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A SPECTROSCOPICALLY NORMAL TYPE Ic SUPERNOVA FROM A VERY MASSIVE PROGENITOR

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ABSTRACT

We present observations of the Type Ic supernova (SN Ic) 2011bm spanning a period of about one year. The data establish that SN 2011bm is a spectroscopically normal SN Ic with moderately low ejecta velocities and with a very slow spectroscopic and photometric evolution (more than twice as slow as SN 1998bw). The Pan-STARRS1 retrospective detection shows that the rise time from explosion to peak was ∼40 days in the R band. Through an analysis of the light curve and the spectral sequence, we estimate a kinetic energy of ∼7–17 foe and a total ejected mass of ∼7–17 $M_{\odot}$, 5–10 $M_{\odot}$ of which is oxygen and 0.6–0.7 $M_{\odot}$ is ^{56}Ni. The physical parameters obtained for SN 2011bm suggest that its progenitor was a massive star of initial mass 30–50 $M_{\odot}$. The profile of the forbidden oxygen lines in the nebular spectra shows no evidence of a bi-polar geometry in the ejected material.

Key words: supernovae: general – supernovae: individual (SN 2011bm)

1. INTRODUCTION

The standard classification scheme for the explosions of massive stars consists of two different branches: stars retaining their hydrogen envelope at the time of the explosion produce Type II supernovae (SNe II), while those losing it before the explosion produce Type Ib or Ic SNe, depending on the strength of He lines in the spectra. In addition, some SNe Ic, labeled BL-Ic, show broad lines in the spectra, the signature of a very high kinetic energy/ejected mass ratio. Over the past five years, the above scenario has changed dramatically with the discovery of new classes of transients that may originate from different explosion channels. Pair-instability, pulsational pair-instability, and magnetar-powered explosions have been suggested to explain the properties of a group of hyper-luminous and slowly evolving transients (SN 2007bi, Gal-Yam et al. 2009; SN 2006gy, Smith et al. 2007; SN 2010gx, Pastorello et al. 2010, Quimby et al. 2011), while fallback on the collapsed remnant, electron-capture, and failed-deflagration scenarios have been proposed to explain faint and fast-evolving transients (e.g., SN 2008ha, Valenti et al. 2009, Foley et al. 2009, Pumo et al. 2009; SN 2005E, Perets et al. 2010). Alternatively, some of these events can still be explained if a more *canonical* core-collapse scenario but an extended range of physical conditions of the progenitor at the moment of its explosion is invoked (e.g., SN 2006gy, Agnoletto et al. 2009; SN 2007bi, Young et al. 2010; Moriya et al. 2010; SN 2005cz, Kawabata et al. 2010). Here, we present the observations of a stripped-envelope supernova that evolved in an extremely slow fashion, much more slowly than any other *spectroscopically normal* core-collapse SN studied in the literature.

2. OBSERVATIONS

SN 2011bm was discovered by the "La Sagra Sky Survey" on 2011 April 5 in the galaxy IC 3918[10] (Vida et al. 2011) and classified on April 11 at the 1.82 m Mt. Ekar Copernico Telescope as a Type Ic SN close to maximum light (Gall et al. 2011). The Palomar Transient Factory claimed an independent discovery of SN 2011bm on 2011 March 29 and a stringent pre-discovery limit on March 23 down to 20.8 mag in the R band (Gal-Yam et al. 2011). Since the Panoramic Survey Telescope and Rapid Response System-1 (PS1) 3π survey has already been very useful to constrain the explosion epoch of other nearby SNe (e.g., SN 2010ay; Sanders et al. 2011), we retrospectively inspected PS1 data and detected SN 2011bm in r_{P1}- and i_{P1}-band images on March 26.5 UT at magnitudes $r = 18.71$ mag and $i = 18.82$ mag, and in a g_{P1}-band image on March 29.6 UT at a magnitude $g = 18.78$ mag. This is the earliest detection of the supernova and strongly constrains the explosion to have occurred between 2011 March 23 and March 26. After announcement, we immediately started a follow-up campaign in the framework of the NTT European Large Programme (ELP) collaboration and we extensively monitored SN 2011bm using the telescopes available to us. We collected a large amount of data in the optical domain, complemented by near-infrared data, especially useful to investigate the presence of He in the

[10] The following parameters have been used for IC 3918 in this paper: $\mu =$ 34.90 mag (radial velocity corrected for in-fall onto Virgo of 2799 km s^{-1} and a Hubble constant of 72 km s^{-1} Mpc^{-1}), $z = 0.0221$ (from narrow emission lines of the host galaxy), $E(B - V)_{\rm IC3918} = 0.032$ mag (assuming a similar dust-to-gas ratio in IC 3918 and in the Milky Way and comparing the equivalent width of the narrow Na I D absorption lines from IC 3918 with that from the Milky Way), and $E(B - V)_{\rm Gal} = 0.032$ mag (Schlegel et al. 1998).

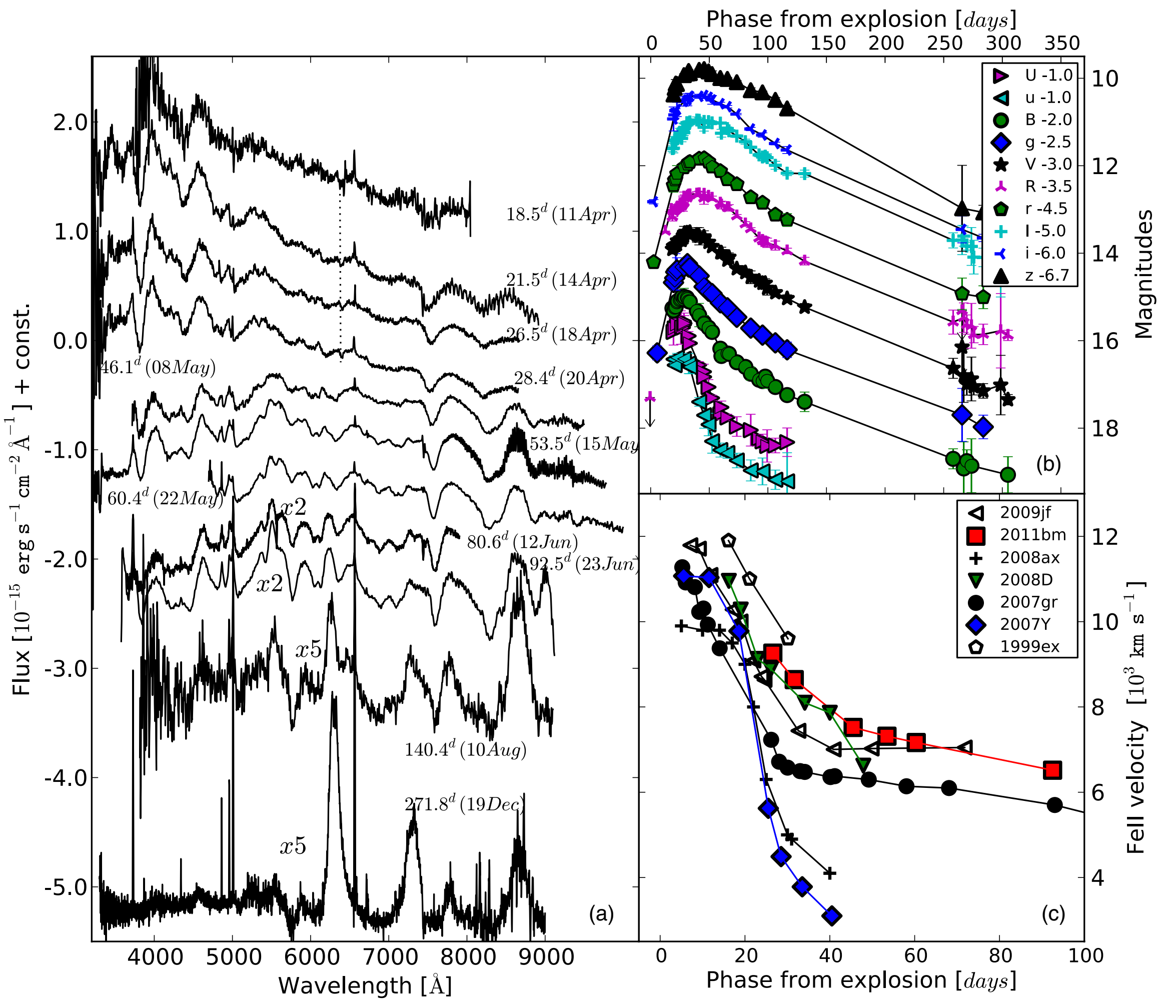

Figure 1. Spectroscopic and photometric follow-up of SN 2011bm. All data have been reduced with standard IRAF routines, using the QUBA pipeline (see Valenti et al. 2011 for information). For the NOT spectra, a second-order correction was performed using the method described in Stanishev (2007). (a) Sub-sample of our spectra in the host-galaxy frame. The dashed line marks the position of the narrow absorption line at ∼6390 Å visible in our earliest four spectra. (b) Multi-band light curves of SN 2011bm. (c) Photospheric velocities (measured from Fe II λ4924, λ5018, and λ5169) for a sample of stripped-envelope core-collapse SNe. Data sources: SN 2007gr, Hunter et al. (2009); SN 2008D, Mazzali et al. (2008); SN 2007Y, Stritzinger et al. (2009); SN 2008ax, Taubenberger et al. (2011); SN 2009jf, Valenti et al. (2011); SN 1999ex, Stritzinger et al. (2002).

SN ejecta (cf. Tables 1 and 2). A sub-set of the spectroscopic and photometric data collected by the NTT ELP collaboration is shown in Figures 1(a) and (b), respectively. In Figure 1(c), the expansion velocity as derived from the position of the minima of Fe II lines[11] is shown and compared with those of normal SNe Ib/c. SN 2011bm shows typical velocities, but a slow velocity evolution similar to those of SNe 2009jf or 2007gr.

The classification spectrum taken on April 11 (18 days after the explosion) is rather blue ($B-V \sim 0.35$ mag). Such a blue color is unusual for SN Ic spectra at this epoch. Early spectra of SN 2011bm show the classical Type Ib/c SN features: Fe II, w, Ca II, and a faint P-Cygni absorption at ∼6100 Å, usually identified as Si II. A narrow line is visible at ∼6530 Å (∼6390 Å in the host galaxy rest frame) in the first four spectra (see Figure 1(a), marked with a vertical dotted line). A similar feature was also observed in very early spectra of SN 2007gr up to few days before maximum and was identified as C II λ6580, with Hα or He I λ6678 as possible alternatives. Using the spectrum synthesis code SYNOW,[12] we confirm that C II is a consistent identification for this feature. This supports the idea that our 18 day spectrum of SN 2011bm is similar to those of younger, canonical SNe Ic. Prominent features of He I or H are not detected in the optical domain, and there is no evidence for the He I line at ∼2 μm in our near-infrared SOFI spectrum obtained on 2011 May 9, consistent with the classification as an SN Ic.

The best match for the spectra of SN 2011bm is found with those of SN 2007gr (Hunter et al. 2009), persisting along the whole evolution (Figures 2(a) and (b)). What is different, however, is the timescale of the transition from optically thick to optically thin ejecta. At 18 days past core-collapse the spectrum of SN 2011bm is still blue (like those of normal Type Ic SNe a few days after the explosion). Three months after the explosion SN 2011bm is still optically thick, and the best match is found with spectra of SN 2007gr at a phase of only one month. Later on, at 305 days the spectrum of SN 2011bm shows nebular lines, though the detection of [w] λ5577 is unexpected, as this line usually disappears in the spectra of SNe Ic by ∼150–200 days after core-collapse. The spectrum of SN 2007gr at 172 days shows a stronger Mg I] λ4571 line than that of SN 2011bm. This may be due to a lower abundance of magnesium in SN 2011bm than in SN 2007gr or to a different ionization/excitation state of the ejecta in the two SNe or simply due to the fact that the O–Ne–Mg layer is still not completely exposed, while we are

[11] Average of the velocities obtained for the lines at λ4924, λ5018, and λ5169.
[12] http://www.nhn.ou.edu/∼parrent/synow.html

Table 1
Photometric Data[a]

Date	JD−2400000	*u*	*g*	*r*	*i*	*z*	Telescope + Instrument
2011 Mar 26	55646.53	···	···	18.71 0.10	18.82 0.06	···	PS1 + GPC1
2011 Mar 29	55649.56	···	18.78 0.16	···	···	···	PS1 + GPC1
2011 Apr 11	55663.50	17.42 0.08	17.17 0.16	16.95 0.15	16.93 0.27	17.07 0.12	Liverpool Telescope + RATCAM
2011 Apr 12	55664.50	17.56 0.03	17.07 0.19	16.84 0.18	16.84 0.07	16.92 0.05	Liverpool Telescope + RATCAM
2011 Apr 13	55665.37	···	16.93 0.42	16.81 0.05	16.74 0.04	16.82 0.09	Liverpool Telescope + RATCAM
2011 Apr 14	55666.42	17.39 0.10	16.88 0.28	16.69 0.19	16.71 0.16	16.83 0.06	Liverpool Telescope + RATCAM
2011 Apr 20	55672.42	17.42 0.06	16.82 0.06	16.54 0.11	16.53 0.11	16.63 0.03	Liverpool Telescope + RATCAM
2011 Apr 23	55675.38	···	16.74 0.09	16.48 0.08	16.49 0.14	16.59 0.02	Liverpool Telescope + RATCAM
2011 Apr 24	55676.41	17.52 0.23	16.82 0.04	16.43 0.04	16.43 0.05	16.53 0.03	Liverpool Telescope + RATCAM
2011 Apr 25	55677.44	17.60 0.15	16.82 0.09	16.42 0.08	16.41 0.07	16.58 0.03	Liverpool Telescope + RATCAM
2011 May 3	55685.37	18.40 0.10	17.02 0.06	16.34 0.07	16.41 0.05	16.51 0.02	Liverpool Telescope + RATCAM
2011 May 7	55689.60	18.71 0.20	17.27 0.04	16.33 0.04	16.39 0.03	16.49 0.03	Liverpool Telescope + RATCAM
2011 May 11	55693.38	18.92 0.26	17.37 0.03	16.41 0.03	16.44 0.01	16.54 0.02	Liverpool Telescope + RATCAM
2011 May 14	55696.40	19.30 0.27	17.42 0.07	16.52 0.07	16.49 0.10	16.60 0.07	Liverpool Telescope + RATCAM
2011 May 21	55703.45	19.50 0.16	17.63 0.05	16.62 0.05	16.58 0.03	16.69 0.04	Liverpool Telescope + RATCAM
2011 May 27	55709.47	19.57 0.12	17.75 0.08	16.81 0.07	16.65 0.03	16.71 0.03	Liverpool Telescope + RATCAM
2011 Jun 4	55717.49	19.74 0.17	17.96 0.04	16.92 0.04	16.82 0.02	16.79 0.03	Liverpool Telescope + RATCAM
2011 Jun 16	55729.40	19.97 0.24	18.21 0.08	17.22 0.08	17.16 0.04	16.97 0.05	Liverpool Telescope + RATCAM
2011 Jun 26	55739.42	19.99 0.31	18.37 0.06	17.35 0.06	17.30 0.05	17.02 0.03	Liverpool Telescope + RATCAM
2011 Jul 7	55750.39	20.18 0.22	18.55 0.06	17.62 0.05	17.49 0.03	17.19 0.05	Liverpool Telescope + RATCAM
2011 Jul 17	55760.44	20.22 0.65	18.71 0.18	17.74 0.14	17.64 0.08	17.39 0.05	Liverpool Telescope + RATCAM
2011 Dec 14	55909.69	···	20.20 0.61	19.43 0.36	19.46 0.31	19.67 0.98	Liverpool Telescope + RATCAM
2011 Dec 31	55927.77	···	20.47 0.27	19.51 0.26	19.65 0.08	19.77 0.16	Liverpool Telescope + RATCAM

Date	JD−2400000	*U*	*B*	*V*	*R*	*I*	Telescope
2011 Apr 10	55662.56	···	17.26 0.11	16.91 0.11	16.67 0.10	16.61 0.06	1.82 m Ekar Telescope + AFOSC
2011 Apr 11	55663.49	16.80 0.30	17.31 0.04	16.85 0.11	16.56 0.11	16.60 0.11	Liverpool Telescope + RATCAM
2011 Apr 12	55664.50	16.72 0.09	17.25 0.04	16.83 0.04	16.52 0.08	16.42 0.09	Liverpool Telescope + RATCAM
2011 Apr 13	55665.36	···	17.23 0.10	16.82 0.04	16.51 0.06	16.44 0.05	Liverpool Telescope + RATCAM
2011 Apr 14	55666.41	16.63 0.11	17.12 0.05	16.80 0.05	16.48 0.03	16.39 0.02	Liverpool Telescope + RATCAM
2011 Apr 14	55666.87	···	17.10 0.07	16.72 0.06	16.45 0.07	16.37 0.04	Faulkes Telescope North + EM01
2011 Apr 16	55668.86	···	17.07 0.11	16.70 0.09	16.44 0.11	16.24 0.09	Faulkes Telescope North + EM01
2011 Apr 17	55669.80	16.70 0.38	17.05 0.08	16.67 0.08	16.39 0.08	16.25 0.08	Faulkes Telescope North + EM01
2011 Apr 18	55670.45	16.68 0.08	17.00 0.08	16.71 0.08	16.42 0.08	16.37 0.08	Calar Alto 2.2 m Tel. + CAFOS
2011 Apr 19	55671.58	16.70 0.11	17.02 0.12	16.65 0.10	16.37 0.17	16.17 0.15	Calar Alto 2.2 m Tel. + CAFOS
2011 Apr 19	55671.80	16.61 0.06	17.05 0.15	16.61 0.15	16.32 0.09	16.18 0.08	Faulkes Telescope North + EM01
2011 Apr 20	55672.40	16.64 0.07	17.02 0.05	16.61 0.05	16.35 0.04	16.24 0.07	Calar Alto 2.2 m Tel. + CAFOS
2011 Apr 20	55672.42	16.56 0.19	17.00 0.19	16.58 0.20	16.22 0.12	16.15 0.11	Liverpool Telescope + RATCAM
2011 Apr 20	55672.90	16.60 0.18	17.02 0.06	16.54 0.03	16.23 0.07	16.14 0.10	Faulkes Telescope North + EM01
2011 Apr 23	55674.89	···	17.02 0.07	16.53 0.07	16.24 0.03	16.02 0.04	Faulkes Telescope North + EM01
2011 Apr 23	55675.38	···	17.04 0.09	16.54 0.09	16.20 0.07	16.04 0.06	Liverpool Telescope + RATCAM
2011 Apr 24	55676.41	16.89 0.10	17.10 0.06	16.54 0.05	16.17 0.05	16.04 0.05	Liverpool Telescope + RATCAM
2011 Apr 25	55677.44	17.06 0.05	17.11 0.02	16.52 0.02	16.17 0.04	16.00 0.03	Liverpool Telescope + RATCAM
2011 May 1	55683.41	···	17.32 0.09	16.58 0.17	16.15 0.06	15.95 0.07	1.82 m Ekar Telescope + AFOSC
2011 May 3	55685.37	17.56 0.08	17.41 0.27	16.61 0.20	16.14 0.06	15.96 0.05	Liverpool Telescope + RATCAM
2011 May 7	55689.49	17.71 0.17	17.58 0.16	16.63 0.14	16.24 0.14	16.12 0.09	Calar Alto 2.2 m Tel. + CAFOS
2011 May 7	55689.60	17.83 0.04	17.61 0.05	16.65 0.05	16.15 0.05	15.99 0.04	Liverpool Telescope + RATCAM
2011 May 11	55693.37	18.06 0.17	17.70 0.03	16.75 0.03	16.20 0.04	15.99 0.04	Liverpool Telescope + RATCAM
2011 May 14	55696.39	18.31 0.06	17.80 0.07	16.85 0.07	16.24 0.05	16.02 0.04	Liverpool Telescope + RATCAM
2011 May 21	55703.45	18.68 0.12	18.18 0.03	16.99 0.03	16.36 0.03	16.02 0.02	Liverpool Telescope + RATCAM
2011 May 22	55704.36	18.52 0.14	18.35 0.13	16.99 0.13	16.40 0.09	16.26 0.09	Calar Alto 2.2 m Tel. + CAFOS
2011 May 27	55709.47	18.76 0.07	18.29 0.04	17.16 0.04	16.46 0.04	16.15 0.04	Liverpool Telescope + RATCAM
2011 May 29	55710.77	···	18.30 0.10	17.09 0.10	16.46 0.07	16.20 0.03	Faulkes Telescope North + EM01
2011 Jun 4	55717.49	18.96 0.22	18.49 0.06	17.35 0.06	16.65 0.03	16.32 0.03	Liverpool Telescope + RATCAM
2011 Jun 11	55724.81	···	18.60 0.09	17.44 0.08	16.83 0.05	16.45 0.06	Faulkes Telescope North + EM01
2011 Jun 16	55729.39	19.05 0.36	18.76 0.14	17.55 0.14	16.94 0.03	16.58 0.02	Liverpool Telescope + RATCAM
2011 Jun 24	55736.50	19.24 0.07	18.89 0.06	17.63 0.05	17.15 0.04	16.75 0.04	NTT + EFOSC2
2011 Jun 26	55739.42	19.30 0.16	18.92 0.09	17.69 0.09	17.21 0.10	16.80 0.09	Liverpool Telescope + RATCAM
2011 Jun 28	55741.77	···	18.82 0.10	17.69 0.10	17.24 0.11	16.78 0.04	Faulkes Telescope North + EM01
2011 Jun 30	55743.39	19.42 0.37	18.92 0.17	17.80 0.16	17.26 0.11	16.82 0.09	Calar Alto 2.2 m Tel. + CAFOS
2011 Jul 7	55750.39	19.40 0.17	19.06 0.07	17.90 0.06	17.33 0.10	16.99 0.09	Liverpool Telescope + RATCAM
2011 Jul 17	55760.44	19.32 0.33	19.24 0.08	18.04 0.08	17.45 0.06	17.17 0.06	Liverpool Telescope + RATCAM
2011 Aug 1	55775.38	···	19.40 0.22	18.23 0.08	17.68 0.09	17.18 0.08	TNG + LRS
2011 Dec 6	55902.07	···	20.70 0.23	19.63 0.23	19.08 0.27	18.71 0.17	Faulkes Telescope North + EM01
2011 Dec 14	55911.11	···	20.92 0.61	19.80 0.60	18.97 0.34	18.61 0.23	Faulkes Telescope North + EM01
2011 Dec 17	55913.72	···	20.75 0.26	20.00 0.25	19.13 0.22	18.84 0.09	TNG + LRS

Table 1
(Continued)

Date	JD−2400000	U	B	V	R	I	Telescope + Instrument
2011 Dec 21	55917.67	...	20.86 0.62	19.88 0.50	19.16 0.51	18.85 0.43	WHT + ISIS
2011 Dec 23	55919.67	...	...	20.05 0.19	19.36 0.19	19.09 0.39	Calar Alto 2.2 m Tel. + CAFOS
2011 Dec 31	55927.76	...	...	20.15 0.17	19.36 0.23	19.10 0.21	Liverpool Telescope + RATCAM
2012 Jan 19	55948.83	...	21.07 0.41	20.35 0.12	19.38 0.12	19.08 0.06	NTT + EFOSC2
Date	JD−2400000	J	H	K	...	...	Telescope
2011 May 9	55690.13	15.78 0.16	15.58 0.16	15.32 0.11	...	...	NTT + SOFI
2011 Jun 24	55736.97	16.23 0.18	15.90 0.18	16.05 0.17	...	...	NTT + SOFI
2011 Jun 24	55736.50	...	16.11 0.10	...	...	...	LBT + LUCIFER
2012 Jan 21	55947.37	19.91 0.25	19.167 0.25	...	...	...	NTT+SOFI

Note. [a] *ugriz* magnitudes are calibrated to the Sloan photometric system (AB system) using the SDSS catalog (Abazajian et al. 2009); *UBVRI* magnitudes are in the Bessell system, calibrated with Landolt fields observed during photometric nights (Landolt 1992). Near-infrared images are calibrated to 2MASS catalog (Skrutskie et al. 2006).

Table 2
Spectra Collected

Date	JD−2400000	Phase[a]	Telescope	Instrument	Range (Å)	Resolution (Å)
2011 Apr 11	55662.54	18.5	1.82 m Ekar	AFOSC+GR04	3800–8200	20
2011 Apr 14	55665.55	21.5	NOT	ALFOSC+grism-4	3250–9100	14
2011 Apr 18	55670.48	26.5	2.2 m Calar Alto	CAFOS+blue-200	3400–8900	14
2011 Apr 20	55672.43	28.4	2.2 m Calar Alto	CAFOS+blue-200	3400–8900	14
2011 Apr 24	55675.62	31.6	NOT	ALFOSC+grism-4	3300–9100	14
2011 May 8	55690.12	46.1	2.2 m Calar Alto	CAFOS+green-200	3790–10000	14
2011 May 15	55697.49	53.5	TNG	LRS+LRB/LRR	3200–10000	13
2011 May 22	55704.39	60.4	2.2 m Calar Alto	CAFOS+green-200	4800–10200	13
2011 Jun 12	55724.58	80.6	TNG	LRS+LRB	3200–8700	12
2011 Jun 24	55736.52	92.5	NTT	EFOSC2+Gr13	3700–9250	18
2011 Aug 10	55784.36	140.4	2.2 m Calar Alto	CAFOS+green-200	3900–9300	14
2011 Aug 11	55785.37	141.4	2.2 m Calar Alto	CAFOS+green-200	3900–9300	14
2011 Dec 18	55913.75	269.7	TNG	LRS+LRR	5000–10100	10
2011 Dec 20	55915.77	271.8	WHT	ISIS+R158R	3300–10000	6/10
2012 Jan 22	55948.86	304.9	NTT	EFOSC2+Gr13	3700–9250	18
2011 May 5	55686.62	42.7	TNG	NICS +IJ	9000–15000	20
2011 May 9	55690.69	46.7	NTT	SOFI+GB/GR	9000–25000	20/30
2011 Jun 24	55737.50	93.5	NTT	SOFI+GB	9000–15000	20

Note. [a] Phase with respect to the estimated explosion epoch.

still seeing the C/O-rich layer. In the latter case, the Mg I] λ4571 line is expected to become more prominent with time.

Even more intriguing is the luminosity evolution of SN 2011bm. After the earliest detection by PS1, the light curve rises for several weeks, reaching its maximum in the R band on 2011 May 2 (JD = 2455684.3), 40 days after the explosion (see Figure 1(b)). No other *normal* SN Ib/c has shown such a slowly rising light curve. The post-maximum evolution is qualitatively similar to those of other SNe Ic, with a more rapid initial luminosity drop followed by a slower decline. However, for SN 2011bm the inflection points occur much later than in other SNe Ic. Comparing the light curves of SN 2011bm with those of SNe 1998bw (R band; Patat et al. 2001) and 1997ef (V band; Iwamoto et al. 2000), which are among the most slowly evolving BL-Ic SNe available in the literature, we find that SN 2011bm is evolving ∼1.5 times more slowly than SN 1997ef and ∼2.2 times more slowly than SN 1998bw.[13] SN 2011bm also evolves 2.7 times more slowly than SN 2007gr (Hunter et al. 2009) in the R band, in good agreement with the different timescales of the spectral evolution highlighted in Figure 2.

3. PHYSICAL PARAMETERS

A direct estimate of the host-galaxy metallicity can be obtained from the fluxes of nebular emission lines in the vicinity of the SN location. We measured the following narrow lines of the host-galaxy detected in our WHT spectrum of 2011 December 19: [O II] $\lambda\lambda$3726, 3729, Hβ, [O III] λ4959, [O III] λ5007, Hα, [N II] λ6583. Using different metallicity indicators, we obtain the following values: the N2 index calibration of Pettini & Pagel (2004) gives 12+log(O/H) = 8.41 dex, while the O3N2 index provided by the same authors gives a value of 8.31 dex. The method adopted by Kobulnicky & Kewley (2004) (see their Equation (18)) yields 12+log (O/H) = 8.58 dex.[14] These values are only marginally subsolar. From the Hα emission we also estimate a star formation rate of ∼0.06 $M_\odot$ yr^{-1} that is typical of H II regions and similar to that of other stripped envelope SNe (Valenti et al. 2008).

[13] The time evolution is computed stretching the light curves around maximum until the shapes of the light curves match.

[14] With the caveat that this value may be slightly dependent on the used value for the galactic extinction.

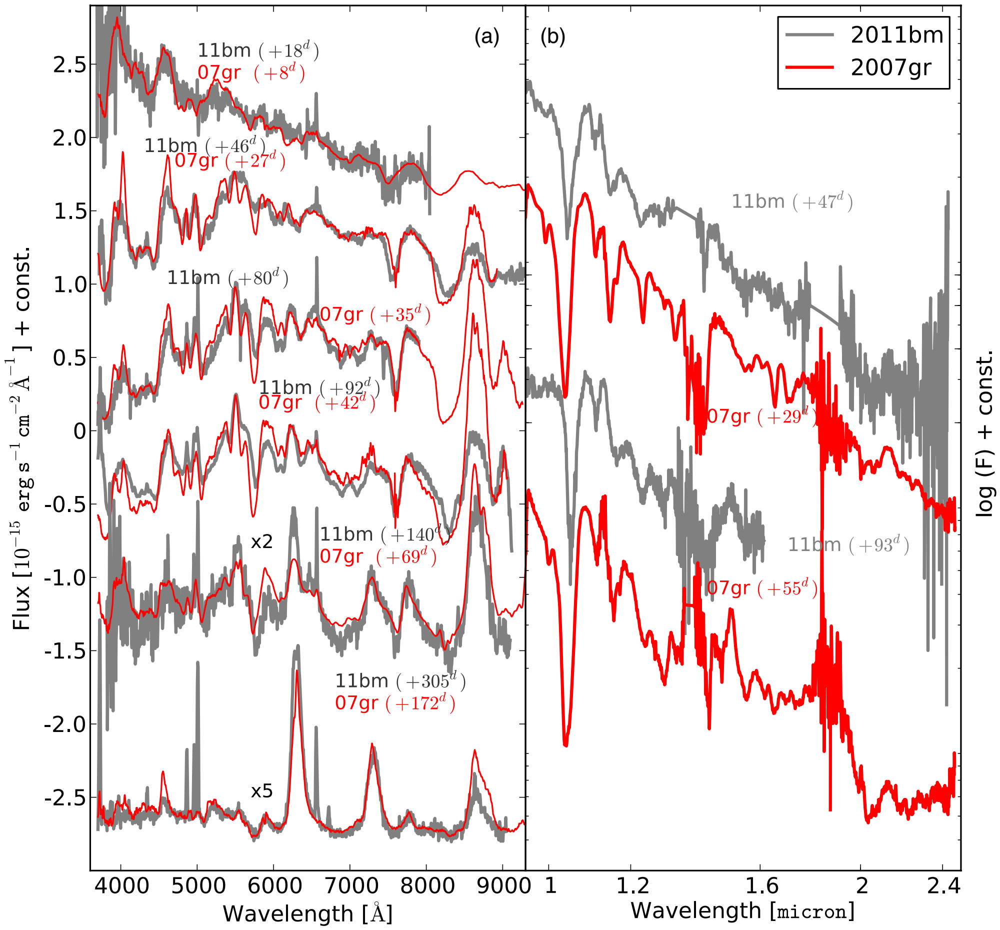

Figure 2. (a) Spectral evolution of SN 2011bm and comparison with spectra of SN 2007gr. The spectra of SN 2007gr have been scaled to match those of SN 2011bm. (b) Infrared spectra of SN 2011bm compared with spectra of SN 2007gr.

Our observations of SN 2011bm can be used to understand the physical conditions of the progenitor at the moment of the explosion. Important insights come from the nebular spectra, the shape of the light curve, and the bolometric luminosity. The spectrum obtained on 2011 December 18 (∼270 days after the explosion) provides additional information on the progenitor's properties. The presence of the [w] λ5577 feature is remarkable: this line is usually visible only up to ∼150–200 days after the explosion because it requires a relatively high electron density. Using Equation (2) of Houck & Fransson (1996) and a temperature of 4000–4500 K,[15] the flux ratio [w] λ6300/λ5577 of about 20–40, as measured from our TNG spectrum, indicates an electron density of $\geqslant 10^8$ cm^{-3}. The flux of the [w] λλ6300, 6364 feature measured at 270 days (3.7×10^{-14} erg cm^{-2} s^{-1}) can also be used to roughly estimate the ejected oxygen mass. Using the equation from Uomoto (1986) that is appropriate for our electron density and temperature regimes, we obtain an oxygen mass of $M_{\rm O} \sim 5$–$10\,M_\odot$. As a comparison, the oxygen masses obtained with the same method for SNe 1990I (0.7–1.35 $M_\odot$; Elmhamdi et al. 2004) and 2009jf (1.34 $M_\odot$; Sahu et al. 2011) are significantly smaller. Also the oxygen mass of SN 1998bw (∼3 $M_\odot$, Mazzali et al. 2001), computed via spectral modeling, is a factor of two smaller than that of SN 2011bm. Such a large oxygen mass in the ejecta is expected when the progenitor is either a very massive star ($\geqslant 30\,M_\odot$) or a lower-mass star formed in a very low metallicity environment (Thielemann et al. 1996; Limongi & Chieffi 2003; Hirschi et al. 2005; Nomoto et al. 2006). Given the metallicity measurement reported above, it is likely that the progenitor of SN 2011bm must have been very massive. Since most explosion models of massive stars predict that the oxygen mass represents 60%–70% of the total ejected mass (see, e.g., Limongi & Chieffi 2003; Nomoto et al. 2006), we can estimate the total ejected mass to be in the range 7–17 $M_\odot$.

In Figure 3(a) we show the quasi-bolometric light curve of SN 2011bm obtained by integrating our multi-band (*UBVRI*) observations. We also show the *uvoir* bolometric luminosity obtained for the few epochs in which *JHK* photometry of SN 2011bm is available (labeled as *uvoir* in Figure 3(a)) and a computed *uvoir* bolometric light curve using the fractional near-IR (NIR) contribution of SN 2009jf (Valenti et al. 2011). The late-time tail of this light curve is flatter than those of other stripped-envelope SNe, but still steeper than those of H-rich core-collapse SNe powered by ^{56}Co decay. This is a clear indication that the γ-rays produced in the ^{56}Co decay are not fully trapped. However, a larger trapping fraction than in other Type Ic SNe confirms that the ejecta of SN 2011bm are quite massive. We used the toy model described in Valenti et al. (2008)[16] to independently estimate the physical conditions at the moment of the

[15] This excitation temperature for SNe Ib/c at late phases is obtained from specific models of nebular spectra (Mazzali et al. 2001, 2007, 2010).

[16] The toy model is based on the Arnett's rule (Arnett 1982) for the photospheric phase, Equations (1) and (2) from Cappellaro et al. (1997), and a simple γ-ray deposition function (Clocchiatti & Wheeler 1997).

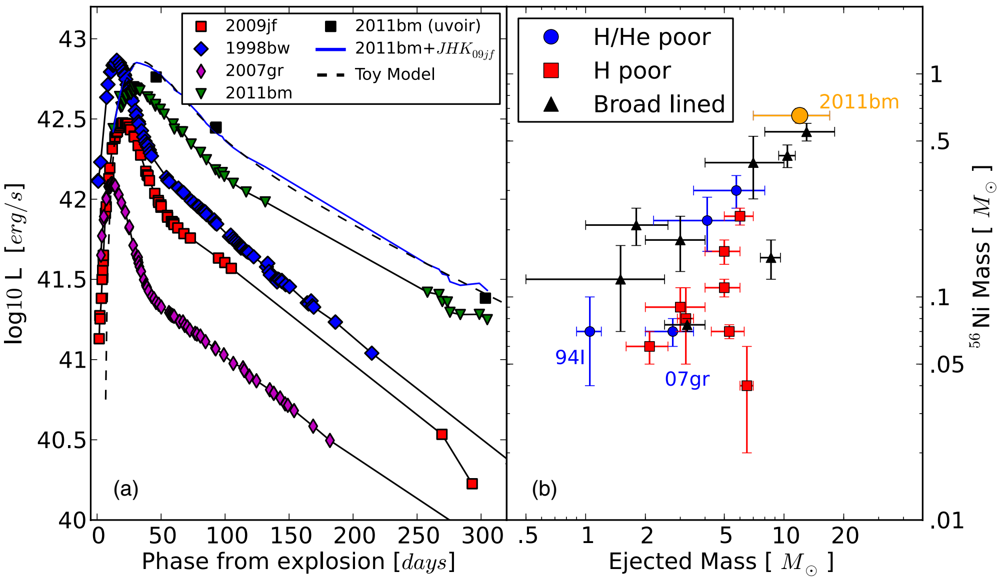

Figure 3. (a) Pseudo-bolometric (*UBVRI*) light curve of SN 2011bm, compared with a set of pseudo-bolometric light curves of other stripped-envelope SNe. The blue solid line is the *uvoir* bolometric luminosity of SN 2011bm, computed with the *UBVRI* light curve mentioned before corrected by the fractional NIR contribution of SN 2009jf (Valenti et al. 2011). The resulting *uvoir* bolometric light curve is consistent with the *uvoir* bolometric luminosity obtained for the few epochs in which *JHK* photometry of SN 2011bm is available (labeled as *uvoir*). The dashed line corresponds to the fit to the computed *uvoir* bolometric luminosity with the toy model described in Valenti et al. (2008). (b) Synthesized ^{56}Ni mass vs. ejecta mass for a heterogeneous sample of core-collapse SNe. Data are from Tanaka et al. (2009), Hunter et al. (2009), Valenti et al. (2011), and Stritzinger et al. (2009).

explosion. The *uvoir* bolometric light curve can be reproduced with an explosion of a massive star releasing 7–16 foe of kinetic energy in ejecta of 7–10 $M_{\odot}$, 0.6–0.7 $M_{\odot}$ of which is synthesized ^{56}Ni. These values are in agreement with those given above. The Nickel mass is surprisingly high, if we consider that SN 2011bm was less luminous than SN 1998bw at maximum.

4. DISCUSSION AND CONCLUSION

The extremely slow evolution of the light curve and spectra of SN 2011bm have never been observed in other *normal* stripped-envelope SNe. Despite this, its spectral features are very similar to those observed in typical SNe Ic, and much narrower than in broad-lined events. These observables are consistent with the explosion of a very massive star (with a main-sequence mass of $\geqslant 30\ M_{\odot}$) that ejected 7–17 $M_{\odot}$ of material, 5–10 $M_{\odot}$ of which is oxygen and 0.6–0.7 $M_{\odot}$ is ^{56}Ni. The kinetic energy lies between 7 and 17 foe. SN 2011bm is the first stripped-envelope SN with such a slow evolution and such peculiar physical parameters. The intrinsic rareness of these events supports the idea that they arise from very massive stars. To our knowledge, only one other *normal* stripped envelope SN has been proposed to come from a similarly massive star (SN 1984L; Swartz & Wheeler 1991).

An alternative, more exotic scenario to explain the luminous and broad light curve of SN 2011bm without invoking exceptionally high ^{56}Ni and total ejected masses is that of a magnetar-powered core-collapse SN. In this case the light curve of SN 2011bm would be dominated by the energy released in the spin-down of a newly formed magnetar. However, the slope of the late-time light curve of SN 2011bm (until a phase of 300 days) is consistent with that expected in a normal radioactively powered SN, without the need of an additional source as proposed in models of magnetar-driven events (Kasen & Bildsten 2010; Woosley 2010).[17]

Another characteristic of a magnetar-powered SN would be a bi-polar geometry of its ejecta (Kasen & Bildsten 2010). Evidence of a bi-polar explosion may be found in the profiles of the oxygen lines in nebular spectra. Double-peaked profiles would support the idea of a bi-polar explosion, whereas the absence of a double peak is not sufficient to rule out such an explosion geometry. Following the approach of Taubenberger et al. (2009), we inspected the oxygen feature and, though a weak double peak is marginally visible, it appears consistent with the doublet nature of [w] λλ6300, 6364. In conclusion, our observations neither require nor support a magnetar–SN scenario. Instead, the traditional framework of a ^{56}Ni-powered core-collapse SN from a very massive star seems to provide a coherent explanation. This makes SN 2011bm the most massive and ^{56}Ni-rich *normal* (i.e., not broad-lined) SN Ic ever observed. Further analysis and modeling will certainly help to better understand this exceptional event.

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[17] In addition, the handful of candidate magnetar-powered SNe recently discovered have never shown a late-time light-curve flattening onto the ^{56}Co tail (see, e.g., Pastorello et al. 2010; Quimby et al. 2011).

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