DETECTION OF A LIGHT ECHO FROM SN 1998bu

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ABSTRACT

About 500 days after the explosion, the light curve of the Type Ia supernova SN 1998bu suddenly flattened, and at the same time the spectrum changed from the typical nebular emission to a blue continuum with broad absorption and emission features reminiscent of the SN spectrum at early phases. We show that in analogy to SN 1991T, this can be explained by the emergence of a light echo from a foreground dust cloud. Using a simple model, we argue that the amount of dust required can consistently explain the extinction that has been estimated by completely independent methods. Because of the similar echo luminosity but much higher optical depth of the dust in SN 1998bu compared with SN 1991T, we expect that the echo ring size of SN 1998bu grows faster than in SN 1991T. Hubble Space Telescope observations have indeed confirmed this prediction.

Subject headings: dust, extinction — supernovae: general — supernovae: individual (SN 1991T, SN 1998bu)

1. INTRODUCTION

The Type Ia supernova (SN Ia) SN 1998bu was discovered on May 9.9 UT by Villi (1998) in a spiral arm of NGC 3368 (M96), a nearby Sab galaxy. It had very good photometric and spectroscopic coverage by several groups (Jha et al. 1999; Hernandez et al. 2000; Suntzeff et al. 1999), showing that the luminosity decline was slower than the average $\Delta m_{15}(B)$, the magnitude decline in the first 15 days after maximum, was $1.01 \pm 0.05$ mag. This is almost as slow as the slowest SN Ia on record, SN 1991T, although, unlike SN 1991T, SN 1998bu was spectroscopically normal before and around maximum. The distance to the host galaxy was measured using Cepheid variables (Tanvir, Fergusson, & Shanks 1999) as $\mu = 30.25 \pm 0.19$. However, a calibration of the absolute luminosity of the SN depends also on the estimated reddening, which in the case of SN 1998bu is significant. Hernandez et al. (2000) estimated $E(B-V) = 0.86 \pm 0.15$ based on the comparison of the spectral energy distribution of SN 1998bu with that of the template SN Ia 1981B.

SN 1998bu was included in our program of monitoring of the nebular phase of SNe Ia. During this monitoring, we realized that SN 1998bu was not declining with the expected rate; this, combined with the change in the spectral appearance, gave the first evidence of the emergence of a light echo in SN 1998bu (Cappellaro et al. 2000). These observations are presented here for the first time along with a simple modeling.

2. EVIDENCE FOR A LIGHT ECHO IN SN 1998bu

When the SN Ia ejecta become optically thin, about 100 days after the explosion, the SN luminosity is determined essentially by the deposition of the kinetic energy of the positrons released by the decay of $^{56}$Co. There is evidence that even positron deposition may not be complete (Cappellaro et al. 1997; Milne, The, & Leising 1999), and so at advanced phases the light curve declines either at the $^{56}$Co rate (0.98 mag/100 days) or faster. The only previously known case of an SN Ia with a decline slower than the $^{56}$Co rate was SN 1991T, whose slow late decline and peculiar spectra were interpreted as due to a light echo (Schmidt et al. 1994).

A first indication that SN 1998bu was beginning to deviate from the normal exponential decline came on 1999 December 4, roughly 500 days after maximum. At this epoch, the observed magnitude ($V = 20.75 \pm 0.08$) was already 2 mag brighter than the extrapolation of the radioactive decay tail. Additional photometric observations over the following few months showed that the SN luminosity remained almost constant (the decline was only $-0.5$ mag in 100 days). Also, the color at these epochs was unusually blue ($B-V \approx -0.1$). This behavior was reminiscent of that exhibited by SN 1991T (Schmidt et al. 1994; Sparks et al. 1999).

Figure 1 shows the absolute $V$ light curves of SN 1998bu and SN 1991T (Cappellaro et al. 1997). Both light curves have been calibrated using the Cepheid-based distances (Saha et al. 2001; Tanvir et al. 1999) and corrected for total extinction (see Table 1). The striking similarity of the two light curves suggests that the same mechanism causing the flattening of the light curve of SN 1991T was also acting in the case of SN 1998bu.

Although this is not clearly visible in Figure 1, the absolute magnitude of SN 1998bu at maximum was about 0.5 mag fainter than that of SN 1991T. Based on the $\Delta m_{15}(B)-M_V$ relation (Phillips et al. 1999), the difference should be only 0.05 mag. The gap increases slightly with time, and it reaches about 0.8–0.9 mag 1 yr after maximum. That SNe Ia with a very similar $\Delta m_{15}(B)$ actually show significant dispersion in some of their other properties is a well-known fact (Mazzali et al. 1998) and is one of the main caveats for the use of SNe Ia as distance indicators. However, this is not essential for the discussion presented here.

The slow photometric evolution of SN 1998bu makes it a viable target for spectroscopy even 2 yr after the explosion. Spectra of SN 1998bu were obtained using the ESO 3.6 m telescope (and EFOsc2) at La Silla at two epochs, 2000 March 3 and March 30. We used grism 11, which, combined with the 172 slit, allowed one to cover the range 3300–7500 Å with a resolution of about 15 Å. Eventually, since no spectral evolution was apparent between the two epochs, the two spectra were merged to improve the signal-to-noise ratio. The total integration time was 9000 s. The resulting spectrum, labeled

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Fig. 1.—Light curve of SN 1998bu compared with that of SN 1991T (circles are our own measurements, whereas triangles are data from literature). For reference, the solid line represents the V absolute light curve of SN 1996X, a normally declining SN Ia (the star marks the epoch of the last measurement of SN 1996X, and below that the line is simply an extrapolation). The dotted line is the fit of the observations with the simple model described in § 2.

with the average phase of 670 days, is shown in Figure 2. For comparison we also show the spectrum of SN 1991T obtained with the same telescope at a similar phase. We also show spectra of the two SNe at a much earlier epoch, when the luminosity decline was still tracking the radioactive exponential tail.

The similarity of the spectral evolution of the two SNe is remarkable. About 300 days after maximum, the spectra are dominated by the strong emission lines of Fe II] and Fe III], which are typical of SNe Ia in the nebular phase. These emission lines originate in the iron nebula and are powered by the radioactive decay of $^{56}$Co to $^{56}$Fe (Kuchner et al. 1994).

Corresponding to the flattening of the light curve, the spectra change completely, showing a blue continuum with superposed broad absorption and emission features. These spectra resemble the photospheric epoch spectra, but they do not match any specific early-time epoch. For SN 1991T, it was convincingly suggested (Schmidt et al. 1994) that the peculiar late-time light curve and spectrum can be explained assuming that the emission at these epochs is dominated by the echo from circumstellar dust of the light emitted by the SN near maximum. Our observations suggest that the same mechanism is at work also in SN 1998bu.

The key element for such a mechanism to work is the presence of a dust layer in the vicinity of the SN, scattering toward the observer a fraction of the light emitted by the SN. Because of the different travel times, the observed spectrum is a combination of the early-time scattered spectra and of the direct, late-time spectrum. In principle, the details of the echo (intensity, duration, spectrum) depend on the spatial distribution of the dust and on the physics of the scattering process. A careful analysis and modeling of time-distributed observations may allow one to derive useful constraints. Such a detailed study is the subject of future work (F. Patat et al. 2001, in preparation), while here we illustrate the basic principles of the phenomenon.

In general, the light curve of the echo is related to the light emitted by the SN by the following relation (Chevalier 1986):

$$F_{\text{echo}}(t) = \int_0^t F_{\text{SN}}(t - t')f(t')dt',$$

where $F_{\text{SN}}(t - t')$ is the flux of the SN at time $t - t'$ and $f(t)$, the fraction of this light that is scattered toward the observer, depends on the geometry of the system and on the properties of the dust $[f(t) \text{ is in units of s}^{-1}; \text{see eq. (2)}]$. As a first approximation, we can assume that the SN light curve is a short pulse with a duration $\Delta t_{\text{SN}}$, during which the emitted flux $F_{\text{SN}}$ is constant. Under this assumption, equation (1) becomes $F_{\text{echo}}(t) = F_{\text{SN}}f(t)\Delta t_{\text{SN}}$, where $\Delta t_{\text{SN}}$ can be obtained by a numerical integration of the observed light curve as $F_{\text{SN}}\Delta t_{\text{SN}} = \int_0^\infty F_{\text{SN}}(t)dt$.

In the case of the V light curve of SN 1991T (Schmidt et al. 1994; Sparks et al. 1999), this gives $\Delta t_{\text{SN}} = 0.11$ yr.

As one of the possible geometries that are consistent with the observations, we consider a thin dust sheet lying in front of the SN and extended perpendicularly to the line of sight.

### Table 1

| Supernova | Galaxy | V(max) | $A_V$ | $A_V^{\text{e}}$ | $\Delta m_{15}(B)$ | Reference               | $\mu$ | Reference         |
|-----------|--------|--------|-------|-----------------|------------------|--------------------------|-------|------------------|
| 1991T     | NGC 4527 | 11.51 ± 0.02 | 0.07  | 0.53 ± 0.17     | 0.94 ± 0.05      | Phillips et al. 1999     | 30.74 ± 0.12 | Saha et al. 2001 |
| 1998bu    | NGC 3368 | 11.88 ± 0.02 | 0.08  | 0.94 ± 0.15     | 1.01 ± 0.05      | Jha et al. 1999           | 30.25 ± 0.19 | Tanvir et al. 1999 |
For the sake of simplicity, we make the hypothesis that the sheet thickness $\Delta D$ is much smaller than the distance between the SN and the dust elements, and we consider only single scattering. Given this idealized configuration and assuming the scattering phase function by Henyey & Greenstein (1941), an analytic expression for the function $f(t)$ can be derived relatively easily (Chevalier 1986; Xu, Crotts, & Kunkel 1994) as

$$f(t) = \frac{c}{8\pi} \frac{\omega_p}{D + ct} \frac{1 - g^2}{[1 + g^2 - 2g(Dt + ct)]^{3/2}},$$

where $D$ is the distance of the dust layer from the SN, $\tau_p$ is the optical depth of the dust layer, $\omega_p$ is the dust albedo, and $g$ is a parameter that represents the degree of forward scattering. The value of $g$ ranges from 0 for isotropic scattering to 1 for purely forward scattering. Empirical estimates and numerical calculations (White 1979) give $g \approx 0.6$. For the dust albedo, we have adopted $\omega_p \approx 0.6$ (Mathis, Rumpl, & Nordsieck 1977).

Equation (2) shows that if the dust is too close to the object, even if it survives the exposure to the enormous radiation flux of the SN, it would not produce a constant, long-duration echo. This is because of both the angular dependence of the scattering phase function and the SN radiation dilution. In the case of SN 1991T, the echo luminosity declined by a factor of 4 over a phase function and the SN radiation dilution. In the case of SN 1991T, shown in Figure 1, gives $D \approx 120$ lt-yr. In the case of SN 1998bu the light curve is similar to that of SN 1991T—hence $\Delta \tau_{\text{SN}} \approx 0.1$ yr—but the optical depth of the dust is about a factor of 2 larger; therefore, we obtain $D \approx 230$ lt-yr. Note that these estimates are independent of the adopted distance for the parent galaxies, because they depend only on the ratio between the luminosity of the echo and that of the SN at maximum.

The distance $D$ is related to the linear diameter of the ring through the relation $2R = 2[ct(2D + ct)]^{1/2}$. In the case of SN 1991T the echo has been resolved with a diameter of 0.4. Based on the Cepheid distance to NGC 4527, this results in a linear diameter $2R = 120$ lt-yr, and hence $D = 150$ lt-yr. Given the observational uncertainties, this is in very good agreement with the estimate based on the light echo modeling. In the case of SN 1998bu, because of the much higher optical depth of the dust, we had to place the dust layer at a larger distance than for SN 1991T. In turn, this causes the echo ring diameter at any given time to be larger. Based on the geometry described earlier, we obtain that at the time of writing, 2.5 yr after the explosion, the diameter of the echo should be $\sim 0.3$. Indeed, the echo of SN 1998bu has already been resolved using the Hubble Space Telescope (B. Leibundgut 2000, private communication).

A consistency check of the light echo interpretation for the peculiar light curve of SN 1998bu can be obtained by comparing the observed and computed spectrum of the light echo. Clearly the most important contribution to the light echo comes from the light emitted near maximum. Spectra of SN 1998bu at eight different epochs from $-6$ to 50 days after maximum were published by Hernandez et al. (2000). Weighting the spectra according to the integrated luminosity around each observed epoch and using our assumed geometry (see eq. [1]), we computed the contribution of each early-time spectrum to the emerging echo spectrum at phase 670 days. The input spectra were corrected for reddening using a standard extinction law and assuming that the scattering function has a similar $\lambda^{-1}$ dependence. These corrected spectra were co-added to compute the expected spectrum of the echo (at 670 days, the SN nebular spectrum is several magnitudes fainter than the echo and does not give a measurable contribution). This is compared with the observed spectrum in Figure 3. Given the crudeness of some of the assumptions and the incomplete spectral coverage of the near-maximum phase, the agreement between the observations and the model is excellent, which we consider a strong argument in favor of the light echo scenario. Moreover, even if we stress that similar results can be obtained for different geometries, the fact that with the configuration we have chosen it is possible to explain the observed light curve, spectrum, and reddening is suggestive.

3. ARE BRIGHT SNe Ia LINKED TO DUSTY STAR-FORMING REGIONS?

The observation and interpretation of light echos can tell us about dust properties and distribution in galaxies but may have significant extinction from interstellar dust associated with the host galaxy, $A_{\text{ext}} = 0.46$ for SN 1991T and $A_{\text{ext}} = 0.86$ for SN 1998bu (Table 1). These values were derived mainly by photometric methods based on the analysis of the light curve and the SN color, and therefore they are affected by large uncertainties. In a simplified scenario, one can assume that there is only one cloud that is causing both the observed extinction and the light echo. In this case, since we fix the column density of the cloud, we can derive the distance $D$ of the cloud itself from the SN through a fit to the echo luminosity. The light curve fit for SN 1991T, shown in Figure 1, gives $D \approx 120$ lt-yr. In the case of SN 1998bu the light curve is similar to that of SN 1991T—hence $\Delta \tau_{\text{SN}} \approx 0.1$ yr—but the optical depth of the dust is about a factor of 2 larger; therefore, we obtain $D \approx 230$ lt-yr. Note that these estimates are independent of the adopted distance for the parent galaxies, because they depend only on the ratio between the luminosity of the echo and that of the SN at maximum.
far-reaching applications and consequences. One such application is to measure distances of galaxies (Sparks et al. 1999).

SN 1998bu is only the second SN Ia for which a light echo was observed, the other being SN 1991T in the Sbc galaxy NGC 4527. It is remarkable that both SNe are very slow decliners. SN 1991T was also spectroscopically peculiar at and before maximum, indicating a higher photospheric temperature than in normal SNe Ia, as shown by the presence of strong Fe ii lines and by the absence of Fe ii lines before maximum (Filippenko et al. 1992). This was confirmed by spectroscopic modeling, which also revealed that SN 1991T had an abnormally high abundance of Fe group species in the outer, fast-moving part of the ejecta (Mazzali, Danziger, & Turatto 1995). Such a peculiar element distribution suggested that SN 1991T may have been the result of an unusual explosion mechanism. Further studies revealed that SN 1991T had very broad Fe nebular lines (Mazzali et al. 1998). This and the brightness of the SN at maximum led various authors to conclude that SN 1991T produced an unusually large amount of $^{56}\text{Ni}$, about 1 $M_\odot$ (Spyromilio et al. 1992; Mazzali et al. 1995, 1998; Cappellaro et al. 1997), although this may be challenged by the recent calibration of the SN absolute luminosity (Saha et al. 2001; Richtler et al. 2001; Gibson & Stetson 2001). Finally, Fisher et al. (1999) suggested that SN 1991T may have been the result of the explosion of a super-Chandrasekhar mass progenitor.

SN 1998bu shares many of the properties of SN 1991T; it was bright at maximum, it had a slow decline, and it had broad nebular lines, although not quite as extreme in these respects as SN 1991T. It is therefore very interesting that both SNe are significantly reddened and show a dust echo. Two other nearby SNe Ia were heavily reddened; SN 1989B was a normal SN Ia for which indeed there may be some evidence of a light echo (Milne et al. 1999), while SN 1986G was a fast decliner and spectroscopically peculiar object for which, despite an early claim (Schaefer 1987), there was no evidence of a light echo (Turatto et al. 1990). The latter requires that the dust was more distant from SN 1986G than in SN 1998bu or SN 1991T (by placing the dust cloud 10 times further, the echo magnitude becomes 2.5 mag fainter).

Historically, the fact that SNe Ia were seen as very homogeneous was attributed to their progenitors arising from a single stellar population. Adding to this that SNe Ia were found in all types of galaxies, even in ellipticals, contributed to the standard paradigm that the progenitors of all SNe Ia belong to the old stellar population. Now there is evidence that slow decliners (or high-luminosity SNe Ia) may be preferably associated with a younger stellar population (and therefore conceivably more massive progenitors), a suggestion first made by van den Bergh & Papader (1992) and confirmed by Hamuy et al. (1996, 2000). Our result that both SN 1991T and SN 1998bu are located close to dusty regions is coherent with this scenario.

Obviously, one needs to improve the statistics by adding more cases. In this respect one interesting object is SN 1998es. This is an SN Ia whose spectrum near maximum was very similar to that of SN 1991T (Jha et al. 1998) and shows the signature of quite similar interstellar reddening (F. Patat et al. 2001, in preparation). Therefore, SN 1998es maybe an interesting candidate to search for a light echo, although, because of the relatively large distance ($\mu = 33.2$), the apparent magnitude may be quite faint ($V \sim 24$ if the echo has the same intensity as SN 1991T and SN 1998bu).

4. CONCLUSIONS

The peculiar late light curve and spectrum of SN 1998bu are attributed to the echo from circumstellar dust of the light emitted near maximum. Based on a simple model and on the comparison with SN 1991T (which also experienced a similar phenomenon), we estimate that the dust cloud is located in front of the SN and relatively nearby ($\sim 100$ pc). Because of the similar echo luminosity but much higher optical depth of the dust in SN 1998bu compared with SN 1991T, we expect that the dust layer is more distant and hence the echo ring of SN 1998bu grows faster than in SN 1991T.

The association of dust with SNe Ia, possibly of a specific subtype, may have interesting implications for the progenitor scenario and prompts a renewed effort for monitoring SNe Ia at late phases.

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