THE ASTROPHYSICAL JOURNAL, 315:L129–L134, 1987

INFRARED PHOTOMETRY AND SPECTROSCOPY OF SUPERNOVA 1986g IN NGC 5128–CENTAURUS A

JAY A. FROGEL,[1] BROOKE GREGORY,[2] KIMIAKI KAWARA,[2] DAVE LANEY,[3] M. M. PHILLIPS,[2] DON TERNDRUP,[4] FREDERICK VRBA,[5] AND ALBERT E. WHITFORD[4]
Received 1986 December 16; accepted 1987 January 21

ABSTRACT

Infrared light curves of SN 1986g in NGC 5128 show significant quantitative differences from other Type Ia SN. The colors of SN 1986g are bluer, their variation with time is smaller, and the time scale for variation appears to be shorter. These differences are probably related to the fact that SN 1986g is the first Type Ia SN of β class 12 (i.e., rapidly declining blue light curve) to have adequate infrared *and* optical data.

Spectroscopy in the 1.0–2.4 μm region of SN 1986g shows the broad J band depression detected photometrically in other Type Ia supernovae. Photometry at L indicates a depression in this band as well. Narrower absorption features in the H and K bands could be due to Na I, He I, and Mg I at a redshift of only one-third that derived from the optical spectrum.

Two estimates for the distance modulus of NGC 5128 with respect to Virgo, dependent on assumptions about the luminosity of SN 1986g relative to other Type Ia supernovae, are that it is 3.37 or 3.6 mag closer. A more reliable relative distance, based on infrared and optical data, is with respect to NGC 5055; we find that NGC 5128 is 2.1 mag closer than NGC 5055. The use of Type Ia supernovae as distance indicators via their infrared magnitudes is clearly compromised by our results on SN 1986g. Considerably more data are needed to define the photometric differences between the different β classes and to begin to understand the physical origin of these differences.

Subject headings: infrared: spectra — photometry — stars: supernovae

I. INTRODUCTION

Infrared photometry of Type I supernovae (Elias *et al.* 1981, 1985) reveals the following:

1. The light curves can be divided into two well defined groups—Types Ia and Ib.
2. Light curves of the former type predominate among objects so far observed and have a dispersion in color and absolute magnitude not more than a couple of tenths of a magnitude.
3. The J band of type Ia supernovae is strongly affected by variable absorption of unknown origin.

Because of the first two results, and the fact that measurements in the infrared are considerably less affected by reddening than in the optical, infrared light curves of supernovae have considerable potential for use as distance indicators.

When Evans (1986) announced the discovery of a bright supernova in NGC 5128 (Centaurus A) it was hoped that infrared photometry of it would improve the distance estimate to this unusual galaxy. Also we wished to obtain infrared spectra to investigate the strong J band absorption. As we will show, however, infrared light curves for SN 1986g differ substantially from fiducial ones for Type Ia supernovae. The blue light of 1986g (Phillips *et al.* 1987) exhibited a rate of decline after maximum substantially higher than that of any other supernova with adequate infrared data.

II. INFRARED PHOTOMETRY

Table 1 and Figure 1 give the infrared photometry for 1986g. CTIO data are from the 4 m with the D3 InSb system or with the monitor channel of the Infrared Spectrometer (IRS). Filters and detectors in both systems are essentially identical. Aperture diameters of 6".2 and 9".3 and a beam separation of 10" in a north-south direction were used. Differences in the K magnitudes through the two apertures were about 0.02 mag and could be attributed entirely to seeing effects. There was no evidence that background light from the galaxy itself affected these data. Standard stars were from Elias *et al.* (1982).

Observations from the South African Astronomical Observatory (SAAO) were made on the 0.8 m and 1.9 m reflectors at Sutherland with photometers described by Glass (1973, 1985) and standards from Carter (1984). The 1.9 m observations were made with a 12" diameter aperture and a 30" beam separation. Although no measurement was made of the contribution from background galaxy flux, the agreement between these data and data points from other telescopes on the same dates indicates that any such correction would be small.

[1] Kitt Peak National Observatory, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by the Associated Universities for Research in Astronomy, Inc. under contract with the National Science Foundation.

[2] Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories.

[3] South African Astronomical Observatory.

[4] Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, and Visiting Astronomer, Cerro Tololo Inter-American Observatory.

[5] United States Naval Observatory, Flagstaff, Arizona, and Visiting Astronomer, Cerro Tololo Inter-American Observatory.

TABLE 1

PHOTOMETRY OF SN 1986g IN NGC 5128

DATE	OBSERVED MAGNITUDES AND COLORS[a]					OBSERVATION
(JD − 2,440,000)	$J-H$	$H-K$	$V-K$	H	$K-L$	CODE[b]
6556.4	0.14	0.06	2.00	9.96	...	1
6557.4	0.09	0.10	1.87	9.97	...	2
6562.2	0.13	0.12	1.57	9.99	...	2
6563.4	0.18	0.07	1.43	10.10	...	2
6565.8	...	0.08	1.45	10.10	0.12 (10)	3
6567.3	0.74	−0.04	1.56	9.99	−0.08 (10)	1
6568.3	0.84	−0.03	1.62	10.02	...	1
6568.4	0.78	−0.05	1.59	10.03	...	2
6569.3	0.92	−0.05	1.73	9.96	...	2
6569.3	0.99	−0.04	1.75	9.95	...	1
6570.7	1.07	−0.01	1.84	9.97	...	4
6571.4	1.01	0.08	2.02	10.00	...	2
6573.4	1.01	0.01	2.05	10.00	...	2
6575.5	1.08	−0.05	2.17	10.03	...	2
6575.5	1.15 (5)	0.01 (5)	2.26	10.00 (5)	...	5
6576.5	0.97	0.06	2.24	10.03	...	2
6580.5	0.87 (5)	0.02 (5)	2.51	10.17 (5)	...	5
6581.3	0.78	0.01	2.55	10.21	...	1
6581.4	0.72	−0.04	2.48	10.23	...	2
6581.5	0.88 (5)	0.00 (5)	2.50	10.21 (5)	...	5
6582.5	0.87 (5)	0.00 (5)	2.55	10.29 (5)	...	5
6583.5	0.84	−0.03	2.51	10.39	−0.59 (7)	5
6584.5	0.86	−0.04	2.49	10.49	−0.53 (7)	5
6585.5	0.90	−0.05	2.47	10.60	−0.54 (10)	5
6587.5	1.07 (8)	−0.05 (5)	2.32	10.85	...	5
6596.4	1.15	−0.12	2.25	11.27	...	1
6607.3	1.40	−0.22	2.07	11.75	...	1
6638.2	1.40 (10)	−0.42 (7)	1.44	13.10	...	1
6662.5	1.06 (12)	−0.54 (16)	1.53	13.56 (7)	...	1

[a] The observations from the SAAO 0.8 m have been corrected by galaxy contamination as discussed in the text. Uncertainties in percent if greater than 3 are given in parentheses after the observations. These do not take into account uncertainties in the correction for galaxy contamination. *V* data from Phillips *et al.* 1987.

[b] Telescope: (1) SAAO 0.8 m. (2) SAAO 1.9 m. (3) UKIRT 3.8 m. (4) CIT 5 m. (5) CTIO 4 m.

The 0.8 m data from Sutherland were obtained with a 36″ diameter aperture and a 170 separation. Corrections to these data for background light from NGC 5128 were determined in two ways. First, there are four nights on which the supernova was observed with both the 0.8 and 1.9 m telescopes. The mean difference between the two sets of data (with a 1 σ scatter of less than 10% of the difference in each of the three filters) was assumed to arise from the background light of the galaxy. Second, measurements with the 0.8 m on 1986 July 9 and 31 should have been completely dominated by galaxian flux and, therefore, give a direct estimate of the correction. Data from the two nights agreed to within the statistical uncertainties; the mean values of these data are within 10% of the means for the corrections determined by the first method, so a straight average was taken. The resulting corrections in magnitudes are 11.86, 10.69, and 10.27 at *J*, *H*, and *K*, respectively, with 10% uncertainties.

Finally, there is one set of *JHK* data obtained on the 5 m Hale Reflector referenced to a standard from Elias *et al.* (1982) at a similar air mass and another at *HKL* obtained on the United Kingdom Infrared Telescope in Hawaii by Charles Jenkins and communicated to us by James Graham.

Because the spectral energy distribution of a supernova in the *JHK* bands is so different from that of normal stars and galaxies, no attempt was made to put the data on any one "standard" system.

III. THE INFRARED SPECTROSCOPY

The IRS was used on the CTIO 4 m to obtain the spectra shown in Figure 2. Order separation is done by filters essentially identical to those used for photometry with the addition of one with half-power wavelengths at 0.99 and 1.15 μm. The two gratings used give spectral resolutions of about 1000. The entrance aperture was 4 × 4 mm. The detector array consists of eight Cincinnati Electronics InSb detectors of size 0.25 by 0.8 mm on 0.275 mm centers. The grating was stepped by an amount equal to 8 times the detector spacing. Approximately 10% of the light passing through the entrance aperture is picked off by a BaF_2 beam splitter and sent to a second set of filters and a single 0.5 mm diameter InSb detector. When the outputs of the spectroscopic channels are divided by this monitor channel, the effects of variation in the signal due to poor seeing, guiding errors, and clouds can be reduced to the 1% level or better.

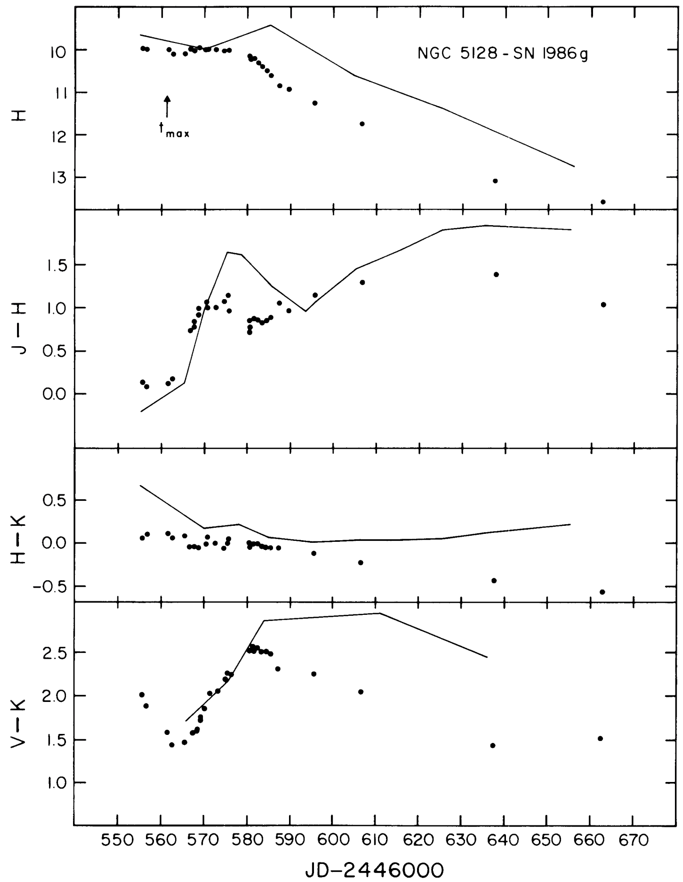

FIG. 1.—Photometry from Table 1. Fiducial light curves for a Type Ia supernova (Elias *et al.* 1985) are shown. These curves have been reddened by 2.64, 0.19, 0.32, and 0.45 mag in $V - K$, $H - K$, $J - H$, and H, respectively, corresponding to an $E(B - V) = 0.9$.

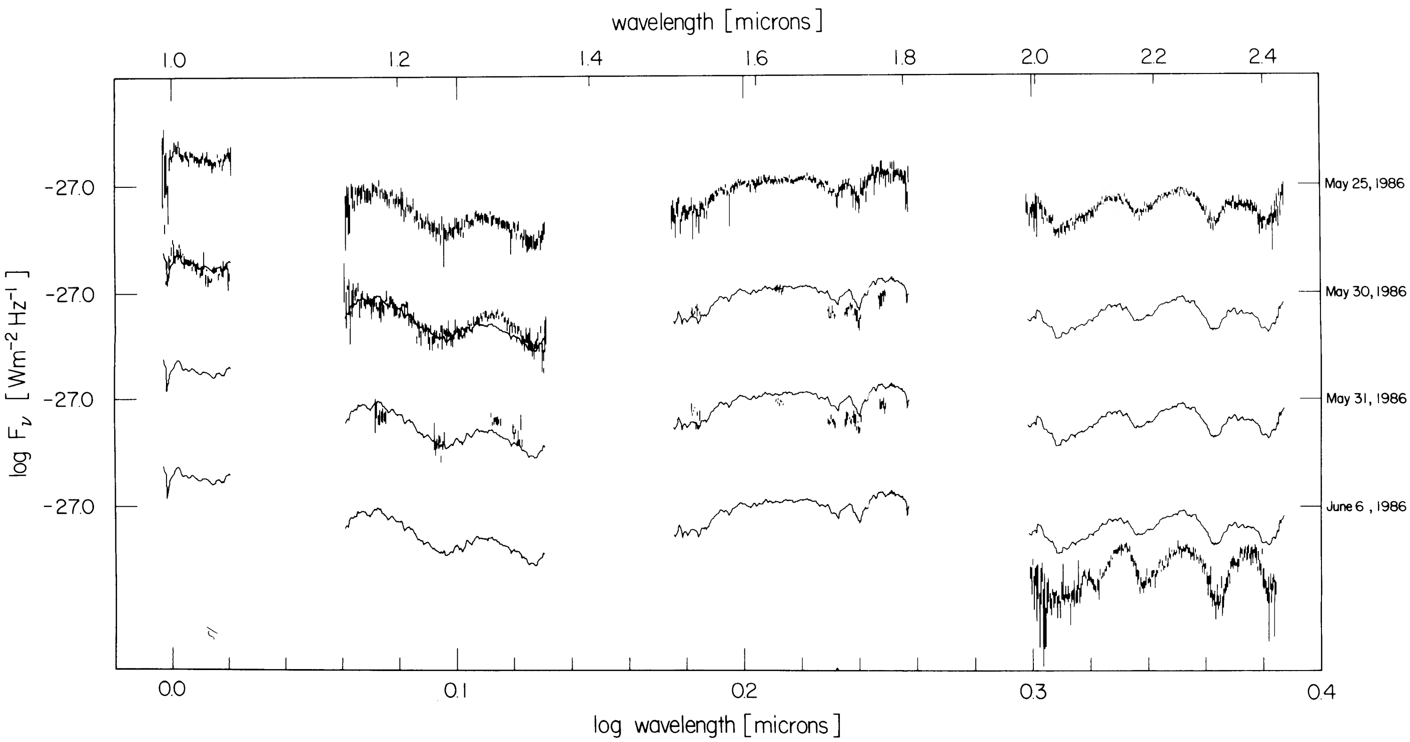

FIG. 2.—Spectrophotometry of SN 1986g in NGC 5128. For each of the nights after 1986 May 25 the continuous lines represent the smoothed spectra from the latter night as an aid to show the changes in shape and absolute level. Note that only parts of the spectrum were scanned on the nights subsequent to the first.

Two unreddened A-type infrared standards were used to calibrate the spectra. Details of the reduction procedure closely follow that employed for the reduction of optical digital spectra. On the first night, 1986 May 25, all bandpasses were scanned. On subsequent nights only parts of some bands were observed so as to monitor changes in the overall spectral shape. In Figure 2 the measurement at each wavelength is represented by a vertical bar that indicates the 1 σ uncertainty in the measurement. The thin continuous line is a running mean over 3 pixels of the spectrum from the first night to facilitate comparison with the subsequent nights.

IV. DISCUSSION

Phillips *et al.* (1987) present detailed optical and spectroscopic data for SN 1986g. The strong blueshifted Si II feature at λ6355 observed near maximum light unambiguously identifies this supernova as Type Ia rather than Ib. There are, however, a number of small, but real differences between the spectrum of SN 1986g and those of other well-studied Type Ia supernovae. These differences, the time variation of the spectrum, and the shape of the light curves of SN 1986g are consistent with observations of $\beta = 12$ supernovae, where β is defined as the extrapolated decline in blue magnitude in the 100 day period after maximum (Pskovskii 1977). Such objects are uncommon: supernovae with $\beta \geq 12$ comprise only 10% of a sample of 54 supernovae with known β classes (Pskovskii 1984). The three Type Ia supernovae (1980n, 1981b, and 1981d) used by Elias *et al.* (1985) to derive fiducial infrared light curves all had β values less than 10. Only SN 1971i in Table 1 of Elias *et al.* has $\beta = 12$. A number of others do not have sufficient optical observations to determine their β class.

a) *Infrared Light Curves*

The fiducial infrared light curves for a Type Ia supernova (Elias *et al.* 1985) are shown in Figure 1 superposed on the data for SN 1986g. The fiducial curves were reddened by an amount corresponding to $E(B - V) = 0.90$ (Phillips *et al.* 1987). Following Elias *et al.* (1985) we have set t_0 at 5 days before maximum blue light. The H curve is plotted with the assumption that NGC 5253, in which occurred SN 1972e (Fig. 3 of Elias *et al.*), is at approximately the same distance from us as NGC 5128 (Sandage and Tammann 1975; de Vaucouleurs 1975).

Although there are qualitative similarities between the fiducial and observed curves, there are significant quantitative differences (infrared light curves of Type Ib supernovae, however, provide an even worse fit to the SN 1986g data): The size of the initial rise in $J - H$ for 1986g is more than 0.5 mag smaller than that of other Ia's; the maximum redness achieved in SN 1986g's initial phase is bluer by nearly the same amount. $J - H$ beyond 70 days after maximum light is also blue by this amount. $H - K$ of SN 1986g is consistently bluer than the fiducial curve. The H light curve does not show the initial dip exhibited by the fiducial curve but is flat for the first 20 days then declines steadily. If NGC 5128 and 5253 are at similar distances, then SN 1986g would appear to be between 0.5 and 1.0 mag fainter in H than a typical Ia supernova in the later stages of decline. A similar trend is claimed to exist in optical light (Pskovskii 1977, 1984; Branch 1981). The fiducial $V - K$ curve is based on a small number of data points. It would appear, though, that for SN 1986g $V - K$ is considerably bluer than it with perhaps a smaller total variation.

SN 1986g is the first supernova of $\beta = 12$ or greater to have been extensively observed in the infrared. Can the striking differences seen in Figure 1 be understood on the basis of the characteristics of supernovae with rapidly declining light curves (cf. Pskovskii 1977, 1984; Branch 1981)? Both the $J - H$ and H curves appear to be compressed with respect to the fiducial curves in that the ultimate H decline starts earlier while the initial $J - H$ peak and secondary minima occur sooner. Both these patterns could be viewed as consistent with the compressed optical light curve of a $\beta = 12$ supernova.

Elias *et al.* (1981) argued that "the minima and secondary maxima in the infrared light curves are best explained as a temporary increase in absorption rather than a later increase in emission." Thus, the sharply reduced peak in $J - H$ would imply much less absorption which in turn would result in a removal of the early minimum in the H curve and, instead, cause the nearly constant H magnitude observed in 1986g over the first 20 days. Pskovskii and Branch note that supernovae with high β values have relatively lower expansion velocities in their atmospheres. This is confirmed for SN 1986g by Phillips *et al.* (1987). The reduced infrared absorption could result from less matter being pushed out into the cooler regions surrounding the supernova.

Elias *et al.* (1985) noted the possible existence of strong absorption at L in Type Ia supernovae. The present data show strongly negative $K - L$ colors and confirm the presence of such absorption. However, it does not appear to be simply related to the J absorption: in mid-May with $J - H = 0.7$, $K - L$ was -0.1 while by early June with $J - H$ between 0.8 and 0.9, $K - L$ was -0.55.

The only other $\beta = 12$ supernova to be observed in the infrared is SN 1971i in NGC 5055 for which there are only three measurements at K (Elias *et al.* 1985). Elias *et al.* estimated a very faint value (13.28) of H_{20} for 1971i, quite inconsistent with the distance of NGC 5055 (Fig. 6 of their paper). Our light curves of SN 1986g show the source of the problem: the three data points for 1971i were obtained late enough after maximum to fall on the part of the light curve where a $\beta = 12$ supernova is considerably fainter than one with $\beta = 9$ (cf. Fig. 1) for any of our distance estimates to NGC 5128 (see discussion below). If we compare the measurements of SN 1971i with the light curve of 1986g instead of with the fiducial curve of Elias *et al.*, we infer a value of $H_{max} = 11.60 \pm 0.2$ and $H_{20} = 11.65 \pm 0.2$, quite close to the mean line in Figure 6 of Elias *et al.*

b) *Infrared Spectra*

The infrared spectra in Figure 2 are the first such data to be published of a supernova. They are quite similar in detail to spectra obtained on the same date on the UKIRT (J. Graham, private communication). The first set of spectra corresponds closely in time to the maximum observed $J - H$ color. Broad absorption, strongly affecting the redward half of the J bandpass, is clearly evident. In fact, the entire J band is depressed below the 1.0 μm part of the spectrum. The spectra on May 30 and 31 indicate relatively less J band absorption as reflected in a $J - H$ color 0.2 mag bluer than that on May 25.

A number of discrete absorption features are visible in the spectra. We have attempted to make identifications which are plausible with respect to abundance and energy level considerations. In the K band, Na I at 2.206, 2.208 and at 2.335 and 2.338 μm and He I at 2.058 μm fit the observed features at 2.178, 2.306, and 2.031 if $z = -0.0133$. (J. Graham [private communication] has independently deduced the Na I identification). In the H band Mg I features at rest wavelengths of 1.7109 and 1.7408 μm provide a good match to the spacing observed between the features at 1.707 and 1.736 μm for a $z = -0.0025$. These redshifts are considerably at variance with an optically determined z of -0.03. Absorption due to Fe I and Si I lines in the solar spectrum (Hall 1973) was integrated and compared with H and K band features. There were no obvious correlations. Si II and Fe II lines in the K band arise from lower states at implausibly high energies. The states which are important for the optical spectrum do not result in transitions visible in the K band. We found no promising candidates for the features in the J and the 1.0 μm bands including Fe I lines.

c) The Distance to NGC 5128

The small dispersion in the absolute infrared magnitudes of Type Ia supernovae gave one hope that they might be used as distance indicators (Elias *et al.* 1981, 1985). Elias *et al.* (1985) pointed out, though, that it would first be necessary to distinguish between Type Ia and Type Ib supernovae. From the data presented here it is clear that we have yet a third type of supernova, at least insofar as the infrared light curves are concerned. From these data alone, though, it is not clear if the differences between the β classes are restricted just to the colors or if the absolute magnitudes at maxima differ. Furthermore, there are insufficient data to determine whether the infrared characteristics vary continuously with β class or if there are distinct groups. In short, how to use infrared magnitudes of Type Ia supernovae to determine distances is not nearly as clear as originally thought. In spite of these caveats, we can make some distance estimates to SN 1986g based on various assumptions.

First, assume that the peak H magnitude is independent of β class and only the shape and time dependence of the H light curve varies. The extinction corrected H_{max} for SN 1986g is 9.55. From the data and fiducial curves in Elias *et al.* (1985) we derive $H_{max} = 12.92$ for SN 1984a in NGC 4419 in the Virgo Cluster (since $H_{20} = H_{max} + 0.36$). Comparing these values we find $\Delta(m - M)_0 = 3.37$ [hereafter, $\Delta(m - M)_0$ will signify the distance modulus with respect to that of Virgo].

A second estimate for the relative distance to NGC 5128 is based on the fact that SN 1971i in NGC 5055 has an optical light curve and β value very similar to SN 1986g (Phillips *et al.* 1987). Of the three infrared observations of SN 1971i (Elias *et al.* 1985), only one is of reasonable accuracy. If the K light curves of the two supernovae are identical, we obtain a weighted mean difference in distance moduli of 2.17. A difference in extinction to the two objects of $E(B - V) = 0.65$ (yielding $\Delta A_H = 0.3$) has been taken into account (Phillips *et al.* 1987). This difference in moduli is close to that derived by Phillips *et al.* (1987) from a comparison of the optical light curves—2.05 ± 0.2. We will use a mean of 2.1. For NGC 5055 Aaronson *et al.* (1982) give $d/d_{\rm Virgo} = 0.51$ or $\Delta(m - M)_0 = 1.46$. Sandage and Tammann (1975) given $d/d_{\rm Virgo} = 0.49$ or $\Delta(m - M)_0 = 1.55$ for the M51 group of which NGC 5055 is a member, essentially identical to Aaronson *et al.*'s value. So, for NGC 5128 we derive $\Delta(m - M)_0 = 3.6$—quite close to the first estimate. Note that this approach makes no assumptions about the relative magnitudes of supernovae with different β classes.

For a third approach assume that NGC 5128 and 5253 are at the same distance (de Vaucouleurs 1975; Sandage and Tammann 1975). From the H_{20} magnitudes for SN 1972e in NGC 5253 and SN 1984a in NGC 4419 (Elias *et al.* 1985), we directly derive $\Delta(m - M)_0 = 3.98$. If the assumption is correct, Figure 1 shows that SN 1986g has a maximum H luminosity 0.5 mag fainter than the $\beta = 9$ SN 1972e.

To summarize, two different assumptions about the luminosity of SN 1986g in NGC 5128 yield estimates for the distance modulus to the galaxy of 3.37 and 3.6 mag with respect to Virgo—the latter value depends on the distance to NGC 5055, the only other galaxy for which there is any infrared data for a known $\beta = 12$ supernova. These values are to be compared with a relative modulus of 3.93 mag if NGC 5128 is at the same distance as NGC 5253. We feel that because of the close similarity of the supernovae in NGC 5128 and 5055, the relative distances of these two galaxies—2.1 mag—is well established. If we take $(m - M)_0 = 31.0$ for Virgo, then NGC 5128 is at 27.4 or 3.0 Mpc, near the lower limit of what is expected from a comparison of NGC 5128's globular cluster luminosity function (Harris *et al.* 1984).

We are grateful to Brian Carter, Robin Catchpole, Michael Feast, Ian Glass, and Patricia Whitelock for obtaining many of the observations at the SAAO; to Charles Jenkins and James Graham for allowing us to use the UKIRT data; and to Gerry Neugebauer and the Caltech IRA for use of their data. J. A. F. thanks the director and staff of the SAAO for their hospitality in Cape Town where part of this paper was prepared. He also acknowledges valuable conversations with Jay Elias and James Graham about the photometry and spectroscopy of supernovae.

Roger Smith, Gabriel Perez, and Gary Webb are responsible for the demonstrated excellence of the electrical, mechanical, and software design and performance of the CTIO IRS.

REFERENCES

Aaronson, M., *et al.* 1982, *Ap. J. Suppl.*, **50**, 241.
Branch, D. 1981, *Ap. J.*, **248**, 1076.
Carter, B. S. 1984, M. Sc. thesis, University of Cape Town.
de Vaucouleurs, G. 1975, in *Stars and Stellar Systems*, *Galaxies and the Universe*, Vol. **9**, ed. A. Sandage, M. Sandage, and J. Kristian (Chicago: University of Chicago Press), p. 557.

Elias, J. H., Frogel, J. A., Hackwell, J. A., and Persson, S. E. 1981, *Ap. J. (Letters)*, **251**, L13.
Elias, J. H., Frogel, J. A., Matthews, K., and Neugebauer, G. 1982, *A.J.*, **87**, 1029.
Elias, J. H., Matthews, K., Neugebauer, G., and Persson, S. E. 1985, *Ap. J.*, **296**, 379.
Evans, R. 1986, *IAU Circ.*, 4208.
Glass, I. S. 1973, *M.N.R.A.S.*, **164**, 155.
______. 1985, *M.N.A.S. So. Africa*, **44**, 45.
Hall, D. N. B. 1973, *Atlas of Infrared Spectra of the Solar Photosphere and of Sunspot Umbrae* (Tucson: Kitt Peak National Observatory).
Harris, G. L. H., Hesser, J. E., Harris, H. C., and Curry, P. J. 1984, *Ap. J.*, **287**, 175.
Phillips, M. M., *et al.* 1987, *A.J.*, submitted.
Pskovskii, Yu. P. 1977, *Soviet Astr.*, **21**, 675.
______. 1984, *Soviet Astr.*, **28**, 658.
Sandage, A., and Tammann, G. 1975, *Ap. J.*, **196**, 313.

JAY A. FROGEL: Kitt Peak National Observatory, P.O. Box 26732, 950 North Cherry Avenue, Tucson, AZ 85726

BROOKE GREGORY, KIMIAKI KAWARA, M. M. PHILLIPS, and DON TERNDRUP: Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile

DAVE LANEY: South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa

FREDERICK VRBA: U.S. Naval Observatory, P.O. Box 1149, Flagstaff, AZ 86001

A. E. WHITFORD: Lick Observatory, University of California at Santa Cruz, Santa Cruz, CA 95064