The absolute infrared magnitudes of type Ia supernovae

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ABSTRACT
The absolute luminosities and homogeneity of early-time infrared (IR) light curves of type Ia supernovae are examined. Eight supernovae are considered. These are selected to have accurately known epochs of maximum blue light as well as having reliable distance estimates and/or good light curve coverage. Two approaches to extinction correction are considered. Owing to the low extinction in the IR, the differences in the corrections via the two methods are small. Absolute magnitude light curves in the $J$, $H$ and $K$-bands are derived. Six of the events, including five established “Branch-normal” supernovae show similar coeval magnitudes. Two of these, SNe 1989B and 1998bu, were observed near maximum infrared light. This occurs about 5 days before maximum blue light. Absolute peak magnitudes of about $-19.0$, $-18.7$ and $-18.8$ in $J$, $H$ & $K$ respectively were obtained. The two spectroscopically peculiar supernovae in the sample, SNe 1986G and 1991T, also show atypical IR behaviour. The light curves of the six similar supernovae can be represented fairly consistently with a single light curve in each of the three bands. In all three IR bands the dispersion in absolute magnitude is about 0.15 mag, and this can be accounted for within the uncertainties of the individual light curves. No significant variation of absolute IR magnitude with $B$-band light curve decline rate, $\Delta m_{15}(B)$, is seen over the range $0.87 < \Delta m_{15}(B) < 1.31$. However, the data are insufficient to allow us to decide whether or not the decline rate relation is weaker in the IR than in the optical region. IR light curves of type Ia supernovae should eventually provide cosmological distance estimates which are of equal or even superior quality to those obtained in optical studies.

Key words: supernovae: general - infrared: stars - distance scale

1 INTRODUCTION

It is increasingly believed that the optical light curves of type Ia supernovae (SNe Ia) differ between events in intrinsic peak luminosity and shape. Moreover, the SN Ia peak luminosity appears to correlate with its optical decline at early times; slower declining SNe Ia have greater peak luminosity (Pskovskii 1977, 1984; Phillips 1993; Hamuy et al. 1995; Riess, Press & Kirshner 1995; Hamuy et al. 1996a; Riess et al. 1998; Saha et al. 1999; Phillips et al. 1999). Work by Hamuy et al. (1996a), Tripp (1998), Saha et al. (1999) and Phillips et al. (1999) indicate slopes of between 0.5 and 0.8 for the variation of the absolute $B$ magnitude at maximum light, $M_{B_{\text{max}}}$, with $\Delta m_{15}(B)$, the decline in $B$ magnitude at 15 days post-$t_{B_{\text{max}}}$. ($t_{B_{\text{max}}}$ is the epoch of maximum light in the $B$-band. Supernova epochs in this paper will usually be relative to this fiducial time.) It is suggested by some that the relation also contains a non-linear component (Riess et al. 1998, Saha et al. 1999, Phillips et al. 1999).

It has been established that, even after correction has been made for the decline-rate relations, the absolute magnitude at $t_{B_{\text{max}}}$ varies with colour. Phillips et al. (1999) endeavour to derive decline-rate relations free of the effects of host galaxy dust reddening. They find that, in a sample which includes events which are notably red at maximum viz. $(B_{\text{max}} - V_{\text{max}}) > 0.2$, a plot of $M_{B_{\text{max}}}$ against $(B_{\text{max}} - V_{\text{max}})$ (both decline-rate corrected) yields a slope of $3.5 \pm 0.4$ which is consistent with the Galactic reddening law. Even if the sample is restricted to those SNe Ia having $(B_{\text{max}} - V_{\text{max}}) < 0.2$ (the great majority), Phillips (private communication) still finds a slope of $3.9 \pm 1.3$. This tends to support their contention that most of the decline-rate corrected colour variation is due to dust reddening.

Tripp (1998) and Saha et al. (1999) examine samples restricted to $(B_{\text{max}} - V_{\text{max}}) < 0.2$. These are very simi-
lar to the \((B_{\text{max}} - V_{\text{max}}) < 0.2\) subset of the Phillips et al. sample. Unlike Phillips et al., neither Tripp nor Saha et al., try to separate out possible competing effects of intrinsic colour variation and dust reddening in these samples. For their decline-rate corrected \(M_{B_{\text{max}}}\) versus \(B - V\) slope, Tripp (1998) finds 2.4 ± 0.4 and Saha et al. (1999) find 1.7, smaller than the value found by Phillips et al. (although, as indicated above, the uncertainties are large). If extinction is negligible in the \((B_{\text{max}} - V_{\text{max}}) < 0.2\) SN samples then the Tripp and Saha et al. results may indicate that significant intrinsic colour variation in SNe Ia is present even after decline-rate correction. However, if the colour variation has a significant component due to dust extinction effects then it is less clear what the results of Tripp and Saha et al. signify.

In order to exploit fully the SN Ia phenomenon as a valuable distance indicator, it is desirable to find as many ways as possible for dealing with the effects of extinction. In this paper I examine light curves in the near-infrared (\(JHK\)) where it might be hoped that the effects of interstellar dust are less. This approach was anticipated in the pioneering paper of Elias et al. (1981), where high quality \(JHK\) light curves were presented for the type Ia supernovae 1980N, 1981B and 1981D. Two of these, SNe 1980N and 1981D occurred in the same galaxy, NGC 1316 (Fornax A). By simply shifting the SN 1981B light curves by 0.4 mag, they found that the resulting scatter in the individual light curves appeared to be 0.1 mag or less, which was barely larger than the uncertainties in the photometry. This was a lower scatter than that seen in optical light curves at that time, and Elias et al. suggested that this was due to the much reduced effects of internal reddening in the IR. They suggested that, consequently, IR light curves of supernovae might be useful as distance indicators out to a few tens of Mpc. In Elias et al. (1985), fiducial IR light curves (“templates”) were produced, made up of a series of straight line segments. These were based on \(JHK\) data points for the three supernovae from Elias et al. (1981) together with additional IR photometry from eight other supernovae. The light curves of individual supernovae were adjusted in relative magnitude to provide the best fits to the fiducial curves. Relative epochs were fixed by the estimated \(t_{B_{\text{max}}}\). In spite of the sometimes large uncertainty in \(t_{B_{\text{max}}}\), they found that the uncertainty in the fiducial curves was roughly \(±0.03\) mag between days \(t=+5\) and \(t=+40\). They suggested that SNe Ia have a dispersion in absolute IR magnitude of \(±0.2\) mag, and possibly \(±0.1\) mag, making them potentially valuable for distance determination within the Local Supercluster.

Before the work of Elias et al., Kirshner et al. (1973) acquired the first ever IR measurements of a SN Ia viz. SN 1972E, but only a part of their data are of quality comparable to that of modern photometry. Between the publications of Elias et al. (1981, 1985) and the advent of SN 1998bu, very little IR photometry of SNe Ia was reported. While good coverage of the SN 1986G IR light curves was achieved by Frogel et al. (1987), this was a highly atypical, subluminous event. A few \(JHK\) points were obtained for SNe 1984A (Graham et al. 1988); 1989B (Kidger et al. 1989; Wells et al. 1994) and 1991T (Menzies & Carter 1991; Harrison & Stringfellow 1991). SN 1998bu in NGC 3368 (M96) was the first normal type Ia since the 3 events described in Elias et al. (1981) for which reasonably good IR photometric coverage was achieved (Jha et al. 1999, Meikle & Hernandez (1999), Hernandez et al. 2000). In addition to the occurrence of SN 1998bu, an important development since the work of Elias et al. has been the establishment of more accurate distances to some of the host galaxies. Given these developments, it is timely to carry out a re-examination of the extent to which SNe Ia are homogeneous in the IR.

2 THE SAMPLE

I examine the IR \((JHK)\) luminosities for eight SNe Ia viz. SNe 1972E, 1980N, 1981B, 1986G, 1989B, 1991T, 1998bu (Table 1). These were selected to have accurately known epochs of maximum blue light as well as having reliable distance estimates and/or good light curve coverage. The photometric data are listed in the Appendix (Table 3). Only measurements for which the quoted error was no greater than \(±0.2\) mag were included. (Owing to its peculiarity and very sparse IR coverage an exception to this rule was made for the peculiar SN Ia SN 1991T.) Elias et al. (1985) also present IR photometry for the type Ia SNe 1971H, 71I, 83G, 83R, 83U, & 84A, as do Graham et al. (1988) for SN 1984A, but these were excluded on the basis of the selection criteria. In view of the rather unusual spectral energy distribution of SNe Ia in the \(JHK\) bands, I make no attempt to correct for differences in the detectors, filters or standards used between different observatories.

2.1 Distances

The adopted distance moduli are given in Table 1, col. 4. For SNe 1972E, 1981B, 1989B & 1998bu, HST-Cepheid distances to the host galaxies are available. For all except SN 1972E I use the recalibrated Cepheid distance moduli given in Gibson et al. (2000). I show only their random errors in Table 1. They also estimate a systematic error of 0.16 mag, which would affect all their distance moduli by the same amount. The distance modulus to NGC 5253, the host galaxy of SN 1972E, is still subject to quite substantial uncertainty, with Saha et al. (1999) and Gibson et al. (2000) disagreeing by 0.5 mag. In view of this discrepancy, I have adopted the mean of their values, viz. 27.86 ± 0.25 for SN 1972E.

NGC 4527, the host galaxy of SN 1991T, lies close to NGC 4536 and NGC 4496, both of which have HST Cepheid distances (Fisher et al. 1999) and references therein). I therefore adopt the mean distance modulus of these two galaxies for NGC 4527.

SNe 1980N and 1981D both occurred in the same galaxy, NGC 1316 (Fornax A). Unfortunately there is not yet a Cepheid distance to this galaxy, and the value of the distance is currently subject to some disagreement. Claridullo, Jacoby & Tonry (1993) use the planetary nebula luminosity function (PNLF) distance indicator to obtain a distance modulus of 31.19 ± 0.07 based on a distance modulus of 24.43 for M31. A similar value for the Fornax Cluster is obtained by Bureau, Mould & Staveley-Smith (1996) who
derive \(31.10 \pm 0.45\) based on an \(I\)-band Tully-Fisher distance relative to the Virgo Cluster, and the HST-Cepheid distance to Virgo (Freedman et al. 1994). Madore et al. (1999) have determined an HST-Cepheid distance to the Fornax Cluster galaxy, NGC 1365, finding a modulus of \(31.35 \pm 0.07\). They suggest that the distance to NGC 1316 is about the same. However, Saha et al. (1999) state that there are reasons to suspect that NGC 1365 is in the foreground of the Fornax Cluster. Ferrarese et al. (2000) use their Cepheid-based calibration of the \(I\)-band surface brightness fluctuation (SBF) distance indicator to obtain a distance modulus to NGC 1316 of \(31.71 \pm 0.19\) and a Fornax Cluster distance modulus of \(31.59 \pm 0.04\). They find that where \(I\)-band SBF and direct Cepheid distance measurements to a galaxy are available good agreement is obtained, while the PNLF distance indicator produces systematically smaller distances. (Ferrarese et al. also suggest that NGC 1365 is towards the front of the Fornax Cluster, similar to the conclusions of Saha et al.). Of course, one might use SN 1980N itself to estimate its distance. Hamuy et al. (1996b) obtain \(31.60 \pm 0.15\). Equations (17) & (18) in Phillips et al. (1999) yield \(31.70 \pm 0.08\), while Saha et al. (1999) quote a value of \(31.84 \pm 0.21\). However, in a study such as this, where we are attempting to investigate the homogeneity of SNe Ia, it is inadvisable to use distances determined from the phenomena we are examining. In view of the uncertainty in the distance to NGC 1316, I have adopted the Ferrarese et al. (2000) Fornax Cluster distance modulus of 31.59 for this galaxy. However, given the typical random errors given by Ferrarese et al. and the uncertainty of the location of NGC 1316 within the Fornax Cluster, I am free to use a larger error of \(0.1\) mag in the distance modulus of NGC 1316.

There are no Cepheid distance measurements for NGC 5128 (Centaurus A), the host galaxy of SN 1986G. Therefore I used the weighted mean distance obtained from Cepheid-calibrated tip of the red giant branch and \(I\)-band SBF methods (Ferrarese et al. 2000). This gives a distance modulus of 28.01 \(\pm 0.12\).

### 2.2 Extinction Correction

As indicated above, for most SNe Ia there is disagreement as to how much of the decline-rate-corrected colour distribution can be attributed to dust extinction. I have therefore investigated two approaches to correcting the extinction. In the first approach I have followed the work of Phillips et al. (1999) which provides estimates of \(E(B-V)\) for seven of the supernovae in my sample. They did not consider SN 1981D, but Mark Phillips kindly provided his estimate for this supernova, using the same technique as in Phillips et al. (1999). He obtains a total \(E(B-V) = 0.18 \pm 0.09\). The IR data were then de-reddened assuming the extinction law of Cardelli, Clayton & Mathis (1989) with \(R_V = 3.1\).

In the second approach, no reddening corrections were made to the four supernovae for which \((B_{max} - V_{max}) < 0.2\). For the four that exceeded this value (SNe 1981D, 1986G, 1989B & 1998bu) I made a correction for extinction using the Cardelli, Clayton & Mathis law. However, I used a lower value of \(R_V\), viz. 2.6, which is the value found by Phillips et al. (1999) from a fit to colour-magnitude plots for events for which they derived non-zero \(E(B-V)\). The estimated total extinctions are shown in Table 1, cols. 6–11.

### 3 LIGHT CURVES AND COLOUR EVOLUTION

In this section, I examine the individual light curves and colours of the eight supernovae. For each supernova I converted the photometry to intrinsic absolute magnitudes using the distance moduli and extinctions given in Table 1. It was found that the two approaches to dealing with the extinction correction made little qualitative difference to the conclusions. Of course, a major reason for this IR study was to try to reduce effects of extinction uncertainties. As would be expected, the luminosities derived by method (1) were slightly higher. Further details are given in Section 4. In the presentation of the absolute light curves and colour evolution that follows, de-reddening is by means of method (2).

#### 3.1 Light Curves

In Figures 1, 3 & 5 I show the intrinsic absolute magnitude IR light curves for the \(J\), \(H\) and \(K\) bands covering the period up to \(+110\) days. In order to display clearly the much greater density of data at early times, I show the same light curves in Figures 2, 4 & 6, but plotted out to just \(+60\) days. Also plotted are the template IR light curves of Elias et al. (1985). These are based on \(JHK\) light curves of SNe 1972E, 80N, 81B & 81D plus a few points from other SNe Ia. I adjusted the templates in epoch to give the best match to SN 1980N. This required Elias et al.’s fiducial time, \(t_0 = 0\), to be set to \(-6.25\) days (i.e. \(6.25\) days before \(t_{B_{max}}\)). I also truncated the templates at \(+2\) days since this is the earliest epoch for which Elias et al. (1981, 1985) presented data. The vertical positions of the templates are set at the average absolute magnitude values for six of the events. This is discussed in detail in Section 4. It can be seen that, with the exception of SN 1986G, the templates provide a useful representation of the IR light curves and that the dispersion in coeval magnitudes is not great. I now examine the IR light curves by era.

#### 3.1.1 \(t < t_{B_{max}}\)

There are four SNe for which data in this era are available viz. SNe 1986G, 1989B, 1991T & 1998bu. The earliest-ever IR measurement of a type Ia supernova is the single \(JHK\) observation of SN 1991T by Menzies & Carter (1991) at about \(-11\) days. This is discussed later.

The observations of SN 1998bu show that SNe Ia peak in the IR about \(5\) days before \(t_{B_{max}}\). At \(t = -5\) days we have data for SN 1986G, 1989B and 1998bu. SNe 1989B and 1998bu have a similar \(J\)-magnitude of about \(-19.0\) at \(-5\) days. At \(H \& K\), SN1998bu peaks at \(-18.7\) in \(H\) and \(-18.8\) in \(K\), while SN 1989B is brighter by about 0.25 mag. Given the uncertainty in the distances of SNe 1989B and 1998bu, this difference is not significant. SN 1986G is 0.4–0.5 mag fainter than SN 1998bu. Random errors in distance moduli and extinction corrections are probably insufficient to account for the apparent lower luminosity of SN 1986G.
I conclude that this supernova was indeed significantly underluminous at this time.

3.1.2 \( t_{\text{Bmax}} < t < +25 \text{ d} \)

Since the work of Elias et al. (1981) it has been known that Type Ia supernovae light curves exhibit two maxima in the \( JHK \) bands. A similar double peak is also seen in the \( I \)-band (Ford et al. 1993). In the \( J \)-band, a particularly pronounced minimum is seen at \( t = +15 \text{ d} \) (cf. Figs. 1 & 2). In the \( H \) and \( K \)-bands (Figs. 3-6), a less pronounced minimum is seen, occurring somewhat earlier, at about \( t = +10 \text{ d} \). Interestingly, in spite of its peculiar nature, the light curves of SN 1986G exhibit absolute magnitudes similar to those of the other supernovae around \( +7 \text{ days} \). Nothing can be said about SNe 1972E or 1991T as no IR observations are available during this time.

3.1.3 \(+25 \text{ d} < t < 110 \text{ d}\)

For three of the four events for which we have post-\(+25 \text{ d}\) light curves, we can see that the decline rates and coeval absolute magnitudes are similar. The exception is SN 1986G which is fainter in \( JHK \) by typically one magnitude during much of this period. It is unlikely that such a large factor is the result of errors in the estimates of distance or extinction.

3.2 Colours

In Figs. 7 & 8 I plot the \((J - H)\) and \((H - K)\) evolution, respectively. As above, I consider only the case in which the extinction was corrected by method (2). Also in Figs. 7 & 8 I show the colour evolution templates of Elias et al. (1985), again truncated at day \(+2\).

3.2.1 \((J - H)\) colour

The \( t = -11 \text{ d} \) point of SN 1991T is at about \((J - H) = +0.6\). However, given that this is the only point at this epoch and that 91T had an unusual optical spectrum at early times (Fishter et al. 1999), such a red colour may not be typical. Between \(-8 \text{ days} \) and \(+2 \text{ days}\), data exist for only SNe 1986G and 1998Bu, plus SN 1989B at a single epoch. There is little evidence of colour change in this period. SN 1998Bu remains at \((J - H) \sim -0.2\) with SN 1986G somewhat redder at \( \sim -0.05\). (It should be remembered that these colours have already been corrected for extinction). Between \(+2 \text{ d} \) and \(+10 \text{ d}\) the behaviour of the six supernovae observed is quite uniform. At \(+4 \text{ d} \) the \((J - H)\) colour moves sharply to the red, reaching \((J - H) = +1.0\) by day \(+10\). Even SN 1986G is not strikingly different in its colour evolution during this period. Between \(+10 \text{ and} \:+15 \text{ days}\), the general trend is continued reddening, reaching \((J - H) = +1.3\) by day \(+15\). The colour then moves to the blue reaching \(+0.65\) by day \(+30\). After that the colour redens again, levelling out at about \(+1.6\) by \(+65 \text{ d}\). The post-\(+2 \text{ d}\) evolution is essentially that described by Elias et al. (1985). The only clear exception to this behaviour is that exhibited by SN 1986G. It begins to move back to the blue at only \(+10 \text{ days}\), and then to the red again at only \(+20 \text{ days}\). SN 1986G seems to mimic the \((J - H)\) behaviour of the other supernovae, but at a higher rate of evolution, and never attaining quite the same amount of redness.

3.2.2 \((H - K)\) colour

Again, the very early SN 1991T point shows an apparently unusually red colour. During the \(8 \text{ days before} t_{\text{Bmax}}\), the \((H - K)\) evolution of SN 1998Bu shows a gradual reddening from \(-0.1\) to \(+0.25\). After \( t_{\text{Bmax}}\), there is a gradual move to the blue, reaching \((H - K) = -0.15\) at \(+40 \text{ days}\). The behaviour of SN 1986G is again different. Up to about \(+50 \text{ days}\) it is slightly bluer than typical. From the very few post-\(+80 \text{ d}\) observations, we note that SNe 1980N & 1981B show a gradual drift to the red again. In contrast, SN 1986G shows a very striking move to the blue. The unusually blue \((H - K)\) behaviour of SN 1986G was pointed out by Frogel et al. (1987). The post-\(+2 \text{ d}\) \((H - K)\) behaviour of the other supernovae is essentially as described by Elias et al. (1981).

The non-monotonic behaviour of the IR light curves and the development of the IR colours have been considered by a number of authors. Höflich, Khokhlov & Wheeler (1995) have found that in some of their models, the second maximum in the light curve is reproduced in some regions of the IR. They attribute this to a time-dependent opacity causing the effective emitting area to peak at a delayed time in the IR compared with the optical region. However, they have difficulty in reproducing the strength of the effect as observed in all bands from \(I\) to \(K\). From analyses of IR spectra, Spyromilio, Pinto & Eastman (1994), and Wheeler et al. (1998) conclude that the appearance of the red \((J - H)\) colour can be attributed to the relatively large reduction of line-blanketing opacity in the \(1.2 - 1.5 \mu \text{m}\) region. Wheeler et al. show that the depth of the \(J\)-band deficit can provide a valuable temperature diagnostic for the silicon layers.

4 QUANTITATIVE COMPARISON OF ABSOLUTE MAGNITUDES

The presentation given above suggests that the IR behaviour of SNe Ia is generally quite homogeneous. I now endeavour to quantify this behaviour. A problem is that the coverage of IR light curves is still much inferior to that achieved in the optical region. In particular we cannot, as optical studies do, compare directly the absolute magnitudes at maximum light. However, even in optical studies maximum light is sometimes missed. Nevertheless, the magnitude at maximum light can still be estimated by fitting template light curves to the data (e.g. Hamuy et al. 1995). I have adopted a similar approach for this study. As pointed out in the previous section, the IR light curve templates of Elias et al (1985) provide a fair representation of the IR light curve shapes. I have therefore used these templates to compare the IR absolute magnitudes of the supernovae.

I first compared the \(H\)-band template with the SN 1980N \(H\)-band photometry and varied the position of the template in both axes (absolute magnitude and time) to minimise \(\chi^2\). For the 14 points considered, a \(\chi^2\) minimum of 1.7 was achieved by setting \(t_0 = 0\) at \(-6.25 \pm 1.0 \text{ days}\), where \(t_0\) is the epoch as defined by Elis et al. (1995). This is consistent with the value of \(-6 \text{ days}\) adopted by Elias et al.
I fixed all three templates such that \( t_0 = 0 \) is at \(-6.25 \) days. I then adjusted the vertical (absolute magnitude) position of the templates to provide a minimum \( \chi^2 \) fit to the data for all supernovae and all 3 bands. In spite of the fact that the templates were originally largely based on SNe 1972E, 80N, 81B & 81D, some of the best fits to these particular SNe had values of \( \chi^2 \) as large as 10. However, it was found that modest increases in the quoted errors on the data points (up to \( \pm 0.1 \) mag) would bring \( \chi^2 \) close to unity. For the 10–12 points of SN 1998bu, the fits were less satisfactory, yielding a \( \chi^2 \) exceeding 10. Satisfactory fits were only obtained by artificially increasing the errors to around \( \pm 0.15 \) mag. The need to arbitrarily increase the individual errors to achieve satisfactory fits probably indicates that the IR light curves are not completely homogeneous in shape. For SN 1989B good fits were easily obtained for the 2 points which overlapped the timespan of the templates. For SN 1986G, in view of its clearly different light curve shape in all three bands, no template fits were performed. Instead, the weighted mean values for the 4 points in the +12 to +15 day period were used to estimate its \( M_{14}(J) \), \( M_{14}(H) \) and \( M_{14}(K) \) (defined below). For SN 1991T only a single epoch (\( t = +55 \) d) coincided with the template timespan and so the templates were simply adjusted to coincide with the single point at each waveband. However, given the peculiar nature of SN 1991T, it is possible that the templates are not representative of its true IR light curves.

In Table 2 I show the results of the template fitting procedure. The absolute magnitudes (cols. 2, 4 & 6) are expressed in terms of \( M_{14}(J) \), \( M_{14}(H) \) and \( M_{14}(K) \), the absolute magnitudes at \( t = +13.75 \) days. This epoch corresponds to the epoch of the \( H - H_{20} = 0.0 \) point on the original \( H \)-band template of Elias et al. (1985). It lies close to the epoch of first minimum in the \( J \)-band. The tabulated values are those obtained after increasing the errors on the data points up to \( \pm 0.15 \) mag. (When the fitting procedure was performed with the original quoted errors, the absolute magnitudes returned never differed from the values shown by more than a few percent.) The numbers in parentheses give the error in the smallest two decimal places of the \( M_{14} \) values returned by the \( \chi^2 \)-fitting procedure. The only exceptions are SNe 1986G and 1991T where the errors in parentheses are based simply on the published photometry errors (see above). However, given the peculiar nature of SN 1991T and the fact that the epoch of observation is over a month beyond the fiducial \( t = +13.75 \) day epoch, it is possible that the quoted errors on the \( M_{14} \) values are significantly underestimated for this supernova. Columns 3, 5 and 7 give the total random error in the absolute magnitude, comprising the \( \chi^2 \)-fitting or photometry error (shown in parentheses in cols. 2, 4 & 6), random error in the distance (cf. Table 1), and the extinction correction error. The error in the extinction correction was taken to be half of the difference in extinction correction using methods (1) and (2).

Following the work of Phillips et al. (1999) and others, in Figure 9 I compare the intrinsic absolute IR magnitudes at \( t = +13.75 \) d, \( M_{14}(J) \), \( M_{14}(H) \), \( M_{14}(K) \), with \( \Delta m_{14}(B) \), the decline in the \( B \)-band 15 days after maximum blue light (Table 2, col. 8). For six of the eight SNe (the exceptions are SNe 1986G & 1991T) the \( M_{14} \) values are reasonably consistent with zero difference between the events. Single parameter fits to the \( M_{14} \) values for the six events yields \( \chi^2 \) values of 1.6, 1.8 and 1.4 in \( J \), \( H \) and \( K \) respectively. The actual values (i.e. the weighted means) are \( M_{14}(J) = -16.86 \pm 0.06 \), \( M_{14}(H) = -18.22 \pm 0.05 \) and \( M_{14}(K) = -18.23 \pm 0.05 \). These values are indicated by the horizontal dotted lines in Fig. 9. Henceforth, these six supernovae will be referred to as the “IR-normals”. The dispersion in all 3 bands is about 0.15 mag for the IR-normals. As a check, I fitted the templates to the light curves of all six IR-normals simultaneously (about 60 points per band). The same \( M_{14} \) values were obtained. SN 1986G has similar \( M_{14}(H) \) and \( M_{14}(K) \) to those of the IR-normals, but is about 0.5 mag brighter in \( J \) than the IR-normal mean. However, Figs. 1 to 6 show that SN 1986G was clearly underluminous by a substantial amount before \( \sim 0 \) days and after \( \sim 25 \) days. At later epochs (post+25 days), SN 1986G is fainter by as much as one magnitude in the three bands. SN 1991T appears to be overluminous but at a low significance \(- \sim 2 \sigma \) in each band.

It should also be recalled that SN 1991T has only a single set of \( JHK \) observations (at \( t = +55 \) d) which lies within the template temporal span.

Similar results are obtained when the entire analysis is repeated using method (1) for the extinction correction. The mean \( M_{14} \) values for the six IR normals are, respectively, 0.09, 0.04 and 0.02 mags brighter in \( JHK \), with slightly smaller \( \chi^2 \) values viz. 1.3, 1.5 and 1.2.

## 5 DISCUSSION AND CONCLUSION

For all three IR wavebands the template analysis indicates that six of the eight supernovae considered have similar coeval magnitudes. Indeed, to within the uncertainties, they are indistinguishable. Of the six, SNe 1972E, 1981B, 1989B, 1998bu and, probably, SN 1980N are all spectroscopically “Branch-normal” (Branch, Fisher & Nugent 1993). SN 1981D cannot be classified in this way due to insufficient spectroscopic coverage. In contrast, the two exceptions, SNe 1986G and 1991T, have long been recognised as spectroscopically peculiar. Nevertheless, in spite of the peculiar behaviour of SN 1986G, there is evidence that at around +7 days it had a similar IR luminosity to that of the IR-normals.

The IR-normals span \( 0.87 < \Delta m_{15}(B) < 1.31 \). Over this range the dispersion in absolute magnitude is about 0.15 in all three bands, and this can be accounted for almost entirely by the uncertainties. In other words, at this level of uncertainty, the IR-normals show no systematic variation in absolute \( J \), \( H \) or \( K \) magnitude with \( \Delta m_{15}(B) \). For \( 0.87 < \Delta m_{15}(B) < 1.31 \) both Phillips et al. (1999) and Saha et al. (1999) give peak absolute magnitude ranges of about 0.35 in \( B \), falling to about 0.2 in \( I \). It is possible that the absolute magnitude range continues to decline as we move further into the IR, becoming too small to detect in \( JHK \) with our limited data. As a check, I examined the \( B \) and \( V \) band absolute peak magnitudes specifically for the six IR-normals. For SNe 1972E, 1981B, 1989B & 1998bu I used the absolute magnitudes given in Gibson et al. For SNe 1980N & 1981D I used the \( I \)-band SBF Fornax Cluster distance
(Ferrarese et al. 2000) together with the peak apparent magnitudes given in Hamuy et al. (1991). Extinction corrections were made following both methods (1) and (2) of section 2.1. In both the \( B \) and \( V \) bands I find no significant trend of absolute \( B \) or \( V \) magnitude with \( \Delta m_{15}(B) \). The dispersion is similar to that seen in the IR. It is therefore likely that the uncertainties in the absolute IR magnitudes too large to reveal a \( \Delta m_{15}(B) \) relation of even comparable strength to that found in the optical region.

The IR magnitudes of SN 1991T at \(-11\) days are \( J = +11.73, H = +11.16 \) and \( K = +10.93 \) (Menzies & Carter 1991). These translate to the highest-ever IR-luminosities for a type Ia event, especially in the \( H \) & \( K \) region (cf. Figs. 1–6). Although we lack coeval points from other supernovae, it appears that SN 1991T was exceptionally IR-luminous for a SN Ia at this epoch. Menzies & Koen (1991) report simultaneous \( UBV \) photometry yielding \( V = +12.4, B - V = +0.11 \) and \( U - B = -0.71 \). Lira et al. (1998) report similar \( BVR \) magnitudes obtained just 0.3 d after the Menzies & Carter IR measurement, giving \( V = +12.45, B - V = +0.09 \) and \( V - R = +0.06 \). Thus, the IR magnitudes indicate a strong excess with respect to the optical region \( \text{e.g., } V - K \sim +1.5 \).

The next IR observation of SN 1991T was about 10 days later. This took the form of a \( JHK \) spectrum (Meikle et al. 1996), and it shows no evidence of excessive IR luminosity. The \(-11\) day photometry of SN 1991T was the earliest ever observation of a SN Ia in the IR. The next earliest are the IR spectra of SN 1994D (Meikle et al. 1996) and photometry of SN 1998bu, both at about \(-8.5\) d. They show no signs of unusually high luminosity. It may be that the exceptional early-time IR luminosity and redness of SN 1991T are further manifestations of its intrinsic peculiarity. However, for the present, this result is something of a puzzle.

The analysis presented here indicates that most SNe Ia are standard IR candles at a level of about 0.15 mag. As already mentioned, Elias et al. (1995) suggested that SNe Ia might have a dispersion in IR absolute magnitude as low as \( \pm 0.1 \) mag. The present work is consistent with this, although it also shows there can be exceptional events which are much brighter or fainter than the norm. Moreover, although I find no indication of differences in coeval magnitudes for the six IR-normals, there is tentative evidence that the IR light curve shapes are not exactly identical.

It should be kept in mind that this study makes use of only eight supernovae, and that their light curves are generally much less well-sampled than in the optical region. The total number of photometry points for all six IR-normals is only about 60 in each band within the span of the Elias et al templates. It is clearly desirable to pursue the use of SNe Ia IR light curves as distance indicators. As a first step, we need to build up a good set of IR light curves for nearby SNe Ia in order to establish the extent to which they are homogeneous. In addition, this will extend the wavelength range over which colour information is available and so should help to distinguish unambiguously between intrinsic colours and dust reddening. Compared with the optical region, the lower sensitivity to extinction uncertainties in the IR should mean that observations in this wavelength region will provide more reliable estimates of cosmological distances. At the lowest redshifts dominated by the Hubble expansion, \( z = 0.01 - 0.1 \), the peak IR magnitudes of SNe Ia would lie in the range \(+14\) to \(+20\). These magnitudes are well within the range of a 4 m class telescope such as UKIRT (cf. http://www.jach.hawaii.edu/JACpublic/UKIRT/instruments/ufi/sensitivities.html). Indeed, the nearer supernovae could be successfully monitored by only a 2 m class telescope such as the Liverpool Telescope (cf. http://telescope.livjm.ac.uk/inst/index.html).

At higher redshifts, say 0.5, rest frame \( J \)-band and \( H \)-band emission are shifted into roughly the \( H \)- and \( K \)-bands respectively. (Rest frame \( K \)-band emission would be lost in the thermal IR region.) In a flat, \( \Lambda = 0 \) universe an intrinsic peak absolute \( J \)-magnitude of \(-19.0\) yields an apparent magnitude of about \(+22.3\). This estimate includes only an approximate K-correction (Poggianti 1997). As more SNe Ia IR spectra become available, it should be possible to make more accurate estimates of the K-corrections. A \( J \sim +23 \) SN Ia at \( z = 0.44 \) has been successfully detected by J. Sypromilo in a 1-hour integration with the 3.5 m ESO NTT (Riess et al., in preparation). Clearly, even deeper coverage would be possible with an 8 m class telescope such as Gemini (cf. http://www.ast.cam.ac.uk/sciops/instruments/niri/NIRI_INDEX.html).

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The absolute infrared magnitudes of type Ia supernovae

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Table 1. Supernova Sample

| Supernova | $t_{Bmax}$ | Host Gal. | $E(B-V)$ | $A_J$ | $A_H$ | $A_K$ | Source |
|-----------|------------|-----------|----------|-------|-------|-------|--------|
| 1972E     | 41449.0(1.0) | NGC 5253  | 27.86(25) | 0.07(04) | 0.06 | 0.04 | 0.02 | 0.0 | 1 |
| 1980N     | 44585.8(0.5) | NGC 1316  | 31.59(10) | 0.07(05) | 0.06 | 0.04 | 0.02 | 0.0 | 2 |
| 1981B     | 44672.0(0.2) | NGC 4536  | 30.95(07) | 0.13(03) | 0.11 | 0.07 | 0.04 | 0.0 | 1.2 |
| 1981D     | 44679.9(0.5) | NGC 1316  | 31.59(10) | 0.18(06) | 0.16 | 0.13 | 0.10 | 0.08 | 0.05 | 2 |
| 1986G     | 46561.5(1.0) | NGC 5128  | 28.01(12) | 0.16(05) | 0.54 | 0.45 | 0.34 | 0.28 | 0.22 | 3 |
| 1989B     | 47565.3(1.0) | NGC 3627  | 30.06(17) | 0.35(03) | 0.32 | 0.27 | 0.20 | 0.17 | 0.13 | 4,5 |
| 1991T     | 48375.7(0.5) | NGC 4536  | 31.07(13) | 0.16(05) | 0.14 | 0.09 | 0.06 | 0.0 | 0.0 | 6,7 |
| 1998bu    | 50953.3(0.5) | NGC 3368  | 30.20(10) | 0.35(03) | 0.31 | 0.26 | 0.19 | 0.16 | 0.12 | 0.10 | 8,9,10 |

\( a \) Epoch sources - SN 1972E: Leibundgut et al. (1991), SNe 1980N & 1981D: Hamuy et al. (1991), SN 1981B: Shaefer (1995), SN 1986G: Phillips et al. (1987), SN 1989B: Wells et al. (1994), SN 1991T: Lira et al. (1998), SN 1998bu: Hernandez et al. (2000)

\( b \) Julian Date – 2400000.

\( c \) Distance Modulus: the error in parentheses is the random error only - see text.

\( d \) $E(B-V)$ for all SNe except SN 1981D is from Phillips et al. (1999) and includes Galactic reddening. $E(B-V)$ for SN 1981D is from M. Phillips (private communication).

\( e \) The IR extinctions were determined using two methods: (1) & (2) - see text.

\( f \) IR photometry obtained from: 1. Elias et al. (1985), 2. Elias et al. (1981), 3. Frogel et al. (1987), 4. Kidger et al. (1989), 5. Wells et al. (1994), 6. Menzies & Carter (1991), 7. Harrison & Stringfellow (1991), 8. Mayya, Puerari & Kuhn (1998), 9. Jha et al. (1999), 10. Meikle & Hernandez (1999); Hernandez et al. (2000).

\( g \) Numbers in parentheses give random error in the smallest two decimal places.

Table 2. Absolute magnitudes at $t = +13.75$ days.

| SN     | $M_{14}(J)$ | $\Delta M_{14}(J)$ | $M_{14}(H)$ | $\Delta M_{14}(H)$ | $M_{14}(K)$ | $\Delta M_{14}(K)$ | $\Delta m_{15}(B)$ |
|--------|-------------|---------------------|-------------|---------------------|-------------|---------------------|---------------------|
| 1972E  | -17.26(16)  | 0.30                | -18.52(04)  | 0.25                | -18.64(06)  | 0.25                | 0.87(10)            |
| 1980N  | -17.02(03)  | 0.11                | -18.29(01)  | 0.10                | -18.33(01)  | 0.10                | 1.28(04)            |
| 1981B  | -16.70(04)  | 0.10                | -18.03(03)  | 0.09                | -18.00(02)  | 0.08                | 1.10(07)            |
| 1981D  | -16.94(05)  | 0.11                | -18.32(03)  | 0.10                | -18.24(02)  | 0.10                | 1.27(09)            |
| 1986G  | -17.39(04)  | 0.14                | -18.27(02)  | 0.13                | -18.18(02)  | 0.13                | 1.73(07)            |
| 1989B  | -16.71(04)  | 0.18                | -18.03(06)  | 0.18                | -18.24(13)  | 0.21                | 1.31(07)            |
| 1991T  | -17.47(30)  | 0.33                | -18.63(14)  | 0.20                | -18.78(25)  | 0.28                | 0.94(05)            |
| 1998bu | -16.81(07)  | 0.13                | -18.29(03)  | 0.11                | -18.27(04)  | 0.11                | 1.01(05)            |

\( a \) Numbers in parentheses give the error in the smallest two decimal places of $M_{14}(J), M_{14}(H)$ and $M_{14}(K)$ returned by the $\chi^2$-fitting procedure.

\( b \) Total random error in the absolute magnitude. It includes $\chi^2$-fitting error, random error in the distance estimates (cf. Table 1), and extinction correction error (see text).

\( c \) Values of $\Delta m_{15}(B)$ taken from Phillips et al. (1999), apart from SN 1981D. For this supernova the value was provided by M. Phillips (private communication). Numbers in parentheses give the error in the smallest two decimal places.

\( d \) Given the peculiar nature of SN 1991T and the fact that the epoch of observation is over a month beyond the fiducial $t = +13.75$ day epoch, it is possible that the quoted errors on $M_{14}(J), M_{14}(H)$ and $M_{14}(K)$ are significantly underestimated for this supernova.
### Table 3. Appendix: Infrared photometry of type Ia supernovae

| Supernova | \( t_{\text{Bmax}} \) (d) | \( J \) | \( H \) | \( K \) | Source |
|-----------|----------------|------|------|------|--------|
| SN 1972E  | 41459.7         | –    | –    | 9.44(20) | Elias et al. (1985) |
|           | 41461.8         | –    | –    | 9.29(16) |
|           | 41463.6         | –    | –    | 9.32(8)  | 9.35(8) |
|           | 41472.6         | 10.37(12) | 9.07(8) | 9.18(8) |
|           | 41482.8         | –    | –    | 9.00(16) |
|           | 41487.7         | 10.76(10) | 9.76(8) | 9.95(8) |
|           | 41488.7         | –    | 9.83(10) | 9.96(9) |
|           | 41493.7         | –    | 10.19(10) | 10.35(10) |
|           | 41496.7         | 11.16(13) | 10.39(10) | 10.24(11) |
|           | 41502.7         | –    | 10.61(17) | – |
|           | 41516.7         | –    | 11.16(16) | 11.40(17) |
|           | 41517.7         | –    | 11.17(11) | 11.29(8) |
|           | 41518.7         | 12.58(16) | –    | 11.03(13) |
| SN 1980N  | 44590.7         | 13.32(5) | 13.43(5) | 13.23(8) | Elias et al. (1981, 1985) |
|           | 44591.5         | 13.50(7) | 13.46(8) | 13.32(9) |
|           | 44592.7         | 13.61(4) | 13.38(2) | 13.32(5) |
|           | 44596.6         | 14.40(4) | 13.14(3) | 13.38(4) |
|           | 44618.6         | 14.15(3) | 13.47(2) | 13.59(2) |
|           | 44621.6         | 14.47(3) | 13.66(2) | 13.82(2) |
|           | 44624.6         | 14.76(4) | 13.84(2) | 14.01(3) |
|           | 44631.7         | 15.42(5) | 14.18(3) | 14.34(4) |
|           | 44653.5         | 16.74(8) | 15.11(4) | 15.20(11) |
|           | 44657.6         | –    | 15.15(8) | – |
|           | 44667.5         | –    | 15.74(11) | – |
|           | 44676.5         | 17.65(16) | 16.00(8) | – |
|           | 44677.5         | 17.69(20) | 16.24(7) | 16.21(11) |
|           | 44685.5         | 17.54(19) | 16.50(9) | – |
| SN 1981B  | 44674.67        | 12.70(5) | 13.00(5) | 12.60(5) | Elias et al. (1981, 1985) |
|           | 44679.0         | 13.19(7) | 12.95(6) | 12.81(5) |
|           | 44680.73        | 13.75(5) | 13.27(5) | 12.99(5) |
|           | 44685.7         | 14.18(3) | 12.98(2) | 12.89(2) |
|           | 44687.7         | 14.20(3) | 12.90(2) | 12.90(2) |
|           | 44689.0         | 14.29(2) | 12.93(3) | 12.87(4) |
|           | 44689.8         | 14.11(3) | 12.84(2) | 12.67(2) |
|           | 44690.8         | 14.17(2) | 12.82(2) | 12.81(3) |
|           | 44691.7         | 13.85(3) | 12.69(2) | 12.77(2) |
|           | 44692.8         | 13.99(3) | 12.73(5) | 12.81(4) |
|           | 44695.8         | 13.66(3) | 12.59(3) | 12.68(5) |
|           | 44708.7         | 14.01(11) | 13.19(8) | – |
|           | 44737.7         | 16.09(15) | 14.53(7) | 14.67(7) |
|           | 44738.5         | 16.19(6) | 14.53(3) | 14.67(3) |
|           | 44748.5         | 16.65(5) | 15.92(3) | 15.03(5) |
|           | 44768.5         | 17.52(11) | 15.80(4) | 15.71(5) |
|           | 44782.5         | 17.87(13) | 16.22(8) | 15.99(19) |
| SN 1981D  | 44683.5         | 13.38(3) | 13.41(3) | 13.36(4) | Elias et al. (1981, 1985) |
|           | 44685.5         | 13.74(2) | 13.45(2) | 13.43(3) |
|           | 44686.5         | 14.05(2) | 13.56(2) | 13.55(3) |
|           | 44687.5         | 14.27(3) | 13.56(2) | 13.57(3) |
|           | 44688.5         | 14.44(3) | 13.59(3) | 13.58(4) |
|           | 44693.5         | 14.58(4) | 13.28(3) | 13.28(7) |
|           | 44695.5         | 14.49(6) | 13.22(3) | 13.25(6) |

\(^a\) \( JD - 2400000 \)
\(^b\) Numbers in parentheses give the error in the smallest one or two decimal places.
Table 3 (continued). Appendix. Infrared photometry of type Ia supernovae

| Supernova  | $t_{B_{\text{max}}}$ (d) | $B_{\text{max}}$ (d) | $J$ | $H$ | $K$ | Source |
|------------|--------------------------|-----------------------|-----|-----|-----|--------|
| SN 1986G   |                          |                       |     |     |     |        |
| 46556.4    | 10.10(3)                 | 9.96(3)               | 9.90(3) | Frogel et al. (1987) |
| 46557.4    | 10.06(3)                 | 9.97(3)               | 9.87(3) |
| 46562.2    | 10.12(3)                 | 9.99(3)               | 9.87(3) |
| 46563.4    | 10.28(3)                 | 10.10(3)              | 10.03(3) |
| 46568.4    | –                        | 10.10(3)              | 10.02(3) |
| 46569.3    | 10.83(3)                 | 9.96(3)               | 10.01(3) |
| 46569.7    | 10.94(3)                 | 9.95(3)               | 9.99(3) |
| 46570.7    | 11.04(3)                 | 9.97(3)               | 9.98(3) |
| 46571.4    | 11.01(3)                 | 10.00(3)              | 9.92(3) |
| 46573.3    | 11.01(3)                 | 10.00(3)              | 9.99(3) |
| 46575.5    | 11.11(3)                 | 10.03(3)              | 10.08(3) |
| 46578.3    | 11.15(5)                 | 10.00(5)              | 9.99(5) |
| 46576.5    | 11.00(3)                 | 10.03(3)              | 9.97(3) |
| 46580.5    | 11.04(5)                 | 10.17(5)              | 10.15(5) |
| 46581.3    | 10.99(3)                 | 10.21(3)              | 10.20(3) |
| 46581.4    | 10.95(3)                 | 10.23(3)              | 10.27(3) |
| 46581.5    | 11.09(5)                 | 10.21(5)              | 10.21(5) |
| 46582.5    | 11.16(5)                 | 10.29(5)              | 10.29(5) |
| 46583.5    | 11.23(3)                 | 10.39(3)              | 10.42(3) |
| 46584.5    | 11.35(3)                 | 10.49(3)              | 10.53(3) |
| 46585.5    | 11.50(3)                 | 10.60(3)              | 10.65(3) |
| 46587.5    | 11.92(8)                 | 10.85(3)              | 10.90(3) |
| 46596.4    | 12.42(3)                 | 11.27(3)              | 11.39(3) |
| 46607.3    | 13.15(3)                 | 11.75(3)              | 11.97(3) |
| 46638.2    | 14.50(10)                | 13.10(3)              | 13.52(3) |
| 46662.5    | 14.62(12)                | 13.56(7)              | 14.10(7) |
| SN 1989B   |                          |                       |     |     |     |        |
| 47560.5    | 11.28(3)                 | 11.21(3)              | 11.04(3) | Kidger et al. (1989) |
| 47571.8    | 12.80(7)                 | 12.40(7)              | 12.20(11) | Wells et al. (1994) |
| 47584.9    | 13.22(5)                 | 11.91(5)              | 11.58(10) |
| SN 1991T   |                          |                       |     |     |     |        |
| 48364.4    | 11.73(3)                 | 11.16(3)              | 10.93(3) | Menzies & Carter (1991) |
| 48429.9    | 14.97(30)                | 13.72(14)             | 13.72(25) | Harrison & Stringfellow (1991) |
| SN 1998bu  |                          |                       |     |     |     |        |
| 50944.8    | 11.77(5)                 | 11.73(5)              | 11.81(5) | Mayya, Puerari & Kuhn (1998) |
| 50945.6    | 11.76(6)                 | 11.88(6)              | 11.81(5) | Jha et al. (1999) |
| 50947.7    | 11.67(5)                 | 11.66(5)              | 11.67(5) | Hernandez et al. (2000) |
| 50948.6    | 11.49(5)                 | 11.58(5)              | 11.42(5) |
| 50949.4    | 11.55(3)                 | 11.59(3)              | 11.42(3) |
| 50950.4    | 11.68(3)                 | 11.86(3)              | 11.44(3) |
| 50951.9    | 11.66(4)                 | 11.84(4)              | 11.60(3) |
| 50952.7    | 11.71(4)                 | 11.88(4)              | 11.63(3) |
| 50953.4    | 11.89(5)                 | 11.95(5)              | 11.60(5) |
| 50955.4    | 11.87(5)                 | 11.83(5)              | 11.66(5) |
| 50957.4    | 12.06(5)                 | 11.88(5)              | 11.61(5) |
| 50958.4    | 12.05(5)                 | 11.96(5)              | 11.75(5) |
| 50959.8    | 12.42(3)                 | 11.97(3)              | 11.88(3) |
| 50970.3    | –                        | 11.75(5)              | 11.84(4) |
| 50970.7    | 13.32(6)                 | 11.94(5)              | 11.95(5) |
| 50974.9    | 13.23(6)                 | 11.68(6)              | 11.89(5) |
| 50976.0    | 13.12(4)                 | 11.79(3)              | 11.77(3) |
| 50976.8    | 13.08(1)                 | 11.74(2)              | 11.92(2) |
| 50976.9    | 13.06(6)                 | 11.65(6)              | 11.77(5) |
| 50978.6    | 12.81(6)                 | 11.73(6)              | 11.74(5) |
| 50978.9    | –                        | 11.67(10)             | 11.77(10) |
| 50984.8    | 12.68(5)                 | 12.00(3)              | 12.05(4) |

* JD – 2400000
* Numbers in parentheses give the error in the smallest one or two decimal places.
Figure 1. $J$-band light curves of type Ia supernovae. The absolute magnitudes were derived as explained in the text, using method (2) to correct for the extinction. The error bars give the photometry errors only. The data set for each supernova is also subject to uncertainty in distance and extinction correction. The continuous line is the template light curve of Elias et al. (1985) with their $t_0 = 0$ set at −6.25 days, and with $M_{14}(J) = -16.86$ (see text).
Figure 2. Detail of Figure 1.
Figure 3. $H$-band light curves of type Ia supernovae. The template light curve has $M_{14}(H) = -18.22$. Other details as in Fig. 1 caption.
Figure 4. Detail of Figure 3.
Figure 5. $K$-band light curves of type Ia supernovae. The template light curve has $M_{14}(K) = -18.23$. Other details as in Fig. 1 caption.
Figure 6. Detail of Figure 5.
Figure 7. Evolution of the \((J - H)\) colour of type Ia supernovae. The colours have been de-reddened by method (2) as described in the text. The error bars represent random error only. The data set for each supernova is also subject to uncertainty in extinction correction. The continuous line is the template light curve of Elias et al. (1985) with their \(t_0 = 0\) set at \(-6.25\) days.
Figure 8. Evolution of the \((H - K)\) colour of type Ia supernovae. Other details as in Fig. 7 caption.
Figure 9. Absolute $JHK$ magnitudes of type Ia supernovae at +13.75 days ($M_{14}$) plotted against the blue light curve decline rate parameter $\Delta m_{15}(B)$. The weighted mean values of $M_{14}(J)$, $M_{14}(H)$ and $M_{14}(K)$, for the six "IR-normal" supernovae are indicated by the horizontal dotted lines.