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THE INFRARED LIGHT CURVE OF SN 2011fe IN M101 AND THE DISTANCE TO M101


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ABSTRACT

We present near-infrared light curves of supernova (SN) 2011fe in M101, including 34 epochs in H band starting 14 days before maximum brightness in the B band. The light curve data were obtained with the WIYN High-Resolution Infrared Camera. When the data are calibrated using templates of other Type Ia SNe, we derive an apparent H-band magnitude at the epoch of B-band maximum of 10.85 ± 0.04. This implies a distance modulus for M101 that ranges from 28.86 to 29.17 mag, depending on which absolute calibration for Type Ia SNe is used.

Key words: galaxies: distances and redshifts – galaxies: individual (M101) – supernovae: individual (SN 2011fe)

Online-only material: color figures

1. INTRODUCTION

Supernova (SN) 2011fe was discovered soon after explosion in the nearby galaxy M101 (NGC 5457) by the Palomar Transient Factory (Rau et al. 2009; Law et al. 2009) on 2011 August 24.167 UT (all calendar dates herein are UT) and rapidly classified as a supernova of Type Ia (SN Ia; Nugent et al. 2011a, 2011b, identified initially as PTF11kly). This was the brightest SN Ia since SN 1972E in NGC 5253 (see, e.g., Kirshner et al. 1973), although SN 1986G remains the nearest SN Ia since SN 1972E in NGC 5253 (see, e.g., Hamuy et al. 1996; Rieß et al. 1996; Parodi et al. 2000; Guy et al. 2005; Jha et al. 2007; Conley et al. 2008; Hicken et al. 2009; Kessler et al. 2009; Folatelli et al. 2010; Burns et al. 2011; Mandel et al. 2009, 2011). SNe Ia are thus largely free of any Malmquist bias, and by virtue of their brightness, are cosmological probes at distances where peculiar motions of galaxies are insignificant compared to the expansion velocity of the cosmic manifold. Their consequent use as probes of cosmic acceleration is now well known (e.g., Riess et al. 1998; Perlmutter et al. 1999; Astier et al. 2006; Wood-Vasey et al. 2007; Sullivan et al. 2011).

Photometry of SNe Ia in the near-infrared (NIR) has shown even greater promise for use as a standard candle (for a recent review of the NIR properties of SNe Ia; see Phillips 2011). The effects of extinction are greatly reduced and they appear to have relatively constant peak magnitudes in J, H, and Ks (Meikle 2000; Krisiunas et al. 2004a, 2004b, 2007). The scatter in the NIR Hubble diagram is ∼0.15 mag without the light curve shape corrections necessary for optical bands (Krisiunas et al. 2004a; Wood-Vasey et al. 2008; Folatelli et al. 2010). Motivated by this, we began a Director’s discretionary time program to observe SN 2011fe with the WIYN High-Resolution Infrared Camera (WHIRC) NIR camera at the WIYN 3.5 m telescope on Kitt Peak, taking advantage of the instrumentation deployment that allows for the use of the NIR camera even when other instruments are scheduled for a given night.

2. OBSERVATIONS AND DATA REDUCTION

We imaged the SN on 34 nights between 2011 August 27 and 2011 October 26 with WHIRC. The WHIRC camera (Meixner et al. 2010) contains a 2048 × 2 Hg–Cd–Te array with a field of view of 3.3 × 3.3 and a pixel scale of ∼0.1 pixel−1. We obtained observations in the H band during each visit and observations in the J and Ks bands for most of the visits (see Table 1 for...
15 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
bands. Optical photometry of SN 2011fe indicates that it is a “normal” SN Ia with a $\Delta m_{15}(B)$ value of $\sim 1.2$ (Richmond & Smith 2012), so we will not make any corrections for decline rate (as the correction suggest by Kattner et al. 2012 is minimal at this decline rate). Wood-Vasey et al. (2008) provide templates of light curves of SNe Ia in $J$, $H$, and $K_s$. We fit our data to the templates using a $\chi^2$ minimization. We restricted the fit to epochs ranging from 10 days before $B$-band maximum light (the earliest points in the templates) to 25 days after $B$-band maximum (when differences in filter bandpasses and spectral features combine to create deviations from the templates). We restricted the fit to 19 days after $B$-band maximum for the $J$ band as it showed larger deviations from the templates. The $J$ filter in WHIRC is significantly different than the $J$ filter used for the Wood-Vasey et al. (2008) templates (and the $K_s$ filter has differences as well). Details on the WHIRC filter bandpasses are available from the WHIRC Web site and are shown compared to 2MASS and Carnegie Supernova Program (CSP; Contreras et al. 2010) filter bandpasses in Figure 2.

The Wood-Vasey et al. (2008) templates are defined relative to $B$-band maximum. We did not have optical photometry, so both the scaling in magnitude and the epoch were free parameters in the fit. For all three bandpasses, we derived the same epoch of $B$-band maximum, 2011 September 9.9 ± 0.2 (MJD 55813.9, consistent with the time derived by other groups; W. Li 2003, private communication).

From the Wood-Vasey et al. (2008) templates we can derive the maximum in each passband (we missed a measurement of that epoch as a result of poor weather) as well as the magnitude at the time of $B$-band maximum. The values at $B$-band maximum are the fiducial points of the Wood-Vasey et al. (2008) templates. For the maximum in each passband, we find

\[ J_{\text{max}} = 10.51 \pm 0.04 \text{ mag}, \]
\[ H_{\text{max}} = 10.75 \pm 0.04 \text{ mag}, \]
\[ K_{s,\text{max}} = 10.64 \pm 0.05 \text{ mag}. \]

To evaluate the uncertainty for each value, we used the Wood-Vasey et al. (2008) light curves that had at least three points within three days of $B$-band maximum to calculate the error of the mean for the template in each band. Templates derived from data taken by the CSP (Contreras et al. 2010) as well as the Wood-Vasey et al. (2008) data (B. J. Shappee & S. Jha, in preparation) show essentially the same structure near maximum brightness where we are performing the fit and result in similar fits.

Krisciunas et al. (2004b) present a third-order polynomial fit for their NIR light curves of SNe Ia. This curve is not a
good match for our points over the nominal range given by Krisciunas et al. (2004b), most likely as a result of their data set having few points before maximum. If we restrict the fit to just the points near maximum, we derive $J_{\text{max}} = 10.49 \pm 0.06$ mag, $H_{\text{max}} = 10.76 \pm 0.08$ mag, and $K_{\text{max}} = 10.65 \pm 0.08$ mag (uncertainties are dominated by the rms values from Krisciunas et al. 2004b fits). All derived magnitudes are consistent with those found using the Wood-Vasey et al. (2008) templates.

We have not applied any $K$ corrections to our photometry. The redshift of M101 is 0.000804 ± 0.000007 (de Vaucouleurs et al. 1991), so any $K$ correction will be minimal. The Schlegel et al. (1998) dust maps imply a foreground extinction of $A_V = 0.028$ mag, and thus values in the $J$, $H$, and $K_s$ bands less than 0.01 mag. Based on narrow Na absorption lines in the spectra of SN 2011fe, Nugent et al. (2011b) derive a host-galaxy extinction of $A_V = 0.04$ mag (Patat et al. 2011) report a similar result). Again, this implies extinctions in the $H$ and $K_s$ bands less than 0.01 mag, while the extinction in the $J$ band is $\sim$0.01 mag. Given these minimal values, we do not apply any correction to our photometry.

4. DISCUSSION

To establish the absolute luminosity calibration of SNe Ia, we need SNe in nearby galaxies to which distances can be determined by other methods. There is a rich history of obtaining Cepheid-based distances to such host galaxies, using the Hubble Space Telescope (HST) (e.g., Sandage et al. 2006; Gibbon et al. 2000; Freedman et al. 2001; Riess et al. 2009). A discussion of the details associated with these techniques is beyond the scope of this paper. Rather, we recognize that M101 provides a better platform for the absolute magnitude calibration, because it is nearby and its distance is better determinable, if not already determined. In addition, the demonstration by Krisciunas et al. (2004a, 2004b) and Wood-Vasey et al. (2008) that the $H$-band light curves and peak brightnesses of SNe Ia are independent of second parameter characteristics of individual SNe (in addition, of course to being almost unaffected by reddening), provides a method that mitigates many of the issues that have plagued the earlier attempts and resulted in controversy. The weak relationship between luminosity and decline rate in the $J$ and $H$ bands found by Kattner et al. (2012) does add some potential complications for SNe Ia in the infrared in general, but not for the particular case of SN 2011fe as its $\Delta m_{15}(B)$ value is 1.2 (Richmond & Smith 2012). Here, we use our data for SN 2011fe to discuss the absolute magnitude anchor for the $H$-band calibration of SNe Ia, by comparing against currently available Cepheid distances to M101.

For the purpose of comparing our data to absolute calibrations of SNe Ia in the infrared, we will focus on the $H$ band, although similar results can be found using the $J$ and $K_s$ bands. As can be seen in Figure 2, the $H$ filter bandpass is the most similar across the data sets used for absolute calibration (PAIRITEL and CSP) as well as the WHIRC data. In addition, not all derivations of absolute calibrations include the $K_s$ band. As an example, Wood-Vasey et al. (2008) use $H$-band magnitudes at $B_{\text{max}}$ and the Hubble diagram (recession velocity versus apparent magnitude) to, in effect, derive that the absolute $H$-band magnitude at $B_{\text{max}}$ is

$$M(H_{B_{\text{max}}}) - 5 \log(H_0/72) = -18.08 \pm 0.15. \quad (1)$$

Table 2

<table>
<thead>
<tr>
<th>Calibration Source</th>
<th>Filter</th>
<th>Absolute Magnitude</th>
<th>Distance Modulus to M101 (mag)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandel et al. (2009)$^b$</td>
<td>$J$</td>
<td>$-18.25 \pm 0.17$</td>
<td>28.87 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>$H$</td>
<td>$-18.01 \pm 0.11$</td>
<td>28.86 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>$K_s$</td>
<td>$-18.25 \pm 0.19$</td>
<td>28.93 ± 0.20</td>
</tr>
<tr>
<td>Wood-Vasey et al. (2008)$^{b,c}$</td>
<td>$J$</td>
<td>$-18.29 \pm 0.33$</td>
<td>28.91 ± 0.33</td>
</tr>
<tr>
<td></td>
<td>$H$</td>
<td>$-18.08 \pm 0.15$</td>
<td>28.93 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>$K_s$</td>
<td>$-18.32 \pm 0.26$</td>
<td>29.00 ± 0.26</td>
</tr>
<tr>
<td>Krisciunas et al. (2004a)$^d$</td>
<td>$J$</td>
<td>$-18.57 \pm 0.14$</td>
<td>29.08 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>$H$</td>
<td>$-18.24 \pm 0.18$</td>
<td>28.99 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>$K_s$</td>
<td>$-18.42 \pm 0.12$</td>
<td>29.06 ± 0.13</td>
</tr>
<tr>
<td>Folatelli et al. (2010)$^b$</td>
<td>$J$</td>
<td>$-18.42 \pm 0.18$</td>
<td>29.04 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>$H$</td>
<td>$-18.23 \pm 0.19$</td>
<td>29.08 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>$K_s$</td>
<td>$-18.30 \pm 0.27$</td>
<td>28.98 ± 0.27</td>
</tr>
<tr>
<td>Folatelli et al. (2010)$^d$</td>
<td>$J$</td>
<td>$-18.43 \pm 0.18$</td>
<td>29.94 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>$H$</td>
<td>$-18.42 \pm 0.19$</td>
<td>29.17 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>$K_s$</td>
<td>$-18.47 \pm 0.27$</td>
<td>29.11 ± 0.27</td>
</tr>
<tr>
<td>Burns et al. (2011)$^d$</td>
<td>$J$</td>
<td>$-18.44 \pm 0.12$</td>
<td>29.94 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>$H$</td>
<td>$-18.26 \pm 0.10$</td>
<td>29.01 ± 0.11</td>
</tr>
<tr>
<td>Kattner et al. (2012)$^{d,e}$</td>
<td>$J$</td>
<td>$-18.57 \pm 0.14$</td>
<td>29.08 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>$H$</td>
<td>$-18.42 \pm 0.14$</td>
<td>29.17 ± 0.15</td>
</tr>
</tbody>
</table>

Notes.

$^a$ Distance modulus calculated by combining absolute magnitude with the apparent magnitudes for SN 2001fe derived from our light curves (see the text for details). This is conditional on $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$.

$^b$ Using Fiducial time is B-band maximum brightness.

$^c$ Using PAIRITEL subsample only.

$^d$ Fiducial time is maximum brightness in the given filter ($J$, $H$, or $K_s$).

$^e$ Using subsample 2 of Kattner et al. (2012).

They then quote $M(H_{B_{\text{max}}}) = -18.08 \pm 0.15$ mag, by adopting $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$. Our measured value of $H_{B_{\text{max}}} = 10.85 \pm 0.04$ mag for SN 2011fe yields a distance modulus $(m - M)_0 = 28.93 \pm 0.16$ mag if $H_0$ is indeed 72 km s$^{-1}$ Mpc$^{-1}$. More precisely, SN 2011fe gives the distance modulus to M101 as

$$(m - M) + 5 \log(H_0/72) = 28.93 \pm 0.16 \text{ mag.} \quad (2)$$

Note that the main uncertainty comes from the intrinsic rms of 0.15 mag in $H$-band absolute calibration as reported by Wood-Vasey et al. (2008), and not from the relatively insignificant uncertainty in the determination of the $H$ magnitude at the epoch of $B_{\text{max}}$. Table 2 lists the various absolute infrared calibrations for SNe Ia (all essentially based on a cosmology that assumes $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$) and the distance moduli to M101 derived from these calibrations using our apparent magnitudes for SN 2011fe. Again, in each case the uncertainty is dominated by the absolute calibration, not the photometry of SN 2011fe. There is a wide range in the absolute calibrations, yielding a span of 0.31 mag in distance modulus depending on the specific calibration used. The source of this dispersion is not clear, but may be the result of different filters, corrections to those filters, and assumptions that went into the individual analyses. Note also that these calibrations are not all independent, as many use the same data sets and analysis tools. Until the infrared absolute magnitudes of SNe Ia are more firmly settled, there will be some question about their cosmological utility.

17 Using only the PAIRITEL subsample of Wood-Vasey et al. (2008) to facilitate cross-comparisons with independent samples.
Freedman et al. (2001) concluded that the distance modulus to M101 from Cepheids is $29.13 \pm 0.11$ mag, where the Cepheid distance scale zero point rests on an adopted LMC distance modulus ($\mu_0$) of 18.50 mag. Saha et al. (2006) give $29.17 \pm 0.09$ mag from an alternative analysis of the same data and an adopted $\mu_0$(LMC) of 18.54 mag. A more recent comprehensive and completely independent study of Cepheids in M101 yields $29.04 \pm 0.19$ mag (Shappee & Stanek 2011), where the Cepheid scale is based on the maser distance to NGC 4258, which is tantamount to $\mu_0$(LMC) $= 18.41$ mag. The differences among these three results thus rest entirely on the adopted zero point for the respective Cepheid period–luminosity relations used by the three sets of authors. Comparing the conditional ($H_0 = 72$) $H$-band distance moduli to M101 from Table 2 to the Cepheid distances and using Equation (2) (with the appropriate infrared calibration), one finds the infrared distances can accommodate $H_0$ values from 64 to 74 km s$^{-1}$ Mpc$^{-1}$. Using $H$-band photometry with NICMOS on HST, and an assumed LMC modulus of 18.50 mag, Macri et al. (2001) obtained distance moduli of 29.53 and 29.19 mag from Cepheids (relative to LMC Cepheids, without any metallicity dependence modeling) in outer and inner fields of M101, respectively. They concluded that in addition to metallicity differences, photometry errors from blending are a likely contributor to the observed difference (with the inner field distance erring on the side of appearing too close).

In addition, there are published distances to M101 using non-Cepheid based methods. Tip of the red giant branch (TRGB) results span the gamut from $(m - M)_0 = 29.05 \pm 0.14$ mag (Shappee & Stanek 2011) to 29.34 $\pm 0.09$ mag (Rizzi et al. 2007) and $29.42 \pm 0.11$ mag (Sakai et al. 2004). Tammann & Reindl (2011) adopt the mean of the last two values when deriving $H_0$ from the visible light curve of SN 2011fe. Using the planetary nebulae luminosity function method Feldmeier et al. (1996) obtained $(m - M)_0 = 29.42 \pm 0.15$ mag. Figure 3 graphically demonstrates the distance estimates for M101 discussed herein (using the $H$-band calibration for SN 2011fe). Presented with this range of results, and given the state-of-the-art uncertainties in our understanding of metallicity dependence and its interaction with de-reddening procedures there is no compelling argument that can pinpoint the determined distance to M101 better than the likely range from 29.04 to 29.42 mag. For this range of possible moduli and the range of conditional moduli implied by the $H$-band magnitude of SN 2011fe, values of $H_0$ from 56 to 76 km s$^{-1}$ Mpc$^{-1}$ cannot be ruled out from this SN alone.

It is sobering that M101, which is nearer than any of the SNe Ia-calibrating host galaxies used by Freedman et al. (2001) or Riess et al. (2011), and for which there are multiple independent distance determinations, has resulting distance moduli that span a range of $\sim0.4$ mag. Other calibrator host galaxies at distances comparable to Virgo and beyond do not offer such cross-validation to scrutinize the robustness of their derived distances. The source of uncertainty in the distance moduli derived from the magnitudes of SN 2011fe is not just the measurement or the calibration of the SNe Ia. It is also necessary to resolve the Cepheid and TRGB distance scales and their systematics before a better than 5% accuracy for $H_0$ can be asserted.

5. CONCLUSIONS

We have presented $J$, $H$, and $K_s$ light curves of SN 2011fe in M101. The light curves appear to be those of a normal SN Ia. Our apparent magnitude in the $H$ band at the epoch of $B$-band...
maximum is $10.85 \pm 0.04$, implying distance moduli to M101 based on various infrared absolute calibrations that span a range from 28.86 to 29.17 mag. This dispersion is comparable to that for traditional distance measures to M101 (29.04–29.42 mag). This is, however, only one object in a class that still exhibits a small, but significant, intrinsic spread in peak magnitudes. From the dispersion in absolute calibrations of SNe Ia in the infrared, it is clear that they are not yet fully understood.

We thank the referee, Mark Phillips, for extremely useful comments and suggestions. We also thank the WIYN Observatory for their support of this program. T.M. acknowledges many useful conversations with Chris Burns on the nature of SN light curves in the infrared. T.M. dedicates this paper to the memory of his friend and colleague, Dr. Weidong Li.

**Facility:** WIYN

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