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INFRARED LIGHT CURVES OF TYPE I SUPERNOVAE

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ABSTRACT

Two Type I supernovae in NGC 1316 and one in NGC 4536 have been observed at *J*, *H*, and *K*. The data provide the best available Type I supernova light curves at these wavelengths. These light curves are characterized by a double maximum; the effect is strongest at *J*. This is probably due to the development of a transient absorption feature during the intervening minimum. The three sets of infrared light curves are very similar, and their dispersion in absolute magnitude is less than the uncertainty in relative distances of the supernovae. Infrared light curves of supernovae may therefore be useful as distance indicators within a few tens of Mpc.

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

I. INTRODUCTION

The only Type I supernova that has been extensively observed in the infrared is SN 1972e in NGC 5253 (Kirshner *et al.* 1973*b*; Lee *et al.* 1972). Since then, the sensitivity of near-infrared measurements has substantially improved and it is now possible to obtain high quality data for supernovae fainter than SN 1972e and to follow them further into their decline. The discovery by Wischnjewsky (Maza and Wischnjewsky 1980) of a bright, Type I supernova in the nearby galaxy NGC 1316 (Fornax A) provided an excellent opportunity to obtain infrared data, as did the fortunate occurrences of a second supernova in the same galaxy (Cragg *et al.* 1981) and a third in NGC 4536 (Aksenov and Tsvetkov 1981). We have obtained extensive near-infrared photometry of all three supernovae, which we discuss in this *Letter*.

II. OBSERVATIONS

The observations were obtained on the CTIO 4 m and 1.5 m telescopes and on the Las Campanas 2.5 m du Pont telescope and are given in Table 1. The observations are on the natural *JHKL* systems[4] of both observatories rather than transformed to the "CIT" system (Frogel *et al.* 1978), as it is uncertain how well the standard transformations apply to colors of supernovae. Application of the standard transformations does not change the magnitudes in Table 1 by more than 0.01 mag.

The effects of the underlying galaxies on the infrared photometry were determined for each measurement. The contrast in the infrared between a supernova and its galaxy is several magnitudes less than in the visible, so that the corrections can be significant. The galaxy contamination was determined by making measurements at *J*, *H*, and *K* offset from the supernova by a small distance. For beams and chopper throws less than 10″, the corrections proved to be negligible. The approximate size of the correction is indicated by the second character of the observation code in column (6) of Table 1. Corrections greater than 0.10 mag were determined by measurement; some of the smaller corrections were determined by interpolation. The magnitudes in Table 1 include the corrections for galaxy flux, and the uncertainties include any additional uncertainty due to the corrections.

The data in Table 1 include three upper limits at *L*. These, like the upper limits for SN 1972e in Kirshner *et al.* (1973*b*), are sufficient only to rule out the presence of a large flux excess at longer wavelengths during the first few weeks of the supernova outbursts.

A number of preliminary infrared magnitudes for these supernovae have been reported (Koornneef, Lub,

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[4]The filters used at both observatories are nearly identical. Wavelengths of half-peak transmission are: $J = 1.13$–1.37 μm; $H = 1.50$–1.80 μm; $K = 2.01$–2.42 μm; $L = 3.22$–3.76 μm.

TABLE 1

SUPERNOVA PHOTOMETRY

SUPERNOVA	DATE (JD −2,444,000)	OBSERVED MAGNITUDES[a] J	H	K	OBSERVATION CODE[b]	PHASE (days)[c]
NGC 1316, No. 1 ...	590.7	13.32(5)	13.43(5)	13.23(8)	2a	10.0
	591.5	13.50(7)	13.46(8)	13.32(9)	2a	10.8
	592.7	13.61(4)	13.38(2)	13.32(5)	2a	12.0
	596.6	14.40(4)	13.44(3)	13.38(4)	2a	15.9
	618.6[d]	14.15(3)	13.47(2)	13.59(2)	1a	37.9
	621.6	14.47(3)	13.66(2)	13.82(2)	1a	40.9
	624.6	14.76(4)	13.84(2)	14.01(3)	1a	43.9
	631.7	15.42(5)	14.18(3)	14.34(4)	1a	51.0
	653.5[e]	16.74(8)	15.11(4)	15.20(11)	1a	72.8
	657.6	16.80(22)	15.15(8)	...	2b	76.9
	667.5	...	15.74(11)	...	2a	86.8
	676.5	17.65(16)	16.00(8)	...	1a	95.8
	677.5	17.69(20)	16.24(7)	16.21(11)	1a	96.8
	685.5	17.54(19)	16.50(9)	...	1a	104.8
NGC 1316, No. 2 ...	683.5	13.38(3)	13.41(3)	13.36(4)	1a	10.5
	685.5	13.74(2)	13.45(2)	13.43(3)	1a	12.5
	686.5	14.05(2)	13.56(2)	13.55(3)	1a	13.5
	687.5	14.27(3)	13.56(2)	13.57(3)	1a	14.5
	688.5[f]	14.44(3)	13.59(3)	13.58(4)	1a	15.5
	693.5	14.58(4)	13.28(3)	13.28(7)	3a	20.5
	695.5	14.49(6)	13.22(3)	13.25(6)	3c	22.5
NGC 4536..........	685.7	14.18(3)	12.98(2)	12.89(2)	1a	17.5
	687.7	14.20(3)	12.90(2)	12.90(2)	1a	19.5
	689.0[g]	14.29(2)	12.93(3)	12.87(4)	1a	20.8
	689.8	14.11(3)	12.84(2)	12.67(2)	1a	21.6
	690.8	14.17(2)	12.82(2)	12.81(3)	1a	22.6
	691.7	13.85(3)	12.69(2)	12.77(2)	3a	23.5
	692.8[e]	13.99(3)	12.73(5)	12.81(4)	3c	24.6
	695.8	13.66(3)	12.59(3)	12.68(5)	3c	27.6
	708.7[e]	14.01(11)	13.19(8)	...	2c	40.5
	738.5	16.19(6)	14.53(3)	14.67(3)	1b	70.3
	748.5	16.65(5)	15.02(3)	15.03(5)	1b	80.3
	768.5	17.52(11)	15.80(4)	15.71(5)	1c	100.3
	782.5	17.87(13)	16.22(8)	15.99(13)	1c	114.3

[a]Magnitudes corrected for galaxy contamination (see text). Uncertainties in percent are given in parentheses after the individual magnitudes.

[b]Number indicates telescope used: (1) CTIO 4 m; (2) CTIO 1.5 m; (3) Las Campanas 2.5 m. Letter gives size of galaxy correction: (a) less than 2%; (b) 2–10%; (c) more than 10%. Code is for largest correction applied.

[c]Time after point in light curve chosen to approximate first maximum (see text).

[d]3 σ upper limit at $L = +13.0$.

[e]Marginal photometric conditions.

[f]3 σ upper limit at $L = +11.7$.

[g]3 σ upper limit at $L = +11.9$.

and Barbier 1980; Rafanelli, Birkle, and Hefele 1981; Salinari and Moorwood 1981*a*, *b*; Williams and Zealey 1981; Tanzi and Tarenghi 1981). In general the agreement is good between published values and nearly simultaneous measurements given in Table 1, though there are some discrepancies. The published data have been used in the analysis (§ III) only where coverage by data from Table 1 is inadequate.

III. DISCUSSION

a) *Light Curves*

The three sets of data are so similar that it is possible to form mean light curves at J, H, and K; these are shown in Figure 1. The infrared light curves are characterized by two maxima, the first of which was chosen as "time = 0". None of the curves covers the time of first maximum well, so it has been estimated approximately. The various times given in column (7) of Table 1 are days after the first maximum. The *relative* times for the three data sets are accurate to about a day, as judged by the quality of the fits, though the estimated times of maximum are absolutely accurate to ~ 3 days at best. The NGC 4536 SN data were shifted in magnitude, by +0.4 mag, to give the best fit. In addition to the data from Table 1, Figure 1 includes early data from Rafanelli, Birkle, and Hefele (1981) and Salinari and Moorwood (1981*b*) for the NGC 4536 SN. The scatter

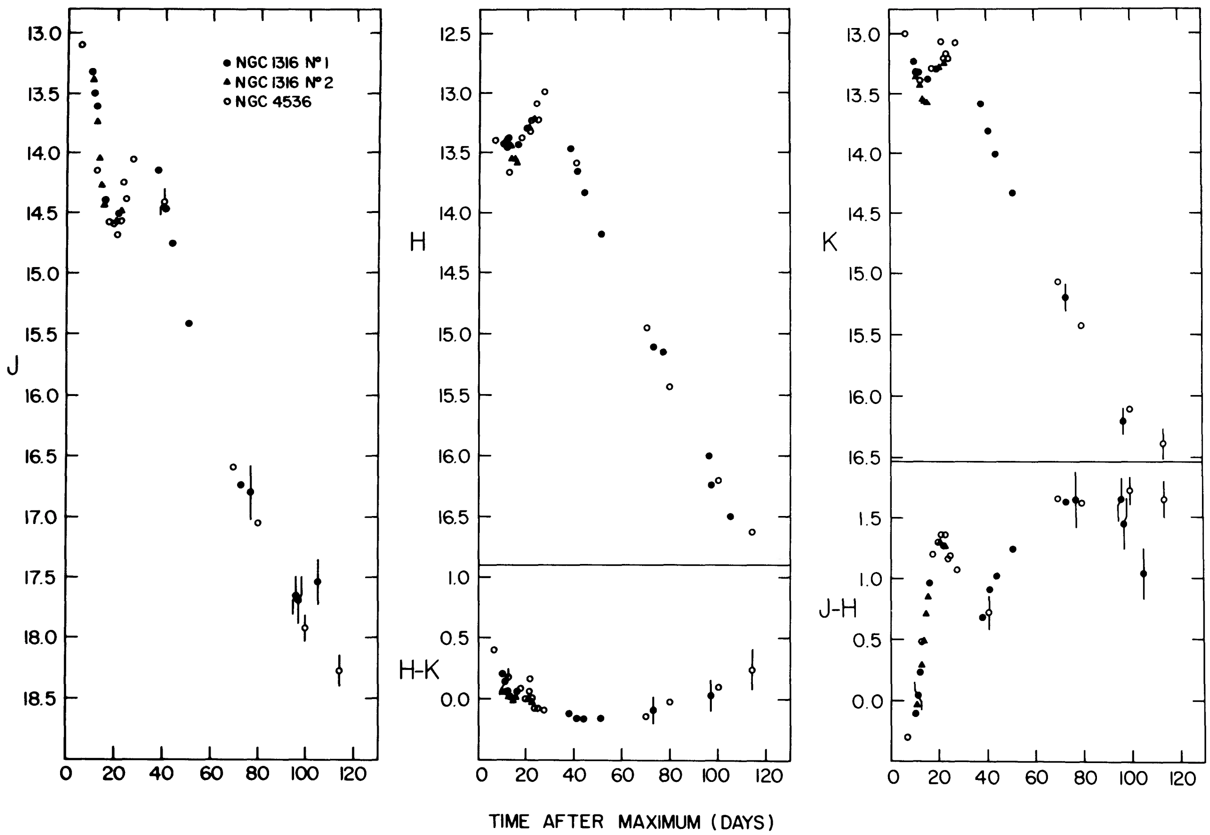

FIG. 1.—Combined infrared light curves of Type I supernovae. All points except for the NGC 4536 SN points at $t = 6.5$ and $t = 12.5$ are from Table 1 (see text). Error bars less than ± 0.10 mag have been omitted for clarity. The NGC 4536 SN magnitudes have been shifted by $+0.4$ mag to agree with the data for the NGC 1316 SNs (see text).

in the individual light curves appears to be 0.1 mag or less, which is barely larger than the uncertainties in the photometry.

The light curves at J, H, and K are rather different from the U, B, and V light curves of Type I supernovae (cf. Ardeberg and deGroot 1974; Barbon, Ciatti, and Rosino 1974) in that they show *two* maxima; the intervening minimum is especially deep at J. The times of minimum and second maximum occur several days later at J than at H or K. The J minimum occurs around $t = 20$ and the second maximum sometime after $t = 30$, whereas at H and K the minimum is near $t = 15$ and the second maximum is probably close to $t = 30$. Examination of the photometric data of Lee *et al.* (1972) for SN 1972e indicates that the I light curve shows similar behavior, while the R light curve has a shoulder rather than a minimum and second maximum.[5] Similar variations also seem present beyond 7000 Å in the low resolution spectrophotometry of SN 1972e of Kirshner *et al.* (1973*a*).

The minima and second maxima in the infrared light curves are best explained as a temporary increase in absorption rather than a later increase in emission. The wavelengths which show the largest variations (mainly J) are strongly depressed below a smooth continuum at minimum (see Kirshner *et al.* 1973*b*) and show no excess at the second maximum. Also, the 8500 Å P-Cygni-like feature in the Kirshner *et al.* (1973*a*) data for SN 1972e shows greatest contrast near the I second maximum, consistent with reduced continuum opacity at that time.

The complexity of the light curves is best illustrated by the evolution of the $J - H$ color (Fig. 1), which starts off near zero and rapidly increases to about $+1.3$, indicating that the 1.2 μm flux is being depressed relative to the 1.6 μm flux. Subsequently the $J - H$ color becomes bluer, reaching a minimum of about $+0.6$, only to reverse this trend and become redder, reaching a new maximum of $+1.6$ around $t = 70$ days. There may be additional changes after $t = 90$ days, but the photometry is of limited accuracy at that point. The $H - K$ light curve shows much simpler behavior: a slow change from about $+0.4$ to about -0.15 at $t = 45$; later the color becomes somewhat redder.

These complex light curves are quite similar for the three supernovae. They show two general characteris-

[5]Unpublished *RI* photometry by Eggen (private communication) for SN 1972e shows roughly similar behavior.

tics: first, a general increase in overall redness with time which is also seen at shorter wavelengths (cf. Ardeberg and deGroot 1974; Lee *et al.* 1972; Kirshner *et al.* 1973*b*); second, a transient absorption which is strongest at 1.2 μm but affects the spectrum from 0.7 μm to at least 2 μm. The general reddening can be explained as due to the effects of a slowly cooling photosphere and increased blanketing at shorter wavelengths (Kirshner *et al.* 1973*a*; Kirshner and Oke 1975).

The transient absorption is less readily explicable. The depth of the feature at J and its presence to some degree over a large range in wavelength implies that it is due to a continuous source or to a large number of bound-bound transitions. The rapidity with which the feature appears and disappears suggests that a single species is responsible, though there is no single obvious candidate.

b) Supernovae as Distance Indicators

The two light curves for the NGC 1316 supernovae superpose with no obvious shift in magnitude. Since the scatter in absolute visual amplitudes of Type I supernovae at maximum appears to be 0.2–0.3 mag (Kowal 1968; Branch 1974), it is possible that infrared data may provide better distance estimates. This may be because the effects of internal reddening in supernova apparent magnitudes are much less in the infrared than at B and V, where they are uncertain and possibly large (cf. Maza and van den Bergh 1976; Tammann 1977). As a test of this, the data for the NGC 4536 SN and SN 1972e (NGC 5253) were examined to see how the differences in apparent magnitude, relative to NGC 1316, compare with the differences in distance. The NGC 4536 supernova appears 0.4 ± 0.1 mag brighter than the NGC 1316 supernovae (§ III*a*). For NGC 5253 the data in Kirshner *et al.* (1973*b*) are 3.9 ± 0.2 mag brighter than the NGC 1316 supernovae data.

The relative distance moduli of the galaxies involved are more uncertain. NGC 4536 is probably a Virgo cluster member (de Vaucouleurs 1975) despite its high redshift. It is therefore thought to be 0.4 ± 0.3 mag closer than NGC 1316 (cf. Sandage and Tammann 1975; Tammann, Yahil, and Sandage 1979; Aaronson *et al.* 1980, 1981; and Mould, Aaronson, and Huchra 1980). The uncertainty includes the uncertainty in the relative distances of the Fornax group and the Virgo cluster and the possible displacement of the individual galaxies with respect to the mean cluster distances. For NGC 5253 the range in distance estimates is large (cf. Sersic, Carranza, and Pastoriza 1972; de Vaucouleurs 1979); the modulus difference probably lies between 3.5 and 4.5 mag. Thus there is no evidence for a significant dispersion in infrared absolute magnitudes of Type I supernovae, though more data are needed to set useful upper limits on the dispersion.

Infrared data on supernovae should be useful for relative distance determinations within some tens of Mpc. This limit is set by the need to get reasonable time coverage and by the difficulty of correcting for galaxy flux for more distant supernovae (the galaxy corrections will increase with distance). Further infrared observations of Type I supernovae will therefore help both in understanding supernova envelopes and in determining cosmological distances.

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