INFRARED AND OPTICAL STUDY OF THE TYPE Ia SN 1998bu IN M96

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\textbf{ABSTRACT.} The type Ia SN 1998bu was discovered in the galaxy M96 on 9 May 1998. It is one of the closest type Ia events of modern times and good temporal coverage has been achieved. Moreover its distance is well-determined. We describe here some of the first-season photometric and spectroscopic observations. While SN 1998bu is unusually highly reddened, we can still deduce that it was a typical type Ia event. Preliminary analysis suggests that for an $H_0$ of about 60 km s$^{-1}$ Mpc$^{-1}$, its (de-reddened) peak luminosity, light curve shape and spectroscopic behaviour confirms the relationships found between these parameters in other classic type Ia supernovae.

1. Introduction

SN 1998bu in the Sab galaxy M96 (NGC 3368) was discovered by Mirko Villi (1998) on May 9.9 UT at a magnitude of about 13, 10 days before maximum blue light, $t_{B_{\text{max}}}=\text{May 19.7}\pm0.5 \text{ UT (see below)}$. The supernova was identified by Ayani \textit{et al.} (1998) and Meikle \textit{et al.} (1998) as being of type Ia. A prediscovery observation on May 3.14 UT was reported by Faranda & Skiff (1998). This was about 16.5 days before $t_{B_{\text{max}}}$. This makes it one of the earliest ever observations of a type Ia supernova (A. Riess, private communication). Theoretical models indicate a rise time to $t_{B_{\text{max}}}$ of 16–18 days (Höflich \textit{et al.} 1998). Faranda’s point constrains this to 16.6–18 days for SN 1998bu. We therefore estimate an explosion date of May 2.0$\pm1.0$ UT. The Faranda & Skiff measurement was made with an unfiltered CCD, and converts to a V magnitude of $+16.70\pm0.10$ (A. Riess, private communication).

An important aspect of the discovery of this supernova is that its parent galaxy, M96, already had an HST-Cepheid-determined distance of 11.6$\pm0.8$ Mpc (Tanvir \textit{et al.} 1995). More recently, using PN distances Feldmeier \textit{et al.} (1997) obtained an even closer distance of 9.6$\pm0.6$ Mpc. However, for ease of comparison with other type Ia supernovae with HST-Cepheid distances, we shall adopt the value of Tanvir \textit{et al.}. SN 1998bu is one of the closest type Ia’s of modern times, as well as being one of the earliest ever observed.

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Fig. 1. Relative magnitude optical light curves for SN 1998bu. For clarity they have been vertically displaced by arbitrary amounts. The epoch of maximum blue light, $t_{B\text{max}}$, corresponds to 1998 May 19.7 UT.

2. Light Curves

Good coverage was achieved by observers at the IAC80 (Tenerife) and the JKT (La Palma). Some data were also provided by the WIYN at Kitt Peak. Relative magnitude light curves are shown in Figure 1. They show the supernova magnitude relative to a comparison star (GSC 00849–00931) on the same CCD frame.

The epochs of maximum light were estimated by comparison with the templates of Leibundgut (1988) and Schlegel (1995) (Figure 2). Maximum light in the B-band was on May 19.7±0.5 days. Henceforth, this epoch will be adopted as the fiducial $t_{B\text{max}}=0$ days. The V-band fluxes peaked at $\sim+1$ d, while the R and I-band fluxes peaked at $-3$ to $-4$ d i.e. before $t_{B\text{max}}$. This behaviour has been noted in other type Ia such as SN 1990N and SN1992A (Suntzeff 1993, Leibundgut 1998, Lira et al. 1998). It follows from the fact that, even at this relatively early phase, the type Ia photosphere cannot be regarded as a simple black body. The extent to which the photosphere is not a black body becomes clear when we inspect contemporary spectra (see below). We also see a pronounced secondary maximum in I at about $+25$ d together with an inflection in R. Again, this behaviour has been seen in other type Ia (Schlegel 1995). Using Landolt standards (Landolt 1992), we deduce a preliminary value for $m_{V\text{max}}$ of $+11.89\pm0.04$.

SN 1998bu has yielded one of the earliest sets of near-IR photometry ever obtained. Indeed, this is the first time that IR photometry for a normal type Ia event has been acquired before $t_{B\text{max}}$. IR photometry obtained at the OAN (Mayya et al. 1998), TCS, IRTF, UKIRT and WHT telescopes are shown in Figure 2. Interestingly, the pre-$t_{B\text{max}}$ IR light-curve data peak at about $-5$ d and thus continue the trend of pre-$t_{B\text{max}}$ max-
Fig. 2. Relative magnitude infrared and optical light curves for SN 1998bu. For clarity they have been displaced vertically by arbitrary amounts. The IR photometry was obtained at the OAN (Mayya et al. 1998), TCS, IRTF, UKIRT and WHT telescopes. Also shown are template light curves in B & V (Leibundgut 1988), R & I (Schlegel 1995) and J, H & K (Elias et al. 1985). The BVR & I templates were shifted in both axes to give the best match to the data. The JHK templates were shifted only vertically. Their horizontal position was fixed by the epoch of \( t_{B_{max}} \) as indicated in Elias et al..

ima seen in the R and I-bands. Also shown in Figure 2 are the JHK-band template light curves of Elias et al. (1985). (We have slightly truncated Elias et al.’s original templates so that the earliest epoch of the template corresponds to Elias et al.’s earliest observation.) The position of these templates were fixed in the time axis by the epoch of \( t_{B_{max}} \) and have only been shifted vertically to provide the best match to the data. While the IR observations after \( \sim +10 \) days are rather sparse, we can see that the data are consistent with the Elias et al. templates.

The absolute peak magnitudes and reddening for SN 1998bu are discussed below.

3. Spectra

Examples of the optical spectra are shown in Figure 3. The \(-6.8\) d spectrum, taken with the ISIS spectrograph at the WHT (Meikle et al. 1998) is the earliest reported. The \(-0.8\) d spectrum is from the IDS at the INT. The \(+13\) d spectrum was obtained at the WIYN telescope, Kitt Peak. It is composed of a blue spectrum taken on May 31.2 UT and a red spectrum taken on June 4.2 UT. The spectra were scaled to match in their overlap region. Inspection of Figure 3 immediately reveals the characteristic deep, broad Si II absorption at 6120 Å, as well as other absorption lines (at 5750, 5440, 5270, 4860, and 4270 Å.) typical of a normal type Ia supernova at early times. The expansion ve-
Fig. 3. Optical spectra of SN 1998bu. The epochs shown are with respect to $t_{B_{\text{max}}} = 1998$ May 19.7. The –6.8 d and –0.8 d spectra have been shifted vertically for clarity. Their zero flux axes are indicated by the dotted lines. Fluxing is approximate only. The –6.8 d spectrum was taken at the WHT, the –0.8 d spectrum at the INT and the +13 d spectrum at the WIYN telescope. The WIYN spectrum is composed of a blue spectrum taken on May 31.2 UT and a red spectrum taken on June 4.2 UT, scaled to match in their overlap region.

Fig. 4. Spectra of three type Ia supernovae close to $t_{B_{\text{max}}}$. The SN 1981B and SN 1998bu spectra have been shifted vertically and scaled for clarity. Their zero flux axes are indicated by the dotted lines on the left hand axis. The SN 1981B spectrum is courtesy of B. Leibundgut and P. Nugent. The SN 1994D spectrum is from Meikle et al. (1996).
In Figure 5 we compare SN 1998bu at maximum light with the type Ia SNe 1981B and 1994D. Apart from the greater degree of reddening in the SN 1998bu spectrum, the three spectra are quite similar. The spectra of SNe 1998bu and 1981B are particularly alike.

We were unable to obtain any early-time IR spectra as the IR spectrograph at UKIRT (CGS4) was undergoing upgrading during May and early June. An IR spectrum was obtained on June 24.2 UT (t=+35.5 d), spanning 8,300–25,000 Å (Figure 5). As usual, we see the dramatic drop in the 10,000 to 12,000 Å region responsible for the red J–H colour at this time. The strong feature at about 8,700 Å is due to the calcium triplet. There is a particularly prominent feature at 10,000 Å. Comparison with the IR spectrum of the type Ia SN 1995D (Bowers et al. 1997) at 92 d (Figure 6) suggests that it fades quite rapidly. P. Höffich (private communication) has recently identified it as a very strong Fe II line. Many of the other features in the IR spectrum are probably to doubly ionised cobalt and iron (Bowers et al. 1997).

The lack of any early-time IR spectra for SN 1998bu meant that we do not know if it exhibited the 10,500 Å absorption feature seen in SNe 1991T and 1994D (Meikle et al. 1996). However, we did obtain IR spectra for the type Ia SN 1998aq at ~8.5 d and ~6.5 d. In these the 10,500 Å feature was clearly present but was of somewhat smaller depth than in SN 1994D.
4. Reddening and Absolute Peak Magnitude

As already mentioned, SN 1998bu exhibited an unusually high degree of reddening. We consider two methods for estimating the extinction viz. interstellar absorption and supernova colours. Measurements of interstellar NaI D absorption by Munari et al. (1998) indicate an E(B-V)=0.15 (EW=0.35 Å) in the parent galaxy, with a further 0.06 (EW=0.19 Å) arising in our own Galaxy. Thus, we have $A_V=0.65$, which is unusually high for a type Ia supernova. (The median $A_V$ in Mazzali et al. (1998) for 14 well-observed type Ias is 0.13). However, Suntzeff et al. (1999) argue that the Munari et al. estimate is actually an upper limit and so is inconsistent with extinction derived using supernova colours.

The other approach is to use the supernova colours themselves and compare them with those expected for an unreddened type Ia supernova of the same sub-type. Given the high degree of similarity in the spectral features of SNe 1998bu and 1981B, we assumed that the two supernovae are intrinsically identical. We then used the empirical reddening law of Cardelli et al. (1989) and gradually reddened the SN 1998bu optical spectrum to provide the best match to the SN 19981B spectrum. From this we derive a relative reddening of E(B-V)=0.26±0.02 for SN 1998bu. For the total reddening to SN 1981B we adopt E(B-V)=0.138±0.020 (Suntzeff et al. 1999).

After de-reddening, we compared our SN 1998bu observations with the light curve studies of Phillips (1993) and Riess et al. (1995) and with the spectroscopic sequence study of Nugent et al. (1996). We find that for SN 1998bu to match the trends indicated by these studies it is necessary to adopt an $H_0$ of 55–60 km s$^{-1}$ Mpc$^{-1}$. Using the Phillips et al. (1999) relation relating $M_{V_{\text{max}}}$ with the decline rate parameter $\Delta m_{15}(B)$,
we obtain an $H_0$ of $61\pm6$ km s$^{-1}$ Mpc$^{-1}$, which is consistent with Suntzeff et al.’s (1999) V-band-derived value of $64.7\pm7.6$ km s$^{-1}$ Mpc$^{-1}$. However, we emphasize that our result is preliminary. A more comprehensive description and analysis of this work is in preparation.

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References

Ayani, K., Nakatani, H., Yamaoka, H.: 1998, *IAU Circ.* No. 6905.
Bowers, E.J.C. *et al.*: 1997, *Mon. Not. R. Astr. Soc.* 290, 663.
Cardelli, J., Clayton, G., Mathis, J.: 1989, *Astrophys. J.* 345, 245.
Elias, J.H., Matthews, K., Neugebauer, G., Persson, S.E.: 1985, *Astrophys. J.* 296, 379.
Faranda, C., Skiff, B.A.: 1998, *IAU Circ.* No. 6905.
Feldmeier, J.J., Ciardullo, R., Jacoby, G.H.: 1997, *Astrophys. J.* 479, 231.
Höflich, P., Wheeler, J.C., Thielemann, F.K.: 1998, *Astrophys. J.* 495, 617.
Landolt, A.U.: 1992, *Astron. J.* 104, 340.
Leibundgut, B.: 1988, PhD thesis, Univ. Basel.
Leibundgut, B.: 1998, in *Supernovae and Cosmology*, eds. L. Labhardt, B. Binggeli, R. Buser, publ. U. Basel.
Lira, P., *et al.*: 1998, *Astron. J.* 115, 234.
Mayya, Y.D., Puerari, I., Kuhn, O.: 1998, *IAU Circ.* No. 6907.
Mazzali, P.A., Cappellaro, E., Danziger, I.J., Turatto, M., Benetti, S.: 1998, *Astrophys. J. Lett.* 499, L49.
Meikle, W.P.S. *et al.*: 1996, *Mon. Not. R. Astr. Soc.* 281, 263.
Meikle, W.P.S., Hernandez, M., Fassia, A., Iglesias, J.: 1998, *IAU Circ.* No. 6905.
Munari, U., Barbon, R., Tomasella, L., Rejkuba, M.: 1998, *IAU Circ.* No. 6902.
Nugent, P.N., Phillips, M., Baron, E., Branch, D., Hauschildt, P.: 1996, *Astrophys. J. Lett.* 455, L147.
Phillips, M.M., Lira, P., Suntzeff, N.B., Schommer, R.A., Hamuy, M., Maza, J.: 1999, *Astron. J.* submitted.
Riess, A.G., Press, W.H., Kirshner, R.P.: 1995, *Astrophys. J. Lett.* 438, L17.
Schlegel, E.M.: 1995, *Astron. J.* 109, 2620.
Suntzeff, N.B.: 1993, in *Supernovae and Supernova Remnants*, p. 41, eds. R. McCray, Z. Wang, publ. CUP.
Suntzeff, N.B. *et al.*: 1999, *Astrophys. J.* in press.
Tanvir, N.R., Shanks, T., Ferguson, H.C., Robinson, D.R.T.: 1995, *Nature* 377, 27.
Villi, M.: 1998, *IAU Circ.* No. 6899.