 5 and 1997 June 14, Landolt standard stars (Landolt 1983, 1992) and the "dipper asterism" in M67 (Schild 1985) were observed to calibrate the local standards around SN 1996cb.

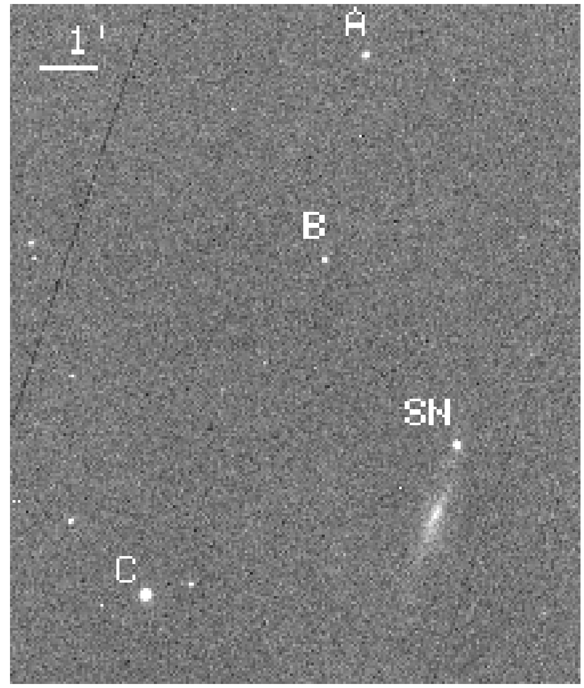

FIG. 1.—CCD image of NGC 3510 in the V band taken on 1997 January 5. SN 1996cb and local standards A–C are labeled. North is at the top, east is at the left.

The CCD image of SN 1996cb and surrounding stars is presented in Figure 1. Stars A, B, and C were chosen as the local standards. We usually used stars A and C, since these two stars were measured with a higher precision. The photometric results for all three stars are presented in Table 1.

The photometric results for SN 1996cb are presented in Table 2. B, V, and R_C light curves are presented in Figure 2, in which the photometric results for SN 1993J in B, V, and R_C obtained at the Observatorio del Roque de los Muchachos, La Palma (Lewis et al. 1994), during the first 120 days, are also plotted for comparison. In Figure 3, we give both the $B-V$ color curve for SN 1996cb and the $B-V$ color curve for SN 1993J, obtained from La Palma.

2.2. *Spectroscopy*

The optical and near-infrared low-dispersion spectra of SN 1996cb were obtained with the OptiMetrics Research

TABLE 1

PHOTOMETRIC SEQUENCE AROUND NGC 3150

Identification	B	V	R_C
A	15.38 ± 0.05	14.72 ± 0.02	14.38 ± 0.02
B	16.74 ± 0.10	15.88 ± 0.04	15.48 ± 0.04
C	13.48 ± 0.01	12.86 ± 0.01	12.51 ± 0.01

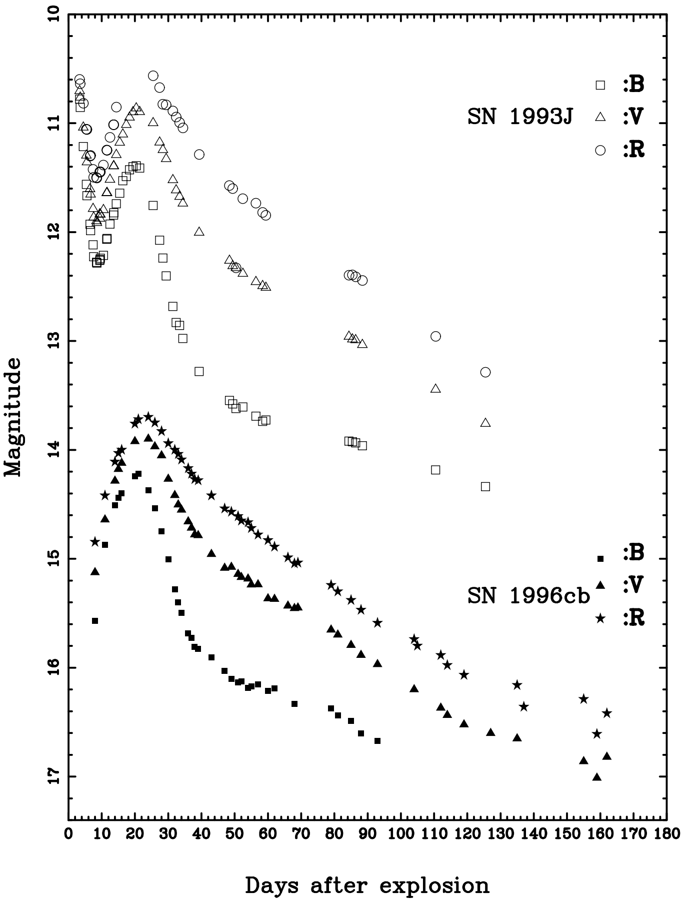

FIG. 2.—*BVR* light curves of SN 1996cb and SN 1993J

spectrograph at the BAO 2.16 m telescope. The CCD is a Tektronix 1024 × 1024. Except on 1996 December 23, we used two low-dispersion gratings, the dispersions of which are about 200 and 400 Å mm^{-1}, respectively. The spectral coverage of the two gratings is about 3800–8200 and 3800–9200 Å. Their resolutions are about 4.9 and 9.8 Å pixel^{-1}, respectively. To investigate the absorption strength of the interstellar Na I D line, we used a grating of 50 Å mm^{-1} (1.25 Å pixel^{-1}) on 1996 December 23. All the data were bias-subtracted, flat-fielded, and extracted with the IRAF packages. Wavelength calibrations were performed using the spectra of FeAr or HeNeAr lamps. The supernova flux was calibrated in reference to observations of spectroscopic standards (Oke & Gunn 1983).

Most of spectra were obtained on the nonphotometric nights. We usually used slit widths of 3″–5″. Since these slit widths were not wide enough to include all the light from the stars, we could not accurately determine the absolute flux. We used the yearly average extinction parameters of Xinglong Station in the spectral reduction. Our spectroscopic observations of SN 1996cb were usually conducted near the zenith, and we chose standards with almost the same air mass so that the bias of the relative flux caused by the nonphotometric condition and average extinction parameters was negligible, making the relative flux of the spectra more reliable. Table 3 presents our journal of the spectroscopic observations.

TABLE 2

PHOTOMETRIC OBSERVATIONS OF SN 1996cb

Date (UT)	JD (2,440,000+)	*B*	*V*	R_C
1996 Dec 20.88	10,438.38	15.57	15.13	14.85
1996 Dec 23.89	10,441.39	14.87	14.64	14.42
1996 Dec 26.88	10,444.38	14.51	14.28	14.11
1997 Dec 27.87	10,445.37	14.44	14.18	14.03
1997 Dec 28.89	10,446.39	14.40	14.12	14.00
1997 Jan 1.90	10,450.40	14.24	13.92	13.76
1997 Jan 2.84	10,451.34	14.22	...	13.72
1997 Jan 5.87	10,454.37	14.37	13.90	13.70
1997 Jan 7.76	10,456.26	14.53	13.97	13.75
1997 Jan 9.75	10,458.25	14.75	14.05	13.83
1997 Jan 11.84	10,460.34	15.01	14.27	13.94
1997 Jan 13.81	10,462.31	15.28	14.42	14.00
1997 Jan 14.80	10,463.30	15.40	14.50	14.04
1997 Jan 15.68	10,464.18	15.50	14.55	14.09
1997 Jan 17.81	10,466.31	15.69	14.66	14.17
1997 Jan 18.76	10,467.26	15.73	14.72	14.22
1997 Jan 19.78	10,468.28	15.81	14.78	14.27
1997 Jan 20.81	10,469.31	15.83	14.78	14.28
1997 Jan 24.79	10,473.29	15.91	14.96	14.42
1997 Jan 28.75	10,477.25	16.03	15.08	14.54
1997 Jan 30.70	10,478.20	16.10	15.08	14.57
1997 Feb 1.75	10,481.25	16.13	15.14	14.61
1997 Feb 2.74	10,482.24	16.13	15.17	14.65
1997 Feb 4.78	10,484.28	16.19	15.18	14.66
1997 Feb 5.78	10,485.28	16.17	15.24	14.72
1997 Feb 7.80	10,487.30	16.15	15.24	14.78
1997 Feb 10.78	10,490.28	16.21	15.36	14.83
1997 Feb 12.78	10,492.28	16.19	15.37	14.89
1997 Feb 16.66	10,496.16	...	15.43	14.90
1997 Feb 18.72	10,498.22	16.33	15.45	15.04
1997 Feb 19.71	10,499.21	...	15.45	15.04
1997 Mar 1.71	10,509.21	16.38	15.65	15.24
1997 Mar 3.67	10,511.17	16.44	15.70	15.30
1997 Mar 7.70	10,515.20	16.49	15.79	15.38
1997 Mar 10.65	10,518.15	16.60	15.88	15.47
1997 Mar 15.65	10,523.15	16.67	15.97	15.59
1997 Mar 26.66	10,534.16	...	16.20	15.74
1997 Mar 27.67	10,535.17	...	...	15.80
1997 Mar 29.62	10,537.12	...	16.37	15.89
1997 Apr 3.64	10,542.14	...	16.44	15.98
1997 Apr 8.59	10,547.09	...	16.52	16.07
1997 Apr 16.65	10,555.16	...	16.60	...
1997 Apr 24.54	10,563.04	...	16.65	16.16
1997 Apr 26.54	10,565.04	...	...	16.36
1997 May 14.53......	10,583.03	...	16.86	16.29
1997 May 20.59......	10,589.09	...	17.01	16.61
1997 May 23.56......	10,592.06	...	16.82	16.42

3. PHOTOMETRIC AND SPECTROSCOPIC EVOLUTION

3.1. *Photometric Evolution*

In Figure 2, we present the *BVR* light curves of SN 1996cb. For comparison, the light curves of SN 1993J obtained at La Palma Observatory for the first 120 days (Lewis et al. 1994) are plotted in the same figure.

SN 1996cb was rising when we began to do photometry on 1996 December 20. *B* rose quickly (-0.15 mag day^{-1}) from December 20 to December 26, then it rose more slowly (-0.04 mag day^{-1}), reaching a maximum on 1997 January 2. After the maximum, it declined at the rate of 0.05 mag day^{-1} for the first 6 days. It then declined linearly at the rate of 0.16 mag day^{-1} between 1 and 20 days after

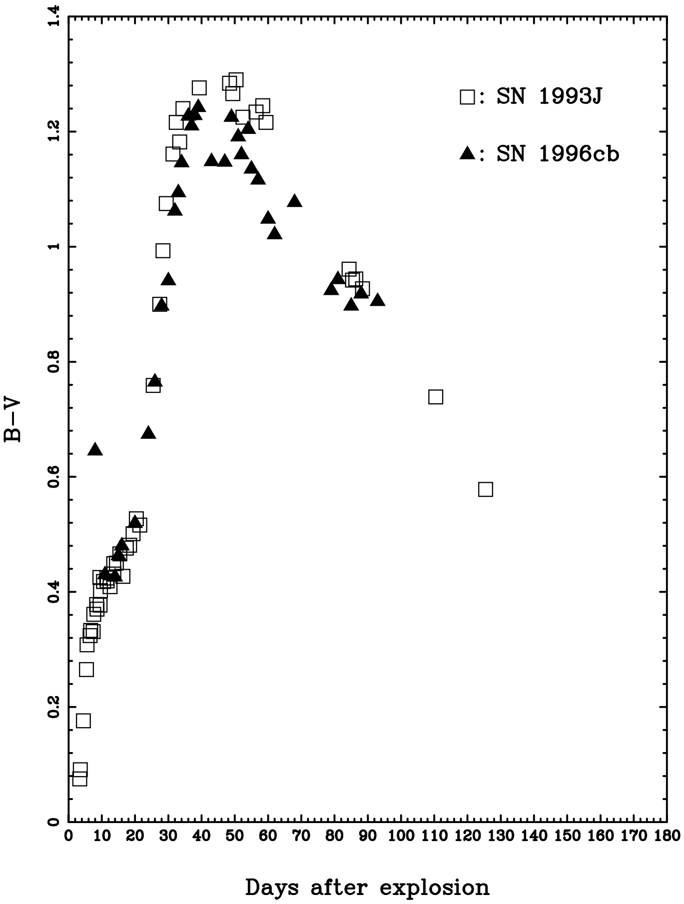

FIG. 3.—$B-V$ color curves of SN 1996cb and SN 1993J. The color curve of SN 1996cb is shifted 0.2 mag vertically for a better comparison with that of SN 1993J.

maximum. From 20 to 50 days after maximum, the B-band light curve exhibited a conspicuous plateau, during which the supernova declined at the rate of 0.011 mag day^{-1}. The V-band light curve showed a slow decline rate (0.017 mag day^{-1}) and an inconspicuous plateau during this time. The light curve of the R band showed no plateau at all. Light curves in the B and V bands declined more rapidly later than 50 days after the maximum (0.024 and 0.022 mag day^{-1} for B and V, respectively).

The V band maximum occurred 2 days later than it did in the B band, but the maximum in the R band seemed to be nearly the same as that of the V band.

The $B-V$ color curve of SN 1996cb is plotted in Figure 3, together with that of SN 1993J (Lewis et al. 1994). The $B-V$ color curve of SN 1996cb has been shifted 0.2 mag vertically. It is easy to see that the two curves are very similar, except for the color excess. The explosion date of SN 1993J was better estimated on 1993 March 27.5 (Wheeler et al. 1993). Assuming that SN 1996cb and SN 1993J are the same in their color evolution, we estimate that SN 1996cb exploded on UT 1996 December 12. The $B-V$ color was peculiar on December 20, with the supernova appearing to be too red compared with its neighboring data. The spectroscopic data (see § 3.2) showed that the excessive redness was due to the effect of the strong absorption of Balmer lines (Hδ, Hγ, and Hβ) in the B band at early times.

The spectra of SN 1996cb (see § 3.2) also showed that the absorption of the interstellar Na I D line was very weak. This indicates that the extinction of SN 1996cb was small. The reddening of SN 1993J was quite uncertain and has been estimated by many authors. Wheeler et al. (1993) gave $E(B-V) = 0.15 \pm 0.02$ and Richmond et al. (1994) gave a large range, from 0.08 to 0.32. If we set the color excess of SN 1996cb to be 0.2 mag lower than that of SN 1993J, the

TABLE 3

JOURNAL OF SPECTROSCOPIC OBSERVATIONS

Date (UT)	Exposure (s)	Range (Å)	SW (arcsec)	Resolution (Å)	Flux Standards[a]
1996 Dec 19.83	3600	3810–8290	2.7	13	1, 2
1996 Dec 22.87	3000	3650–9200	2.3	22	3
1996 Dec 23.91	6600	5650–6850	2.0	3	3
1996 Dec 27.83	2400	3650–9200	2.8	27	4
1997 Jan 1.88	2400	3600–7840	3.7	18	4
1997 Jan 5.89	1800	3600–9200	3.0	29	4
1997 Jan 11.83	1200	3890–8120	2.5	12	4
1997 Jan 18.87	1500	3900–9200	3.5	33	4
1997 Jan 27.76	3600	3900–8000	2.9	14	4
1997 Feb 1.87	1800	3900–9200	2.9	28	4
1997 Feb 5.83	1800	3900–9200	2.5	24	4
1997 Feb 19.87	1200	3900–9200	2.4	23	4
1997 Mar 1.70	1800	3900–8260	2.5	12	4
1997 Mar 8.65	1200	3900–9200	2.6	25	1, 4
1997 Mar 18.69	1800	3990–8100	2.5	12	5
1997 Mar 28.73	3600	3900–8100	2.8	14	1, 3
1997 Apr 4.71	3600	3900–8360	3.0	15	1
1997 Apr 28.78	3600	3900–9210	3.0	29	1
1997 Jun 9.80	3600	3900–7700	3.0	15	1

[a] (1) Hz 44; (2) Feige 110; (3) Hilt 600; (4) Feige 34; (5) Feige 98.

two colors coincide for the most part. We can thus estimate the upper limit of the reddening of SN 1996cb to be about 0.12.

The light curves showed that the maxima of SN 1996cb occurred at nearly the same epoch, 20 days after the explosion, as the second peak of the light curve of SN 1993J. SN 1993J experienced two maxima in the light curves. It rose dramatically from the explosion to the first peak and took about 20 days to rise to the second peak. The two peaks have been explained (Schmidt et al. 1993) as resulting from the energy of the shock deposited very soon after the explosion. Although our data for SN 1996cb did not include observations of the first 8 days after the explosion, the light curves showed no indication of two maxima. The unfiltered CCD magnitudes of 16.5 and 15.6 on December 15 and 18 obtained by Aoki et al. (see Nakano 1996) and Qiao et al. (1996) provided additional evidence that SN 1996cb was rising 3 days after the explosion, implying that there was only one peak in its light curve.

The light curves of SN 1996cb, compared with those of SN 1993J, showed broad peaks at maxima and a slow decline rate after the maxima. The most prominent feature was the short plateau in the *B*- and *V*-band light curves from 20 to 50 days after maxima. As we know, a plateau is the defining feature of the light curve of SNe II-P (SN 1986I; Pennypacker et al. 1989) which result from stars with a large amount of hydrogen in the outer envelope when they explode. It is reasonable for us to assume that there was some quantity of hydrogen in the outer envelope of SN 1996cb, even though it was much less than that of the progenitor of a typical Type II-P supernova.

Woosley et al. (1994) modeled the progenitor of SN 1993J with a helium core of mass $4.5 \pm 0.5\ M_\odot$ and a hydrogen core of mass $0.2 \pm 0.05\ M_\odot$. This model results from a star of mass 13–16 $M_\odot$ on the main sequence that lost almost all of its hydrogen-rich envelope in an exchange with a binary companion during the evolution process. The shapes of the light curves indicate that there is more hydrogen in the outer envelope of SN 1996cb than in that of SN 1993J. We can easily understand that the inhomogeneity of Type IIb supernova light curves is caused by different physical structures in the progenitor when the supernova explodes, which are themselves the result of the differing conditions of the respective progenitor and its companions.

3.2. *Spectroscopic Evolution*

The spectra of SN 1996cb from different epochs are illustrated in Figures 4 and 5. In the first spectrum, obtained on 1996 December 19, all of the Balmer lines exhibited clear P Cygni profiles. The Hα line showed a broad emission and an extremely deep blueshifted absorption. The He I λ5876 line and Na I D line were not conspicuous, but the Ca II H+K lines were very strong. The expansion velocities measured from the absorption minima of Hα, Hβ, and Hγ were 15,990, 11,600, and 10,460 km s^{-1}, respectively. The He I λ5876 expansion velocity was 8870 km s^{-1}, indicating that the Balmer lines and the He I lines were produced in different layers.

The emission component of Hα in the first spectrum was asymmetric, and the emission maximum was not located at the rest wavelength of the host galaxy, but blueshifted by about 90 Å. We assume that the He I λ6678 line had already emerged and its absorption component had eroded the emission component of Hα, creating the blueshifted

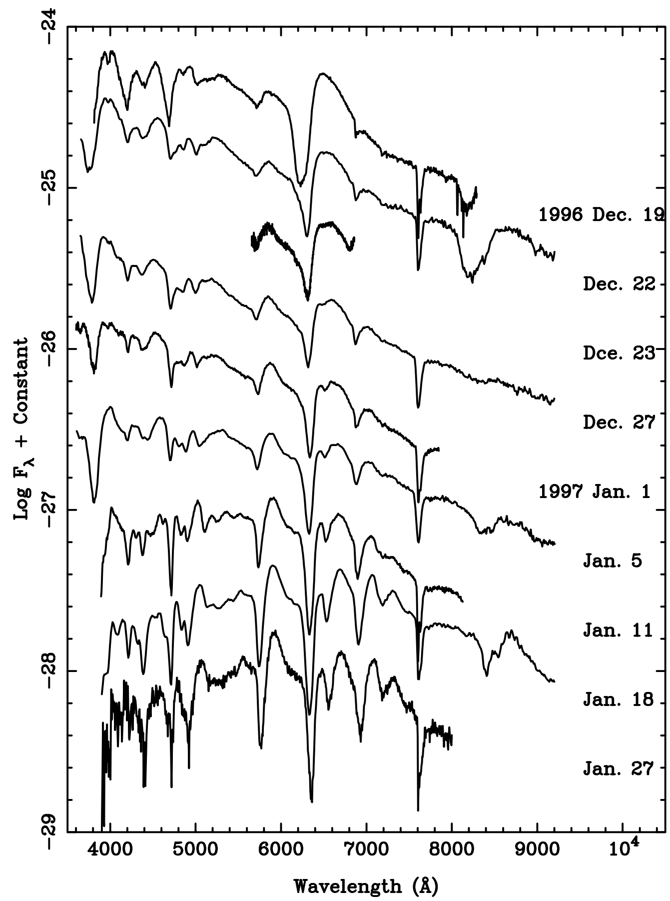

FIG. 4.—Spectra of SN 1996cb at nine epochs from 1996 December 19 to 1997 January 27. Units of F_λ are ergs s^{-1}. All spectra are calibrated at the rest wavelength in the frame of NGC 3510. Spectra have been displaced by an arbitrary constant for clarity.

maximum. Later spectra support this assumption and show that the emission peak of Hα evolved from flat to a dip and eventually to a double peak. Although He I λ5876 was not strong and was perhaps mixed with the Na I D line, the strong emission at 4900 Å was due to He I λ4921 blending with Hβ, which supported the assumption that the He I lines emerged early.

In the first spectrum, Balmer lines in the *B* band showed strong absorption. They became weak in the next spectrum. This change was caused by the outer envelope's becoming more transparent as the supernova expanded quickly. This explains why the first $B-V$ values in the color curves were strangely red compared with subsequent data.

At early times, the spectra of SN 1996cb deviated far from those of typical Type II supernovae, which are primarily dominated by continuum radiation in early phases, showing weak emission and even weaker absorption of Hα. The first spectrum of SN 1996cb also differed in many respects from the spectra of SN 1993J at similar epochs (Lewis et al. 1994), showing the characteristics of typical Type II supernovae 8 to 10 days after explosion. The early spectra of SN 1996cb were similar to those of SN 1987A at very early times, when it exhibited a conspicuous P Cygni profile of Hα. The overall shape of the first SN 1996cb spectrum was similar to that of SN 1993J on April 13, which was 17 days after the explosion. The differences are that Hα absorption was very weak in the spectrum of SN 1993J, but

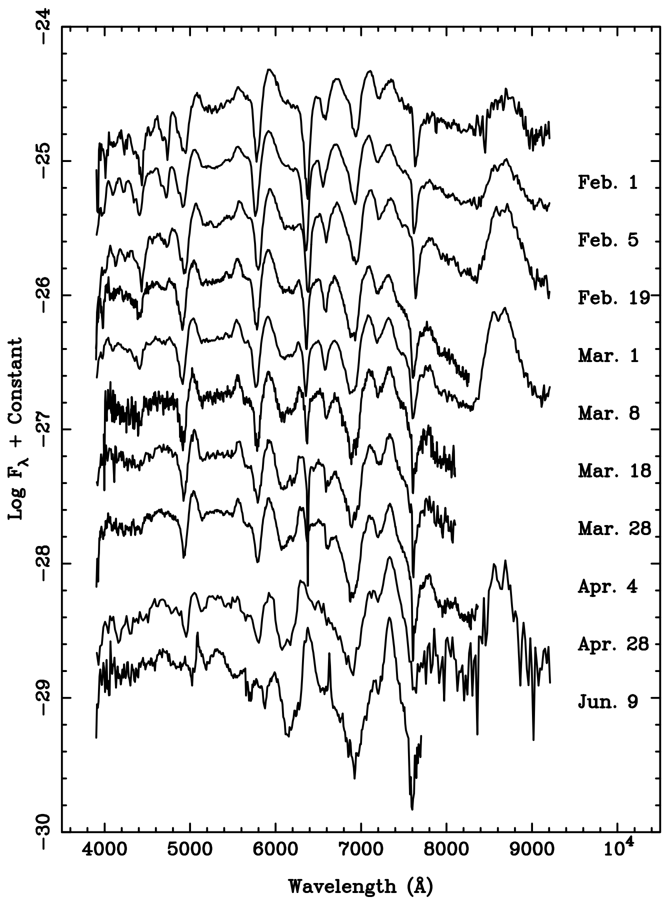

FIG. 5.—Spectra of SN 1996cb at 10 epochs from 1997 February 1 to June 9. Units of F_λ are ergs s^{-1}. Spectra calibrated and displaced as in Fig. 4.

the He I λ5876/Na I D lines were strong and clearly showed a P Cygni profile.

The second spectrum was obtained on 1996 December 22. The profile of Hα changed greatly in comparison with the first spectrum. The top of Hα became slightly flat, which can be attributed to the developing He I λ6678. Hα absorption also became narrow. The expansion velocities from absorption minima of Hα and Hβ were 12,500 and 10,300 km s^{-1}, respectively. He I λ7065 was weak, but can be conspicuously seen. These observations implied that photosphere was receding quickly and some of the He layer was beginning to be exposed.

There was an absorption at 8200 Å in the first two spectra. Since Ca II H+K lines were present and showed strong emission, it was reasonable to assume that this absorption was the blueshifted minimum of the Ca II near-infrared triplet. This feature showed an expansion velocity of 15,000 km s^{-1}. Such a high expansion velocity could be only produced in the H-rich outer layer.

From their spectroscopic observation on 1996 December 17, 2 days before our first spectroscopic observation, Garnavich & Kirshner (see Nakano 1996) reduced an Hα expansion velocity of 21,000 km s^{-1}. The expansion velocities of Hα of SN 1993J derived by Finn et al. (1995) at similar epochs to the first two spectra of SN 1996cb were 17,800 and 16,600 km s^{-1}, decreasing very slowly. SN 1987A showed a rapid change of Hα expansion velocities at early times (Eastman & Kirshner 1989). We conclude that the early evolution of the SN 1996cb Balmer lines was different from that of SN 1993J, and more similar to that of SN 1987A.

To estimate the extinction of SN 1996cb, the 50 Å mm^{-1} dispersion spectrum was obtained on 1996 December 23. It showed that there was no obvious narrow Na I D line, such as the one that appeared in the spectrum of SN 1993J. It can be concluded that the reddening of this supernova was small.

The fourth spectrum represented in Figure 4 was obtained on 1996 December 27. The maximum of Hα exhibited a trough, indicating that the He layer had begun to be exposed. The absorption of the Ca II triplet that appeared in the second spectrum produced from the outer envelope totally disappeared. This also provides evidence that the outer envelope became more transparent.

The fifth and sixth spectra corresponded to the maxima of the optical light curves. The overall shapes of the spectra at these two epochs changed slowly. The He I λ6678 and λ5876 lines became more prominent and He I λ7065 began to emerge. The Ca II near-infrared triplet emerged again on the spectrum of 1997 January 5, implying that the photosphere had already receded into the He layer. Compared with the spectra of SN 1993J, SN 1996cb showed the features of a Type Ib supernova at earlier epochs.

The maximum of He I λ5876 showed a blueshift when it began to emerge. This blueshift diminished gradually. In the spectrum of 1997 January 18, the maximum of He I λ5876 returned to the rest wavelength of the host galaxy. This phenomenon will be discussed in § 4. This behavior suggests a Rayleigh-Taylor instability at the H-He layer. The disappearance of this instability implied that the photosphere had fully receded into the He-rich layer.

The last three spectra in Figure 4 showed that He lines were developing gradually, eventually becoming the most prominent features in the spectra. The Hα line became very narrow. The He I λ7281 line combined with Ca II $\lambda\lambda$7291, 7324 was seen conspicuously. The forbidden line [O I] λ5577 began to emerge. The Ca II triplet lines began to develop. All of these phenomena showed that the SN had begun to enter the nebular phase.

The overall shapes of spectra from 1997 January 27 to February 19 changed very slowly, except for the rapid development of the Ca II triplet. These epochs corresponded to the time of the plateau of the *B* and *V* light curves. At that time, the photosphere had fully receded to the He layer. The supernova displayed all the spectral features of Type Ib, except for the weak absorptions of Balmer lines.

From the spectrum of March 1, the forbidden lines [O I] $\lambda\lambda$6300, 6343 began to emerge. Compared with spectra of SN 1993J at similar epochs, the [O I] emerged late and appeared more weakly. As [O I] $\lambda\lambda$6300, 6343 developed, it eroded the absorption of Hα, causing it to disappear completely in the spectrum taken on April 28. The He λ6678 line gradually became weak, almost disappearing at the same time as Hα. The other He I lines remained conspicuous. The O I λ7600 line became quite prominent, indicating that the photosphere had begun to recede from He-rich layer into a deeper O-rich layer.

Observations made on 1997 April 4, about 100 days following the discovery, showed that the spectra were dominated by He I lines, like a typical Type Ib supernova in the nebular phase, with the exception of the weak Hα line. [O I] λ5577 and $\lambda\lambda$6300, 6343 were prominent, and the O I λ7773

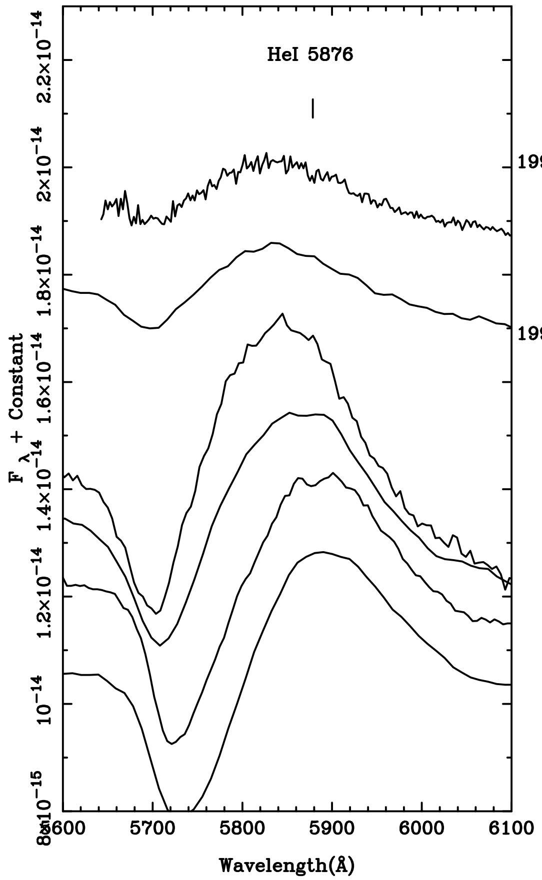

FIG. 6.—Evolution of He I λ6678 profile

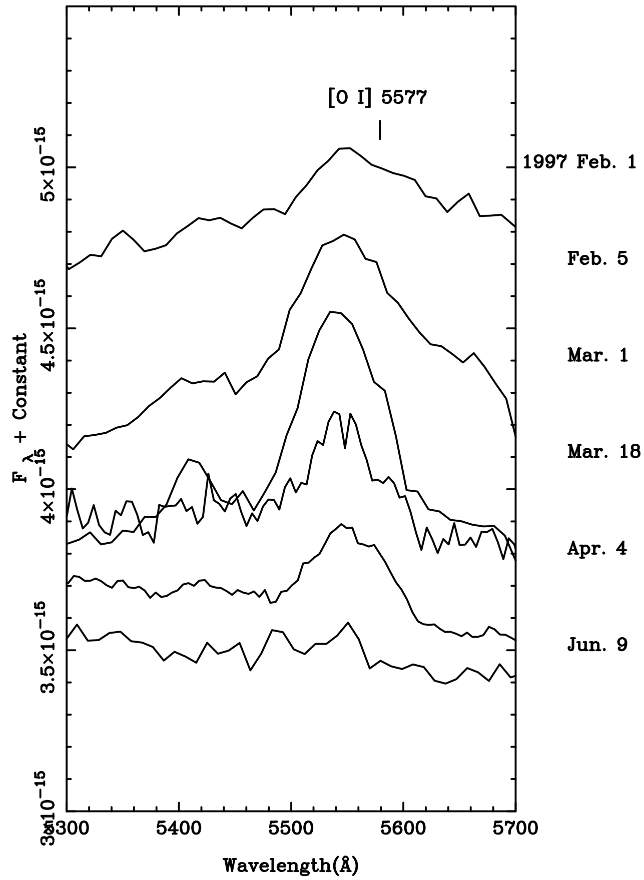

FIG. 7.—Evolution of [O I] λ5577 profile

line also appeared. The emission maximum of [O I] λ5577 returned to its rest wavelength. This behavior indicates that the photosphere had receded from the He-rich layer into a deeper O-rich layer. The He I lines in the spectrum of SN 1993J at the age of 3.1 months (Filippenko, Matheson, & Barth 1994) were less distinct, but the [O I] lines and O I λ7773 were stronger. This indicates that spectra of SN 1996cb evolved rapidly at early times, but more slowly later on, in contrast to the spectra of SN 1993J.

The next spectrum, taken on April 28, showed that the emission of [O I] λ5577 became quite weak, while [O I] λ6300 seemed stronger than in previous data. The spectrum covered the near-infrared band, so it displayed the Ca II triplet. The Ca II triplet and Ca II $\lambda\lambda$7291, 7324 were the strongest lines in the spectrum.

The [O I] λ5577 line, like He I λ5876, showed a blueshift when it emerged. It retained this blueshift until June 9. The discussion in § 4 will show that this behavior is probably the result of instability at the interface of the He and O + C layers.

The last spectrum was obtained on 1997 June 9, about 6 months after the explosion. This spectrum showed features of the nebular phase. Forbidden lines dominated the spectrum. The most prominent lines are [O I] $\lambda\lambda$6300, 6364 and [Ca II] $\lambda\lambda$7291, 7323. The very narrow lines at 5000 and 6600 Å are Hβ and Hα, produced from the H II region of the host galaxy.

4. BLUESHIFTS OF He I λ5876 AND [O I] λ5577

Two phenomena are worth studying more carefully. The first is that the He I lines show blueshifts in the early spectra. In the spectrum of 1996 December 22, He I λ5876 is blueshifted about 2000 km s^{-1}. This blueshift decreased slowly but remained until 1997 January 27. The second phenomenon is that [O I] λ5577 also showed a blueshift when it first emerged. The maximum of emission moves slowly redward and maintains some redshift in the nebular spectra (April 4). We enlarge the spectra around He I λ5876 and [O I] λ5577 and present them in Figures 6 and 7. The blueshifting of [O I] lines also occurred in SN 1993J (Wang & Hu 1994) during the period from 40 to 130 days following the explosion.

As discussed by Wang & Hu (1994), the blueshifts of [O I] λ5577 can be explained by Rayleigh-Taylor instabilities occurring at the interface of the He and O + C layers. The ejecta of supernovae are not smooth and isotropic, but exhibit clumpiness. Can the blueshifts of the He I lines of SN 1996cb be explained in same way?

Two other phenomena coexisting in the spectra of SN 1996cb, which differ from those of SN 1993J, point to this same explanation. One is that the absorption of Hα continues to be strong and does not fade as it did in SN 1993J, indicating that a significant amount of hydrogen remained in the outer envelope of the progenitor of SN 1996cb. Even though the amount is less than that of other typical Type II supernovae, the hydrogen in SN 1996cb may exceed that found in SN 1993J. The second phenomenon is that the He I lines of SN 1996cb emerge earlier and evolve more dramatically than those of SN 1993J. At first sight, these two phenomena seem to be in contradiction. Since more hydrogen exists in the outer envelope, the photosphere should recede to the He-rich layer slowly, and He I should emerge later in SN 1996cb. If the clumpy ejecta occurred at the interface of the H-rich and He-rich layers, which causes the He to emerge earlier in SN 1996cb, this contradiction can be explained.

Rayleigh-Taylor instabilities in a supernova explosion were first confirmed in SN 1987A (Müller, Fryxell, & Arnett 1991). Then they were also applied to explain the clumpy phenomena in SN 1993J (Iwamoto et al. 1997). As discussed by Iwamoto et al. (1997), in supernovae with a large hydrogen envelope such as SN 1987A, the instability is strong at the H-He interface, but weak at the He-O + C interface. In cases with a small hydrogen envelope and large helium envelope such as SN 1993J, the instability at the interface of He-O + C layer is prominent. Since both the permitted and forbidden oxygen lines appeared late and were weak, we can assume that the He layer is thicker in SN 1996cb than in SN 1993J. It is probable that both instabilities occurred at different phases of the evolutionary process of SN 1996cb.

5. SUMMARY

We have presented the photometric and spectroscopic evolution of SN 1996cb, spanning about 6 months following the discovery. The data cover all supernova phases, from before maximum to the nebular phase. The spectra show the details of the metamorphosis. Compared with the well-known Type IIb supernova SN 1993J, SN 1996cb shows some special features. From the above spectral analysis and discussion, we summarize the conclusions as follows:

1. SN 1996cb is clearly a Type IIb supernova. It provides another opportunity to study this class of supernovae and to test some theories based on observations of SN 1993J. The differences between SN 1996cb and SN 1993J imply that, like normal Type II supernovae, Type IIb supernovae are not homogeneous.

2. Photometric results show that SN 1996cb declined at a slightly slower rate after maximum than SN 1993J. It seems that there is only one peak in the light curves. The *B*-band light curve exhibits a short-term plateau between 20 and 50 days after the maximum, which somewhat resembles the plateau feature of Type II-P supernovae resulting from a star with a larger envelope. The absorption of Hα remained strong for over 3 months, which also provides evidence of a relative abundance of hydrogen in the outer envelope of SN 1996cb as opposed to SN 1993J.

3. The spectra of SN 1996cb evolve very dramatically in the early phases, with Balmer lines showing strong P Cygni profiles at that time. This differs from typical Type II SNe and SN 1993J. The spectra at early times are quite like those of SN 1987A, a supernova known to have been produced from a compact blue giant star, showing strong P Cygni profiles of Balmer lines. The He I lines emerge earlier than for SN 1993J. SN 1996cb shows features of Type Ib SNe before maximum. This can be explained in part by Rayleigh-Taylor instabilities occurring at the H-He interface and leading to earlier He exposure. The spectra evolve slowly after the optical maximum. Permitted and forbidden oxygen lines emerge late and appear weakly, perhaps because of the thick He layer.

4. The blueshifts of the He I and [O I] lines imply the probable existence of clumpy ejecta, as were present in SN 1993J. This instability may have existed at an early time at the interface of the H-He layer. The earlier appearance of the He line can be explained by Rayleigh-Taylor instabilities occurring at the H-He interface, which exposes the He earlier. SN 1996cb provides more observational evidence of Rayleigh-Taylor instabilities at H-He and He-O + C interfaces.

5. The [O I] and O I lines emerged very late and seem to be weaker than they were in SN 1993J. This indicates that the He-rich layer is thicker in SN 1996cb than in SN 1993J.

This work was in part supported by Chinese Natural Science Foundation. We thank the anonymous referee for a thorough reading. We are grateful to Wei Jianyang, Miss Cao Li, and Xu Dawei for providing assistance with the spectroscopic observations and reductions, as well to some other astronomers for allowing us to make use of their invaluable observation time.

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