Optical and Infrared Photometry of SN 2005df

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ABSTRACT

We present optical (BVRI) and near-infrared (YJHKs) photometry of the normal Type Ia supernova 2005df, obtained with the CTIO 1.3-m and 0.9-m telescopes. The B- and V-band photometry, S-corrected to the filter prescriptions of Bessell (1990), matches the corresponding photometry from the ANU published by Milne et al. (2010). The R-band photometry from CTIO and ANU matches well without any corrections. A combination of V-band and near-IR photometry shows that SN 2005df is unreddened in its host galaxy. Spectropolarimetry of this supernova was obtained with the VLT, and the distance to the host galaxy is being determined from observations of Cepheids using the Hubble Space Telescope.

Subject headings: supernovae: individual (SN 2005df) — techniques: photometric — extinction: interstellar

SN 2005df was discovered visually by R. Evans on 2005 August 4.625 UT some 15" east and 40" north of the nucleus of NGC 1559 (Evans 2005), the heliocentric radial velocity of which is 1304 km s\(^{-1}\) (Koribalski et al. 2004). The supernova was located at RA = 04\(^{h}\) 17\(^{m}\) 37.85, DEC = -62\(^{\circ}\) 46\('\) 09.09 (J2000). See Fig. 1 for a finder chart. SN 2005df was confirmed to be a Type Ia supernova by Salvo & Schmidt (2005) from a spectrum of August 5.83 UT taken with the Australian National University 2.3-m telescope at Siding Spring.

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All of our photometry (except on one night) was taken with the CTIO 1.3-m telescope and the optical/IR imager ANDICAM. ANDICAM contains standard Johnson $UBV$ filters, Kron-Cousins $R$ and $I$ filters and standard Caltech/CTIO $JHK_s$ filters. Read out in $2 \times 2$ binning mode, ANDICAM gives a plate scale on the 1.3-m telescope of $0''369 \text{ px}^{-1}$ for optical imaging and $0''274 \text{ px}^{-1}$ for IR imaging. The optical field of view was 6'3 by 6'3, while the IR field of view was 2'34 by 2'34. ANDICAM also contains a 1.03 $\mu$m filter known as $Y$. This is an interesting photometric band for observing Type Ia supernovae, because the second $Y$-band maximum of such an object is almost always brighter than the first maximum.

Using optical standards of Landolt (1992), we calibrated 11 tertiary standards in the field of SN 2005df based on five nights of all-sky photometry with the CTIO 0.9-m telescope in November and December of 2006. The optical color terms for the CTIO 1.3-m telescope were determined from observations of the Landolt (1992) field T Phe on two clear nights in September of 2005. These color terms were consistent with the mean color terms from four nights of February 2004. The $JHK_s$ magnitudes of two of the tertiary standards were calibrated on two clear nights in September 2005, using the near-IR standards P9104 and P9109 of Persson et al. (1998). We adopted the $Y$-band magnitudes of these two Persson stars from Krisciunas et al. (2017, Appendix D) to calibrate the $Y$-band magnitudes of the two tertiary standards. All of the CTIO 1.3-m photometry of the supernova was then calibrated using observations of the tertiary standards. A final night of $BVRI$ photometry of SN 2005df was obtained with the CTIO 0.9-m telescope about $\sim 100$ days after the time of maximum light.

The optical and infrared photometry of the tertiary standards is given in Tables 1 and 2. The optical and infrared photometry of SN 2005df is given in Tables 3 and 4.

We present all but one night of our photometry of SN 2005df in Fig. 2. The brightness and location of the SN did not require the use of host galaxy subtraction templates. Our CTIO 1.3-m photometry is based on aperture photometry using a typical aperture of radius 10 px. On nights of bad seeing a larger software aperture was used.

Milne et al. (2010) also present optical photometry of SN 2005df, from the Australian National University 1.0-m and 2.3-m telescopes. By applying S-corrections to the CTIO $B$- and $V$-band data (Krisciunas et al. 2003) and putting our photometry on the system of Bessell (1990), we can effectively reconcile the photometry in these two bands. Our $R$-band photometry requires no correction. We cannot reconcile differences in the $I$-band photometry from different telescopes (up to 0.17 mag at $t = +15$ days). The near-IR $JHK_s$ photometry was S-corrected to the photometric system of Persson et al. (1998). The $BVJHK_s$ S-corrections are given in Table 5.
From a fourth order polynomial fit the \( B \)-band data we find that maximum light occurred on JD 2,453,599.2 ± 0.3, at which time \( B_{\text{max}} = 12.320 \) and \( B - V = -0.083 \). \( V_{\text{max}} = 12.396 \), \( R_{\text{max}} = 12.375 \), and the near-IR maxima are best estimated from the photometry of our second night (JD 2,453,596.89). The maximum magnitudes have uncertainties of ±0.02 mag. The decline rate (Phillips 1993) \( \Delta m_{15}(B) = 1.12 \) mag, like many normal Type Ia SNe.

We find that SN 2005df is bluer than SN 2001el by these amounts: \( \Delta(V - J) = -0.420 \pm 0.032 \), \( \Delta(V - H) = -0.422 \pm 0.017 \), \( \Delta(V - K_s) = -0.500 \pm 0.039 \) mag. For SN 2001el we adopt a value of the total extinction of \( A_V = 0.586 \) mag and host extinction of \( A_V = 0.472 \pm 0.025 \) mag (Krisciunas et al. 2007). Using values of \( A_{\lambda}/A_V \) for dust with \( R_V = 2.15 \) in the host of SN 2001el, and \( R_V = 3.1 \) dust in our Galaxy and in the host of SN 2004S (Krisciunas et al. 2006), the resulting host galaxy color excesses of SN 2005df are as follows: \( E(V - J) = -0.041 \pm 0.032 \), \( E(V - H) = 0.000 \pm 0.017 \), and \( E(V - K_s) = -0.053 \pm 0.039 \). This gives three estimates of the \( V \)-band host galaxy extinction, namely \(-0.057 \pm 0.045, 0.000 \pm 0.021, \) and \(-0.060 \pm 0.044 \). The weighted mean is \( A_V = -0.018 \pm 0.017 \) mag. At face value we can say that SN 2005df is unreddened in its host galaxy. In that case we only need to correct the photometry of SN 2005df for the Galactic reddening along the line of sight, namely \( E(B - V) = 0.030 \pm 0.003 \) mag (Schlegel, Finkbeiner & Davis 1998). Using conversion factors of (Krisciunas et al. 2006, Table 8), this translates to extinctions of \( A_B = 0.122 \), \( A_V = 0.093 \), \( A_R = 0.077 \), \( A_I = 0.056 \), \( A_Y \approx 0.040 \), \( A_J = 0.026 \), \( A_H = 0.017 \), and \( A_{K_s} = 0.011 \) mag.

NGC 1559, the host of SN 2005df, is presently being observed by the Hubble Space Telescope to determine its distance using Cepheids (L. Macri, private communication). This will allow us to calibrate the absolute magnitudes at maximum light of the supernova. Spectrophotometry of SN 2005df has also been obtained at the VLT (A. Cikota, in preparation). Thus, SN 2005df is not just “one more nearby supernova”. It will be a “gold star” object.

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Table 1. Optical Tertiary Standards near SN 2005df\textsuperscript{a}

| Star ID\textsuperscript{b} | B    | V    | R    | I    |
|--------------------------|------|------|------|------|
| 1                        | 13.551 | 12.990 | 12.648 | 12.308 |
| 2                        | 13.697 | 13.051 | 12.674 | 12.315 |
| 3                        | 13.818 | 13.307 | 12.994 | 12.686 |
| 4                        | 15.573 | 14.961 | 14.600 | 14.240 |
| 5                        | 13.328 | 12.852 | 12.568 | 12.266 |
| 6                        | 13.671 | 13.056 | 12.693 | 12.335 |
| 7                        | 14.147 | 13.326 | 12.855 | 12.391 |
| 8                        | 14.678 | 13.878 | 13.433 | 13.022 |
| 9                        | 15.690 | 14.771 | 14.237 | 13.767 |
| 10                       | 16.403 | 15.515 | 15.009 | 14.562 |

\textsuperscript{a}The mean errors of the mean of the photometry are ± 0.010 mag or less.
\textsuperscript{b}The identifications are the same as in Fig. 1.

Table 2. Infrared Tertiary Standards near SN 2005df\textsuperscript{a}

| Star ID\textsuperscript{b} | Y \ (\sigma) | J \ (\sigma) | H \ (\sigma) | K_s \ (\sigma) |
|--------------------------|-------------|-------------|-------------|---------------|
| 10                       | 14.234 (0.015) | 13.905 (0.016) | 13.497 (0.013) | 13.358 (0.026) |
| 11                       | 12.524 (0.024) | 12.308 (0.013) | 12.040 (0.002) | 11.922 (0.016) |

\textsuperscript{a}The numbers in parentheses are 1-\sigma uncertainties (mean errors of the mean).
\textsuperscript{b}The identifications are the same as those in Fig. 1.
Table 3.  \textit{BVRI} Photometry of SN 2005df$^a$

| JD$-2,453,000$ | $B$   | $V$   | $R$   | $I$   |
|---------------|-------|-------|-------|-------|
| 591.87        | 12.909 (0.040) | 12.911 (0.021) | 12.846 (0.024) | 12.962 (0.026) |
| 596.89        | 12.441 (0.028) | 12.475 (0.026) | 12.464 (0.032) | 12.707 (0.037) |
| 600.86        | 12.415 (0.042) | 12.399 (0.031) | 12.425 (0.050) | 12.836 (0.028) |
| 606.91        | 12.717 (0.028) | 12.538 (0.036) | 12.579 (0.024) | 13.099 (0.032) |
| 614.87        | 13.530 (0.027) | 13.003 (0.027) | 13.018 (0.022) | 13.412 (0.028) |
| 618.84        | 13.998 (0.029) | 13.234 (0.022) | 13.091 (0.024) | 13.287 (0.026) |
| 624.80        | 14.597 (0.030) | 13.528 (0.024) | 13.250 (0.025) | 13.179 (0.029) |
| 629.82        | 15.008 (0.040) | 13.817 (0.027) | 13.484 (0.030) | 13.222 (0.027) |
| 632.76        | 15.173 (0.041) | 13.999 (0.018) | 13.695 (0.022) | 13.402 (0.027) |
| 635.72        | 15.309 (0.039) | 14.156 (0.026) | 13.878 (0.024) | 13.600 (0.039) |
| 700.79        | 16.401 (0.040) | 15.935 (0.030) | 16.012 (0.025) | 16.333 (0.040) |

$^a$This photometry is in the photometric system of \textit{Landolt} (1992). The numbers in parentheses are 1-$\sigma$ uncertainties (mean errors of the mean). The first 10 nights’ data were taken with the CTIO 1.3-m telescope. The final night’s data were taken with the CTIO 0.9-m telescope.
Table 4. Near Infrared Photometry of SN 2005df\(^a\)

| JD−2,453,000 | \(Y\)     | \(J\)     | \(H\)     | \(K_s\)     |
|----------------|-----------|-----------|-----------|-------------|
| 591.87         | 13.076 (0.018) | 13.081 (0.054) | 13.234 (0.012) | 13.136 (0.044) |
| 596.89         | 13.010 (0.018) | 12.888 (0.013) | 13.134 (0.010) | 12.938 (0.026) |
| 600.86         | 13.357 (0.022) | 13.132 (0.016) | 13.335 (0.019) | 13.265 (0.036) |
| 606.91         | 13.764 (0.028) | 13.865 (0.020) | 13.470 (0.022) | 13.426 (0.043) |
| 614.87         | 13.724 (0.018) | 14.677 (0.017) | 13.388 (0.009) | 13.337 (0.018) |
| 618.84         | 13.449 (0.018) | 14.583 (0.018) | 13.289 (0.010) | 13.263 (0.024) |
| 624.80         | 13.149 (0.018) | 14.416 (0.021) | 13.213 (0.012) | 13.155 (0.024) |
| 629.82         | 12.886 (0.017) | 14.147 (0.015) | 13.310 (0.009) | 13.342 (0.024) |
| 632.76         | 12.919 (0.017) | 14.204 (0.015) | 13.449 (0.009) | 13.724 (0.039) |
| 635.72         | 13.085 (0.021) | 14.516 (0.027) | 13.684 (0.016) | 13.941 (0.089) |

\(^a\)This photometry is in the natural system of the CTIO 1.3-m telescope. The numbers in parentheses are 1-\(\sigma\) uncertainties (mean errors of the mean).
Table 5. Photometric Corrections for SN 2005df$^a$

| JD−2,453,000 | $\Delta B$ | $\Delta V$ | $\Delta J$ | $\Delta H$ | $\Delta K_s$ |
|--------------|------------|------------|------------|------------|------------|
| 591.87       | −0.044     | −0.002     | 0.042      | 0.003      | 0.001      |
| 596.89       | −0.043     | 0.009      | 0.059      | −0.008     | 0.018      |
| 600.86       | −0.044     | 0.017      | 0.068      | −0.019     | 0.033      |
| 606.91       | −0.040     | 0.023      | 0.009      | −0.043     | 0.054      |
| 614.87       | −0.019     | 0.026      | −0.058     | −0.046     | 0.022      |
| 618.84       | −0.006     | 0.028      | −0.084     | −0.060     | 0.008      |
| 624.80       | −0.027     | 0.032      | −0.067     | −0.070     | −0.012     |
| 629.82       | −0.069     | 0.037      | −0.075     | −0.031     | −0.011     |
| 632.76       | −0.069     | 0.039      | −0.093     | −0.009     | −0.007     |
| 635.72       | −0.068     | 0.040      | −0.107     | 0.007      | −0.006     |

$^a$The values are to be added to the corresponding photometry in Tables 3 and 4. This places the $BV$ photometry on the system of Bessell (1990) and the $JHK_s$ photometry on the system of Persson et al. (1998).
Fig. 1.— NGC 1559, SN 2005df, and the field stars nearby. This is a 40 second V-band exposure obtained with the CTIO 0.9-m telescope on 23 December 2006 UT. The field of view is 10'56 by 10'56, which is considerably larger than the ANDICAM field of view.

Fig. 2.— Optical $BVRI$ and near-infrared $YJHK_s$ light curves of SN 2005df. For the optical photometry the colored circles are data from the CTIO 1.3-m telescope, while the triangles are data from ANU published by Milne et al. (2010). All the near-IR photometry is from the CTIO 1.3-m telescope. The CTIO $BV$ photometry has been S-corrected to the system of Bessell (1990), while the $JHK_s$ photometry has been S-corrected to the photometric system of Persson et al. (1998). The $BV$ data have been fitted with a fourth order polynomial, while the $R-$band data have been fitted with a sixth order polynomial. The RMS residuals of the $B$-, $V$-, and $R$-band fits are $\pm$ 0.031, 0.021, and 0.028 mag, respectively.

Fig. 3.— $V-[J, H, K_s]$ colors of SN 2005df. The solid black lines are from fits to data of SN 2001el. They have been shifted in the Y-direction to minimize the reduced $\chi^2$ value of the fits.
Rest frame days since JD 2,453,599.2

Magnitudes:
- B + 1
- V
- R
- I
- J
- H
- Ks

SN 2005df

Krisiuninas et al. Fig. 2
Krisciunas et al. Fig. 3