SN 1991bg - A type IA supernova with a difference

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SN 1991bg: A TYPE Ia SUPERNOVA WITH A DIFFERENCE[1]

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ABSTRACT

We present 13 spectra and 31 photometric observations covering the first 150 days of SN 1991bg in NGC 4374 (M 84). Although SN 1991bg was a type Ia supernova displaying the characteristic Si II absorption at 6150 Å near maximum and the Fe emission lines at late phases, it varied from the well-defined norm for SNe Ia in several important respects. The peculiarities include faster declines in the B and V light curves after maximum, a distinct color evolution, a very red $B-V$ color near maximum, relatively faint peak luminosity, a distinct spectral evolution, and a short peak phase. The narrow peak of the luminosity and the rapid declines of the light curves suggest a smaller mass in the

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ejecta and larger energy losses than for most SNe Ia. The unusually red color at maximum is not a result of normal extinction, since SN 1991bg was as blue as other SNe Ia at late times and no narrow interstellar lines are observed in the spectra. The faint absolute magnitude of SN 1991bg is established beyond doubt by comparison with SN 1957B, another type Ia supernova in the same galaxy, which was ~ 2.5 magnitudes brighter than SN 1991bg. The spectral evolution reveals minor differences near maximum compared to other well-observed SNe Ia, mainly in relative line strengths. At later phases several wavelength regions display discrepancies when compared to spectra of normal SNe Ia. Although other SNe Ia, such as SN 1986G and SN 1939B, have light curves with fast decline rates, SN 1991bg is unique, with deviations in both light curves and spectra. In particular SN 1991bg is the only SN Ia observed to date with a distinct spectrum at ~ 40 days past maximum. Although SN 1991bg is an extreme case, with unusual photometric and spectroscopic properties, we believe it can be understood in the context of exploding white dwarf models, and is properly grouped with type Ia. SN 1991bg demonstrates the need for detailed observations of SNe Ia as part of their use as standard candles for cosmology. While there is a well-defined prototype with homogeneous properties, unusual cases like SN 1991bg must be identified and separated to avoid misleading results.

1. INTRODUCTION

The discovery of a number of bright supernovae of type Ia (SNe Ia) in recent years has focused unprecedented attention on these events (Phillips *et al.* 1987, 1992; Frogel *et al.* 1987; Leibundgut 1988; Filippenko 1989; Leibundgut *et al.* 1991a,b; Hamuy *et al.* 1991; Filippenko *et al.* 1992a,b; Ruiz-Lapuente 1992; Ruiz-Lapuente *et al.* 1992; Wells *et al.* 1992). The homogeneity of the spectral and photometric appearance of this class of supernovae is often taken to indicate a single explosion mechanism and has independently generated interest in the possible uses of SNe Ia as distance indicators. Such a hypothesis must, however, be checked with each well-observed supernova to test the assumptions, and to explore intrinsic differences among individual events. Deviations from the norm, like distinct light curves or variations in spectral evolution, are important clues to the nature of SN Ia explosions, and provide valuable information on possible variations on a general theme.

Supernovae are divided into two main classes on the basis of the presence (type II) or absence (type I) of hydrogen lines in their maximum light spectrum (Minkowski 1941, 1964; Kirshner *et al.* 1973; Harkness & Wheeler 1990). Separations into more classes (Zwicky 1962, 1965) have been abandoned, since only one object of each peculiar type was known. A potential pitfall of any spectral classification system is that it might be based on insignificant details of surface conditions and might not provide a physically based separation of fundamentally different events. On the other hand, a classification scheme should provide an easy tool to distinguish different types on observational grounds—so spectra near maximum are practical. This contradiction is not readily resolved in all circumstances, but sometimes subtle differences point to new subdivisions of a class. For example, the separation of SNe Ib/c from SNe Ia is, by now, well-established and based on several independent signatures, including spectral differences near maximum, infrared light curves, and spectral evolutions at late phases (e.g., Harkness & Wheeler 1990, and references therein). Nevertheless, because the differences near maximum light are subtle, the two subclasses were confused for many years. Now it appears that they have very different progenitor stars and unrelated explosion mechanisms. Indeed, the type Ib/c subclass may have more in common with the type II supernovae than with SNe Ia.

More than any other subclass of supernovae, SNe Ia display a remarkable degree of similarity. Earlier investigations tried to subdivide the class based on differences in the light curve shapes (e.g., Pskovskii 1967, 1971, 1984; Barbon *et al.* 1973). These analyses, however, suffered from poor data and systematic errors and most of the old data sets are consistent with a uniform light evolution (e.g., Leibundgut *et al.* 1991a). Yet detailed observations over the last few years show that SNe Ia are not identical. Branch (1987) showed that SN 1984A had a significantly higher expansion velocity near maximum light than SN 1981B. Photometric variations were displayed by SN 1986G in NGC 5128 (Centaurus A), where the *B* and *V* light curves declined faster after maximum than those of SN 1981B (Phillips *et al.* 1987; Christiani *et al.* 1992) and the infrared light curves were also unusual (Frogel *et al.* 1987). Small but significant anomalies were observed in the optical spectrum of SN 1986G at maximum (Phillips *et al.* 1987) and later in SN 1990N (Leibundgut *et al.* 1991b). Much more spectacular deviations were revealed recently in the premaximum observations obtained of SN 1991T (Filippenko *et al.* 1992a; Ruiz-Lapuente *et al.* 1992; Phillips *et al.* 1992). These differences, however, disappeared within two weeks after maximum, and have been interpreted as possible abundance differences at the surface of the explosion (Jeffery *et al.* 1992). Interestingly, the *B*

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and *V* light curves of SN 1991T resembled those of typical SNe Ia, and the peak luminosity also was normal (Phillips *et al.* 1992; see, however, Filippenko *et al.* 1992a; Ruiz-Lapuente *et al.* 1992). These variations among SNe Ia are poorly understood signatures of differences among progenitor stars and explosion mechanisms, but the unusual early time spectra of both SN 1990N and SN 1991T can be explained within the framework of an exploding C—O white dwarf (Jeffery *et al.* 1992). As we will show below, SN 1991bg is an unusual case with significant spectroscopic and photometric peculiarities. Despite these differences, the main signatures of SNe Ia, i.e., lines of intermediate mass elements near maximum, iron lines at late phases, and the color and decline rates of the light curves at late epochs argue for a similar explosion mechanism for SN 1991bg and do not warrant creation of a new subdivision of the SN Ia class.

The discovery of SN 1991bg in the E1 galaxy NGC 4374 (Kosai *et al.* 1991) has added a truly peculiar event to the list of SNe Ia. SN 1991bg occurred 61″ due south of the nucleus of NGC 4374, a member of the Virgo cluster of galaxies. It is the second supernova recorded in this galaxy after SN 1957B. Early reports recognized that SN 1991bg did not follow the evolution of most SNe Ia (Filippenko *et al.* 1991; Benetti *et al.* 1991; Della Valle *et al.* 1991; Phillips & Hamuy 1991). The red color at maximum, the strength of the Si II lines, and the low velocities in the ejecta all pointed toward an event outside the normal range of SNe Ia (see also Filippenko *et al.* 1992b). Its discovery close to maximum makes it a good candidate for thorough testing of current ideas of SN Ia explosions in an extreme case. Our investigation centers on the question whether SN 1991bg can be understood as a variation of the SN Ia theme, or whether it demands a different physical explanation.

Although SN 1991bg is unusual, it may not be unique. Shortly after the peculiarities of SN 1991bg had been recognized another supernova with a similar spectrum near maximum was discovered. A spectrum of SN 1992K in ESO 269-G57 shows strong correspondence with maximum light spectra of SN 1991bg (Hamuy *et al.* 1992).

Our observations of SN 1991bg are presented in Sec. 2. The light curves and spectra are discussed in Secs. 3 and 4. The discussion (Sec. 5) delineates the differences between this supernova and most other SNe Ia and examines some possible explanations for those differences. We conclude with Sec. 6.

2. OBSERVATIONS

The night following the discovery announcement of SN 1991bg (13 December 1991 (UT); Kosai *et al.* 1991) we initiated photometric and spectroscopic observations at the F. L. Whipple Observatory, the MMT, and CTIO. The location of the supernova in the sky (minimum hour angle 2 and 3 hours at Whipple Observatory and CTIO, respectively) restricted observations to morning twilight for the first few weeks, nevertheless we obtained several spectra and images. The photometric record of SN 1991bg is detailed in Table 1. We concentrated on the *B* and *V* filters and only occasional *R* and *I* observations were obtained. The zero point of the photometry is based on several photometric nights at Mt. Hopkins and at CTIO, during which standard stars from the Selected Areas (Landolt 1983) and the E-Regions (Graham 1982) were observed. These data

TABLE 1. Photometry of SN 1991bg.

Date			JD (2448000+)	V	B-V	V-R	V-I	Notes
1991	Dec	3.78	594.28	14.90	—	—	—	1
		9.84	600.36	14.50	—	—	—	2
		10.80	601.30	14.40	—	—	—	2
		10.80	601.30	14.30	—	—	—	2
		13.50	604.00	14.02	0.74	0.26	0.33	3
		14.50	605.00	13.96	0.85	0.33	0.48	3
		15.50	606.00	13.97	0.89	0.33	0.40	3
		16.50	607.00	14.01	0.95	0.36	0.55	3
		17.35	607.85	14.01	1.02	—	—	4
		18.34	608.84	14.06	1.16	—	—	4
		19.34	609.84	14.15	1.19	—	—	4
		20.33	610.83	14.24	1.35	—	—	4
		27.36	617.86	15.11	1.51	—	—	5
		30.36	620.86	15.36	1.42	—	—	6
1992	Jan	2.35	623.85	15.51	1.37	—	—	6
		4.34	625.84	15.62	1.32	—	—	7
		5.35	626.85	15.71	1.36	—	—	8
		6.34	627.84	15.74	1.31	—	—	8
		7.34	628.84	15.76	1.31	—	—	8
		10.35	631.85	15.88	1.29	—	—	9
		11.35	632.85	15.94	1.26	—	—	9
		20.34	641.84	16.36	1.02	—	—	10
	Feb	4.32	656.82	16.78	0.95	0.27	0.72	11
		6.29	658.79	16.95	0.87	0.15	0.61	12
		8.33	660.83	17.01	0.86	0.11	0.70	12
		10.33	662.83	17.06	0.82	0.09	0.51	12
		21.29	673.79	17.53	0.72	0.12	0.86	13
		24.37	676.87	17.42	0.73	—	—	14
		26.30	678.80	17.58	0.68	—	1.02	15
	Mar	6.41	687.91	17.96	—	—	—	16
		7.41	688.91	17.92	0.69	—	—	17
		11.24	692.74	18.00	0.53	—	—	18
	Apr	8.19	720.69	18.49	0.39	—	—	19
		30.29	742.79	19.48	0.20	—	—	20
	May	19.98	762.48	19.74	—	1.35	1.70	21
	Jun	3.29	776.79	20.03	-0.07	—	—	20
1991	Dec	27.34	617.84	15.05	1.39	—	—	22
1992	Jan	7.34	628.84	15.82	1.22	—	—	23
	Feb	5.31	657.81	16.98	0.87	—	—	23

Notes to Table 1

1 photovisual; Y. Kushida (Kosai et al. 1991)
2 photoelectric; T. Kato (Kosai et al. 1991)
3 Mt. Hopkins 1.2m SAO telescope with Loral CCD; B. Leibundgut
4 CTIO 0.9m with Tek 1024 (#2); N. Caldwell
5 CTIO 0.9m with Tek 1024 (#2); L. Gonzalez
6 CTIO 0.9m with Tek 1024 (#2); D. Rehner
7 CTIO 0.9m with Tek 1024 (#2); A. Walker
8 CTIO 0.9m with Tek 1024 (#2); R. Schommer
9 CTIO 0.9m with Tek 1024 (#2); J. Parker
10 CTIO 0.9m with Tek 512 (#4); T. Barnes
11 CTIO 0.9m with TI (#3); P.Schmidtke
12 CTIO 0.9m with Tek 2048 (#1); P. Hintzen and K. Cheng
13 CTIO 4m with Tek 1024 (#2); N. Suntzeff
14 CTIO 0.9m with Tek 1024 (#1); L. Siciliano
15 CTIO 0.9m with Tek 1024 (#1); N. Suntzeff
16 CTIO 4m with Tek 1024 (#2); N. Suntzeff and M. Navarrete
17 KPNO 2.1m with T1KA; B. Leibundgut
18 CTIO 4m with Tek 1024 (#2); A. Walker and R. Schommer
19 CTIO 0.9m with Tek 1024 (#2); Y. Kim
20 KPNO 2.1m with T1KA; A. Porter
21 CTIO 0.9m with Tek 1024 (#1); G. Williger
22 CTIO 1.5m CSCCD/GEC10 (spectrophotometry); M. Phillips
23 CTIO 4m CSCCD/Reticon (spectrophotometry); M. Hamuy

TABLE 2. Photometry of comparison stars in the field of SN 1991bg.

designation	V	σ	n	B-V	σ	n	V-R	σ	n	V-I	σ	n
A	14.59	0.04	12	1.42	0.03	12	0.87	0.02	2	1.73	0.04	2
B	16.62	0.03	13	0.50	0.06	13	0.35	0.06	3	0.56	0.04	3
C	15.95	0.04	8	0.60	0.04	8	—	—	—	—	—	—
D	15.42	0.04	8	1.02	0.02	8	—	—	—	—	—	—
E	16.17	0.04	11	0.82	0.03	11	0.42	0.08	3	0.89	0.02	3
F	17.25	0.07	8	1.09	0.07	8	—	—	—	—	—	—
G	17.19	0.03	3	1.40	0.10	3	—	—	—	—	—	—
H	15.82	—	1	1.16	—	1	—	—	—	—	—	—
I	16.76	0.06	4	0.62	0.07	4	0.31	0.04	3	0.67	0.00	3
J	12.31	0.29	6	0.38	0.23	6	—	—	—	—	—	—
K	16.60	0.06	4	0.52	0.07	4	0.38	0.06	3	0.75	0.05	3
L	17.01	0.06	3	0.47	0.07	3	0.30	0.13	3	0.71	0.12	3
M	16.69	0.02	3	0.53	0.03	3	0.31	0.02	3	0.61	0.10	3

TABLE 3. Spectroscopy of SN 1991bg.

Date			JD (2448000+)	Wavelength coverage	Telescope Instrument	Observer
1991	Dec	13.49	603.99	4650–7050	1	a
		15.36	605.86	3200–7500	2	b
		15.52	606.02	6200–6800	3	c
		16.51	607.01	6200–6800	3	c
		27.34	617.84	3000–7750	4	d
		28.34	618.84	5150–9650	4	e
		31.50	622.00	4600–7200	1	f
		31.56	622.06	3200–7900	5	g
1992	Jan	7.34	628.84	3250–7500	2	h
		8.34	629.84	6300–10650	2	h
		14.40	635.90	3700–8780	3	i
		28.30	649.80	3150–7800	4	j
	Feb	5.31	657.81	3200–7500	2	h
	Mar	7.28	688.78	3700–8000	3	k
	Apr	4.17	716.67	3250–7500	2	h

Notes to TABLE 3

1 1.5m Tillinghast; z–machine
2 CTIO 4m; CSCCD/Reticon
3 MMT; RedChannel/TI 5
4 CTIO 1.5m; CSCCD/GEC 10
5 MMT; BlueChannel/Reticon

a J. Peters and B. Leibundgut
b J. Maza
c B. Whitney and M. Gomez
d P. Ugarte
e M. Phillips
f J. Peters
g R. Marzke
h M. Hamuy
i B. Schmidt
j M. Hamuy and R. Williams
k F. Chaffee and C. Foltz

were used to calibrate local standards in the field of SN 1991bg which are identified in Fig. 1 (Plate 8). The Mt. Hopkins and CTIO data sets were reduced completely independently using aperture photometry within IRAF.[6] Comparing the magnitudes and colors of stars in both data sets of images revealed no systematic difference ($\leqslant 0^{m}02$) between them. Table 2 gives the magnitudes and colors of the local standard stars based on the combined data sets. The errors given are the standard deviations of the measurements of each star, which typically amount to less than 0.05 mag for the brighter stars and up to 0.1 mag for stars as faint as 17th mag. The final light curves (Fig. 2) are based on differential photometry of the supernova carried out with respect to the local standards. The supernova is located at about 1.4 effective radii of the elliptical galaxy (Burstein *et al.* 1987), and galaxy background clearly affects the photometry (Fig. 1). Hence, special attention was given to determining the background. Subtracting the background by fitting the surface brightness of the galaxy or subtracting a smoothed image where the stellar objects had been removed did not yield significant improvements over aperture photometry. Around maximum light all the background corrections correspond to less than 0.05 mag in all filters. At later epochs the background contamination is a larger fraction of the supernova light, but the background subtraction in an annulus around the supernova corrects for the smooth galaxy brightness to within 0.1 mag. We are confident that the effects of background contamination on the shapes of the light curves (Boisseau & Wheeler 1991) are negligible during the period covered by our observations.

Our spectroscopic observations of SN 1991bg start near maximum, which occurred on 14.7 December in V (see below), and continue well into the nebular phase of the supernova. Low-dispersion spectra were obtained at CTIO with the 4 and 1.5 m telescopes, at the MMT, and with the Tillinghast 1.5 m telescope on Mt. Hopkins. A log of the spectroscopic observations can be found in Table 3. All spectra were wavelength calibrated and fluxed with IRAF tasks to remove the instrumental sensitivity variations. Spectra from CTIO were further observed with two slit widths (2″ and 10″) to assure spectrophotometry on photometric nights. Subtraction of background light was accomplished using pixels adjacent to the supernova in the long slit images. (The spectral evolution of SN 1991bg is displayed in Fig. 4.)

3. LIGHT CURVES AND COLOR CURVES

Figure 2 displays our CCD photometry together with synthetic magnitudes derived from the CTIO spectrophotometry. Also plotted are the premaximum photovisual magnitude estimates of Kushida and the V magnitude measured photoelectrically by Kato (Kosai *et al.* 1991). Our earliest photometry was evidently obtained close to maximum light. Maximum brightness in V occurred on 1991 December 14.7±0.5 days (JD 2448605.3±0.5) at $m_V = 13.95 \pm 0.02$ in excellent agreement with the values found by Filippenko *et al.* (1992b). The maximum in B is not covered by our data, and we can only estimate that the peak was reached at least one day earlier than in V. Other SNe Ia show a typical time interval of 1 to 2 days between B and V maxima (Phillips *et al.* 1987; Leibundgut 1988; Hamuy *et al.* 1991; Leibundgut *et al.* 1991b; Phillips *et al.* 1992), but due to the unusually red color of SN 1991bg, establishing the B maximum date based on comparison with other SNe Ia does not seem prudent. Instead we will deviate from the usual practice of using the B maximum as the time zero point and describe phases for this supernova *relative to the V maximum*. Figure 2 also shows the light curve templates for SNe Ia of Leibundgut (1988) which are a good representation of most SNe Ia (Leibundgut *et al.* 1991a,b; Hamuy *et al.* 1991; Phillips *et al.* 1992; Wells *et al.* 1992). The V template is matched with the observations at the maximum. Since the B maximum is not determined we matched the B template with the first observation available. It is clear from the figure that the templates are not an adequate representation of the light curves of SN 1991bg. The templates represent the photom-

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[6] IRAF is distributed by National Optical Astronomy Observatories.

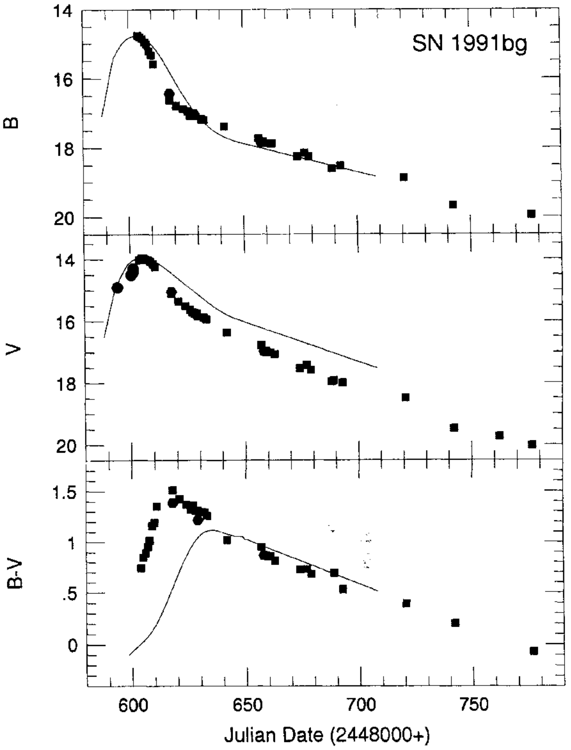

FIG. 2. The B (top) and V (bottom) light curves of SN 1991bg. The squares are CCD photometry from CTIO and Mt. Hopkins and the hexagons spectrophotometry from CTIO. Also shown as filled circles are the premaximum observations reported by Kosai *et al.* (1991). The template light curves for SNe Ia are shown for comparison.

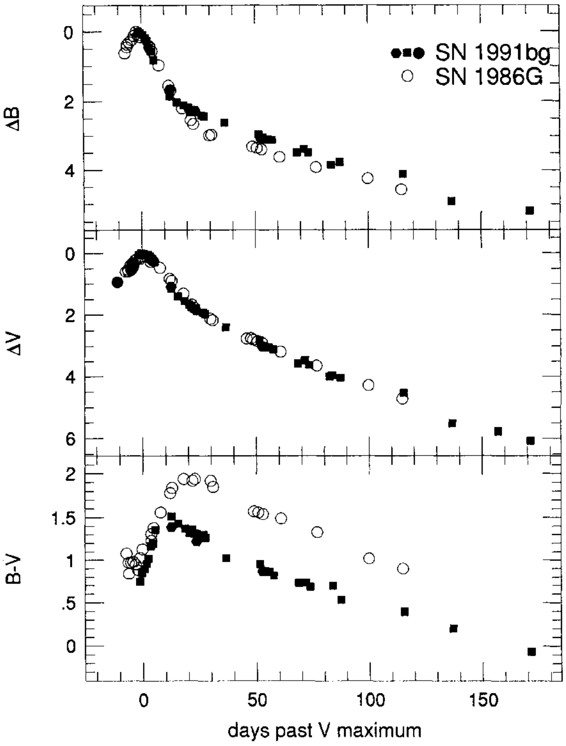

FIG. 3. Comparison of the light curves of SN 1991bg and SN 1986G. The two light curves are matched at maximum. Note the steeper declines in SN 1991bg and the shorter decline phase after maximum.

etry of most well-observed SNe Ia to better than 0ᵐ2 (Leibundgut 1991), with SN 1986G and SN 1939B being the most notable exceptions. The light curves of SN 1991bg fall by 2.05 and 1.42 mag during the first 15 days past maximum in B and V, respectively, while the declines in the templates amount to only 1.22 and 0.64 in the same filters. The B and V light curves of SN 1991bg decline between 15 and 40 days at rates of 0.029 ± 0.003 mag/day and 0.047 ± 0.001 for B and V, respectively. The light curves change slope again between 35(B) and 45(V) days after V maximum comparable to the templates with change slope 44(B) and 41 days (V) after V maximum. The decline rates after 50 days past V maximum are 0.021 ± 0.001 in B and 0.028 ± 0.001 in V for SN 1991bg which are marginally larger than the rates of the templates (0.017 in B and 0.026 in V; Leibundgut 1988).

The premaximum observations of Kushida and Kato suggest a faster rise time for SN 1991bg than for the template. If this is correct, then SN 1991bg had a much narrower peak than other type Ia supernovae. The width of the V light curve measured one magnitude below maximum corresponds to ~23 days for SN 1991bg compared to ~33 days for the V template.

The $B-V$ color evolution is displayed in the bottom panel of Fig. 2. In this diagram, the peculiarities described above are most obvious. We have plotted the comparison template with an assumed color at maximum of $B-V$ $=0.0$ (Hamuy *et al.* 1991), fixing the phases by the occurrence of the V maximum. The unusually red color of SN 1991bg at early epochs is strikingly evident in this figure. Note also that the maximum in the color curve is reached after only 15 days, while the template rises for about 30 days. The $B-V$ color evolution at late phases resembles most other SNe Ia. SN 1991bg is as blue as the template at these epochs. The slope of the curve is -0.010 ± 0.001 mag/day which is almost identical with the slope of the template of -0.009.

The fast decline of SN 1991bg after maximum resembles the well-observed SN 1986G (Phillips *et al.* 1987; Frogel *et al.* 1987). Comparison of the light and color curves of the two objects, however, reveals distinct differences (Fig. 3). While the light curves of SN 1986G bend at ~30 days past maximum, SN 1991bg changes slope 15 days earlier. At an epoch of 15 days, SN 1991bg had declined by ~0.2 mag more in B than SN 1986G, and by ~0.6 mag more in V. Thus, SN 1991bg had an even steeper decline after maximum than SN 1986G. The rates of decline in the exponential tails of SN 1986G were 0.019 ± 0.001 in B and 0.029 ± 0.0003 in V. The latter is almost identical with SN 1991bg, while the decline in B is intermediate between the templates and SN 1991bg. The lower panel of Fig. 3 is particularly revealing of the differences between the two supernovae. The phase of redward evolution of SN 1991bg

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is much shorter than that of SN 1986G and the slope of the redward evolution is not the same. SN 1991bg changes the $B-V$ color from 0.75 to 1.5 in the 12 days past V maximum when the peak in the $B-V$ curve is reached, whereas SN 1986G evolves from 1.0 to 1.9 in 21 days. The decline of SN 1991bg at late times, however, is again comparable to the templates and SN 1986G (-0.011 ± 0.0004).

Another supernova with a fast decline after maximum is SN 1939B in NGC 4621 (Shapley 1939; Hoffleit 1939; Campbell 1939; Baade 1964) which dropped by 3.3 mag in the photographic band during the first 15 days. This decline is even larger than those observed in the B band for SN 1986G or SN 1991bg.

We searched the atlas of SNe Ia light curves (Leibundgut *et al.* 1991a) for other events with such a steep initial decline. Such a search is hampered by scanty photometry for many supernovae and observational problems in many of the data sets. Only two supernovae were found with possible longer or steeper decline phases than the templates. SN 1963P appears to have faded a little faster in B than the template suggests (Bertola *et al.* 1965), and SN 1984A (Kimeridze & Tsvetkov 1986; Barbon *et al.* 1989) might have declined longer than the template, although the data are quite noisy.

4. SPECTRAL EVOLUTION

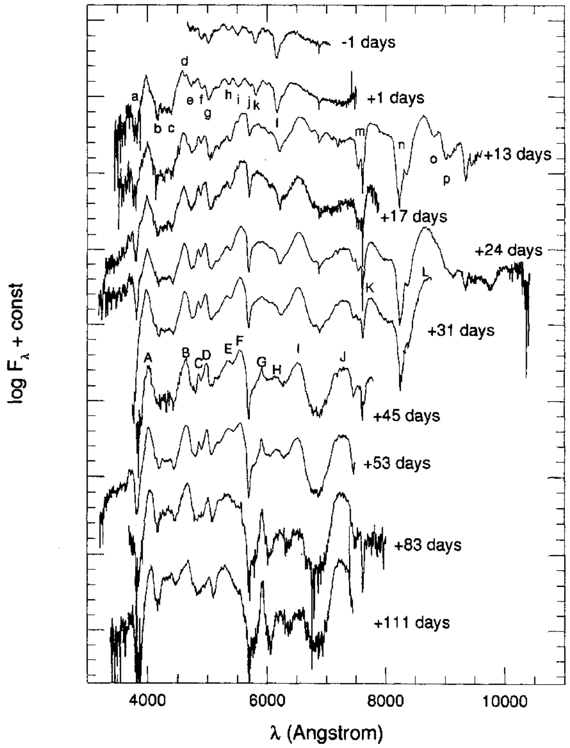

FIG. 4. Spectral evolution of SN 1991bg. The spectra have been displaced on the ordinate by arbitrary amounts for clarity. Absorption lines are labeled by lowercase letters, emission lines with uppercase letters.

Beginning with the first observations SN 1991bg displayed several peculiarities in its spectrum. The strong Si II ($\lambda_0 = 6355$ Å) absorption at 6150 Å clearly marks this event as a type Ia supernova (Kirshner *et al.* 1991; Filippenko *et al.* 1991, 1992b), but the atypical strengths of other lines were noted immediately (Filippenko *et al.* 1991; Phillips & Hamuy 1991). In the following we adopt the line identifications for SNe Ia of Jeffery *et al.* (1992) which agree with those given by Filippenko *et al.* (1992a,b); Ruiz-Lapuente *et al.* (1992) and, with the exception of Fe III lines, the earlier ones of Branch *et al.* (1983, 1985) and Harkness (1991a,b). At late phases the identifications are drawn from Axelrod (1980a). The line identifications for SN 1991bg cannot be definitive, since they are not the result of spectral synthesis calculations. We chose to label the minima with lowercase and maxima in uppercase characters in order to include unidentified lines in the discussion. This is potentially dangerous as it is not clear which features are in absorption and which in emission, and we expect a shift from absorption to emission lines as the supernova evolves.

The spectral evolution of SN 1991bg is illustrated in Fig. 4. The overall appearance of the supernova changed between the two early spectra near peak light and the third one which was obtained at an epoch ~2 weeks past V maximum. By this time the broad emission features which are ordinarily observed in SNe Ia at late phases (age $\geqslant 40$ days) have already begun to appear.

The spectra at maximum light are dominated by lines of Ca II, Si II, and S II as identified in Table 4. Ca II H & K are seen strong in emission while the absorption component of this scattering line is present but poorly defined due to the low signal-to-noise. We tentatively identify feature c with the usual Mg II and Fe III absorptions observed in other SNe Ia (e.g., Jeffery *et al.* 1992), although the whole wavelength region between 4100–4400 Å appears unusual for a type Ia event. Filippenko *et al.* (1992b) fit this part of the spectrum with Ti II (for our feature b) and Mg II (feature c). This region remains depressed well after a month past maximum and is filled in by emission only after ~50 days. The maximum light spectra are dominated by many lines of intermediate mass elements and the Fe III lines ($\lambda_0 = 4404$ Å and $\lambda_0 = 5129$ multiplets) identified in the spectra of SN 1991T (Filippenko *et al.* 1992a; Ruiz-Lapuente *et al.* 1992; Jeffery *et al.* 1992). Both Fe III absorptions appear quite strong compared to other SNe Ia (see, however, Filippenko *et al.* 1992b for a different interpretation). All S II and Si II lines are relatively well-defined and sharp. The Si II absorption at 5800 Å (designated with k) is stronger than in many other SNe Ia at comparable epochs. The characteristic Si II absorption at 6150 Å appears to be blended with another, unidentified, line at the red end. A possible identification is C II (6580 Å) with an expansion velocity of about 14 500 km s^{-1}. Alternatively, this feature could be Hα at a velocity of ~14000 km s^{-1}. Such an identification, however, appears rather unlikely for a type Ia supernova. The expansion velocity inferred for the Si II absorption at 6150 Å is ~10 600 km s^{-1}, when corrected for the galaxy redshift, which is comparable with

TABLE 4. Line absorptions in spectra of SN 1991bg.

Line designation	Line identification	Date												
		1991						1992						
		December						January				February	March	April
		13.49	15.36	27.34	28.34	31.50	31.56	7.34	8.34	14.40	28.30	5.31	7.28	4.17
		(−1)[a]	(+1)	(+13)	(+14)	(+17)	(+17)	(+24)	(+25)	(+31)	(+45)	(+53)	(+83)	(+111)
a	Ca II (H+K)	—	3800	3780:	—	—	3800	3820	—	—	—	3810	3840	—
b	—	—	4160	4150:	—	—	4170:	4180	—	4170:	4170:	4200	4160	4170
c	Mg II; Fe III	—	4390	4400:	—	—	4410:	4420:	—	4420:	4430:	4440	4440	4450:
d	Si III	—	4610	—	—	—	—	—	—	—	—	—	—	—
e	— (blend)	4720	4720	4740	—	4750:	4720	4750	—	4760	4780:	4780:	—	—
f	Si II	4900	4900	4890	—	4890	4890	4890	—	4900	4890	4900	—	—
g	Fe III (blend)	5010	5030	5060:	—	5040	5070	5070	—	5060	5060	5080	5100	5100
		—	5150	5210:	—	5140:	5200	5200	—	5180	5180	5220	—	—
h	S II (blend)	5350	5340	5380:	5380	5380	5380	5390	—	5400	5420	5430	—	—
i	S II	5500	5510	—	—	—	—	—	—	—	—	—	—	—
j	Si II (blend)	5700	5710	5700	5710	5700	5700	5700	—	5700	5700	5700	5700:	—
		—	—	—	—	5760:	5780	5790	—	5790	5780	5790	5810	—
k	Si II	5800	5810	—	—	—	—	—	—	—	—	—	—	—
l	Si II (blend)	6160	6170	6200	6200	6210	6210	6210	—	6230	6280:	6280:	—	—
		6240	6270	6270	6250	6290:	6310	6320	—	—	—	—	—	—
m	O I	—	—	—	—	—	—	—	7450	7440	7440	—	—	—
		—	—	7530	7540	—	7550:	—	7530	7540	7540:	—	—	—
n	Ca II	—	—	—	8220	—	—	—	8230	8220	—	—	—	—
		—	—	—	8350	—	—	—	8370	8400	—	—	—	—
o	C I?	—	—	—	8810	—	—	—	—	—	—	—	—	—
p	—	—	—	—	9000	—	—	—	—	—	—	—	—	—

Notes to TABLE 4

[a] Phase of observation in days past assumed V maximum (JD 2448605.3)

velocities of other well-observed SNe Ia at maximum (Branch *et al.* 1988; Leibundgut *et al.* 1991b; Phillips *et al.* 1992). The velocity of the Ca II H & K absorption minimum corresponds to $\sim$12 000 km s^{-1}, which is much slower than observed for SN 1990N ($\sim$21 000 km s^{-1}; Leibundgut *et al.* 1991b) but comparable to SN 1991T (12000–13000 km s^{-1}; Phillips *et al.* 1992).

An ultraviolet spectrum was obtained with *IUE* almost exactly at V maximum on 14.8 December (UT). The signal attained in an exposure of 150 minutes integration was very low. We measure an integrated flux between 2400 and 3150 Å of about 6.5×10^{-13} erg s^{-1} cm^{-2}. No features are apparent in the spectrum. The broad emission peak near 2950 Å observed in other SNe Ia (Blair & Panagia 1987) is not discernible due to the low signal in the spectrum. There is, however, an increase of flux with increasing wavelength consistent with the observations of other SNe Ia. The UV flux between 2400 and 3150 Å is about 14 times weaker in SN 1991bg than for SN 1990N at a comparable epoch (Leibundgut *et al.* 1991b), while the observed flux ratios between SN 1991bg and SN 1990N are $\sim$1/7 and $\sim$1/4 in B and V, respectively.

A moderate resolution [$\Delta\lambda$(FWHM)$\approx$3 Å] spectrum of SN 1991bg covering the wavelength range from 6200 to 6800 Å was obtained near maximum. No narrow line features are obvious, although shallow broad absorptions at 6420, 6650, and 6740 Å appear to be present. The spectrum shows no signs of a possible scattering line due to Hα in accord with the observations in other SNe Ia. We also searched for a narrow absorption line due to possible hydrogen absorption in NGC 4374, as reported in the case of SN 1990M (NGC 5493; Polcaro & Viotti 1991), but could not detect any trace of such an absorption.

Two weeks after the V maximum the S II and Si II lines either disappeared or drastically changed their appearance. The same is true for the Fe III absorptions. The Ca II lines and the 6150 Å absorption of Si II remain strong. P Cygni absorptions of O I and Ca II are observed in the near infrared, a region not covered by the earlier spectra. The absorptions o and p are of unknown origin; a possible identification for the absorption o is C II (9111 Å). This is the equivalent transition to the O I (7774 Å) line observed as absorption *m*. Both troughs o and p disappeared 10 days later with only the smooth wing of the Ca II emission blend still visible. The evolution of the supernova is much slower after day 13. The appearance of the spectrum at 30 days is not very different from the one at 13 days. Following Kirshner & Oke (1975) and Axelrod (1980a,b) we identify most of the apparent emission features with [Fe II] and [Fe III] multiplets, although the Ca II (H&K) scattering line persists over the entire period of our observations. From Table 4 a break in the evolution of the supernova around day 13 is also evident; while many absorptions shift to redder wavelength before this phase, most of the lines show little displacement after 13 days. This is also observed in normal SNe Ia, but the slow down in the evolution occurred much earlier in SN 1991bg. As discussed below, this early change in the spectrum and the rapid evolution in the light curve are important clues to the physical difference between SN 1991bg and other SNe Ia. The identifications given in Table 4 refer to the maximum phase and are not applicable at later epochs. The Si III line at 4600 Å (d) and the Si II feature at 5800 Å (k) are not discernible after maximum light. A slight secular trend of the emission to longer wavelengths can be deduced from Table 5, but most measurements are uncertain due to the breadth of the features. The emission F increases in strength until day $\sim$30 after which it decays and blends with emission E

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TABLE 5. Line emissions in spectra of SN 1991bg.

Line designation	Line identification	Date												
		1991						1992						
		December						January				February	March	April
		13.49	15.36	27.34	28.34	31.50	31.56	7.34	8.34	14.40	28.30	5.31	7.28	4.17
		(−1)[a]	(+1)	(+13)	(+14)	(+17)	(+17)	(+24)	(+25)	(+31)	(+45)	(+53)	(+83)	(+111)
A	Ca II (H+K)	—	3970	4000	—	—	3990	4000	—	3980	4010:	4020	4020	4060:
		—	4060	—	—	—	—	—	—	—	4080:	4160:	—	—
B	Fe III	—	4590	4600	—	—	4610	4620	—	4620	4630:	4640	4630	4660
C	—	—	4830	4850	—	4840:	4850	4850	—	4850	4860	4860	—	—
D	Fe III?	—	4940	4950	—	4960	4950	4970	—	4980	4990	5000	4980:	5020:
E	—	5270	5290	5310	—	5320	5320	5340	—	5330	5350:	5370	5340:	5290:
F	Fe III? (blend)	5420	5610	5600:	5580:	5580:	5600:	5570	—	5550	5540	5560	5560:	5520:
G	Co III?	—	—	5850:	5840	5850:	5820:	5890:	—	5910	5920	5920	5930	5920
H	Co III?	—	—	6060:	6040:	6060:	6060:	6070:	—	6070	6150:	6170:	6200:	6220:
I	Fe II?	—	—	6550	6550:	6540:	6520:	6530	6530	6530	6520	6520	6520:	6520:
J	Fe II (blend)	—	—	—	—	—	—	7270:	7280:	7280:	7280:	7260:	7230:	7240:
K	O I	—	—	—	7750:	—	—	—	7750	7740:	—	—	—	—
L	Ca II (blend)	—	—	—	8630	—	—	—	8680	8680:	—	—	—	—

Notes to TABLE 5

[a] Phase of observation in days past assumed V maximum (JD 2448605.3)

(Table 5). The evolution of these two features might indicate the changing ionization states of Fe and the cooling of the nebula. An intriguing feature is the absorption at 5700 Å (j) which does not shift and is very narrow (FWHM ≈ 2500 km s^{-1}). For comparison the width of the Ca II absorption at the same epoch (45 days) is 7000 km s^{-1}. The origin of the 5700 Å line is unclear, but it is remarkable that the emission line at 5900 Å (G), which is clearly visible by day 45, is likewise very narrow suggesting small velocities in the ejecta. A possible identification of either feature would be Na I (see also Filippenko *et al.* 1992b). By day 83 the absorption j has evolved into a blend, as the sharp blue edge prevails, but the red edge is eroded away by another feature. The spectral changes between 83 and 111 days are minor. The emission lines at this stage are well-defined and most likely identified with forbidden lines of Fe and Co.

5. DISCUSSION

The red color of SN 1991bg at maximum contrasts with the observed colors of other SNe Ia. Figure 5 shows a histogram of the observed $(B-V)$ color at maximum for all SNe Ia and SNe I as determined by Leibundgut *et al.* (1991a) supplemented with the measurements of SN 1986G (Phillips *et al.* 1987), SN 1989B (Barbon *et al.* 1990; Wells *et al.* 1992), SN 1990N (Leibundgut *et al.* 1991b), SN 1991T (Phillips *et al.* 1992), and SN 1991bg. Interpretation of this diagram is complicated by several effects. Observational errors increase the overall scatter and widen the distribution in a symmetric way. This is probably the cause for the two bluest supernovae. The sharp increase at about $(B-V)_{\max} \approx -0.25$ is a strong argument for a blue limit to the intrinsic colors of SNe Ia. As discussed by van den Bergh & Pierce (1992), most of the galaxies with such blue supernovae are ellipticals and the spread in color is much larger for SNe Ia in spiral galaxies. In fact, except for SN 1991bg, all supernovae in ellipticals are confined to very blue colors, but some supernovae in $\mathrm{S0_{pec}}$ galaxies have $(B-V)_{\max} \geqslant 0.0$.

Figure 5 shows that only SN 1986G exhibited a larger $B-V$ at maximum than SN 1991bg. The red color of SN 1986G has been attributed to extinction in the prominent dust lane of Cen A. This conclusion is supported by observations of strong interstellar lines of Ca II and Na I in the spectrum of SN 1986G (Phillips *et al.* 1987; Rich 1987; di Serego Alighieri & Ponz 1987; Christiani *et al.* 1992). If we were to assume that this is also the explanation for the red color of SN 1991bg, then a color excess of $E(B-V) \approx 0.7$ would be derived (provided the intrinsic color at maximum is 0.0) which would imply an extinction of A_B

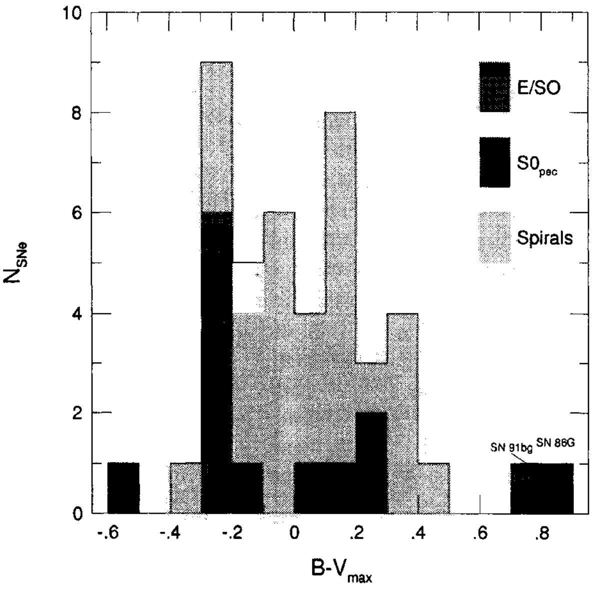

FIG. 5. Histogram of $B-V$ colors observed at maximum for SNe Ia. The data have been taken from Leibundgut *et al.* (1991a) and are corrected for Galactic absorption only. Supernovae in elliptical galaxies are the dark shaded area, light shaded areas denote SNe Ia in spiral galaxies, and the rest occurred in $\mathrm{S0_{pec}}$. Note the sharp turn-on near $B-V_{\max} = -0.3$. SN 1991bg clearly lies outside the main distribution. The blank space in the histogram is for the parent galaxy of SN 1973B for which no galaxy type was available.

$\approx 2^{\mathrm{m}}8$ for a conventional reddening law. Interestingly, this is close to the brightness difference observed between SN 1991bg and SN 1957B or other SNe Ia in Virgo. There are, however, several arguments against this hypothesis. The color of SN 1991bg at late times ($t > 35$ days) is as blue or even bluer than the template (Fig. 2) and much bluer than for SN 1986G (Fig. 3). No interstellar absorption lines are detectable in the spectra of SN 1991bg, and no evidence for dust at the supernova position can be extracted from very deep direct images of NGC 4374. From inspection of the deep frames the local absorption in B can be estimated to be less than $0^{\mathrm{m}}1$ at the position of the supernova assuming a conventional absorption law. Another possibility is that condensation of matter in the supernova ejecta itself could have caused the reddening. Dust was observed to condense in the ejecta of SN 1987A around 600 days after outburst (Lucy *et al.* 1991) without noticeable narrow absorption lines appearing in the spectra (e.g., Phillips *et al.* 1990). The evidence from the color and light curves, however, seem to exclude such an explanation for SN 1991bg.

It has been suggested that SNe Ia are good standard candles (e.g., Miller & Branch 1990, 1992; Leibundgut & Tammann 1990; Tammann & Leibundgut 1990), despite the strong spectral deviations observed in a few cases (Branch *et al.* 1988; Filippenko *et al.* 1992a; Ruiz-Lapuente *et al.* 1992; Phillips *et al.* 1992). A few events, however, have displayed distinct light curves, foremost SN 1986G (Phillips *et al.* 1987; Frogel *et al.* 1987) and possibly SN 1939B (e.g., Leibundgut *et al.* 1991a). Most SNe Ia with well-observed light curves, however, appear to define a narrow zone in a redshift versus apparent magnitude diagram (Leibundgut & Pinto 1992; see, however, van den Bergh & Pierce 1992) and only a small scatter of the absolute B magnitude at maximum is observed (Miller & Branch 1992; Della Valle & Panagia 1992). *SN 1991bg does not fit into this picture.*

The low peak luminosity of SN 1991bg is most readily apparent when contrasted with SN 1957B which occurred in the same galaxy (Bertola 1964; Goetz 1957; Romano 1957; Li Tzin 1957; Greenstein & Minkowski 1973), and reached a maximum magnitude of 12.2 in the photographic bandpass (Leibundgut *et al.* 1991a). The spectrum of SN 1957B at ~24 days published by Greenstein & Minkowski (1973) with comparable epoch spectra of SN 1989B (Wells *et al.* 1992) shows unambiguously that SN 1957B was a type Ia supernova. The magnitude difference between SN 1957B and SN 1991bg amounts to about 2.5 mag in B (assuming that the B maximum of SN 1991bg was around 14.7).

NGC 4374 (M 84) is an E1 galaxy with small H I content (only upper limits have been found to date; van Gorkom *et al.* 1989) and no detection of CO emission (Rupen 1992). A radio jet extends from the center about 1′ in the north–south direction (Laing & Bridle 1987; Gregorini *et al.* 1989). The galaxy has been detected in x-rays (Forman *et al.* 1985; Canizares *et al.* 1987) and at all wavelengths by *IRAS* (Knapp *et al.* 1989). A dust lane in the core extending in the E–W direction (Veron-Cetty & Veron 1988; Hansen *et al.* 1985; Gallagher 1986) coincides with Hα emission (Baum *et al.* 1988; Trinchieri & di Serego Alighieri 1990). NGC 4374 has a radial velocity of 930 km s^{-1} (Huchtmeier & Richter 1989) and is listed as a member of the Virgo cluster in the VCC (Binggeli *et al.* 1985). Distances for NGC 4374 have been obtained with the planetary nebula luminosity functions (Jacoby *et al.* 1990) and surface brightness fluctuations (Tonry *et al.* 1990) and both place the galaxy slightly *behind* the cluster center, but by less than 10%. Samples of SNe Ia in Virgo yield an average of $m_B = 12.0 \pm 0.2$ (Leibundgut & Tammann 1990; Capaccioli *et al.* 1990). The maximum of SN 1957B is consistent with this value, but SN 1991bg was more than 2 mag fainter in B. *Thus, SN 1991bg clearly did not reach a maximum luminosity comparable to other SNe Ia.* This appears to be the first unambiguous example of an intrinsically dim type Ia supernova.

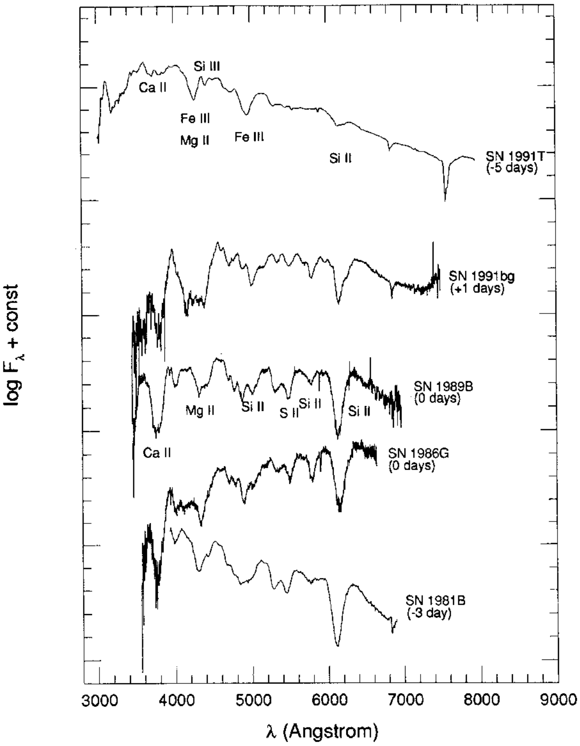

FIG. 6. Spectral comparison of SNe Ia near maximum. The spectra are shifted by arbitrary amounts along the ordinate and have been corrected for the observed galaxy redshifts. The epochs are days past the V maximum of each supernova. The sources for the spectra are Phillips *et al.* (1992; SN 1991T), Wells *et al.* (1992; SN 1989B), Phillips *et al.* (1987; SN 1986G), and Branch *et al.* (1983; SN 1981B).

It is instructive to compare the optical spectra of SN 1991bg with observations at similar epochs of other SNe Ia. At maximum light the SNe Ia spectrum is produced by the outermost material in the ejecta and is composed mainly of lines of intermediate mass elements (Branch *et al.* 1985; Harkness 1991a,b; Jeffery *et al.* 1992). Figure 6 displays the spectrum of SN 1991bg along with four other SNe Ia for which an observation near maximum light was available. All spectra have been corrected for the observed galaxy redshifts tabulated by Huchtmeier & Richter (1990). The line identifications are taken from Jeffery *et al.* (1992) for SN 1991T and Harkness (1991b) for SN 1989B. SN 1986G and SN 1989B were reddened considerably by interstellar material as supported by the strengths of the narrow Na D absorptions in their spectra. The spectrum of SN 1991T is from a significantly earlier phase than the other spectra and the continuum slope is still quite blue. With the exception of SN 1991T, all spectra are similar, but slight differences in line strengths and velocities are clearly present. The characteristic Si II absorption at 6150 Å is visible in all spectra, but with considerably different strengths (see also Filippenko *et al.* 1992a; Ruiz-Lapuente *et al.* 1992; Phillips *et al.* 1987, 1992). As in SN 1991bg this feature is also blended on the red side in SN 1986G. A search for a similar extension of the Si II multiplet at 5900 Å in the spectrum of this SN is hampered by the strong interstellar absorption due to Na I. Another feature which varies significantly among the different supernovae is the Si II line at 5800 Å (Phillips & Hamuy 1991). The Ca II H & K lines are observed in emission in SN 1986G, SN 1989B, and SN 1991bg. The absorption component is also easily visible in all three SNe. Strong differences are observed in the region from ~4000 to ~4200 Å. Si II absorption (from the 4130 Å multiplet) is present at ~4000 Å in the spectra of SN 1981B, SN 1989B, and more weakly in SN 1986G. No trace of this line is visible in SN 1991T and it is possibly filled in by the Ca II H & K emission in SN 1991bg. Note also that the sharpness of the individual features is different among the individual SNe.

Two weeks past maximum SN 1991bg enters into a transitional period when the photosphere recedes to the center and a nebular spectrum begins to emerge. At this stage spectra are composites of newly forming emission features and slowly disappearing absorptions. Spectra at this epoch are shown for five SNe Ia in Fig. 7. In contrast to the situation near maximum light, the supernovae are much more homogeneous at this epoch (Filippenko *et al.* 1992a; Phillips *et al.* 1992). SN 1991T, which was clearly discrepant two weeks earlier, displays the same bumps and wiggles as SN 1990N, SN 1989B, and SN 1981B. The main difference at this phase is the strength of the Si II line at 6150 Å. Slight differences in the 4000–5000 Å region are evident in these SNe Ia, but all features are present. The spectrum of SN 1991bg, however, still clearly deviates from the other SNe. Although most of the lines have counterparts in the spectra of other SNe Ia their relative line strengths are different. The Ca II lines are still very strong and the emission of the infrared triplet shows structure not observed in SN 1990N. The absorption at 4400 Å (Mg II and Fe III), which is seen in all other SNe Ia, is conspicuously absent. On the other hand a strong emission identified with [Fe III] (Axelrod 1980a) has formed at 5580 Å. This emission has alternatively been identified with the [O I] (λ_0=5577 Å) line (Filippenko *et al.* 1992b). However, the strength of this line and the absence of the [O I] doublet at 6300 Å would imply very high densities of the order of 10^{11} O^0 atoms cm^{-3} and low temperatures ($T_e \leqslant 2000$ K) for reasonable electron densities ($n_e/n_{O\,II} = 1$) and ionization ($n_{O\,II}/n_{O\,I} = 10^{-2}$; Leibundgut *et al.* 1991c). The 5577/(6300+6363) ratio would then decrease with the aging supernova. It would imply that we see a substantial fraction of unburnt oxygen in very dense states outside the ejecta. While not completely excluded by the observations, we think that this interpretation is flawed due to the high densities of neutral oxygen required. The Si II (6150 Å) absorption is blended stronger with the unidentified absorption on the red side. Hints of this absorption are also visible in the spectrum of SN 1991T. The emission part of the O I (λ_0=7774 Å) scattering line appears stronger than in SN 1990N and SN 1981B. The strength of the Ca II and O I emissions indicate the presence of these elements in abundance in the ejecta. The emergence of the Fe emission at 5600 Å so early suggests a rapid spectroscopic evolution of SN 1991bg as seen in the light curves.

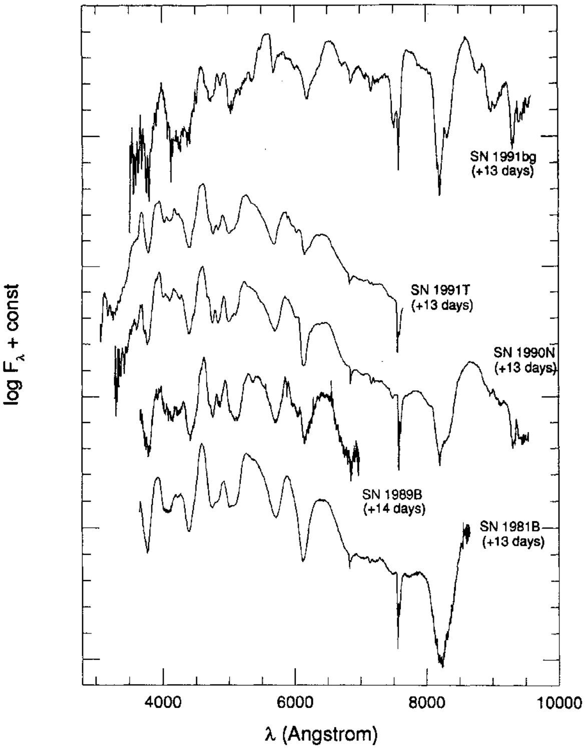

FIG. 7. Same as Fig. 6 for SNe Ia two weeks past maximum. The references are the same as in Fig. 6 with the spectrum of SN 1990N observed on 23.98 July 1990 at CTIO.

At epochs later than a month after maximum, the spectra of typical SNe Ia are dominated by emission due to ions of Co and Fe which were originally deep within the explosion and which are a direct consequence of the basic physical event of a SN Ia—nuclear burning to iron peak elements. As illustrated in Fig. 8, the agreement at these epochs is striking. Differences among the spectra are now dominated by signal-to-noise ratios and resolution. The exception to this rule is again SN 1991bg. Although the general resemblance to a typical type Ia supernova is now much closer, there remain obvious differences. First, the

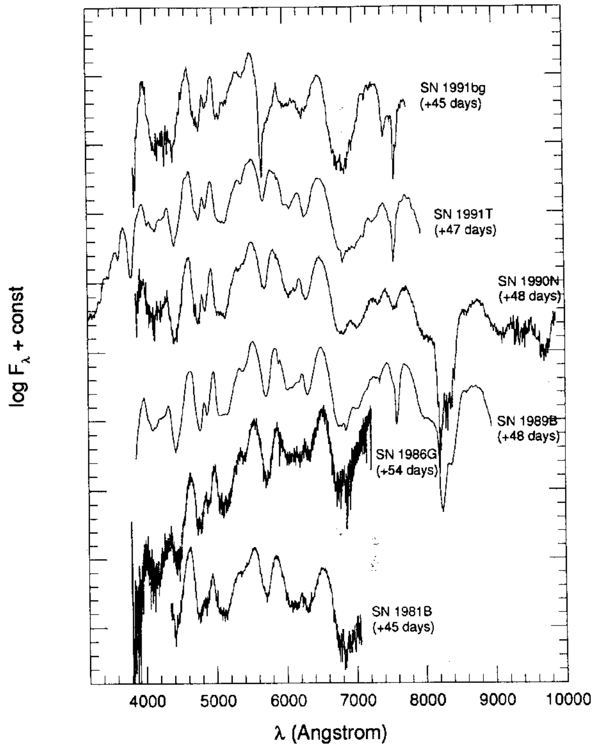

FIG. 8. Same as Fig. 6 for SNe Ia about seven weeks past maximum. Note the homogeneity of all spectra presented except the one of SN 1991bg.

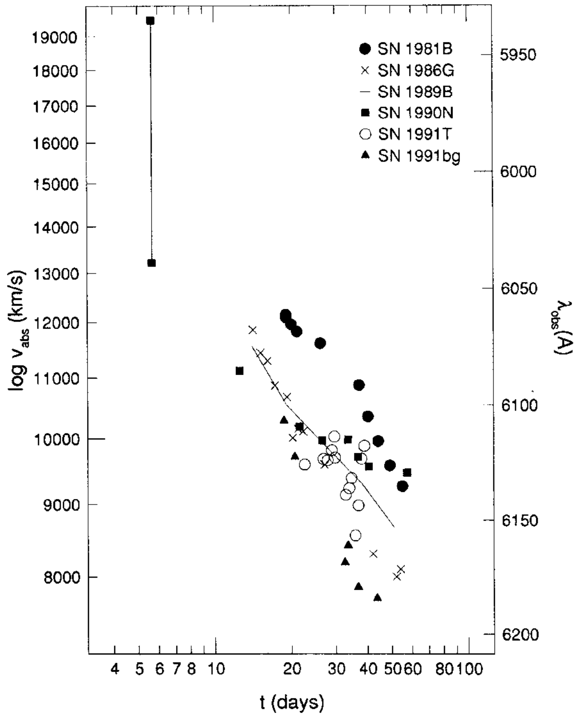

FIG. 9. Expansion velocities inferred from the minimum of the Si II (6355 Å) line vs time since explosion. A rise time between explosion and maximum of 20 days has been assumed for all supernovae. The data for the other well-observed SNe Ia (cf. Phillips *et al.* 1992; Christiani *et al.* 1992) have been included for comparison.

narrow absorption line at 5700 Å (j) and the adjacent emission (G), normally attributed to [Co III], are distinct from all other SNe. An alternate identification for these lines could be the Na I D lines (Filippenko *et al.* 1992b). An apparent absorption is also observed at 7430 Å which is not seen in any of the other supernovae. Finally, the Ca II emission is still strong in the spectrum of SN 1991bg.

The expansion velocity as inferred from the observed minimum of the Si II ($\lambda_0=6355$ Å) line is a diagnostic of SN Ia explosions (Branch 1987; Branch *et al.* 1988; Phillips *et al.* 1992). Figure 9 presents the data for well-observed SNe Ia. All data have been corrected for the observed redshifts of the parent galaxies and a rise time between explosion and maximum of 20 days has been assumed. Near maximum the majority of supernovae have expansion velocities between 10 000 and 13 000 km s^{-1} (Branch *et al.* 1988). SN 1991bg is no exception to this, although its velocity is slightly lower than for most other well-observed SNe Ia. After 10 days SN 1991T and SN 1990N showed little change in the observed velocities. This was interpreted as a strong confinement of the Si layer in the explosion (Phillips *et al.* 1992). SN 1991bg, like SN 1981B, SN 1986G, and SN 1989B, did show decreasing velocities with time. The slopes are comparable for these four SNe, but SN 1991bg has the steepest slope and extends to the lowest velocities at later phases. The rise time of SN 1991bg is not known. We simply assumed that it would be the same as for other SNe Ia, but this might not be a valid procedure in light of the various peculiarities observed in this event. In fact, there might be an indication of a faster rise of SN 1991g in the premaximum observations of Kosai *et al.* (1991). Shortening the rise time of SN 1991bg would result in a shallower slope of the velocity evolution.

Many of the peculiar features of SN 1991bg can be accounted for by a smaller mass in the ejecta. The rapid decline in the light curve and the early color evolution in combination with the almost normal expansion velocities are signs of a smaller column depth in the ejecta than in ordinary SNe Ia. This also suggests that the low luminosity of SN 1991bg is due to less efficient trapping of γ rays from radioactive ^{56}Ni and ^{56}Co and a shorter photon diffusion time near maximum light. The early transition from a spectrum with scattering lines on a photosphere to emission lines is also consistent with this view. Based on the simple arguments presented in Jeffery *et al.* (1992) we estimate an ejecta mass of $\sim$0.5–0.8 $\mathcal{M}_\odot$ for SN 1991bg assuming that the density structure and composition (mainly Fe-peak elements) are similar to normal SNe Ia.

The nearly normal velocities in combination with the smaller total mass would imply a less energetic explosion. The smaller mass of synthesized material would also lower the peak luminosity. Yet the spectroscopic similarities of the interior, as indicated in Fig. 8, demand that the nuclear burning proceed to the usual composition in the inner zones. To some extent, the observed homogeneity of SNe Ia has seemed more plausible because of the very well-defined physical event of exploding a white dwarf at the Chandrasekhar limit. Perhaps the peculiarity of SN 1991bg stems from a variant of an explosion at a somewhat lower mass.

6. CONCLUSIONS

SN 1991bg is an unusual type Ia supernova in several ways—the quick fading after an underluminous maximum, the red $B-V$ color at maximum and its subsequent evolution, the relative strengths of the lines in the spectra and their evolution. Most unusual is the brief duration of the photospheric phase which ended just two weeks after maximum. What SN 1991bg does have in common with other SNe Ia are the strong Si II and Ca II lines near maximum light. Indeed, the classification of SN 1991bg as a type Ia seems reasonable since it has the characteristic Si II 6150 Å line in the maximum light spectra, the usual Fe emission lines and the blue $B-V$ color at late phases ($t \geqslant 40$ days). Furthermore, the slopes in the light and color curves are almost identical with the templates at late times. This implies that SN 1991bg represents a variation of the general SN Ia event rather than a fundamentally different object. Thus, we think that a further subclassification for this supernova is not warranted.

Our discussion has assumed that the red color of SN 1991bg is an intrinsic property and not due to attenuation by dust. Reddening from the Galaxy can be excluded based on the observations of SN 1957B in the same galaxy and the lack of narrow interstellar absorption lines in the spectra. The absence of interstellar lines at the redshift of NGC 4374 also argues for little absorption in the parent galaxy as long as the gas-to-dust ratio is not very small. Moreover, no obvious dust features have been observed at the position of SN 1991bg in NGC 4374. The most convincing argument, however, is the relative blue color at late times, when SN 1991bg exhibits similar colors to other SNe Ia.

The spectral evolution of SN 1991bg is unique but not unrecognizable. The photospheric phase resembles other SNe Ia, but the early changes and the development of emission features clearly distinguish this supernova from other type Ia events. This calls the dating of SNe Ia based on single spectra alone into question. The peculiarities in the maximum light spectra of SN 1991bg consist mostly of changed line ratios compared to normal SNe Ia. Thus, the outer layers of SN 1991bg appear closely related to those of other SNe Ia implying that the end stages of the burning were comparable. The short duration of the photospheric phase is taken as a sign of a smaller ejecta mass in SN 1991bg. The nebular phase spectra are dominated by broad emission lines as is common for SNe Ia. Real differences from normal SNe Ia are, however, still present. Most notable is a narrow absorption trough accompanied by a narrow emission line in the region between 5700 and 6000 Å. A possible explanation for this feature could be blending of a resonance line with a pure emission, the latter possibly from [Co III] lines observed in normal SNe Ia (Axelrod 1980a,b).

Except for SN 1991bg all SNe Ia with observations at late epochs ($t \geqslant 40$ days) display a high degree of uniformity providing evidence that the stellar interiors resemble one another. This is in accord with what is expected from a thermonuclear explosion of a white dwarf (Nomoto *et al.* 1984; Woosley *et al.* 1986; Axelrod 1980b). Even supernovae with peculiarities at earlier phases exhibit very similar spectra at the nebular stage. An excellent example of this is SN 1991T which had a very peculiar premaximum spectrum (Filippenko *et al.* 1992a; Ruiz-Lapuente *et al.* 1992, Phillips *et al.* 1992). Even SN 1986G, which had fast decaying B and V light curves after maximum (Phillips *et al.* 1987) and peculiar infrared light curves (Frogel *et al.* 1987), was spectroscopically indistinguishable from other SNe Ia at late epochs. Hence, the unusual nature of SN 1991bg is even more striking.

Filippenko *et al.* (1992b) discuss several possible explosion scenarios which could explain the observations of SN 1991bg. The facts presented here support their main conclusion that the ejecta mass is lower than for normal SNe Ia. If it is possible to explode a white dwarf at a lower mass or to lock up mass in a compact remnant, an event resembling SN 1991bg might well result.

Finally, this peculiar event complicates the question whether SNe Ia make good standard candles. We think that SN 1991bg is peculiar in so many aspects that it clearly is separable as a distinct event within the class of SNe Ia. Even if the apparent brightness of SN 1991bg were comparable to SN 1957B and other SNe Ia within the Virgo cluster, the photometric and spectroscopic evolution of SN 1991bg is sufficiently different that it would have been recognized as unusual. The faintness of SN 1991bg, nevertheless, demands that future use of SNe Ia as distance indicators has to be tied to an identification scheme that can sort out "suitable" objects for distance determination. One such criterion could be the brightness evolution as measured by the light and color curves and the colors at maximum. Most SNe Ia do follow the template light curves fairly well (to within $0^{m}_{.}2$) and the color at maximum exhibits only a small scatter even when no correction is made for reddening in the parent galaxies (Leibundgut 1991). Peculiar SNe Ia, such as SN 1986G, SN 1991bg, and possibly SN 1939B issue their own warnings that they should be excluded for distance purposes. The danger is that distant supernovae with these characteristics may be included in estimates for the distance scale when the data are incomplete.

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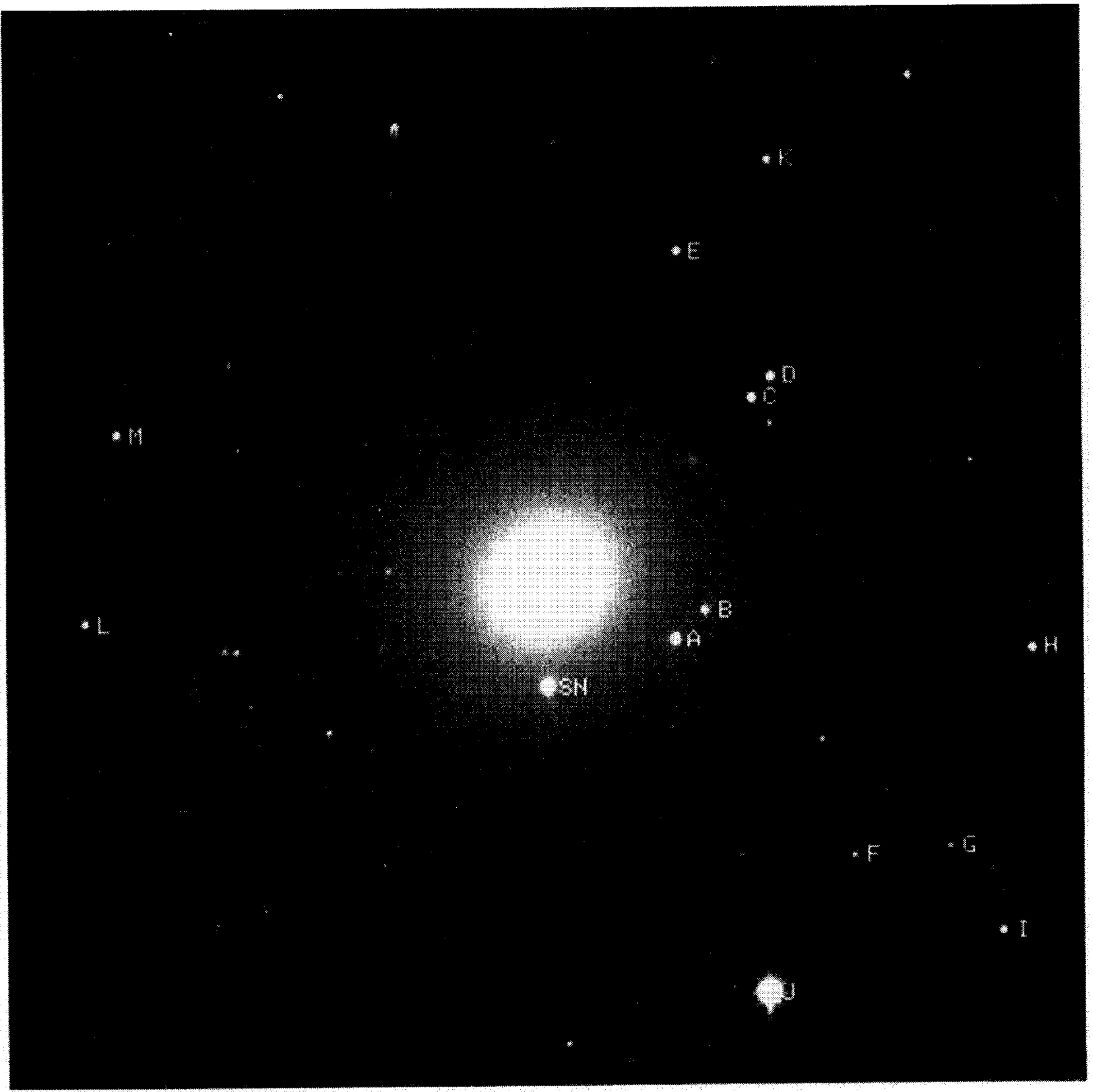

FIG. 1. *B* filter image of SN 1991bg in NGC 4374. This frame was observed with the 1.2 m SAO telescope at the Whipple Observatory with a Loral 2048^2 CCD on 15.55 December 1991 (UT). The picture is the sum of two 300 s. exposures. The supernova and the local standard stars are labeled. North is up and east to the left; the field of view is 10′ on a side.

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