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THE TYPE Ia SUPERNOVA 1986G IN NGC 5128: OPTICAL PHOTOMETRY AND SPECTRA

M. M. PHILLIPS, A. C. PHILLIPS, S. R. HEATHCOTE, V. M. BLANCO, D. GEISLER, D. HAMILTON, AND N. B. SUNTZEFF
Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories,* Casilla 603, La Serena, Chile

F. J. JABLONSKI† AND J. E. STEINER†
Instituto de Pesquisas Espaciais/MCT, C. Postal 515, 12200, São José dos Campos, São Paulo, Brasil

A. P. COWLEY,† P. SCHMIDTKE,† AND S. WYCKOFF†
Department of Physics, Arizona State University, Tempe, Arizona 85287

J. B. HUTCHINGS†
Dominion Astrophysical Observatory, 5071 W. Saanich Road, Victoria, BC V8X 4M6, Canada

J. TONRY†
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

M. A. STRAUSS†
Department of Astronomy, University of California, Berkeley, California 94720

J. R. THORSTENSEN†
Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire 03755

W. HONEY†
Department of Astrophysics, South Parks Road, Oxford, OX1 3RQ, England

J. MAZA† AND M. T. RUIZ†
Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

A. U. LANDOLT† AND A. UOMOTO†
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803

R. M. RICH
Department of Terrestrial Magnetism, 5241 Broad Branch Road, N.W., Washington, DC 20015

J. E. GRINDLAY†
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138

H. COHN†
Department of Astronomy, Indiana University, 319 Swain West, Bloomington, Indiana 47405

H. A. SMITH†
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

J. H. LUTZ†
Program in Astronomy, Washington State University, Pullman, Washington 99164

R. J. LAVERY
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822

AND

A. SAHA
Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington,
813 Santa Barbara Street, Pasadena, California 91101

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†Visiting Observer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories.

ABSTRACT

Optical light curves and spectra of the Type Ia supernova 1986G in NGC 5128 (Centaurus A) are presented. SN 1986G was discovered approximately one week before maximum light. The initial rate of decline of the B light curve was remarkably fast and characteristic of the infrequently observed Pskovskii photometric class $\beta = 12$. Although the spectral evolution closely resembled that of the more common "slower" photometric classes of Type Ia supernovae, subtle differences in the maximum-light spectra were detected. The expansion velocity of the photosphere of SN 1986G decreased rapidly at early phases, suggesting that the outer-envelope density gradient was less steep than in supernovae with smaller values of β. SN 1986G appears to have been heavily obscured ($E(B-V) = 0.90 \pm 0.10$) by the dust lane of NGC 5128. This circumstance accounts for the strong interstellar-absorption lines of Ca II H and K and Na I D observed in the spectra as well as for several weaker absorption features that we identify with the diffuse interstellar bands.

SN 1986G provides graphic confirmation of the existence of intrinsic differences in the optical light curves and spectroscopic properties of Type Ia supernovae. Consequently, these objects must be used with considerable caution as cosmological standard candles. On the basis of the very close resemblance of SN 1986G to SN 1971I in NGC 5055, we derive a relative distance of $D_{\mathrm{NGC}\,5128}/D_{\mathrm{NGC}\,5055} = 0.39 \pm 0.04$. Further distance estimates are hampered due to the lack of other well-observed Type Ia supernovae with $\beta = 12$.

Key words: supernovae–photometry–spectrophotometry

I. Introduction

On 1986 May 3.5 (UT), Evans discovered a supernova in the dust lane of the nearby radio galaxy NGC 5128 (Evans 1986). Optical spectra and photometry obtained shortly thereafter showed that the supernova—designated 1986G—was of Type I (Fairall 1986; Tonry and Strauss 1986; Meurer 1986*a*) and still slowly brightening (Phillips and Geisler 1986). Strong interstellar Na I D and Ca II H and K absorption was observed at the redshift of NGC 5128 (Tonry and Strauss 1986; Heathcote, Cowley, and Hutchings 1986) suggesting that the supernova was reddened substantially by the dust lane that cuts across this peculiar galaxy (see Fig. 1). This conclusion was supported by the large observed $(B-V)$ color at discovery (Hill 1986; Phillips and Geisler 1986) as well as ultraviolet spectra obtained near maximum (Wamsteker *et al.* 1986; Kirshner 1986).

SN 1986G is the first recorded supernova in NGC 5128. The distance to NGC 5128—the nearest of all radio galaxies—is a matter of controversy, with recent estimates ranging from 3 Mpc (Hesser *et al.* 1984) to 6.9 Mpc (Sandage and Tammann 1981). The discovery of a Type I supernova—albeit a heavily reddened one—represents an opportunity to determine independently the distance to NGC 5128 relative to other nearby galaxies with well-observed Type I supernovae. Hence, we began an extended series of photometric and spectroscopic measurements of SN 1986G at optical and infrared wavelengths. In this paper we present optical light curves and spectra covering the initial 120 days of observation. In a separate article (Frogel *et al.* 1987), the infrared properties of SN 1986G over the same period are considered.

II. Observations

Photoelectric and direct CCD observations of SN 1986G were obtained with the 1.5-m, 1-m, and 0.9-m telescopes at Cerro Tololo Inter-American Observatory on 24 nights during the period 1986 May 5 to September 3 (UT). Additional photoelectric measurements were undertaken on six nights in May and June on the 1.6-m and 0.6-m telescopes of the CNPq/Laboratório Nacional de Astrofísica in Brazil. The majority of the observations were made through B and V filters, although some data were obtained at U, R, and I. The combined results of the photometry are listed in Table I.

On most nights the CCD observations were made relative to the two field stars identified in Figure 1. Magnitudes and colors for these determined from CCD images obtained on four photometric nights are given in Table II. Color-term corrections were applied to these relative measurements, although such adjustments were generally quite small. Due to the brightness of this supernova and its location in the middle of the dust lane of NGC 5128 (see Fig. 1), contamination from the background galaxy was not a problem.

Spectroscopic observations of SN 1986G with resolutions ranging from 2.6 Å–16 Å were carried out on eleven nights at CTIO on the 4-m, 1.5-m, and 1-m telescopes, on two nights with the Las Campanas Observatory 2.5-m telescope, and on one night with the University of Hawaii Mauna Kea Observatory 2.2-m telescope. The 1-m telescope spectra were obtained with a "2D-Frutti" two-dimensional photon-counting detector as were the two Las Campanas observations and most of the CTIO 4-m telescope spectra. The remainder of the 4-m observations,

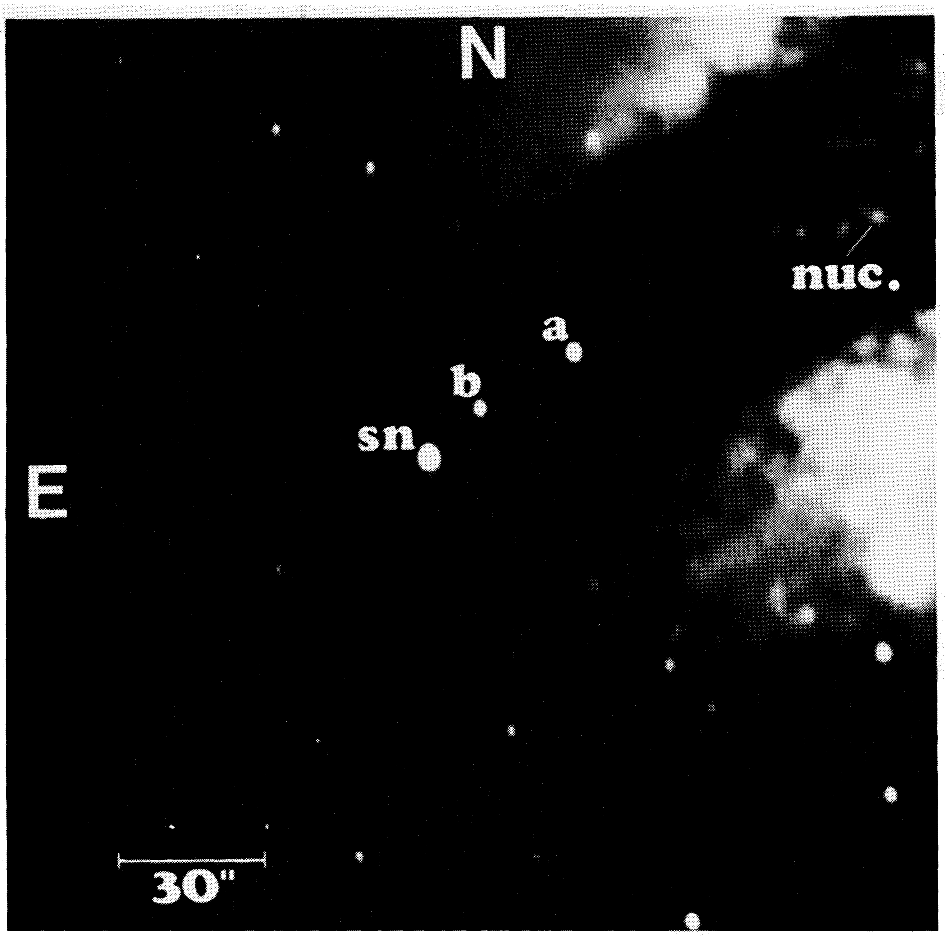

FIG. 1–Broad-band B CCD image of NGC 5128 taken on 1986 June 4 (UT) showing the positions of the supernova and the two field stars used for carrying out relative photometry.

and all of those made with the 1.5-m telescope, were made with a bare GEC CCD. The University of Hawaii 2.2-m telescope spectrum was taken with the Galileo/IFA Camera, which employs a UV-flooded, backside-illuminated TI CCD (Hlivak, Henry, and Pilcher 1984). Relevant parameters for these spectroscopic data are given in Table III.

III. Results

A. *Light Curves*

The B and V light curves of SN 1986G are plotted in Figure 2. Included are published photoelectric observations by Hill (1986), Bues, Duerbeck, and Kohoutek (1986), and Meurer (1986*b*) as well as a photographic B measurement by McNaught and Humphries (1986). From Figure 2 we conclude that maximum light in the blue occurred on JD2446561.5 ± 1 (May 11 ± 1 UT) when the supernova reached a magnitude of $B_{max} = 12.45 \pm 0.05$. Visual maximum was attained approximately 2–3 days later, as is usual for Type Ia supernovae.

Pskovskii (1977, 1984) has developed a useful parameterization scheme for the blue light curves of Type I supernovae based on published photometry of over 50 objects. In Figure 3, an idealized Type I supernova B light curve is shown to help illustrate the key parameters of this method, which are:

t_{max} = the time of maximum blue light
t_{bend} = the time of the bend in the blue light curve where the initial postmaximum decline slows down
B_{max} = the B magnitude at t_{max}
B_{bend} = the B magnitude at t_{bend}
β = the initial postmaximum decline rate in blue light measured between t_{max} and t_{bend} and expressed in units of magnitude per 100 days
γ = the decline rate in blue light measured after t_{bend} and expressed in units of magnitude per 100 days .

Pskovskii has emphasized the fundamental nature of the β parameter, which he calls the "photometric class". For SN 1986G a least-squares fit to the B magnitudes for the first 20 days after maximum yields $\beta = 12.0 \pm 0.1$. Pskovskii found that β is well correlated with γ as well as

TABLE I

Optical Photometry of SN 1986g in NGC 5128

1986 U.T. Date	J.D. 2446000+	V	B–V	U–B	V–R	V–I	Source
May 5.09	555.59	11.95(05)	1.08(05)	....	....	....	a
5.99	556.49	11.89(02)	0.97(01)	0.68(03)	....	....	b
6.13	556.63	11.94(05)	0.84(05)	....	....	....	a
7.06	557.56	11.74(03)	0.97(03)	....	....	....	c
8.08	558.58	11.67(03)	0.98(03)	....	....	....	d
9.14	559.64	11.58(03)	0.95(03)	....	....	....	e
10.10	560.60	11.53(03)	0.88(03)	....	....	....	e
11.09	561.59	11.48(01)	1.03(01)	0.77(02)	....	0.87(02)	f
11.13	561.63	11.53(05)	....	....	....	....	g
12.07	562.57	11.44(03)	1.13(03)	....	....	....	h
16.02	566.52	11.52(02)	1.31(01)	1.15(03)	....	....	b
16.04	566.54	11.63(03)	1.23(03)	....	....	....	e
17.01	567.51	11.59(02)	1.38(01)	1.17(03)	....	....	b
20.03	570.53	11.82(02)	1.56(01)	1.19(03)	....	....	b
24.25	574.75	12.18(02)	1.78(02)	1.29(20)	0.73(01)	1.24(02)	i
25.02	575.52	12.25(02)	1.84(02)	1.30(20)	0.76(01)	1.29(02)	i
30.19	580.69	12.66(03)	1.94(03)	....	....	....	c
Jun 3.05	584.55	13.02(03)	1.92(03)	....	....	....	c
4.07	585.57	13.12(03)	1.94(03)	....	....	....	c
11.07	592.57	13.47(07)	1.92(05)	....	....	....	j
12.05	593.55	13.52(04)	1.85(03)	1.09(06)	....	....	j
27.01	608.51	14.11(03)	....	....	....	....	k
28.98	610.48	14.10(03)	....	....	....	....	k
29.98	611.48	14.15(03)	1.57(03)	....	....	....	k
Jul 1.98	613.48	14.20(03)	1.56(03)	....	....	....	k
3.97	615.47	14.26(03)	1.54(03)	....	....	....	k
12.01	623.51	14.53(03)	1.49(03)	....	....	....	l
28.05	639.55	14.99(03)	1.33(03)	....	....	....	l
Aug 20.03	662.53	15.63(03)	1.02(03)	....	....	....	m
Sep 4.00	677.50	16.07(03)	0.90(03)	....	....	....	n

Note: Estimated errors in the photometry are given in parentheses in units of 0.01 magnitude.

Sources:
(a) D. Geisler (CTIO 0.9m, RCA CCD)
(b) F. Jablonski (CNPq/LNA 1.6m, photoelectric)
(c) M. Phillips (CTIO 0.9m, TI CCD)
(d) S. Heathcote (CTIO 0.9m, TI CCD)
(e) V. Blanco (CTIO 0.9m, RCA CCD)
(f) V. Blanco (CTIO 1m, photoelectric)
(g) J. Lutz (CTIO 0.9m, TI CCD)
(h) P. Schmidtke (CTIO 1.5m, RCA CCD)
(i) A. Landolt & A. Uomoto (CTIO 1.5m, photoelectric)
(j) F. Jablonski (CNPq/LNA 0.6m, photoelectric)
(k) J. Thorstensen & W. Honey (CTIO 1.5m, RCA CCD)
(l) A. Phillips (CTIO 0.9m, TI CCD)
(m) N. Suntzeff & M. Phillips (CTIO 0.9m, TI CCD)
(n) N. Suntzeff & M. Phillips (CTIO 1.5m, RCA CCD)

with the quantities ($t_{bend} - t_{max}$) and ($B_{bend} - B_{max}$). Estimates of these parameters for SN 1986G made directly from the B light curve shown in Figure 2 are given in Table IV. These are compared with mean values calculated for $\beta = 12$ from the relations given by Pskovskii (1984). As is seen, the agreement is excellent.

TABLE II

Photometry of Comparison Stars near NGC 5128

Star	V	B-V
a	15.57(03)	0.81(04)
b	15.84(07)	1.19(02)

Note: The figures in parentheses are the standard deviations (in units of 0.01 mag) of measurements made on four nights.

Such a large value of β is unusual—only 10% of the 54 supernova light curves studied by Pskovskii (1984) had $\beta \geq 12$. The best observed of these was SN 1971I in NGC 5055 (Deming, Rust, and Olson 1973; Barbon, Ciatti, and Rosino 1973*b*) which Pskovskii lists having $\beta = 11.7 \pm 0.4$. A detailed comparison of the *B* and *V* light curves of this supernova with those of SN 1986G shows them to be indistinguishable within the observational errors.

B. *Color Evolution*

In Figure 2 is shown the $(B-V)$ color evolution of SN 1986G. We have fitted Pskovŝkii's (1984) mean $(B-V)$ curve for Type I supernovae with $\beta = 12$ to these observations. As may be seen in Figure 2, the agreement is quite good over the first 40 days if we shift the mean curve by an amount corresponding to $E(B-V) = 0.82 \pm 0.05$. At later epochs the measurements for SN 1986G fall systematically below the mean relation. We note, however, that this part of Pskovskii's curve is based entirely on data for one rather poorly-observed object, SN 1954A, which was spectroscopically peculiar (see Branch 1986, and references therein). In fact the latter stages of the $(B-V)$ evolution of SN 1986G are in reasonable agreement with the available photographic data for the $\beta = 12$ supernova 1971I.

The $(U-B)$ color evolution of SN 1986G is plotted at the bottom of Figure 2. Unfortunately, there is hardly any published *U* photometry for Type I supernovae of the same photometric class, making a meaningful comparison impossible.

C. *Spectral Evolution*

The spectral evolution of SN 1986G at optical wavelengths is displayed in Figure 4. Observations made on the same night have been added in this figure to improve the wavelength coverage. The presence of strong, blueshifted Si II $\lambda6355$ absorption in the maximum light spectra unequivocally identifies the supernova as a Type Ia[1] event (see Uomoto and Kirshner 1985; Wheeler and

TABLE III

Log of Spectroscopic Observations

1986 U.T. Date	J.D. 2446000+	Wavelength Coverage (Å)	Wavelength Resolution (Å)	Telescope	Detector	Observer(s)
May 5.1	555.6	4800-7200	8.4	CTIO 1.5m	GEC CCD	a
6.1	556.6	4800-7200	8.4	CTIO 1.5m	GEC CCD	a
7.1	557.6	4800-7200	8.4	CTIO 1.5m	GEC CCD	a
7.0	557.5	3600-5170	2.6	CTIO 4m	2D-Frutti	b
8.2	558.7	4800-7200	8.4	CTIO 1.5m	GEC CCD	a
8.1	558.6	3600-5170	2.6	CTIO 4m	2D-Frutti	b
9.0	559.5	3600-5170	2.6	CTIO 4m	2D-Frutti	b
10.2	560.7	3920-7000	5.2	CTIO 4m	2D-Frutti	c
11.3	561.8	3560-6640	5.2	CTIO 4m	2D-Frutti	d
12.1	562.6	5000-6600	2.7	CTIO 4m	2D-Frutti	c
12.2	563.7	3560-6640	5.2	CTIO 4m	2D-Frutti	d
13.1	564.6	3700-5260	2.6	CTIO 4m	2D-Frutti	e
15.3	566.8	4370-6330	16.0	U.H. 2.2m	TI CCD	f
17.0	568.5	5990-7010	3.6	CTIO 4m	GEC CCD	g
Jun 8.	589.	3400-5800	4.2	CTIO 1m	2D-Frutti	h
11.1	592.6	3400-5800	4.2	CTIO 1m	2D-Frutti	h
25.0	606.5	3800-7000	5.7	CTIO 1m	2D-Frutti	i
27.1	608.6	4600-6100	4.3	L.C. 2.5m	2D-Frutti	j
29.0	610.5	3800-7000	5.7	CTIO 1m	2D-Frutti	i
Jul 4.0	615.5	3800-7000	5.7	CTIO 1m	2D-Frutti	i
6.0	617.5	3300-6100	6.3	L.C. 2.5m	2D-Frutti	k

Observers:
(a) J. Tonry, M. Strauss
(b) A. Cowley, J. Hutchings
(c) S. Wyckoff
(d) J. Maza, M. T. Ruíz
(e) J. Grindlay, H. Cohn
(f) R. Lavery
(g) D. Hamilton
(h) H. Smith
(i) J. Steiner, F. Jablonski
(j) M. Rich
(k) M. Rich, A. Saha

Levreault 1985). However, a careful comparison with the maximum-light spectra of the more common, "slower" Type Ia supernovae such as 1972E ($\beta = 9.2 \pm 0.1$) in NGC 5253 (Kirshner *et al.* 1973) and 1981B ($\beta = 8.8 \pm 0.1$) in NGC 4536 (Branch *et al.* 1982) reveals small, yet significant, differences. These are illustrated in Figure 5 where the maximum-light spectrum of SN 1986G is shown after correction for a dust reddening amounting to $E(B-V) = 0.90$ (as derived below). Plotted in the same figure is the maximum-light spectrum of SN 1981B. We note the following:

1. The absorption dip at ~ 5790 Å is significantly stronger in the spectrum of SN 1986G. According to Branch *et al.* (1982), this feature is probably due to $\lambda5979$ of Si II, with perhaps a small contribution of He I $\lambda5876$ and Na I D.

2. In the spectrum of SN 1986G, the absorption line at ~ 5310 Å is weaker than the neighboring feature at ~ 5400 Å, whereas in SN 1981B these two features are comparable in strength. Branch *et al.* (1982) have identified these lines with S II $\lambda5454$ and $\lambda5640$, respectively.

3. The absorption dip at ~ 4890 Å, ascribed to Si II $\lambda5051$ by Branch *et al.* (1982), is deeper in SN 1986G.

4. The appearance of the strong absorption feature at ~ 4330 Å, identified by Branch *et al.* (1982) as Mg II $\lambda4481$, is similar in both spectra, but an additional component of absorption just blueward of this line seems to be present in the spectrum of SN 1986G.

[1]In this paper, we adopt the "Ia" nomenclature of Elias *et al.* (1985).

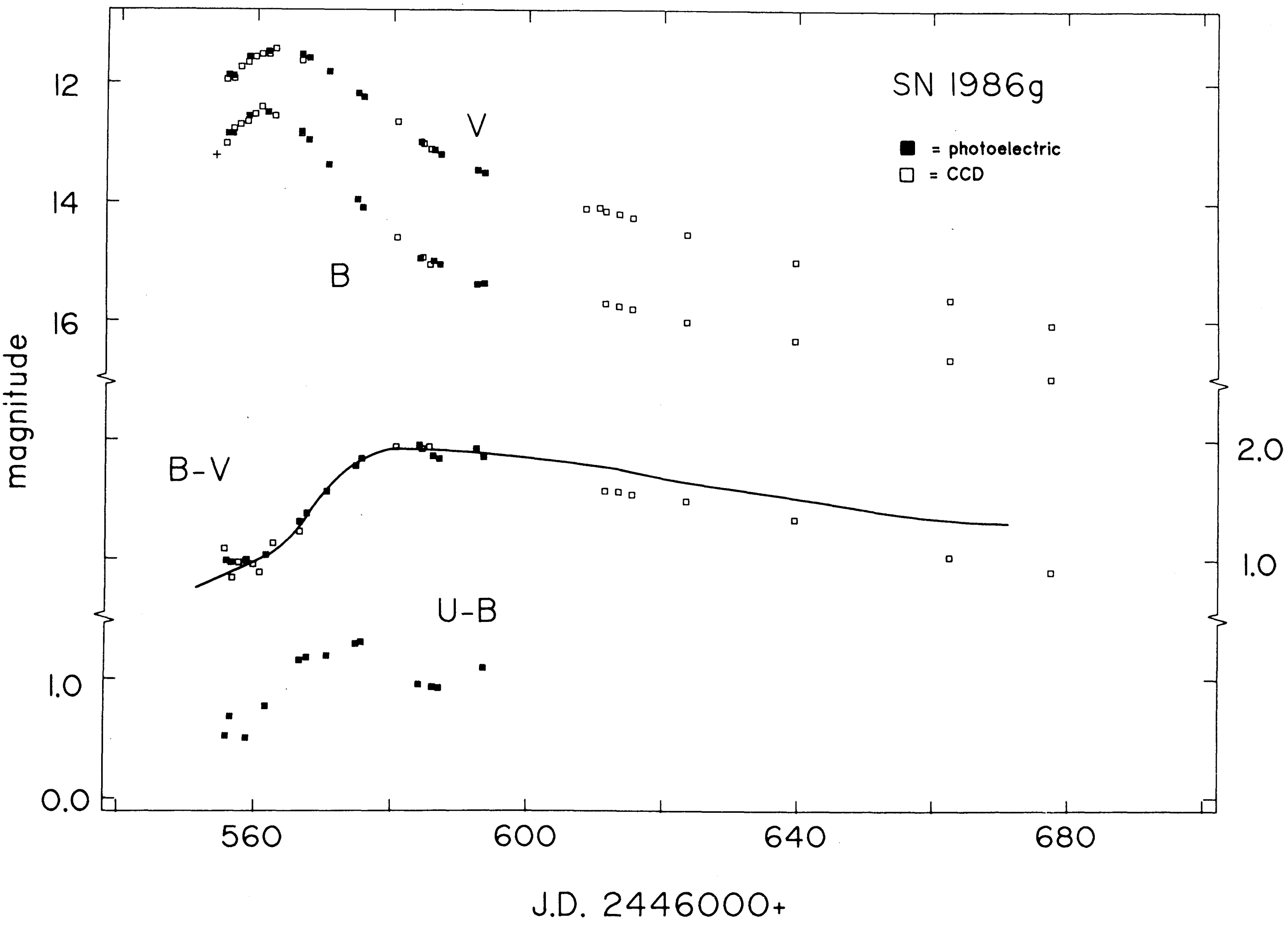

FIG. 2–B, V, $(B-V)$, and $(U-B)$ observations of SN 1986G in NGC 5128 plotted as a function of time. The solid line corresponds to Pskovskii's (1984) mean $(B-V)$ curve for Type Ia supernovae with $\beta = 12$, shifted by an amount equal to $E(B-V) = 0.82$.

Overall, the spectrum of SN 1986G at maximum light is best matched to the spectra of SN 1972E and SN 1981B at 1–2 weeks past maximum. This may account for Meurer's (1986*a*) initial impression (based on blue and red spectra taken on May 8–13) that maximum light had been reached around April 21 (JD2446541.5). Interestingly, a similar situation occurred for the Type Ia supernova 1971I which, as we have pointed out, was a virtual twin of SN 1986G. The first spectra of SN 1971I obtained by Kikuchi (1971) and Barbon and Ciatti (1971) suggested that this supernova was already past maximum. However, photometry carried out over the same period clearly showed that maximum had not yet been attained. Barbon *et al.* (1973*b*) later revised their initial estimate, concluding that their first spectrum of SN 1971I was, in fact, consistent with that of a Type I supernova near maximum. Not surprisingly, a glance at Figure 9 of their paper shows that SN 1971I displayed the same spectral peculiarities near maximum that we have observed in SN 1986G.

In the series of spectra of SN 1986G obtained from May 5–17, a marked shift of the strong absorption features toward longer wavelengths is observed. This is illustrated in Figure 6 for the Si II λ6355 absorption trough. Radial-velocity measurements of this feature are listed in Table V and compared with similar measurements for the $\beta = 9$ supernova 1981B (Branch *et al.* 1983) in Figure 7. Model spectra calculated by Branch *et al.* (1982) show that during this phase the radial velocity of the Si II λ6355 absorption is approximately equal to the expansion velocity of the photosphere. Note that the range in velocities observed for both supernovae is similar but that the velocity for SN 1986G was always less than that of SN 1981B where the phase coverage overlapped. This is consistent with the results of Pskovskii (1977, 1984) and Branch (1981), who found that the expansion velocity of Type Ia supernova envelopes is inversely correlated with the photometric class, β. In addition, the data in Figure 7 suggest that the expansion velocity decreased more rapidly in the case of SN 1986G, although the sparseness of observations at overlapping phases makes this conclusion somewhat tentative. If confirmed, this effect is likely to be related to the steep initial decline in M_B (i.e., the large β

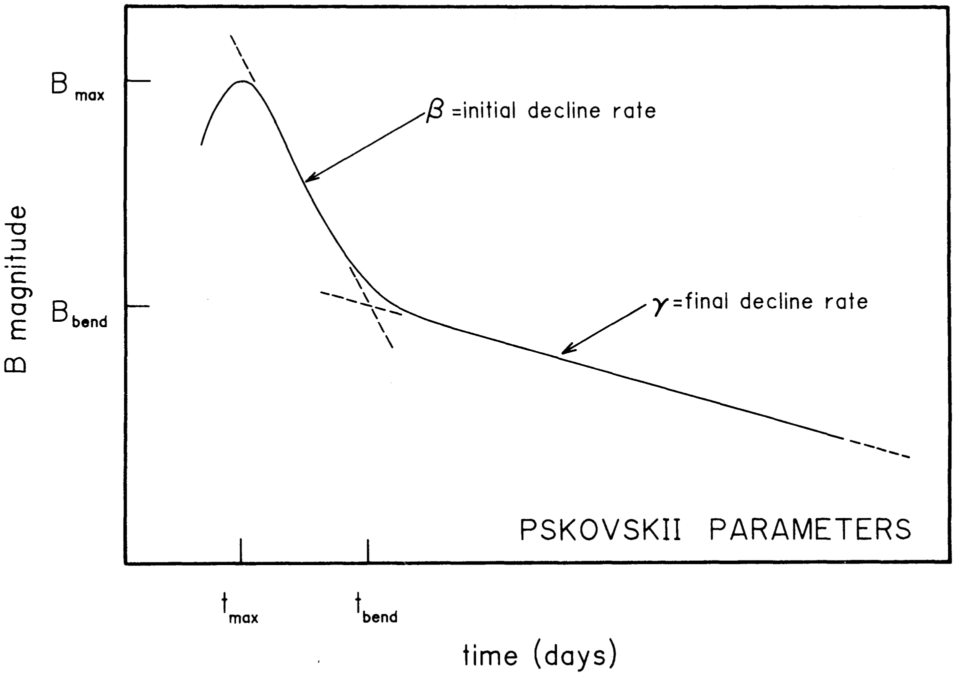

FIG. 3–Idealized B light curve of a Type Ia supernova. The parameters defined by Pskovskii (1977, 1984) and explained in the text have been indicated.

TABLE IV

Photometric Parameters of SN 1986g

Parameter	Observed	Computed from β
B_{max}	12.45 ± 0.05	....
t_{max}	JD 2446561.5 ± 1 (May 11 ± 1)	....
E(B−V)	0.90 ± 0.10	....
A_B (mag)	3.6 ± 0.4	....
t_{bend}	JD 2446585.5 ± 1	....
$t_{bend}-t_{max}$ (days)	24 ± 2	27 ± 3
$B_{bend}-B_{max}$ (mag)	2.8 ± 0.1	3.0 ± 0.2
β (mag/100 days)	12.0 ± 0.1	....
γ (mag/100 days)	1.88 ± 0.04	2.0 ± 0.3

value), since both phenomena can readily be interpreted as being due to a rapid retreat of the photosphere in Lagrangian coordinates. Under the assumption that the velocity stratification in SN 1986G and SN 1981B was similar, this implies that the density gradient in the outer envelope of SN 1986G was *less steep* than that in SN 1981B.

D. *Interstellar Absorption Lines*

As mentioned at the beginning of this paper, the spectrum of SN 1986G was marked by unusually strong interstellar-absorption lines of Ca II H and K and Na I D (see Figs. 4 and 6). High-dispersion observations obtained at these wavelength regions are shown in Figure 8. In addition to a weak component of absorption due to our own Galaxy, these spectra clearly show a much stronger component at a heliocentric radial velocity of 430 ± 10 km s^{-1}. The most obvious source of the latter absorption is the prominent dust lane in NGC 5128. In his extensive study of NGC 5128, Graham (1979) observed interstellar Na I D absorption across much of the dust lane. Graham showed that the gas responsible for the D lines participates in the same rotational motion as the ionized gas in the vicinity. Published Fabry-Perot Hα observations of NGC 5128 (Marcelin *et al.* 1982; Taylor and Atherton 1983) yield a radial velocity for the ionized gas at the location of SN 1986G which is within 50 km s^{-1} of the above-quoted value for the Na I D absorption, confirming the dust lane origin. We note in Figure 6 that the Galactic-absorption component is quite narrow, whereas the component due to the dust lane is slightly resolved. This is consistent with reports that much higher dispersion spectra showed several components of absorption arising in the dust lane (Rich 1986).

Equivalent-width measurements for the Ca II and Na I lines are listed in Table VI. In normal interstellar clouds in the disk of our Galaxy, the Ca II/Na I column density ratio lies between ~ 0.01 and 1.5, with the lower values being generally associated with more opaque clouds. This ratio is enhanced in high-velocity clouds in the disk (Siluk

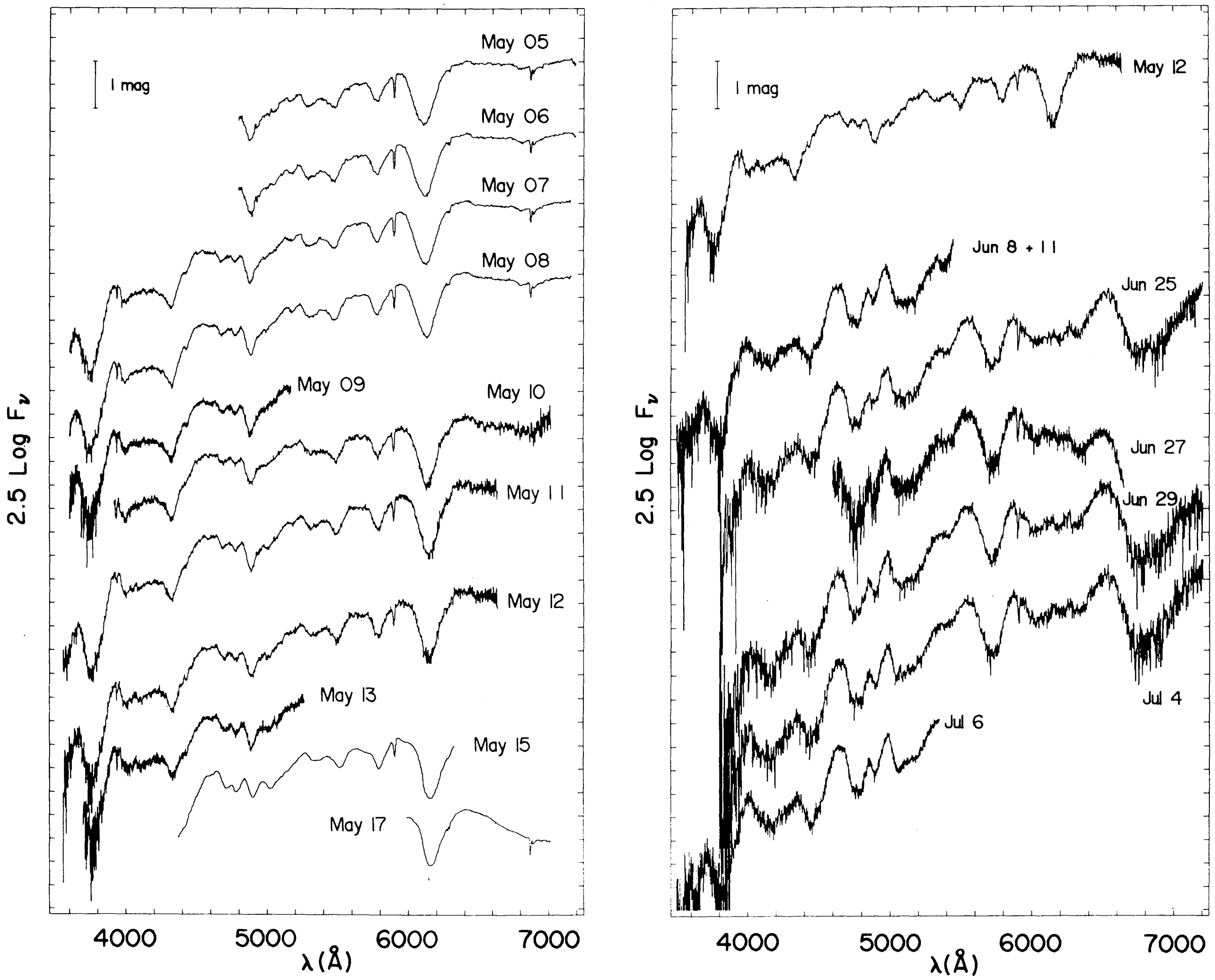

FIG. 4–Spectral evolution of SN 1986G. Fluxes have been converted to relative magnitudes via the relationship $m_\nu = -2.5 \log F_\nu +$ constant. No reddening correction has been applied to these data.

and Silk 1974) and also in material attributed to the halo component of the interstellar medium (Cohen and Meloy 1975; Blades and Morton 1983). These trends are generally interpreted as resulting from the liberation of calcium from interstellar grains which are exposed to a hostile environment. For the absorption component in the spectrum of SN 1986G due to our own galaxy, we derive a Ca II/Na I column-density ratio of ~ 2. Although somewhat high, this value is still probably consistent with a disk origin, which might be expected in view of the relatively low galactic latitude of NGC 5128 (b = 19°). Perhaps more interesting is the column-density ratio of ~ 0.7 which we derive for the strong absorption due to the dust lane. This latter result implies that the degree of calcium depletion onto grains in the dust lane must be similar to that which occurs in the disk of our own galaxy.

In addition to the Ca II and Na I lines, we have identified a few of the diffuse interstellar-absorption bands at the redshift of the dust lane. The strongest of these, the λ6284 band, is clearly visible in Figure 6. The stationary nature of this feature with respect to the evolving supernova features confirms the interstellar origin. We measure an equivalent width of ~ 1 Å for the λ6284 band, which compares reasonably well with the value of 2.0 Å given by Herbig (1975) for the heavily reddened ($E(B-V)$ = 1.26) star HD 183143. Close inspection of the spectra in Figure 6 reveals three further weak absorption features which can be identified with the diffuse interstellar bands at λ5780, λ5797, and λ6269. Rich (1986) has independently reported the detection of the λ6284, λ5780, and λ5797 bands, but points out (private communication) that the redshift of the λ6269 feature causes it to coincide with atmospheric O_2 absorption at 6278 Å. A search of our blue spectra does not clearly show the presence of the well-known λ4430 band, but this feature would be very difficult to detect atop the strong absorption in this wavelength region due to the supernova.

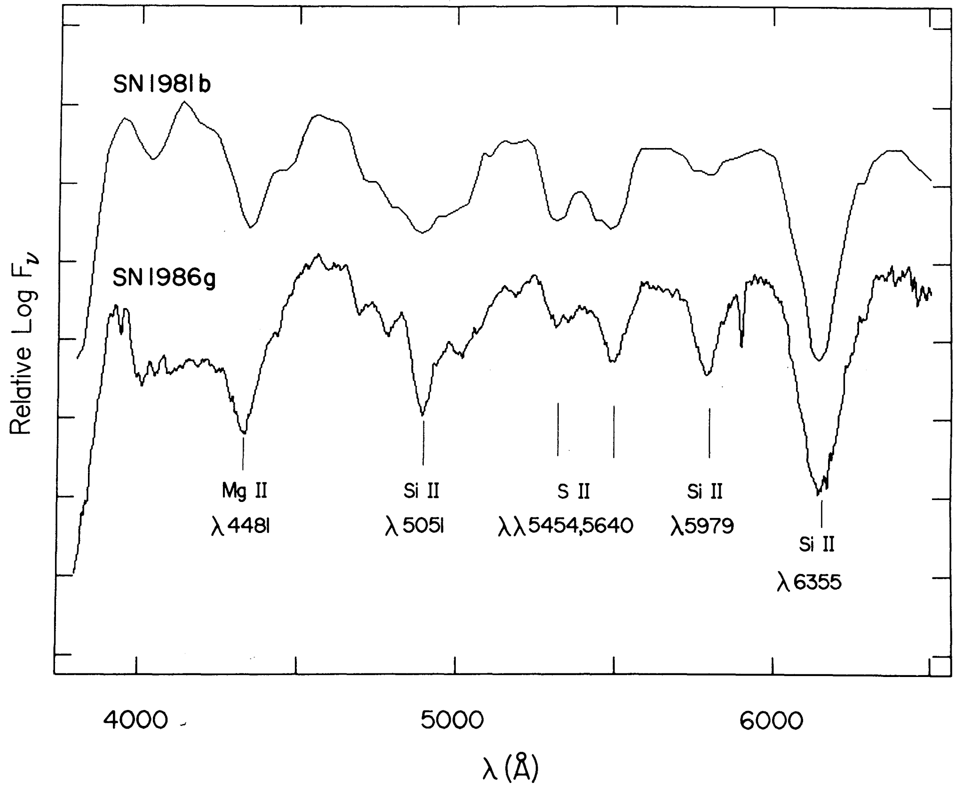

FIG. 5–Comparison of the maximum brightness spectra of SN 1986G (β = 12.0 ± 0.1) and SN 1981B (β = 8.8 ± 0.1). The spectrum of SN 1986G has been corrected for a reddening of $E(B-V)$ = 0.90 using the analytical formulation by Miller and Mathews (1972) of the standard Whitford (1958) extinction curve. The spectrum of SN 1981B is taken from Branch *et al.* (1982).

E. *Effect of Reddening on the* $(B-V)$ *Colors*

The extreme reddening of SN 1986G can influence the broad-band photometry measurements by causing small shifts in the effective wavelengths of the filter. To estimate the magnitude of this effect, we derived "synthetic" *B* and *V* magnitudes for SN 1986G by convolving appropriate filter transmission curves with the observed spectra. This procedure was then repeated for the same spectra after "dereddening" them by an amount $E(B-V)$ = 0.85 (the approximate reddening deduced in § III.B) using the standard Whitford (1958) law. In principle, the difference between the colors derived from the observed and dereddened spectra should be exactly equal to $E(B-V)$ = 0.85. In fact we find that the color excess implied from this procedure is consistently smaller than 0.85 by an amount nearly constant with phase and equal to ~ 0.08 mag. Applying this correction to the photometry of SN 1986G presented in the previous section, we adopt a final estimate of the reddening of $E(B-V)$ = 0.90 ± 0.10.

IV. Discussion and Conclusions

The degree to which Type Ia supernovae are a homogeneous class of objects has been the subject of debate for many years now. While some authors, led principally by Barbon, Ciatti, and Rosino (1973*a*), Pskovskii (1977, 1984), and Branch (1981, 1987), have presented evidence for detectable intrinsic differences in optical spectra and light curves, others (e.g., Cadonau, Sandage, and Tammann 1985) have tended to attribute such results to observational error. *Our observations of SN 1986G unambiguously demonstrate that genuine differences do exist between Type Ia supernovae.* In Figure 9 we have compared the light curves and color evolution of SN 1986G with those of one of the best previously-observed supernovae, SN 1981B (β = 8.8 ± 0.1). The data have been phased relative to the time of *B* maximum and adjusted in brightness so that the *B* and *V* maxima coincide. The faster postmaximum decline rates in *B* and *V* of SN 1986G are obvious in this figure, as is a steeper initial increase in the $(B-V)$ color. Note that the peak value of $(B-V)$ was attained in SN 1986G approximately ten days before that in SN 1981B. (The latter effect is a manifestation of the correlation found by Pskovskii between β and $(t_{bend} - t_{max})$, since the maximum $(B-V)$ color of Type Ia supernovae occurs at t_{bend}.) As shown by Frogel *et al.* (1987), the infrared light curves of SN 1986G are likewise significantly different from those of SN 1981B and other well-observed β = 9 Type Ia supernovae.

The existence of intrinsic differences in Type Ia supernovae light curves potentially complicates the use of these objects as cosmological standard candles. In particular

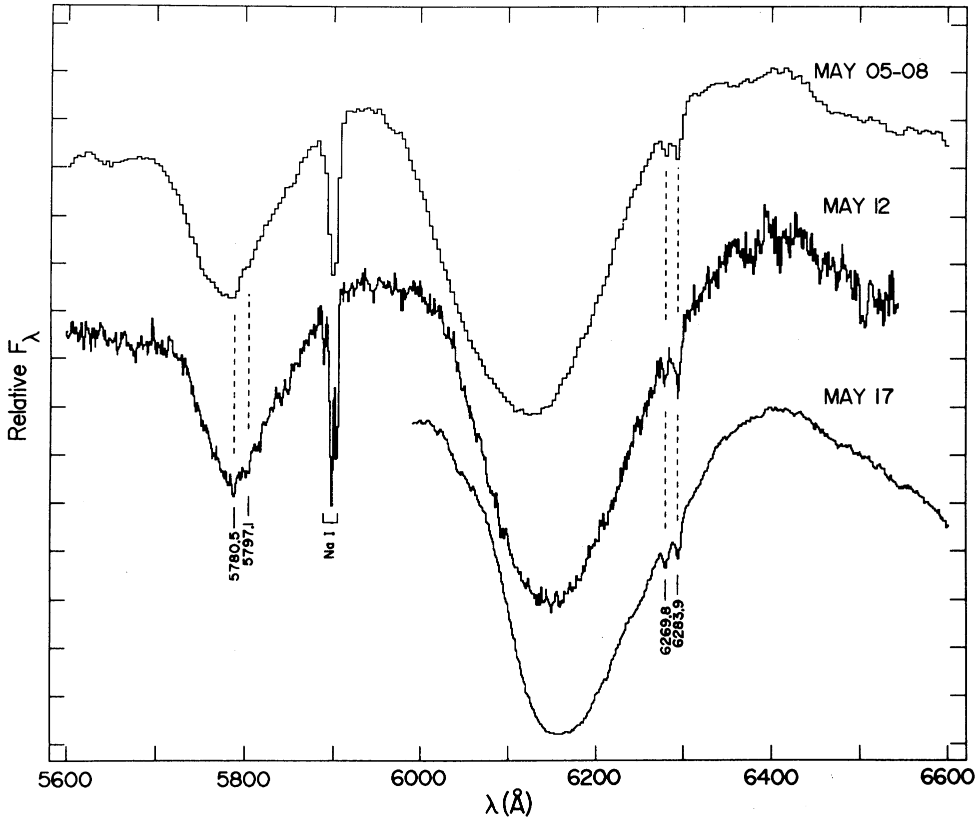

FIG. 6–Red spectra of SN 1986G taken approximately one week apart, showing the progressive blueshift of the Si II λ6355 absorption feature. The Na I D lines and several of the diffuse interstellar-absorption bands produced by gas in the dust lane of NGC 5128 are also identified.

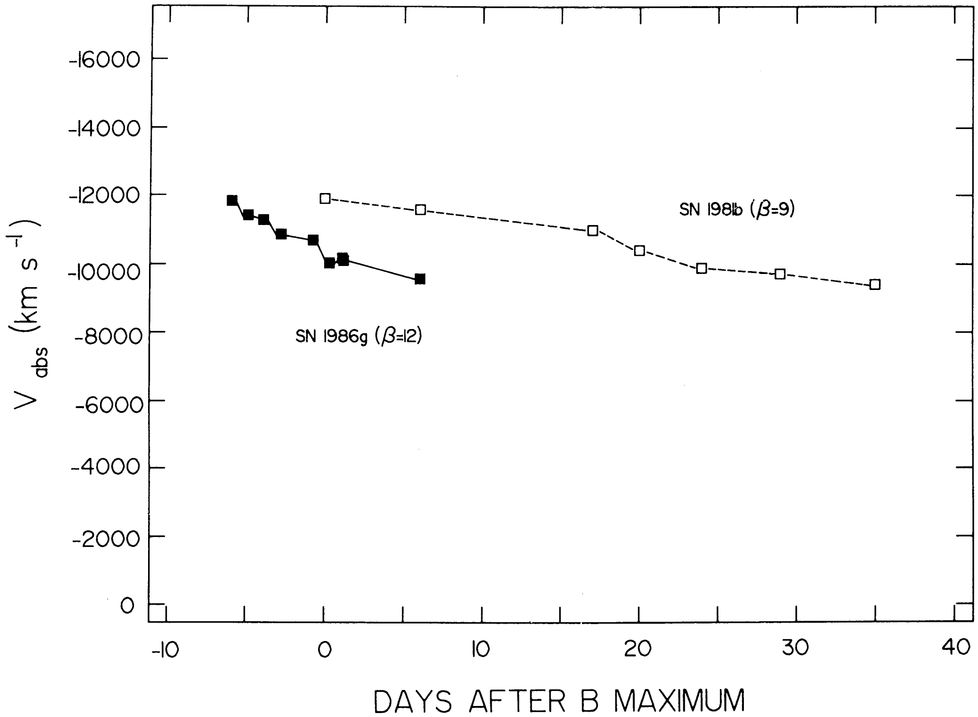

FIG. 7–Radial velocities of the blueshifted absorption features due to Si II λ6355 plotted against time. For comparison, measurements of the same line by Branch *et al.* (1983) for SN 1981B are given.

TABLE V

Si II λ6355 Absorption Radial Velocities

1986 U.T. Date	J.D. 2446000+	Radial Velocity* ($km\ s^{-1}$)
May 5.1	555.6	-11,850
May 6.1	556.6	-11,430
May 7.1	557.6	-11,290
May 8.2	558.7	-10,860
May 10.2	560.7	-10,670
May 11.3	561.8	-10,010
May 12.1	562.6	-10,150
May 12.2	563.7	-10,110
May 17.0	568.5	-9,590

*Measurements are given in the rest frame of the supernova using 430 $km\ s^{-1}$ for the heliocentric radial velocity, assuming that the supernova was associated with the disk of gas, dust, and hot stars. If, instead, the supernova belonged to the elliptical component, a more appropriate value for the heliocentric velocity would be the systemic value of ~550 $km\ s^{-1}$ (Graham 1979).

TABLE VI

Equivalent Widths of Interstellar Lines in the Spectrum of SN 1986g

	I.D.	Rest Wavelength (Å)	Equivalent Width (Å)
Galaxy system (~0 $km\ s^{-1}$):	Ca II H	3934	0.22
	Ca II K	3968	0.58
	Na I	5890	} 0.50
	Na I	5896	
Dust Lane system (~430 $km\ s^{-1}$):	Ca II H	3934	0.55
	Ca II K	3968	1.2
	Na I	5890	} 3.6
	Na I	5896	

Pskovskii (1977, 1984) and Branch (1981, 1982) have presented evidence that the peak absolute magnitudes of Type Ia supernovae are inversely correlated with β. We can attempt to test this by comparing SN 1986G (β = 12) with SN 1972E (β = 9), since the parent galaxies of both supernovae, NGC 5128 and NGC 5253, are considered to be members of the Centaurus group (see Sandage and Tammann 1975). The reddening deduced in the previous section for SN 1986G implies a total blue extinction of $A_B = 3.6 \pm 0.4$ mag.[2] Thus, the corrected apparent magnitude at maximum light for this supernova was $B_0 = 8.85 \pm 0.40$. For SN 1972E in NGC 5253, Branch *et al.* (1983) estimated the observed blue magnitude at maximum to be 8.6 ± 0.1. Correcting for the foreground extinction due to our own galaxy—$A_B = 0.19 \pm 0.02$ mag (Burstein and Heiles 1984)—but assuming no additional source of reddening, we find $B_0 = 8.4 \pm 0.1$. Thus, we deduce that SN 1986G was intrinsically fainter than SN 1972E by 0.45 ± 0.41 mag *if both NGC 5128 and NGC 5253 lie at the same distance*. From the relation between the peak absolute *B* magnitude and β given by Pskovskii (1984), a brightness difference in the same sense of 0.64 mag is predicted. While these values are consistent, it is equally correct within the errors to conclude that the peak magnitudes of SN 1972E and SN 1986G were the same. Moreover, according to de Vaucouleurs (1979*a*), the distance modulus of NGC 5128 may be ~ 0.5 mag greater than that of NGC 5253. Hence, we can neither confirm nor deny the dependence of the peak M_B on photometric class. On the other hand, it is clear that SN 1986G was not significantly *brighter* than SN 1972E, as predicted by carbon-deflagration models of accreting white dwarfs (see below).

As stated in the Introduction, one of the original goals of this study was to better determine the distance of NGC 5128. In view of the possible dependence of M_B on β, we have felt it wise to limit comparison of SN 1986G to other Type Ia supernovae of the same photometric class. Unfortunately, due to the apparent rareness of such objects, there is only one other reasonably well-observed Type Ia supernova with β = 12 photometric class—SN 1971I in NGC 5055. Comparing the $(B-V)$ color evolution of SN 1986G with photoelectric photometry of SN 1971I published by Deming *et al.* (1973), we estimate that SN 1986G was reddened by an amount $E(B-V) = 0.65 \pm 0.05$ *with respect to* SN 1971I. Using this value, along with the estimate by Deming *et al.* of the apparent magnitude at maximum of SN 1971I ($B = 11.9 \pm 0.1$), we conclude that SN 1986G was 2.05 ± 0.22 mag brighter than SN 1971I, yielding a relative distance of $D_{\rm NGC\,5128}/D_{\rm NGC\,5055} = 0.39 \pm 0.04$. This result is in excellent agreement with infrared observations of these two supernovae, which yield a relative distance modulus of −2.17 (Frogel *et al.* 1987). NGC 5055 is considered to be a member of

[2]This estimate assumes $A_B/E(B-V) = 4$ in the dust lane of NGC 5128. Of course, if the absorbing properties of the dust in NGC 5128 are significantly different from those of the interstellar medium in our own galaxy, the value of A_B we derive could be substantially in error.

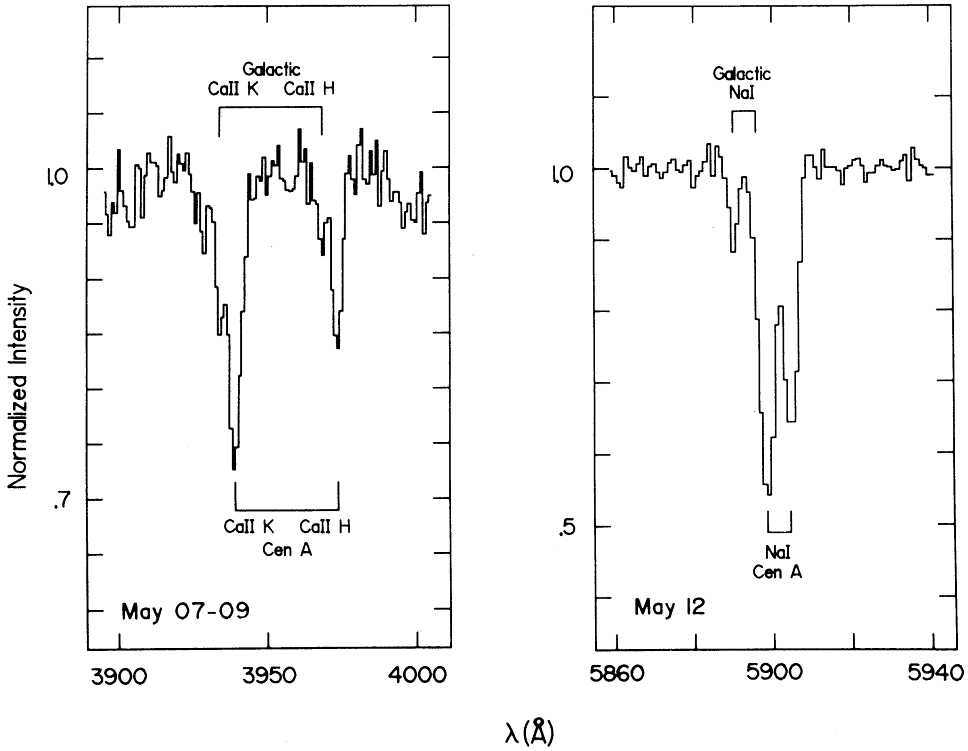

FIG. 8–Expanded and rectified plots of two high-dispersion spectra of SN 1986G showing the two components of interstellar Ca II H and K and Na I D absorption detected.

the M 51 group (Sandage and Tammann 1975), which has a distance modulus $\mu_0 = 29.69 \pm 0.4$ according to Aaronson and Mould (1983). If this is correct, then the distance of NGC 5128 must be 3.3 +0.6/−0.5 Mpc. Alternatively, if we use the Sandage and Tammann (1975) or de Vaucouleurs (1979*b*) distance moduli for NGC 5055 (or the M 51 group), we derive distances of 3.8 and 2.5 Mpc, respectively, with similar errors. We note that all of these values lie at the low end of the range of previous distance estimates.

The underlying physical distinction between Type Ia supernovae with differing values of β is not clear. Nearly all recent work in this field has centered on models of accreting carbon-oxygen white dwarfs, with the most fashionable of these at present being the so-called "carbon deflagration" supernova (see Woosley and Weaver 1986, and references therein). This model, which entails the total disruption of the white-dwarf star by a subsonic wave of thermonuclear burning, has been particularly successful in explaining the spectra of Type Ia supernovae (Branch *et al.* 1985) as well as the global shape of the light curves (e.g., see Nomoto, Thielemann, and Yokoi 1984; Sutherland and Wheeler 1984). However, the brightest models (those where the most ^{56}Ni is produced) are the ones with the steepest postmaximum decline rates and the highest expansion velocities, in contradiction to both the statistical arguments of Pskovskii (1977, 1984) and Branch (1981, 1982) and the direct comparisons made above between SN 1986G and the $\beta = 9$ supernovae 1972E and 1981B. Graham (1987) has recently suggested that the Pskovskii-Branch effect can still be accounted for within the framework of the carbon deflagration model if there are small differences between individual supernovae in the mass of nonradioactive iron-group isotopes produced near the center of the explosion. Alternatively, López *et al.* (1986) have argued that the Pskovskii-Branch correlation implies a variable fraction of mass ejection, which would occur if the white dwarf is only partially disrupted.

A certain class of the helium-shell flash models has been explored by Nomoto (1982) where a helium detonation wave propagates outward and a carbon detonation wave moves inward. These so-called "double-detonation" models hold a certain attraction since they predict a peak luminosity-β dependence which is consistent with the Pskovskii/Branch correlation. A rather severe problem with these models, however, is that the ejected matter is almost exclusively ^{56}Ni. This is inconsistent with the interpretation by Branch *et al.* (1982) of the maximum-light spectrum of SN 1981B, which requires the existence of a significant outer layer of matter consisting of intermediate mass elements such as Ca, Si, Mg, and O. Aside from the subtle differences described in Section III.C, the maximum-light spectrum of SN 1986G was very similar to that

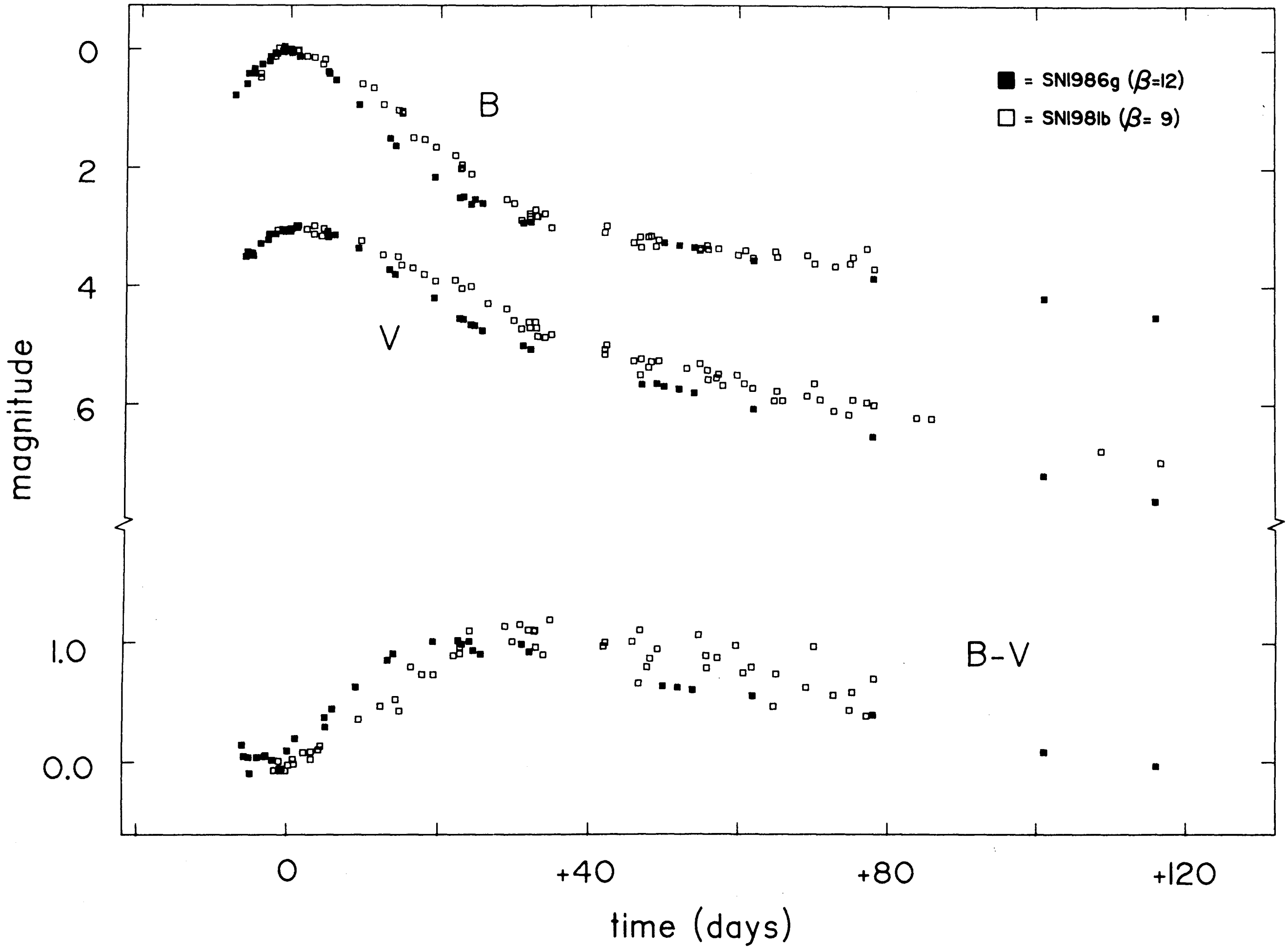

FIG. 9–Comparison of the *B*, *V*, and (*B* – *V*) evolution of a well-observed supernova of photometric class β = 9 (SN 1981B) and SN 1986G (β = 12). The curves have been shifted so that the *B* maxima coincide. The data for SN 1981B are from Buta and Turner (1983), Tsvetkov (1982), and Busko, Jablonski, and Torres (1981).

of SN 1981B, implying that the chemical composition of the outer layers of ejected matter in these two objects must likewise have been similar.

For many years there has been a tendency for theorists and observers alike to brush over evidence of intrinsic differences among Type Ia events. The statistical studies of Pskovskii and Branch demonstrated that such variations do exist, and the case of SN 1986G provides dramatic confirmation. Not only do these inhomogeneities need to be accounted for by the models, but they must also be thoroughly described and calibrated if Type Ia supernovae are to be used with confidence as cosmological standard candles.

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