Type II-P supernovae as standardized candles: improvements using near-infrared data

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ABSTRACT
We present the first near-infrared Hubble diagram for Type II-P supernovae (SNe), to further explore their value as distance indicators. We use a modified version of the standardized candle method, which relies on the tight correlation between the absolute magnitudes of Type II-P SNe and their expansion velocities during the plateau phase. Although our sample contains only 12 II-P SNe and they are necessarily local (z < 0.02), we demonstrate using near-infrared JHK photometry that it may be possible to reduce the scatter in the Hubble diagram to 0.1–0.15 mag. While this is potentially similar to the dispersion seen for Type Ia SNe, we caution that this needs to be confirmed with a larger sample of II-P SNe in the Hubble flow.

Key words: supernovae: general – galaxies: general – distance scale.

1 INTRODUCTION
Cosmology using Type Ia supernovae (SNe) has been established for over a decade since the discovery of cosmic acceleration (Riess et al. 1998; Perlmutter et al. 1999). Since these early results, distance measurements to Type Ia SNe, have been estimated to an accuracy of 7 per cent (Astier et al. 2006). Although there is some consensus on the progenitors of Type Ia SNe, and the physics governing these thermonuclear explosions, direct observational constraints are still lacking. Their use as standardized candles is limited primarily by systematic uncertainties, but significant effort is being expended in understanding and quantifying the source of these (e.g. Astier et al. 2006). Concurrently, several studies have attempted to determine whether there is any evolution in properties between the low- and high-redshift samples (e.g. Riess et al. 1999; Hook et al. 2005) and considered possible correlations with host galaxy properties (e.g. Gallagher et al. 2005; Sullivan et al. 2006). Complementary methods of distance determination out to redshifts roughly comparable to those sampled by Type Ia SNe, would provide a useful and independent check.

In contrast to Type Ia SNe, the progenitors of several types of core-collapse SNe have been unambiguously detected in the local Universe (see Smartt 2009, for a review). Several point sources have been detected in pre-explosion images at the location of Type II-P SNe with colours consistent with those of single red supergiants (Smartt et al. 2004; Li et al. 2005; Maund, Smartt & Danziger 2005; Mattila et al. 2008; Elias Rosa et al. 2009). Type II-P SNe are characterized by the presence of broad P-Cygni lines of hydrogen in their spectra, while an extended plateau of ~80–120 d in the light curve gives the class its name. The light curves and spectra of Type II-P SNe have been successfully modelled by several authors (e.g. Dessart et al. 2008; Kasen & Woosley 2009). Although core-collapse SNe exhibit considerable diversity compared with Type Ia SNe, Type II-P SNe are arguably the most homogeneous subset of core-collapse SNe at optical (Hamuy 2003) and also ultraviolet (Gal-Yam et al. 2008; Bufano et al. 2009) wavelengths, and despite their intrinsically lower luminosities, constitute a promising class of objects that can be exploited to determine distances. The fact that the progenitor stars are constrained to be red supergiants between 8 and 17 M⊙ (Smartt et al. 2009) enhances our confidence that the physics of these explosions are based on firm ground.

Different methods have been investigated to estimate the distance to Type II-P SNe, such as the original expanding photosphere method (Kirshner & Kwan 1974; Schmidt et al. 1994; Hamuy 2001) and the more recent synthetic spectral-fitting expanding atmosphere method (e.g. Baron et al. 2004; Dessart et al. 2008). Both methods rely on high signal-to-noise photometry and spectroscopy, as well as the computation of detailed synthetic spectra for each SN as a function of time. A much simpler method for using Type II-P SNe as standardized candles was introduced by Hamuy & Pinto (2002) and Hamuy et al. (2003). This requires much less input data and is based on the strong correlation between the expansion velocity and the luminosity of a Type II-P SN during the plateau phase.

Nugent et al. (2006) presented refinements to the original method of Hamuy & Pinto (2002) with the aim of increasing the ease with which distances to Type II-P SNe could be measured at cosmological redshifts. The most significant of these was to determine an extinction correction from the V − I colours at +50 d, rather
than at the end of the plateau phase (Hamuy et al. 2003). They also investigated the effect of using different lines to determine the expansion velocity, and presented an empirical relation – based on data available at the time – in the form of a power law that allows the inference of the Fe II λ5169 velocity at the epoch of interest, chosen to be +50 d. Applying their method to a sample consisting of both local as well as five intermediate redshift (z ≤ 0.3) Type II-P SNe, they found a scatter of 0.26 mag in the I-band Hubble diagram, similar to the dispersion obtained by Hamuy et al. (2003) for SNe in the Hubble flow.

Recently, Poznanski et al. (2009) analysed a sample of 40 new and previously published Type II-P SNe using the standardized candle method. They found a scatter of 18 per cent in distance, but noted that three SNe deviated significantly from their best-fitting solution, and that some of these SNe had faster decline rates. They introduced a criterion based on a weak correlation between the and that some of these SNe had faster decline rates. They introduced a criterion based on a weak correlation between the and the deviation from best fit, which rejected six SNe including the three outliers, which left a final sample of 34 objects, with a scatter of 10 per cent. Olivares (in preparation) also applied the SCM to a sample of 37 Type II-P SNe, using a reference epoch of −30 d from the end of the plateau. The scatter of their data in the B, V and I was comparable to that of previous studies but with an unexpected small increase in scatter at longer wavelengths. Furthermore, D’Andrea et al. (2010) compiled a sample of 15 Type II-P SNe from the Sloan Digital Sky Survey–II Supernova Survey (SDSS-SNS) in the redshift range 0.03 < z < 0.14. Applying the standardized candle method to a combined sample of the SDSS-SNS observations and data from the literature, they also found a dispersion comparable to that previously found. However, neither D’Andrea et al. (2010) nor Olivares (in preparation) found fit parameters consistent with those of Poznanski et al. (2009). D’Andrea et al. (2010) concluded for their sample that this discrepancy was most likely due to the SDSS-SNS SNe being intrinsically brighter, but not showing the corresponding increase in ejecta velocities. The early epochs at which the spectra are taken for the SDSS-SNS sample and the subsequent extrapolation using equation (2) of Nugent et al. (2006) are thought to be the main source of this difference in the fit parameters, and highlight the need for reliable measurements of the expansion velocities close to the chosen reference epoch (+50 d). D’Andrea et al. (2010) also find that the ad hoc decline rate culling criterion of Poznanski et al. (2009) does not remove the outliers from their sample.

Given that all previous studies incorporating local and intermediate redshift samples of Type II-P SNe find a scatter of ≥0.2 mag in the I band, we investigate here whether further improvements are possible using photometry in the near-infrared region (NIR). Galactic type dust causes a factor of greater than 5 times less extinction in the H band than in the V band, so one might reasonably expect a reduced scatter in the Hubble diagram of Type II-P SNe. Indeed, it has long been known that Type Ia SNe are excellent standard candles in the NIR (e.g. Meikle 2000; Krisciunas, Phillips & Suntzeff 2004; Wood-Vasey et al. 2008). As a first step, we explore the potential benefits of using NIR imaging for local objects, for which data are currently available.

2 SUPERNOVA SAMPLE

Hamuy (2001) detailed how the bolometric luminosity of a Type II-P SN can be determined from its BVI photometry, an empirical bolometric correction, total extinction and distance to the host galaxy (see also Bersten & Hamuy 2009). He noted that SNe with brighter plateaus have higher expansion velocities. Instead of determining the total bolometric luminosity, we used NIR photometry to derive a relation between expansion velocity and NIR luminosity. This is done for two main reasons: (i) the substantially lower extinction in the NIR region compared to optical wavelengths implies that the corresponding error on the extinction will have a smaller effect on the fit; (ii) NIR plateau phase spectra of Type II-P SNe contain far fewer lines compared to optical regions (e.g. Maguire et al. 2009). Thus, the NIR magnitudes are presumably affected less by variations in line strengths and widths from one SN to another.

We searched the literature for NIR photometry and optical spectroscopy to supplement our own data. The optical (VI) magnitudes for each SN were interpolated to +50 d using a linear fit. For SN 2007aa, which did not have good coverage at the mid-plateau phase, we used the available data at an earlier epoch (+24 d) and scaled this to the magnitude of each of the well observed II-P SNe: 1999em, 2004et and 2005cs at the same epoch. The offset at +50 d was obtained for each SN and the mean value was taken as the magnitude of SN 2007aa. In the NIR, the magnitudes that were obtained from the literature were interpolated using a linear fit if data points were available within five days of this epoch or using a quadratic interpolation if this was not the case. The fitting of quadratic interpolation was necessary to account for the pronounced non-linear behaviour of the plateau in the NIR bands during the photospheric phase (see Maguire et al. 2010). For some SNe (SN 1999br, SN 1999cr, SN 2005ay and SN 2007aa), previously unpublished NIR data were analysed in the standard manner to obtain $HJK$ magnitudes, which could be interpolated to +50 d based on the criteria detailed above. For SN 1999br, SN 1999cr and SN 2002hh, the $K_{short}$ filter was used, which has a long wavelength cut off at 2.3 μm. Transformation equations can be applied that convert from the $K_{short}$ to the $K$ band, but the coefficients of the conversion are smaller than the errors on the photometry and so have not been applied.

We estimated the expansion velocity by measuring the position of the minimum of the Fe II λ5169 feature in spectra taken at +50 d for each SN, except for SNe 1990E, 1999br and 1999cr, where the expansion velocities were taken directly from Hamuy et al. (2003). They also used the minima of the Fe II λ5169 lines and a power-law as described in Hamuy (2001) to determine the expansion velocities at +50 d. The spectra used to re-analyse the expansion velocities were obtained from the references listed in Table 1. When a spectrum at +50 d was not available, we extrapolated the velocities using equation (2) of Nugent et al. (2006), which is reliable from +9 to 75 d and adds an uncertainty of <175 km s$^{-1}$ to the expansion velocity.

The recessional velocities of nearby SNe are affected by the peculiar motion of their host galaxies. Ideally, SNe in the Hubble flow (cz > 3000 km s$^{-1}$) would be preferred because the peculiar motion of the host galaxies would be small compared to their cosmological redshifts. However, given the sample in hand, we proceeded to correct for peculiar motion as follows: we used the parametric flow model of Tonry et al. (2000), which has five velocity components including a Hubble flow, a constant dipole and quadrupole, and components to account for the infall to the Virgo and Great Attractors. The heliocentric velocities of the host galaxies were obtained from NED and a Hubble constant, $H_0$, of 78.4 km s$^{-1}$ Mpc$^{-1}$ is used throughout this Letter to ensure consistency with Tonry et al. (2000). However, the value of $H_0$ is only a scaling factor and affects neither the slope nor the fit.

We investigated the uncertainty in the recessional velocities calculated from the flow model of Tonry et al. (2000) using a sample of galaxies with Cepheid distances from Freedman et al. (2001).
We compared the velocities obtained from the flow model to those obtained using the Cepheid measurements, and found the standard deviation between the two methods to be 342 km s$^{-1}$. This value was added in quadrature to an uncertainty of 187 km s$^{-1}$ obtained using the Cepheid measurements, and found the standard deviation between the two methods to be 342 km s$^{-1}$. We used the Cepheid distance of Poznanski et al. (2009) for their entire sample of 40 SNe, resulting in $\alpha = 4.6 \pm 0.7$ and $M_b = -17.43 \pm 0.10$ mag. We tested the effect of varying $R_f$, and found that the commonly used value of 3.1 results in a worse fit across all bands with the $V$ band being most sensitive to the adopted value of $R_f$, while the scatter in the $I$ band increases by 0.17 mag compared to the best fit. For our sample of SNe, we found that $R_f$ converged to a value of $2.0 \pm 0.8$. However, we opted to use $R_f = 1.5$ in our analysis as this value was derived from the significantly larger sample of objects (Poznanski et al. 2009).

Fig. 1 shows the comparison Hubble diagram for our sample between the $V, I, J, H$ and $K$ bands, with a scatter of $0.56, 0.50, 0.39, 0.46$ and $0.40$ mag in the $V, I, J, H$ and $K$ bands, respectively. The $I$-band data are first shown in combination with the data in Poznanski et al. (2009) for ease of comparison in Fig. 1(b), while Fig. 1(c) shows our sample in isolation. The dispersion is dominated by the scatter in the recessional velocities due to this sample being relatively nearby. Hence, we find a higher dispersion in $V$ and $I$ than previously illustrated by Hamuy & Pinto (2002), Nugent et al. (2006) and Poznanski et al. (2009), as one would expect due to their larger numbers in the Hubble flow. However, in our self-consistent comparisons between the optical and NIR bands, we measure a tighter correlation in the $J$ band than in the $I$, which appears significant. There does not appear to be a further improvement in going to the $K$ band.
However, we note that larger numbers of low luminosity objects are unlikely to be detectable out to high redshifts and so should not affect future samples in the Hubble flow. However, we note that greater numbers of low luminosity Type II-P SNe at low redshift may skew the correlation. Future surveys will allow us to quantify the magnitude of this effect as rates of low-luminosity Type II-P SNe are currently not well known. Larger sample sizes are needed to clarify these results and it also leaves the open question of why with the negligible contribution from extinction in the H and K bands do they not produce measurably tighter fits than the J band. We note that the means and standard deviations of the errors of the $VIJK$ band measurements are 0.14$\pm$0.13, 0.17$\pm$0.13 and 0.18$\pm$0.13, respectively, indicating that there is no significant difference in the accuracy of the magnitudes in the NIR bands.

A definite indicator that a much reduced extinction at NIR wavelengths has a major role to play in the decrease in the scatter going to longer wavelengths, is the case of SNe 2004et and 2002hh, which shares the same host galaxy. In Fig. 1, these two SNe are shown as solid black circles. The convergence in distance moduli is improved by a factor of $\sim 10$ from the $V$ band to the $J$ band.

We also investigate the possibility that the scatter is reduced in the NIR bands due to the relatively few spectral features that are present in photospheric spectra. To quantify this, we have summed the equivalent widths of the spectral features above and below the continuum in spectra of SN 2004et from Maguire et al. (2010) (i.e. the deviation from the continuum) and find that the ratio of the $J/I$ band features is $\sim$50$\pm$20 per cent. The $H/I$ and $K/I$ band ratios were also determined and are $\sim$35$\pm$20 and $\sim$45$\pm$20 per cent, respectively. Thus, the NIR bands have weaker spectral features than are seen in the $I$-band region, which would imply that photospheric temperature variations would produce less variation in the NIR fluxes than in the optical. Further work using spectral models (e.g. Dessart et al. 2008) would be required to quantify this.

$H$ and $K$ bands. However, the $K$ band, where we would expect the tightest fit, has the smallest sample size of all bands considered here, and is possibly most affected by small number statistics. If a similar reduction in the dispersion was observed in II-P SNe in the Hubble flow, one might expect to reduce the scatter from 0.2–0.26 (as found in the $I$-band relations of Hamuy & Pinto 2002; Nugent et al. 2006; Poznanski et al. 2009) to 0.1–0.15. This corresponds to distances accurate to 5–7 per cent, if the NIR photometric accuracy can be sustained at higher redshifts. The two possible physical reasons for the decreased scatter in the NIR bands are the lower effective extinction corrections and the relatively featureless spectra seen at NIR compared to optical wavelengths (Maguire et al. 2010).

Poznanski et al. (2009) had suggested that the extinction term is relatively negligible compared to the velocity correction applied in the optical, which would argue against the former reason. To investigate this further, we performed fits to the data both including and excluding an extinction correction. Doing so, we found as expected, that the contribution to the extinction term is significant from $V - J$ bands, but that the $H$ and $K$ bands are virtually insensitive to the application of this correction. This would suggest that the $H$ and $K$ bands should produce the tightest fits. We also tested the fits excluding the most discrepant point (SN 1999br) and this reduced the scatter across all the bands with the $K$ band, having the lowest scatter at 0.20 mag, while the $J$ and $H$ had similar values of 0.29 and 0.31 mag, respectively. SN 1999br was a low-luminosity SN (Poznanski et al. 2004), but we find no reason to cull it from the sample and believe that it would be inappropriate to do so without a sound scientific basis. These low luminosity objects are unlikely to be detectable out to high redshifts and so should not affect future samples in the Hubble flow. However, we note that larger numbers of low luminosity Type II-P SNe at low redshift may skew the correlation. Future surveys will allow us to quantify the magnitude of this effect as rates of low-luminosity Type II-P SNe are currently not well known. Larger sample sizes are needed to clarify these results and it also leaves the open question of why with the negligible contribution from extinction in the $H$ and $K$ bands do they not produce measurably tighter fits than the $J$ band. We note that the means and standard deviations of the errors of the $JHK$ measurements are 0.14$\pm$0.13, 0.17$\pm$0.13 and 0.18$\pm$0.13, respectively, indicating that there is no significant difference in the accuracy of the magnitudes in the NIR bands.

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4 PROSPECTS AND OUTLOOK

The immediate application of II-P SNe as distance indicators is to independently verify cosmic acceleration between $z \approx 0.3$ and 0.5. This is of interest due to the progenitor channels of SNe II-P and Ia being distinctly different (Hillebrandt & Niemeyer 2000; Smartt 2009), hence one would expect different biases and effects from extinction, star formation rate and progenitor evolution. At $z$ of 0.3, the rest frame $J$-band magnitudes would be $\sim 23.2 - 25$, and would be redshifted to the $H$ band. The Wide Field Camera 3 on Hubble Space Telescope would produce a signal to noise of $\sim 30$ with exposure times between $\sim 1$ and 12 h. The feeder search would of course still be optical; the Supernova Legacy Survey and STRESS have confirmed Type II SNe out to a redshift of $z \sim 0.2 - 0.3$ (Botticella et al. 2008; Bazin et al. 2009). Amongst the Pan-STARRS-1 survey’s early discoveries is a bright Type II-P at $z = 0.18$ (Young et al. 2009, Botticella et al., in preparation) demonstrating that current surveys will harvest a sample of intermediate redshift II-P SNe. The velocity tracer $\lambda 5169$ line would be redshifted to $\sim 6720 - 7750$ Å and a $V$-band rest-frame magnitude of 23.7–25.5, redshifted to the $RI$ bands would mean that 8-m spectroscopy (at low-moderate dispersion) would be currently possible at $z \sim 0.3$, and at $z \sim 0.5$ for the brighter events. If the projected scatter using the standardized candle method for the rest-frame $J$ band of 0.1–0.15 mag can be confirmed in the Hubble flow, then the application of distance measurements with similar accuracy to Type Ia SNe is obviously attractive. A sample of 10–15 well-observed events would be sufficient to match the SNe Ia diagnostic ability at $z \sim 0.3-0.5$ and confirm cosmic acceleration to $3 - 4\sigma$ (Riess et al. 1998; Perlmutter et al. 1999).

Future facilities such as the James Webb Space Telescope (JWST), the European Extremely Large Telescope (E-ELT) and the proposed US and ESA space missions JDEM and EUCLID could significantly increase the redshift to which Type II-P SNe can be observed. At $z$ of $\sim 0.3 - 0.75$, the standardized candle method for Type II-P SNe could be combined with measurements of haryon acoustic oscillations and the cosmic microwave background to derive joint constraints on dark energy (e.g. Sollerman et al. 2009). Both JDEM and EUCLID baseline reference missions target Type Ia SNe in the rest-frame $H$ bands, with JDEM aiming for 1800 Type Ia SNe between $z \sim 0.3$ and 1.2. These sensitivity limits ($25.5 - 26$ mag) would detect II-P SNe in rest-frame $H$ to $z \sim 0.75$, implying around 400 would be detected (if the relative rates by volume are similar to what we see locally; Smartt et al. 2009). Rest-frame optical spectroscopy at $z = 0.75$ is possible with the E-ELT using Laser-Tomography AO/Multi-Conjugate AO with an exposure time of $\sim 1 - 3$ h at $J$-band wavelengths for a signal to noise of 20. Alternatively, the search survey could be optical (the Large Synoptic Survey Telescope could reach the bright events at $z \sim 0.75$) with JWST providing the NIR photometry of these events with the rest-frame $J$ band shifted to the $K$ band with exposure times of 1–3 h.

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