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THE OPTICAL LIGHT CURVES OF SN 1980N AND SN 1981D IN NGC 1316 (FORNAX A)

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ABSTRACT

We present optical photometry of the two supernovae, 1980N and 1981D, which appeared in the peculiar D-type galaxy NGC 1316 (Fornax A). These data are combined with published observations to produce definitive optical light curves. We find that the maximum-light magnitudes of both supernovae were the same to within ± 0.1 mag, in agreement with infrared light curve observations. The shapes of the *UBV* light curves of the best observed of the two supernovae, 1980N, closely resembled those of the type Ia prototype SN 1981B. We also show that an optical spectrum of SN 1980N taken 30 days after *B* maximum was virtually identical to a spectrum of SN 1981B obtained at the same point in its evolution. These findings lend support to claims that the majority of type Ia supernovae form a highly homogeneous class of objects. Nevertheless, the $B - V$ colors at *B* maximum of the NGC 1316 supernovae were 0.3–0.5 mag redder than previous estimates of the intrinsic $B - V$ color of type Ia supernovae at this phase. Although dust extinction within NGC 1316 could explain this difference, there is little evidence to support such a large reddening. By comparing the photometric data of SN 1980N with the light curves of SN 1984A in NGC 4419, and by assuming that the absolute magnitudes of the majority of type Ia supernovae are indeed very similar, NGC 1316 would appear to be at essentially the same distance as the core of the Virgo Cluster.

1. INTRODUCTION

NGC 1316 (Fornax A) is a peculiar Morgan D-type galaxy located in the outskirts of the Fornax I cluster. Early optical studies drew attention to the presence of a central dust lane in this galaxy (e.g., see Evans 1949). Interest increased significantly with the discovery that NGC 1316 was a strong source of radio emission (Stanley & Slee 1950; Mills 1954). In an extensive photographic and spectroscopic study, Schweizer (1980) showed that the dust lane is apparently associated with a rapidly rotating disk of ionized gas. This discovery along with the observation of faint ripples and plumes in the outer isophotes of the spheroid component, suggested to Schweizer that the peculiar morphology of NGC 1316 is the result of a recent merger.

Figure 1 [Plate 14] shows a picture of NGC 1316 with the two supernovae that appeared in this galaxy in close succession. SN 1980N, discovered by M. Wischnjewsky two weeks before maximum on 7 December 1980 (Maza 1980), was a type Ia event showing the characteristic 6150 Å absorption feature of blueshifted Si II λ 6355 (Blanco 1980; Prabhu 1981). This supernova was located at a projected distance of 23 kpc from the center of the galaxy (assuming $\mu_{\text{NGC 1316}} = 31.44$ as derived in Sec. 4). The second supernova, SN 1981D, was discovered by the Rev. R. Evans barely 3 months later on 10 March 1981 (Cragg 1981; Erratum in Evans 1982) at a projected distance of approximately 9 kpc from the nucleus of NGC 1316. Early spectroscopy revealed this object also to be a type Ia event (Menzies 1981).

Soon after the discovery of SN 1980N, Landolt initiated from Cerro Tololo Inter-American Observatory (CTIO) a series of photoelectric observations of this object in the $UBV(RI)_{\text{KC}}$ system. Simultaneously, Maza carried out extensive photographic monitoring of both supernovae, including several observations obtained during the premaximum phase, using telescopes of the University of Chile. These data are presented for the first time in this paper and combined with previously published photoelectric observations obtained at CTIO (Olszewski 1982), the European Southern Observatory (Koornneef *et al.* 1980), and New Zealand (Walker & Marino 1982) to produce definitive light curves for these two type Ia supernovae. We discuss the observations and reductions in Sec. 2. In the same section, we also present a complete photoelectric sequence of stars covering a wide range of magnitudes ($V = 10.6$–18.7) and colors which may be useful for future studies of this interesting galaxy. In Sec. 3, we present the light curves and color evolution of both supernovae and compare these with average curves which have been constructed by previous authors for the type Ia class. Finally, in Sec. 4, we discuss the implications of these observations on the suitability of type Ia events as cosmological standard candles, and attempt to derive a distance of NGC 1316 relative to the Virgo cluster.

2. OBSERVATIONS

2.1 Photometric Sequence

Observations of a photometric sequence around NGC 1316 were obtained using the 0.6, 0.9, and 1 m telescopes at CTIO during several photometric nights from December

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1984 through January 1986. Most of the observations were made with a single-channel photometer in the photon-counting mode, the standard Tololo $UBV(RI)_{\rm KC}$ filters as described by Graham (1982), and a dry-ice cooled GaAs photomultiplier (either an RCA 31034 or a Hamamatsu). All of the stars were observed through a 17 arcsec diaphragm. In order to extend the sequence to stars fainter than the 15th magnitude, it was necessary to switch from photoelectric to CCD photometry. These observations were obtained on two photometric nights in November 1985 using the 0.9 m telescope with an RCA CCD and $BV(R)_{\rm KC}$ filters.

Extinction coefficients were derived for each night. Typical values were $k_v = 0.16$, $k_{u-b} = 0.28$, $k'_{b-v} = 0.13$, $k''_{b-v} = -0.03$, $k_{v-r} = 0.05$, and $k_{r-i} = 0.04$ (see Harris *et al.* 1981). Transformation coefficients to the standard $UBV(RI)_{\rm KC}$ system were calculated each night from observations of at least 20 standard stars. Extinction and standard stars were selected from the list of Graham (1982).

The 30 stars selected for the photometric sequence are identified in Fig. 2 [Plate 15]. The $UBV(RI)_{\rm KC}$ photometry for these is given in Table 1. Column 1 of this table gives the star number, columns 2–6 the mean magnitude and colors (errors are given in brackets in units of 0.01 mag), and column 7 the number of observations for that star. For the stars observed only once, the errors given in Table 1 correspond to the Poisson error yielded by the number of photons accumulated for that star and the brightness of the sky in each filter. For multiple observations, the error quoted in Table 1 is the error of the mean.

2.2 *Photoelectric Photometry of SN 1980N and SN 1981D*

Photoelectric $UBV(RI)_{\rm KC}$ observations of SN 1980N were obtained with the 0.4, 0.9, 1.5, and 4 m telescopes at CTIO. These data were reduced in the manner described by Landolt (1983). The magnitudes and colors are listed in Table 2. A sense of the photometric errors involved may be ascertained from comparing magnitudes and color indices obtained on the same night. This procedure should be valid since supernovae are expected to change little on the timescale of a few hours. The errors determined each night from the standard stars that were used always were 0.01 mag or less, except for $U-B$. Errors for the latter usually were two or three times larger. Reproduced in Table 2 is also the published photoelectric photometry of other observers, as compiled by Cadonau & Leibundgut (1990).

The only photoelectric photometry available for SN 1981D is the published UBV measurements of Walker & Marino (1982). These observations were made through a 31 arcsec aperture, with sky measurements taken clear of the galaxy. As this supernova was much closer to the center of NGC 1316 than SN 1980N, contamination from the background light of the parent galaxy must be taken into account.

TABLE 1. Magnitudes and colors of sequence stars.

(1) Star	(2) V	(3) U-B	(4) B-V	(5) V-R	(6) R-I	(7) n
1	12.89(1)	0.00(1)	0.55(1)	0.34(1)	0.33(1)	5
2	14.08(1)	0.17(1)	0.75(1)	0.44(1)	0.42(1)	4
3	14.45(1)	0.18(2)	0.69(1)	0.38(1)	0.34(2)	7
4	12.75(2)	0.28(1)	0.70(1)	0.40(1)	0.35(2)	3
5	13.53(1)	0.03(2)	0.58(2)	0.33(1)	0.33(1)	3
6	13.35(2)	0.77(2)	1.00(2)	0.62(1)	0.55(1)	4
7	13.79(1)	0.26(2)	0.77(2)	0.42(1)	0.39(1)	3
8	11.57(1)	0.58(1)	0.93(1)	0.51(1)	0.48(1)	4
9	10.60(1)	-0.05(1)	0.51(1)	0.33(1)	0.34(1)	3
10	14.47(1)	0.46(2)	0.79(1)	0.44(1)	0.40(2)	5
11	15.29(1)	-0.07(2)	0.54(2)	0.31(2)	0.36(4)	3
12	10.88(1)	1.13(1)	1.18(1)	0.63(1)	0.58(1)	3
13	12.36(1)	-0.03(1)	0.51(1)	0.28(1)	0.30(1)	3
14	13.18(1)	0.77(1)	0.98(1)	0.52(1)	0.46(1)	4
15	14.65(1)	0.05(2)	0.60(1)	0.33(1)	0.34(1)	4
16	13.73(1)	0.48(2)	0.82(1)	0.47(1)	0.41(1)	5
17	14.06(2)	0.19(1)	0.70(1)	0.41(1)	0.39(2)	5
18	14.97(1)	0.04(1)	0.62(1)	0.36(2)	0.32(3)	4
19	15.41(1)	-	0.71(1)	0.41(1)	-	1
20	16.66(1)	-	0.70(1)	0.39(1)	-	1
21	16.36(1)	-	0.71(1)	0.37(1)	-	1
22	18.65(3)	-	0.73(4)	0.52(3)	-	1
23	17.92(1)	-	0.64(2)	0.34(1)	-	1
24	14.79(1)	-	0.61(1)	0.37(1)	-	1
25	15.47(1)	-	0.83(1)	0.47(1)	-	1
26	14.46(5)	-	0.95(5)	0.49(5)	-	1
27	15.06(1)	-	0.94(1)	0.66(1)	-	1
28	16.68(3)	-	1.17(3)	-	-	1
29	17.70(5)	-	-0.09(6)	0.04(8)	-	1
30	15.65(1)	-	1.34(1)	1.01(1)	-	1

TABLE 2. *UBVRI* photoelectric photometry of SN 1980N.

(1) JD - 2440000	(2) V	(3) U-B	(4) B-V	(5) V-R	(6) R-I	(7) notes
4584.59493	12.544	-0.207	-0.039	0.081	-0.233	a
4584.60067	12.522	-0.205	-0.040	0.007	-0.229	a
4586.63779	12.443	-0.193	0.104	-	-	b
4586.63943	12.459	-0.199	0.064	-	-	b
4586.67308	12.400	-0.198	0.120	-	-	b
4586.67467	12.471	-0.147	0.024	-	-	b
4586.67633	12.471	-0.182	0.027	-	-	b
4587.63476	12.468	-0.052	0.037	0.069	-0.340	b
4587.63760	12.430	-0.036	0.043	0.010	-0.242	b
4588.62995	12.465	0.083	0.047	0.026	-0.182	b
4588.63408	12.473	-0.012	0.072	0.070	-0.380	b
4590.6010	12.45	-	0.27	-	-	c
4595.5900	12.62	-	0.63	-	-	c
4597.5972	12.80	-	0.57	-	-	e
4598.5833	12.84	-	0.61	-	-	e
4599.5792	12.96	-	0.68	-	-	e
4603.6021	13.17	-	0.94	-	-	e
4604.6944	13.24	-	1.00	-	-	e
4605.5562	13.30	-	1.03	-	-	e
4606.6167	13.35	-	1.10	-	-	e
4607.6056	13.41	-	1.11	-	-	e
4634.54990	14.735	0.389	1.027	-	-	d
4634.55385	14.723	0.210	1.088	-	-	d
4634.55635	14.700	0.456	1.049	-	-	d
4634.56088	14.738	0.330	1.048	-	-	d
4634.56863	14.840	0.450	0.964	-	-	d
4635.57074	14.723	0.521	1.021	0.192	0.080	d
4635.57359	14.753	0.617	1.034	0.205	-0.104	d
4636.57268	14.762	0.543	0.936	0.241	-0.006	d
4636.57513	14.751	0.360	1.059	0.217	0.024	d
4637.62511	14.774	0.439	1.012	0.264	-0.053	a
4637.62778	14.779	0.512	0.953	0.260	-0.092	a
4638.62152	14.827	0.563	0.935	0.237	-0.024	a
4638.62415	14.800	0.513	0.973	0.225	-0.038	a
4639.58940	14.841	0.387	0.971	0.241	-0.002	a
4639.59183	14.829	0.600	0.947	0.210	-0.032	a
4640.60163	14.860	0.463	0.888	0.246	-0.024	a
4640.60414	14.921	0.504	0.874	0.286	-0.036	a
4642.55957	14.864	0.390	0.857	0.218	-0.038	f
4642.56248	14.847	0.381	0.904	0.197	-0.097	f
4644.55002	15.013	0.730	0.800	0.227	-0.075	d
4644.55286	14.975	0.360	0.909	0.193	-0.056	d
4818.84203	18.526	-	0.413	-0.317	-0.216	f
4818.84740	18.645	-	1.028	-0.705	-0.691	f

Notes to TABLE 2

a: Landolt 1.5m
b: Landolt 0.4m
c: Koornneef et al. (1980)
d: Landolt 0.9m
e: Olszewski (1982)
f: Landolt 4.0m

We have attempted to correct for this using the isophotal maps of Sérsic (1968) and the *UBV* photometry measurements of NGC 1316 published by Schweizer (1980) which were obtained along a line running due west from the nucleus. Together, these yield the following magnitudes for the background light through a 31 arcsec aperture at the position of SN 1981D: $U = 15.76 \pm 0.15$, $B = 15.40 \pm 0.15$, and $V = 14.54 \pm 0.15$. At maximum light, the implied corrections to Walker & Marino's photometry are 0.06 mag in U, 0.08 mag in B, and 0.14 mag in V. For their last measurements on JD 2444702.8, these increase to 0.46 mag in U, 0.44 mag in B, and 0.32 mag in V. In Table 3, we list Walker and Marino's photometry for SN 1981D modified in this manner. The errors assigned to these magnitudes take into account both the quoted errors in the photometry and our best estimate of the uncertainties in this background light subtraction procedure.

2.3 Photographic Photometry of SN 1980N and SN 1981D

Photographic observations of both supernovae were acquired using the University of Chile astrographic Maksutov Camera (70/100/210 cm) located at Cerro El Roble and the 33 cm Gauthier refractor telescope at Cerro Calán. A total of 92 useful plates of both supernovae were taken between 30 November 1980 and 30 September 1981. Three different emulsion/filter combinations were employed: unbaked Kodak IIa-O and 103a-O plates with no filter, IIa-O plates with a GG-385 filter, and IIa-D plates with a GG-495 filter. These combinations reproduce the standard $m_{\rm pg}$, B, and V bands, respectively. The exposure times ranged from 2 min when the supernovae were at their brightest, to a maximum of 30 min. Under normal photometric conditions, a limiting magnitude of 20 was reached during an exposure of 30 min with the Maksutov Camera. For the Gauthier telescope, a limiting magnitude of 15 was achieved with a typical exposure time of 10 min.

For each plate, we selected approximately ten stars of similar brightness to the supernova(e) from our photometric sequence. We then used an Astromechanics iris-diaphragm photometer in the CTIO laboratory in La Serena to measure these stars along with the supernova(e). To minimize the contribution of background light from NGC 1316 to these measurements, we used as small a diaphragm as possible. Unfortunately, as we have shown, the background light at the position of SN 1981D is sufficiently bright that, even near maximum, the iris photometry magnitudes of this supernova are affected by residual galaxy contamination. SN 1980N, on the other hand, was located far enough from the center of NGC 1316 that background light was never a serious concern.

TABLE 3. *UBV* photoelectric photometry of SN 1981D corrected for background light.

(1)	(2)	(3)	(4)
JD - 2440000	V	U-B	B-V
4674.8593	12.69(05)	-0.30(15)	0.22(10)
4676.8538	12.56(04)	-0.29(13)	0.16(08)
4677.8559	12.53(04)	-0.24(13)	0.10(08)
4683.8845	12.41(03)	0.17(16)	0.30(08)
4691.8282	12.85(05)	-0.05(21)	0.75(12)
4692.8291	12.82(05)	0.24(24)	0.84(12)
4698.8164	13.34(08)	-0.26(25)	0.95(16)
4699.8150	13.37(08)	-0.01(30)	1.31(18)
4702.8268	13.38(08)	0.42(32)	1.26(18)

The iris measurements for each plate were repeated 2–3 times to improve the precision of the photometry. Measurements of the sequence stars for a given plate were then used to derive the transformation to magnitudes. We found that a second-order polynomial fit was appropriate for all plates. Photographic magnitudes for the sequence stars were calculated from the *BV* photometry in Table 1 by means of the equation

$$m_{\rm pg} = B + 0.18(B - V) - 0.29,$$

given by Arp (1961). This equation is applicable to main sequence stars covering a wide range in color $(0.4 < B - V < 1.2)$.

Table 4 lists the resulting magnitudes for SN 1980N. The errors, which are given in brackets in units of 0.01 mag, correspond to the root-mean-square (rms) error of the polynomial transformation from iris readings to standard magnitudes. For a given plate, this value is the typical error in any iris measurement. For our collection of plates, we found that these values range between 0.03–0.24 mag with a formal average of 0.08 mag. The quality of the transformations is a function of many factors, the most important of which are the seeing, focus, guiding, sky brightness, and range of magnitudes of the sequence stars used in the transformation.

For SN 1981D, given that the iris magnitudes were strongly affected by galaxy contamination, we attempted instead a visual estimation of its brightness. An Astrorecord Seiz/Jena XY engine was used to estimate the image diameter of the supernova on each plate along with those of the standard stars from the photometric sequence. These measurements were transformed into magnitudes via a third-order polynomial least squares fit. The results of this procedure are listed in Table 5. The errors given in this table (in units of 0.01 mag) correspond to the rms error of the polynomial transformation, but do not include possible systematic errors associated with the different background levels of the supernova and sequence stars.

2.4 Spectroscopy of SN 1980N

A low-dispersion (~6 Å FWHM) spectrum of SN 1980N covering the wavelength range $\lambda\lambda$ 3200–7200 was obtained on 1981 January 10.5 (JD 2444615.0) with the 3.9 m Anglo–Australian Telescope. The detector was the Image Photon Counting System (Boksenberg & Burgess 1973) and the spectrograph slit width was 2 arcsec. Flux calibration was made via observations of the DA white dwarf LB 227 (Oke 1974). Due to nonphotometric conditions, however, the absolute flux scale of the supernova spectrum is unreliable.

3. RESULTS

3.1 The Optical Light Curves of SN 1980N

Figures 3(a) and 3(b) show the photographic and photoelectric observations of SN 1980N from Tables 2 and 4 plotted as a function of time. Included for comparison in the same figures are Leibundgut's (1988) template *UBV* light curves for type Ia supernovae and the average $m_{\rm pg}$ curve given by Cadonau *et al.* (1985). To fit these curves to the data, we determined the time and the magnitude of maxi-

TABLE 4. Photographic photometry of SN 1980N.

JD -2440000	TEL	EXP (min)	EMUL	FILT	pg	B	V
4573.68056	MAK	20	IIaO	no	14.98(14)	-	-
4580.61493	MAK	17	103aO	no	12.75(11)	-	-
4586.67986	GAU	10	103aO	no	12.21(06)	-	-
4586.69375	GAU	10	103aO	no	12.15(09)	-	-
4586.70278	GAU	2	103aO	no	12.35(03)	-	-
4587.68090	GAU	5	103aO	no	12.30(05)	-	-
4587.69028	GAU	10	103aO	no	12.16(07)	-	-
4588.65660	GAU	5	103aO	no	12.21(05)	-	-
4588.66597	GAU	10	103aO	no	12.25(06)	-	-
4589.69236	GAU	10	103aO	no	12.35(07)	-	-
4590.66111	GAU	10	103aO	no	12.32(06)	-	-
4590.66979	GAU	5	103aO	no	12.38(03)	-	-
4592.65729	GAU	5	103aO	no	12.66(06)	-	-
4592.66424	GAU	5	103aO	no	12.54(13)	-	-
4592.67188	GAU	5	103aO	no	12.91(03)	-	-
4595.62674	GAU	5	103aO	no	12.63(06)	-	-
4595.63299	GAU	5	103aO	no	12.88(05)	-	-
4596.64965	GAU	5	103aO	no	12.96(12)	-	-
4596.65521	GAU	5	103aO	no	13.25(07)	-	-
4597.57014	GAU	10	103aO	no	13.15(04)	-	-
4597.57813	GAU	5	103aO	no	13.41(12)	-	-
4599.62153	GAU	10	103aO	no	13.47(10)	-	-
4599.63125	GAU	10	103aO	no	13.44(07)	-	-
4600.62396	GAU	5	103aO	no	13.67(12)	-	-
4600.63472	GAU	10	103aO	no	13.64(08)	-	-
4600.73750	MAK	2	IIaO	no	13.64(12)	-	-
4600.74444	MAK	2	IIaO	no	13.74(07)	-	-
4601.70174	MAK	5	IIaO	no	13.71(05)	-	-
4601.70764	MAK	2	IIaO	no	13.77(06)	-	-
4603.66736	GAU	10	103aO	no	14.28(12)	-	-
4603.69132	MAK	5	IIaO	GG385	-	14.00(04)	-
4603.69757	MAK	5	IIaO	GG385	-	14.18(07)	-
4603.69965	MAK	5	IIaD	GG495	-	-	13.26(08)
4603.70521	MAK	5	IIaD	GG495	-	-	13.28(07)
4603.70938	MAK	5	IIaO	no	13.83(06)	-	-
4603.71285	MAK	5	IIaO	no	14.10(05)	-	-
4606.69167	MAK	10	IIaD	GG495	-	-	13.35(06)
4606.70174	MAK	5	IIaO	GG385	-	14.41(05)	-
4606.71146	MAK	5	IIaO	no	14.31(08)	-	-
4607.68264	MAK	10	IIaD	GG495	-	-	13.43(07)
4607.69201	MAK	5	IIaO	GG385	-	14.56(07)	-
4607.70451	MAK	5	IIaO	no	14.47(03)	-	-
4607.71979	MAK	15	103aO	no	14.16(10)	-	-
4608.69236	MAK	10	IIaD	GG495	-	-	13.60(06)
4608.70104	MAK	5	IIaO	GG385	-	14.72(05)	-
4608.70938	MAK	5	IIaO	no	14.61(08)	-	-
4609.61806	GAU	10	103aO	no	14.65(08)	-	-
4609.67153	MAK	10	IIaD	GG495	-	-	13.56(10)
4609.68021	MAK	5	IIaO	GG385	-	14.75(06)	-
4609.68785	MAK	5	IIaO	no	14.67(07)	-	-
4610.60625	GAU	10	103aO	no	14.66(17)	-	-
4610.61458	GAU	10	103aO	no	14.80(09)	-	-
4611.63681	MAK	10	IIaD	GG495	-	-	13.63(05)
4611.64826	MAK	5	IIaO	GG385	-	14.92(07)	-
4611.65729	MAK	5	IIaO	no	14.64(06)	-	-
4612.73021	MAK	5	IIaO	GG385	-	15.05(06)	-
4613.60938	GAU	15	103aO	no	14.96(08)	-	-
4613.61667	MAK	10	IIaD	GG495	-	-	13.85(05)
4613.62951	MAK	5	IIaO	GG385	-	15.09(04)	-
4613.63993	MAK	5	IIaO	no	14.86(04)	-	-
4614.70104	MAK	5	IIaO	GG385	-	15.23(06)	-
4614.71007	MAK	5	IIaO	no	14.96(04)	-	-
4615.59931	MAK	10	IIaD	GG495	-	-	14.00(05)
4615.60868	MAK	5	IIaO	GG385	-	15.18(05)	-
4615.61563	MAK	5	IIaO	no	15.04(05)	-	-
4617.60382	MAK	5	IIaO	GG385	-	15.32(07)	-
4617.61458	MAK	10	IIaD	GG495	-	-	14.17(05)
4637.63819	MAK	20	103aO	no	15.54(06)	-	-
4662.55833	MAK	20	IIaO	GG385	-	16.16(05)	-
4662.58194	MAK	30	IIaD	GG495	-	-	15.48(06)
4664.59722	MAK	30	IIaD	GG495	-	-	15.51(15)
4665.55313	MAK	15	103aO	no	16.14(14)	-	-
4665.57292	MAK	20	IIaO	GG385	-	16.13(19)	-
4665.59444	MAK	30	IIaD	GG495	-	-	15.43(10)
4666.56042	MAK	20	IIaO	GG385	-	16.24(04)	-
4667.54167	MAK	20	IIaO	GG385	-	16.10(10)	-
4667.57708	MAK	20	IIaD	GG495	-	-	15.45(08)
4694.52500	MAK	10	IIaO	GG385	-	16.33(14)	-
4694.53924	MAK	15	IIaD	GG495	-	-	16.24(12)
4695.52153	MAK	20	IIaO	no	16.50(10)	-	-
4696.49792	MAK	20	IIaO	no	16.37(09)	-	-
4697.51667	MAK	10	IIaO	GG385	-	16.81(14)	-
4697.53090	MAK	15	IIaD	GG495	-	-	16.20(14)
4698.49896	MAK	15	IIaD	GG495	-	-	16.46(11)
4698.51319	MAK	10	IIaO	GG385	-	16.43(11)	-
4700.51458	MAK	10	IIaO	GG385	-	16.58(06)	-
4700.52882	MAK	15	IIaD	GG495	-	-	16.29(07)
4723.49097	MAK	20	IIaO	no	17.10(15)	-	-
4787.91458	MAK	20	IIaO	no	17.87(07)	-	-
4826.89410	MAK	15	103aO	no	18.74(24)	-	-
4852.76875	MAK	20	IIaO	no	18.87(10)	-	-
4877.81424	MAK	15	103aO	no	18.95(11)	-	-

TABLE 5. Photographic photometry of SN 1981D.

JD -2440000	TEL	EXP (min)	EMUL	FILT	pg	B	V
4664.59722	MAK	30	IIaD	GG495	-	-	17.91(42)
4665.55313	MAK	15	103aO	no	16.96(33)	-	-
4665.57292	MAK	20	IIaO	GG385	-	17.68(31)	-
4665.59444	MAK	30	IIaD	GG495	-	-	16.35(53)
4666.56042	MAK	20	IIaO	GG385	-	16.22(32)	-
4667.54167	MAK	20	IIaO	GG385	-	15.93(35)	-
4667.57708	MAK	20	IIaD	GG495	-	-	15.22(33)
4694.52500	MAK	10	IIaO	GG385	-	14.24(21)	-
4694.53924	MAK	15	IIaD	GG495	-	-	13.44(19)
4695.52153	MAK	20	IIaO	no	14.26(19)	-	-
4696.49792	MAK	20	IIaO	no	14.17(21)	-	-
4697.51667	MAK	10	IIaO	GG385	-	14.38(14)	-
4697.53090	MAK	15	IIaD	GG495	-	-	13.68(14)
4698.49896	MAK	15	IIaD	GG495	-	-	13.60(18)
4698.51319	MAK	10	IIaO	GG385	-	14.78(11)	-
4700.51458	MAK	10	IIaO	GG385	-	14.99(06)	-
4700.52847	MAK	15	IIaD	GG495	-	-	13.60(14)
4723.49097	MAK	20	IIaO	no	15.83(34)	-	-
4787.91458	MAK	20	IIaO	no	16.70(16)	-	-
4826.89410	MAK	15	103aO	no	17.65(16)	-	-
4852.76875	MAK	20	IIaO	no	17.28(19)	-	-
4877.81424	MAK	15	103aO	no	17.61(15)	-	-

mum light for SN 1980N in the B, V, and $m_{\rm pg}$ filters by fitting a 5th or 6th order polynomial to the photometry obtained from discovery through the initial fast-decline phase. The results are listed in Table 6, where column (1) gives the time of maximum light, column (2) the magnitude at the time of maximum light, and column (3) the magnitude at the time of B maximum, t_0^B. (The times of the U, R, and I maxima could not be determined accurately due to insufficient data.) The errors given in this table represent the range of acceptable fits to the data. Within the accuracy of our measurements, the time differences between the B, V, and $m_{\rm pg}$ maxima agree very well with the results of Leibundgut (1988) and Cadonau *et al.* (1985), viz.,

$$t_0^V - t_0^B = 2.5 \pm 1.0 \text{ days},$$

and

$$t_0^{m_{\rm pg}} - t_0^B = 0.0 \pm 0.5 \text{ days}.$$

We thus fit the template light curves to the data in Figs. 3(a) and 3(b) by shifting the curves in unison along the horizontal axis [i.e., maintaining the time differences given by Leibundgut (1988) and Cadonau *et al.* (1985)] to match the time of maximum light in the B filter (t_0^B). The vertical shift

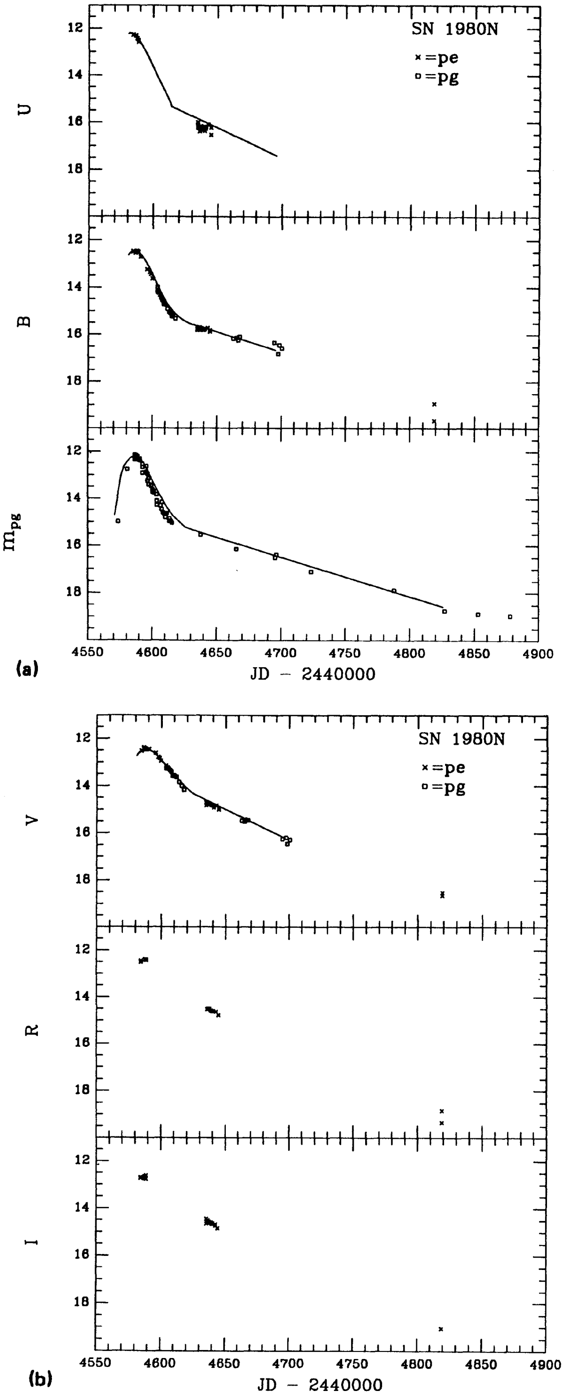

FIG. 3. (a) *U*, *B*, and m_{pg} light curves of SN 1980N. Plotted as solid lines are the type Ia template curves given by Leibundgut (1988) and Cadonau *et al.* (1985). These have been adjusted to fit the data as described in the text. (b) *V*, *R*, and *I* light curves of SN 1980N. Plotted as a solid line is the type Ia template *V* curve given by Leibundgut (1988).

was accomplished independently for each filter by matching the observed magnitude of SN 1980N in that band at t_0^B.

In columns (4)–(6) of Table 6, we also list the observed rate of brightening (α) during the premaximum rise phase, the rate of dimming (β) during the fast-decline phase between days 7–30, and the rate of the slow-decline phase (γ) starting on day 42, respectively [see Pskovskii (1967,1984) for the definition of the parameters α, β, and γ]. Although these parameters for SN 1980N are all in good agreement with the mean values derived by Leibundgut (1988) for type Ia supernovae, it can be seen from Figs. 3(a) and 3(b) that the template curves do not exactly match the observations. The discrepancies in *U*, *B*, and *V* range between 0.1–0.4 mag, which is considerably larger than the errors in the photometry or inaccuracies in the determination of t_0^B. The discrepancies are most pronounced for the *U* and m_{pg} light curves.

TABLE 6. Parameters for the light curves of SN 1980N.

	(1)	(2)	(3)	(4)	(5)	(6)
FILTER	t_0 JD -2440000	MAX	$m(t_0^B)$	α	β (mag/100 days)	γ
	±0.5	±0.02	±0.02		±0.5	±0.3
pg	4586.3	12.22	12.22	-32	10.9	1.5
U	-	-	12.30	-	-	-
B	4585.8	12.49	12.49	-	10.5	1.6
V	4588.5	12.44	12.48	-	6.6	2.1

3.2 *The Optical Light Curves of SN 1981D*

Figures 4(a) and 4(b) show the observed light curves of SN 1981D plotted from the data in Tables 3 and 5, along with the type Ia template curves from Leibundgut (1988) and Cadonau *et al.* (1985). Light curve parameters derived solely from the background-corrected photoelectric photometry for this supernova are summarized in Table 7. The epoch of maximum light in *U* occurred 2.2 ± 0.7 days earlier than in *B*, in reasonable agreement with the value found by Leibundgut from two supernovae, viz., 2.8 ± 0.2 days. The observed difference of 2.9 ± 0.7 days between the *B* and *V* maxima is also in good agreement with Leibundgut's work.

The template *UBV* curves drawn in Figs. 4(a) and 4(b) were shifted to match the observations in the same fashion described for SN 1980N. Taking into account the uncertainties in the background light corrections applied to the observations, the average curves match the photoelectric data surprisingly well. On the other hand, where there is overlap the photographic magnitudes are clearly lower than the photoelectric values by 0.4–0.5 mag in *B* and *V*. This effect may well be a consequence of the fact that the supernova is sitting on a brighter background than the sequence stars, which could lead us to underestimate the size of the object. Since no observations in the m_{pg} band were obtained of this supernova at maximum light, we attempted a comparison with the template curve by adopting the epoch of maximum from the *B* filter and assuming a brightness difference at maximum of $B - m_{pg} = 0.28$ (Cadonau *et al.* 1985; also see the next section). The resulting fit to the observations is reasonable.

3.3 *The Color Curves*

Figure 5 (top panel) shows the $B - V$ color of SN 1980N plotted as a function of time since *B* maximum ($t - t_0^B$). Overplotted in this same figure is Leibundgut's template

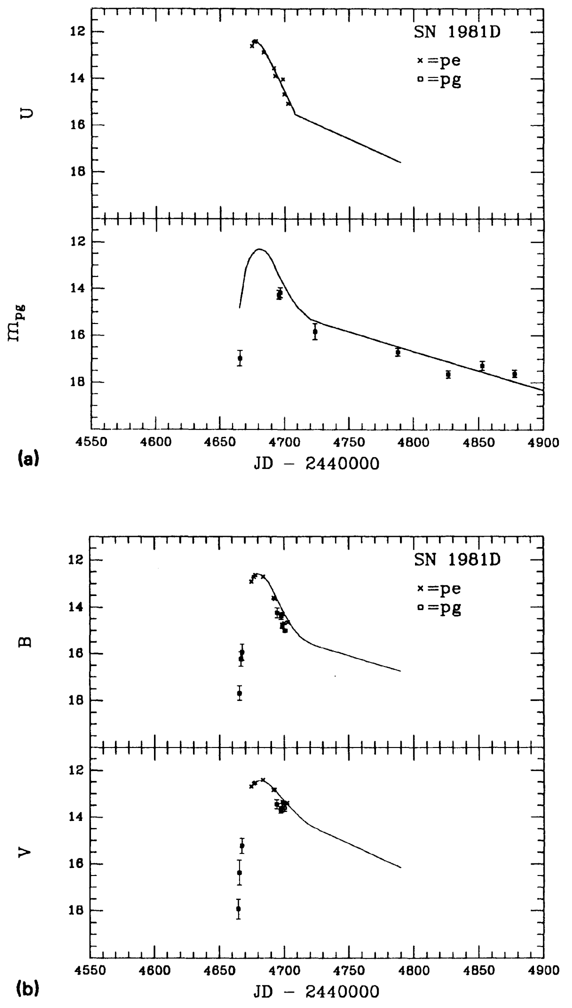

FIG. 4. (a) U and m_{pg} light curves of SN 1981D. Plotted as solid lines are the type Ia template curves given by Leibundgut (1988) and Cadonau *et al.* (1985). These have been adjusted to fit the data as described in the text. (b) B and V light curves of SN 1981D. Plotted as solid lines are the type Ia template curves given by Leibundgut (1988).

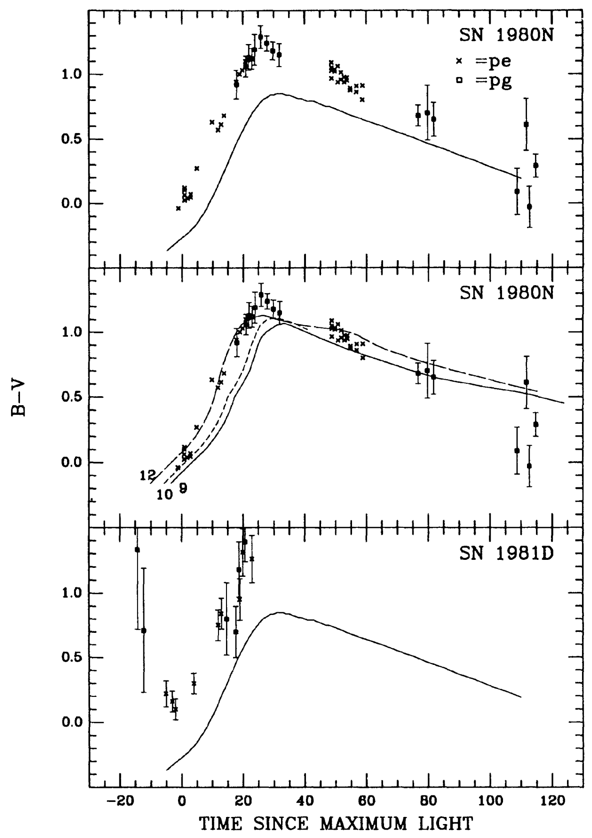

FIG. 5. (Top) $B-V$ evolution of SN 1980N. The solid curve shows the type Ia template curve of Leibundgut (1988) normalized to an intrinsic color at B maximum of $(B-V)_0=-0.27$ (Cadonau 1986). (Middle) Comparison of $B-V$ evolution of SN 1980N with the average curves given by Pskovskii (1984) for type Ia supernovae with β parameters of 9, 10, and 12. (Bottom) $B-V$ evolution of SN 1981D. The solid curve shows the type Ia template curve of Leibundgut (1988) normalized to an intrinsic color at B maximum of $(B-V)_0=-0.27$ (Cadonau 1986).

TABLE 7. Parameters for the light curves of SN 1981D.

	(1)	(2)	(3)
FILTER	t_0 JD -2440000	MAX	$m(t_0^B)$
	±0.5	±0.04	±0.04
U	4677.7	12.41	12.48
B	4679.9	12.59	12.59
V	4682.8	12.40	12.45

curve for type Ia supernovae. For the zero point of the latter, we have used the value of the intrinsic color at B maximum, $(B-V)_0=-0.27$, adopted by Leibundgut, but which is originally due to Cadonau (1986). This figure shows that the shape of the template curve roughly matches the observations. The vertical offset between the data and the template curve implies a color excess of $E(B-V)=0.33\pm0.10$ (rms error). A similar comparison of the $U-B$ observations near maximum light with Leibundgut's $U-B$ template curve, normalized to Cadonau's zero point of $(U-B)_0\approx-0.4$, implies $E(U-B)=0.23\pm0.06$. The ratio of these two color excesses, $E(U-B)/E(B-V)=0.70$, is consistent with typical Galactic interstellar extinction curves (e.g., see Johnson 1968) which suggests that dust may be responsible for the observed colors. However, given that the foreground extinction in the direction of NGC 1316 is negligible (Burstein & Heiles 1984), the dust would have to be located within the parent galaxy. Although there is dust in the central region of NGC 1316, there is no evidence that it extends out to the position of either SN 1980N or 1981D (see Schweizer 1980).

Pskovskii (1984) has suggested that the $B-V$ color evolution of type Ia supernovae is a function of the β parameter. Figure 5 (middle panel) shows a comparison of the observed color curve of SN 1980N with a sample of the curves derived by Pskovskii (1984) for type Ia supernovae. It can be seen from this figure that the data up to 25 days past maximum are reasonably well fitted by a curve with $10<\beta<12$. At later epochs, the colors are best matched by a curve with $9<\beta<12$. Note that the color excess implied is much smaller ($\leqslant 0.1$ mag) than the value derived using Leibundgut's curve with Cadonau's zero point.

Figure 5 (lower panel) shows the $B-V$ evolution of SN 1981D along with Leibundgut's template curve. Comparison of the photoelectric data for SN 1981B with Leibundgut's curve implies a color excess of $E(B-V)=0.55\pm0.10$, which is somewhat greater than the value found for SN 1980N. However, the corresponding color excess derived from the observed $U-B$ colors near maximum is $E(U-B)=0.21\pm0.12$, which is indistinguishable from the value derived for SN 1980N. It is difficult to judge the reality of the $B-V$ color difference between the two supernovae, particularly since the post-facto background corrections we have made to the SN 1981D observations are approximate only. Certainly it is possible that the light of SN 1981D has been slightly reddened by dust with respect to that of SN 1980N. Alternatively, it is just as reasonable to conclude that the intrinsic colors of the two supernovae are slightly different.

The premaximum $B-V$ data for SN 1981D would seem to indicate that this supernova evolved from red to blue until a few days before B maximum, suggesting either an increase in temperature or a rapid change in opacity. Unfortunately, this conclusion relies on the accuracy of the first two photographic measurements which, as we have shown, are most likely affected by systematic errors. Recent CCD photometry of the type Ia SN 1990N obtained at CTIO shows that the $B-V$ color of this object was essentially constant from -11 to $+1$ days from B maximum (Leibundgut *et al.* 1991). These observations are only barely consistent with our photometry of SN 1981D, and so this apparent early blue evolution should be considered with caution. However, we note with interest the finding by Leibundgut *et al.* (1991) that the ultraviolet flux of SN 1990N increased more rapidly than the optical from -14 to -7 days from B maximum.

Our observations of SN 1980N can be used to examine the relationship between the $m_{\rm pg}$ and B magnitudes for type Ia supernovae. Figure 6 shows the observed $B-m_{\rm pg}$ colors plotted as a function of $t-t_0^B$. For comparison, we have plotted Arp's (1961) transformation equation for main-sequence stars, $m_{\rm pg}=B+0.18\ (B-V)-0.29$, as a solid line in the same figure. Although Arp's equation provides a better approximation to the observed points than does a simple constant offset, it is clear that the true relationship has some additional kinks and wiggles. These are almost certainly due to the changing strengths of the supernova absorption and emission features in the respective bandpasses. Given the relative homogeneity of type Ia events, an empirical fit through the observed points in Fig. 6 should provide a more accurate alternative to the use of either Arp's equation (e.g., see Rust 1974) or a simple zeropoint change (e.g., see Cadonau *et al.* 1985) for the transformation of photographic magnitudes of previously observed supernovae into B magnitudes over the first 30 days of evolution.

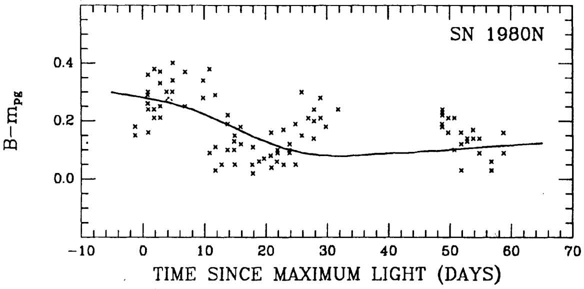

FIG. 6. Plot of $B-m_{\rm pg}$ as a function of time since B maximum $(t-t_0^B)$. The solid line shows the relation predicted using the transformation equation $m_{\rm pg}=B+0.18\ (B-V)-0.29$ given by Arp (1961) for main-sequence stars.

3.4 *The Spectrum of SN 1980N*

Our single spectrum of SN 1980N, which was obtained 29 days after B maximum, is reproduced in the top panel of Fig. 7. In the lower panel of the same figure, a comparable-epoch spectrum obtained by Branch *et al.* (1983) of one of the prototypes of the Ia class, SN 1981B, is displayed for comparison. The overall similarity of these spectra is striking, although minor differences are apparent upon closer inspection. It is unfortunate that so few spectral observations of SN 1980N appear to have been made, since it would be very interesting to extend such a comparison to earlier epochs where differences have been observed between other type Ia supernovae (e.g., see Branch 1987; Phillips *et al.* 1987).

4. DISCUSSION

The light curves of SN 1980N and SN 1981D provide an important check on the suitability of type Ia events as cos-

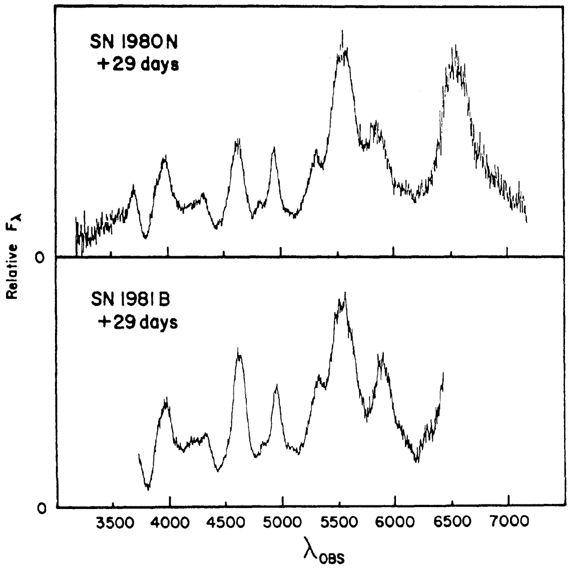

FIG. 7. (Top) Spectrum of SN 1980N obtained 29 days after B maximum. (Bottom) Spectrum of the prototype Ia SN 1981B obtained by Branch *et al.* (1983) at the same epoch in its evolution.

mological standard candles since both supernovae occurred in the same galaxy and were well observed at maximum. A direct comparison of the *UBV* light curves of these two supernovae is shown in Fig. 8. (Due to the large systematic errors present in the photographic photometry for SN 1981D, these data are not included in this figure.) *Note that no adjustment in the magnitude scales for either object has been made in this figure.* As may be seen, the agreement is remarkable. We conclude that the maximum light magnitudes of these two supernovae were identical to within a maximum range of ± 0.1 mag in all three colors. This is consistent with the findings of Elias *et al.* (1981), who found that the *JHK* light curves superposed to a similar degree of accuracy.

As shown in Fig. 9, the shapes of the *UBV* light curves of the best observed of these two supernovae, 1980N, are virtually identical to those of the type Ia prototype, SN 1981B. The close resemblence of the spectra of these two objects a month after maximum reinforces the impression that these two events were very similar. A more detailed examination of Fig. 9 suggests that SN 1980N declined at a slightly faster rate in *B* than SN 1981B for the first month or so following maximum. This difference appears to be real and is reflected in the β parameters for both supernovae (10.5 vs 10.2).[3] Nevertheless, we cannot completely rule out the possibility that the light curves are intrinsically identical, but appear to be distinct due to slight differences between photometer response functions (cf. Hamuy *et al.* 1990). On the other hand, the case of SN 1986G (Phillips *et al.* 1987; Frogel *et al.* 1987) shows that at least some type Ia events can have optical and infrared light curves that are clearly different from those of the prototypes such as SN 1981B.

We have shown that the observed $B-V$ colors at B maximum of both supernovae in NGC 1316 were 0.3–0.5 mag redder than the intrinsic value of $(B-V)_0 = -0.27$ advocated by Cadonau (1986). While dust could explain this difference, we have pointed out the lack of corroborating evidence for such a large extinction. It should be emphasized that Cadonau's value of $(B-V)_0$ was derived from photographic observations of two supernovae in elliptical galaxies, 1970J and 1972J, which were calibrated using the same photographically transferred sequence (Barbon *et al.* 1973; Ciatti & Rosino 1977). Pskovskii's (1984) work as well as a more recent estimate of $(B-V)_0 = -0.04$ by Capaccioli *et al.* (1990) based on the light curves of four type Ia supernovae in early type galaxies in the Coma cluster would appear to be much more consistent with our data for the NGC 1316 supernovae.

If we assume that the majority of type Ia supernovae form a homogeneous class of objects with essentially identical light curves, colors, and absolute magnitudes, we can use the observations of SN 1980N to estimate the distance to NGC

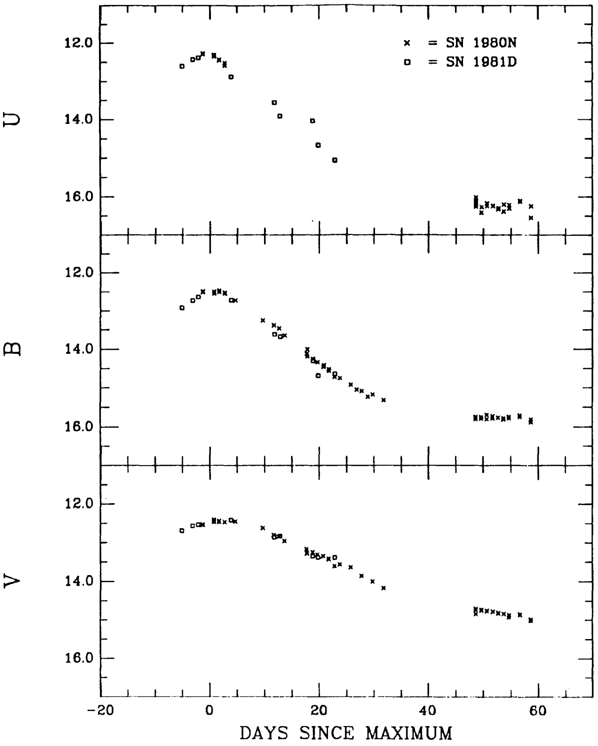

FIG. 8. *UBV* light curves of the two supernovae, 1980N and 1981D, in NGC 1316 plotted as a function of time since B maximum $(t - t_0^B)$. No adjustment has been made to the magnitude scales for either supernova.

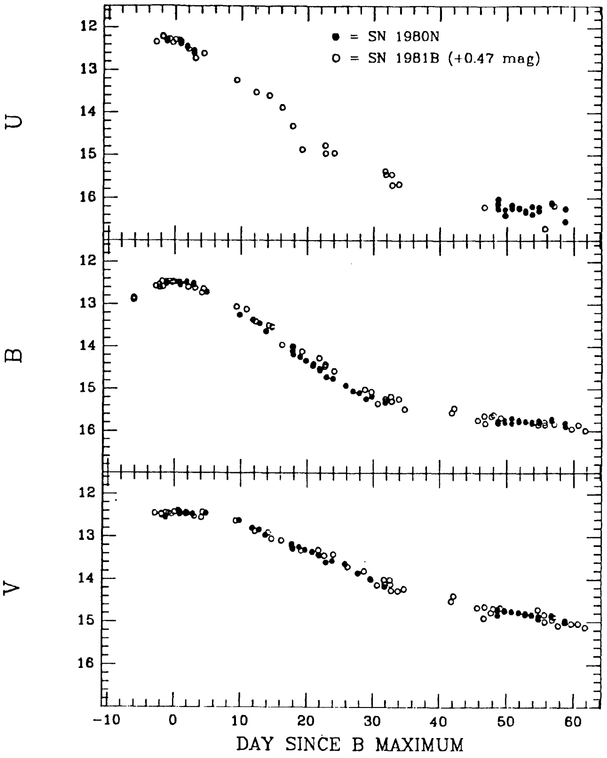

FIG. 9. Comparison of the *UBV* light curves of SN 1980N with those of the prototype Ia SN 1981B. The photometry for SN 1981B is due to Buta & Turner (1983), Tsvetkov (1982), and Busko *et al.* (1981).

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[3] Considerable care must be exercised in comparing the Pskovskii β parameter for different supernovae. Pskovskii (1984) defines β as the mean rate of decline of the blue light curve between the epoch, t_m, of maximum light and the epoch, t_b, of the bend in the light curve where the decline slows down. There are two problems with this definition. First of all, it is difficult to measure t_b with good precision for a typical supernova light curve. Worse yet, the exact value of β derived depends critically on how well the light curve has been sampled. Thus, in measuring the β values that we quote in this paper for SN 1980N, SN 1981B, and SN 1981D, we have used only those observations obtained from 7–30 days after maximum, which is the most linear portion of the initial decline phase.

1316. We shall first attempt to derive a relative distance for NGC 1316 with respect to the Virgo cluster. There have been several attempts to derive a mean apparent magnitude for type Ia supernovae in Virgo (Capaccioli *et al.* 1990; Leibundgut & Tammann 1990). However, these studies are based on a small number of supernovae listed in the *Asiago Supernova Catalog* (Barbon *et al.* 1989) whose parent galaxies lie in the *area* of the Virgo cluster, but which are not all certain cluster members. The photometric quality of the light curve observations of these supernovae is generally poor, and only some of them possess precise spectroscopic classifications. For these reasons, we prefer instead to derive the relative distance for NGC 1316 with respect to Virgo, by comparing the data of SN 1980N with optical and infrared light curves of SN 1984A in NGC 4419. This particular supernova was chosen since it was relatively well observed, and appeared in a galaxy whose association with the Virgo cluster core is very likely given both its projected position in the sky near the center of the cluster and its negative radial velocity (Tully 1988).

Optical photometry of SN 1984A was obtained by Barbon *et al.* (1989) and Kimeridze & Tsvetkov (1986) who found $B_{\max} = 12.5 \pm 0.1$ and $V_{\max} = 12.3 \pm 0.1$. Fitting Leibundgut's $B - V$ template curve to these observations, a color excess for SN 1984A *with respect to SN 1980N* of $E(B-V) = 0.04 \pm 0.23$ is implied (Della Valle 1991), which yields extinction-corrected magnitudes at maximum of $(B_{\max})_0 = 12.34 \pm 0.93$ and $(V_{\max})_0 = 12.18 \pm 0.70$. Comparison with the maximum light magnitudes of SN 1980N given in Table 6 then implies,

$$\mu_{\rm NGC\ 1316} - \mu_{\rm NGC\ 4419} = +0.15 \pm 0.94$$

and

$$\mu_{\rm NGC\ 1316} - \mu_{\rm NGC\ 4419} = +0.26 \pm 0.71$$

for B and V, respectively.

The large errors in these estimates, which are due entirely to the uncertainty in the relative extinction, can be reduced by using infrared photometry. The most common measure of the brightness of type Ia supernovae in the infrared is the parameter H_{20} introduced by Elias *et al.* (1985), which is defined as the H magnitude at ~15 days after B maximum. Elias *et al.* (1985) found from 13 type Ia supernovae that H_{20} is a good distance indicator with a scatter of ~0.2 mag. Infrared photometry of SN 1984A was obtained by Graham *et al.* (1988) who found $H_{20} = 13.35 \pm 0.05$ mag. However, a reanalysis of the photometry using the more precise date of B maximum given by Barbon *et al.* (1989) yields $H_{20} = 13.25 \pm 0.10$. For SN 1980N in NGC 1316, Elias *et al.* (1985) found $H_{20} = 13.31 \pm 0.02$. Including a small correction for differential extinction (0.02 ± 0.10 mag), these data imply,

$$\mu_{\rm NGC\ 1316} - \mu_{\rm NGC\ 4419} = 0.08 \pm 0.14.$$

Taking a weighted average of the optical and infrared results, we derive a final value of,

$$\mu_{\rm NGC\ 1316} - \mu_{\rm NGC\ 4419} = 0.09 \pm 0.14.$$

Thus, the infrared and optical light curves together suggest that NGC 1316 and NGC 4419 are basically at the same distance within a precision of approximately ±0.1–0.2 mag. We may extend this conclusion to the Fornax and Virgo clusters as long as both galaxies are cluster members. This result is in good agreement with recent determinations of the relative Fornax–Virgo distance by Dressler *et al.* (1987), Bothun *et al.* (1989), and Pierce (1989), but in apparent conflict with the the value of $\mu_{\rm Fornax} - \mu_{\rm Virgo} = -0.5 \pm 0.2$ mag derived by Geisler & Forte (1990) from a study of the luminosity function of globular clusters in the Fornax cluster member NGC 1399. It should be pointed out, however, that had we used the mean apparent magnitudes for type Ia supernovae in the Virgo cluster derived by Capaccioli *et al.* (1990) and Leibundgut & Tammann (1990), we would have instead concluded that SN 1980N (and NGC 1316) was ~0.5 mag further (in distance modulus) than the Virgo cluster, which would then imply that NGC 1316 is significantly more distant than the Fornax cluster.

An absolute distance to NGC 1316 can be estimated using the recent calibration by Miller & Branch (1990) of the mean absolute magnitude at maximum for type Ia supernovae. From a sample of type Ia events in elliptical galaxies, these authors derived $M_B = -18.95 \pm 0.32$. This value is based on the distances given by Tully (1988) which were calculated from the galaxy radial velocities, an assumed value of the Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1}, and the model of Tully & Shaya (1984) that describes velocity perturbations in the vicinity of the Virgo cluster. Combining this value of M_B with the observed B magnitude of SN 1980N at maximum yields $\mu = 31.44 \pm 0.32$, which is only slightly larger than Tully's (1988) estimate of $\mu = 31.14$ for the Fornax cluster. This result should be taken as an upper limit to the distance of NGC 1316 since we have made no correction for dust extinction. However, as discussed in the previous section, there is little evidence to support a high value of reddening.

5. CONCLUSIONS

We have combined our new photographic and photoelectric photometry with published observations to produce optical light curves for the two supernovae, 1980N and 1981D, which appeared in NGC 1316 (Fornax A). The major conclusions from this study are as follows:

(1) The maximum light magnitudes of both supernovae were the same to within ±0.1 mag, in agreement with infrared light curve observations.

(2) The shapes of the *UBV* light curves of SN 1980N closely resembled those of the type Ia prototype SN 1981B, although the initial postmaximum decline rate in B of SN 1980N was apparently slightly steeper than that of SN 1981B. An optical spectrum of SN 1980N taken 29 days after B maximum is virtually identical to a similar-epoch spectrum of SN 1981B.

(3) The $B-V$ colors at B maximum of both SN 1980N and SN 1981D were 0.3–0.5 mag redder than the value $(B-V)_0 = -0.27$ derived by Cadonau (1986) for type Ia events. This difference may be due-to-dust extinction, although there is little evidence to support such a high value of the reddening.

(4) NGC 1316 would appear to be at virtually the same distance as the core of the Virgo Cluster.

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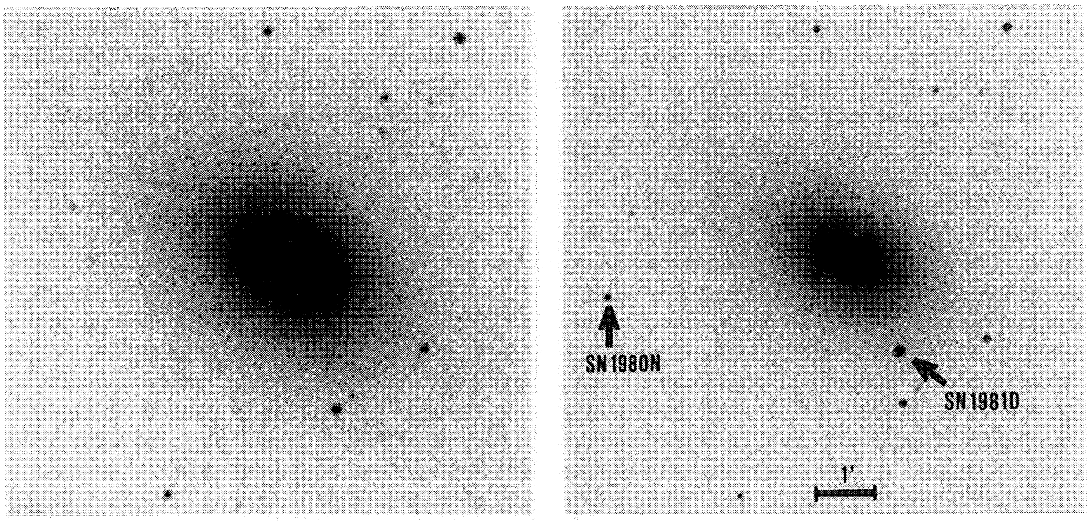

FIG. 1. (Left) Pre-outburst plate of NGC 1316. (Right) Plate of NGC 1316 obtained on 31 March 1981 showing the locations of the two supernovae 1980N and 1981D.

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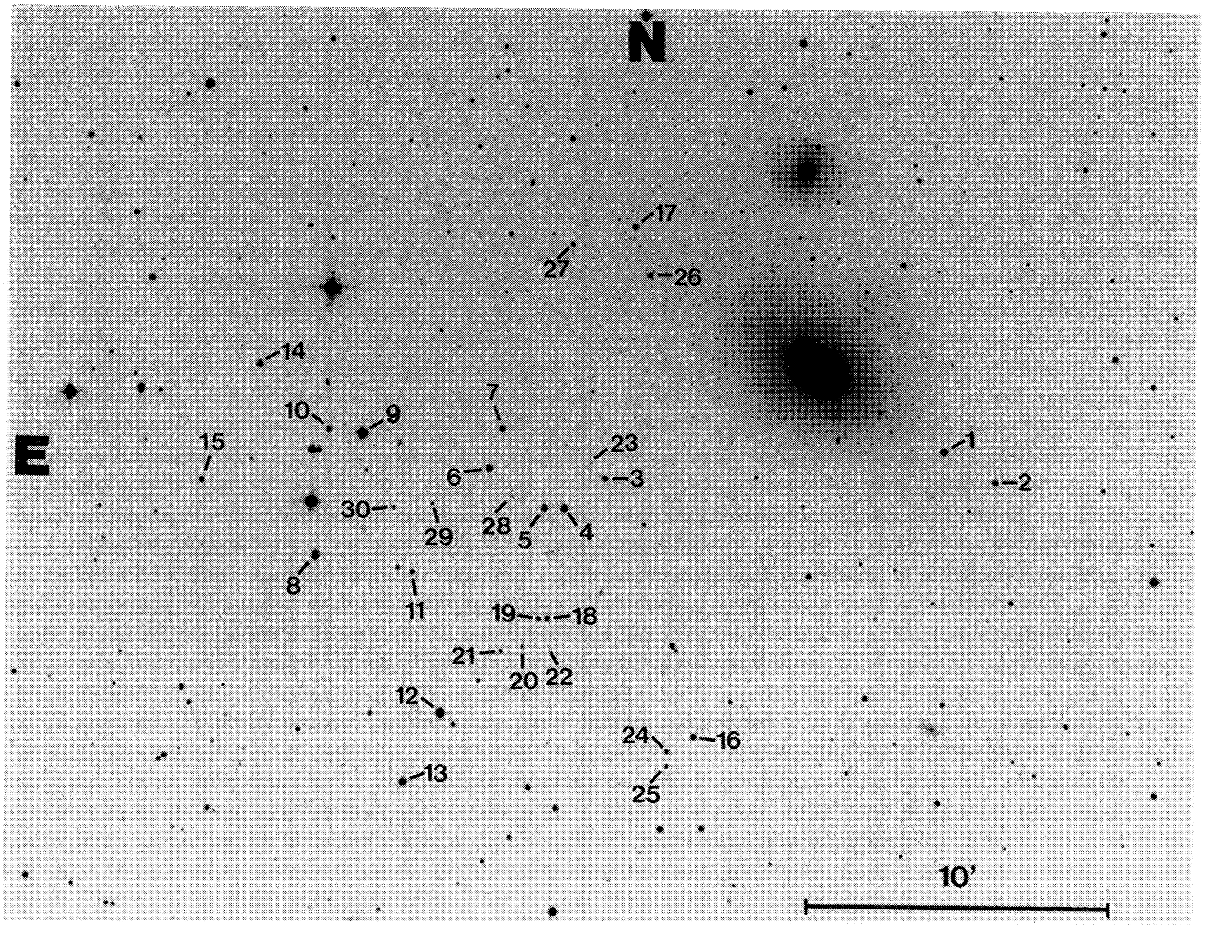

FIG. 2. Photograph of the field of NGC 1316 and its companion (NGC 1317) showing the identifications of the stars in the photometric sequence.

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