Observations of Type Ia Supernovae

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The quality of observational data on Type Ia supernovae has improved remarkably in the last few years, due mainly to monitoring programs with CCD-equipped detectors on small aperture telescopes at observatories across the world, and at the space observatories. I will review the recent observational characteristics of Type Ia supernovae, focusing the discussion on our observations of SN1992A in the S0 galaxy NGC 1380 in the Fornax cluster as a reference to other Type Ia events. We now have strong evidence that Type Ia events are not a homogeneous class, but vary in both color and brightness at maximum light, vary in rise time and decline from maximum, and have spectral characteristics at maximum light that are correlated with these photometric parameters. Insofar as the SBF, PNLF, and infrared Tully-Fisher distance scales are correct, the observed (uvoir) bolometric light curves also indicate that these supernovae are less luminous than expected from the models of the explosion of a C-O white dwarf at the Chandrasekhar mass.

1. Introduction

A stellar explosion is an unlikely physical environment to produce a homogeneous energy flux, given the fantastic brightness of a supernova at maximum light which can reach 10% of the luminosity of the *whole galaxy* for a period of a few weeks. Yet it is the brightness of the event that makes the use of supernovae as "standard candles" so attractive, since they can be readily observed to cosmologically interesting distances. Supernovae with redshifts greater than $z \sim 0.03$ can be used to measure the Hubble constant H_0 almost independent of peculiar velocities and perhaps streaming motions (but with the usual problems of local calibrators). Supernovae with redshifts of $z \sim 0.3$ or greater can be used, in principle, to measure the deceleration parameter q_0.

Almost all of our knowledge of the luminosity evolution of supernovae comes from the heroic work of countless observers who have obtained photographic plates and reduced the photographic images into stellar photometry. The measurement of an accurate magnitude of a stellar image on top of a galaxy of significant surface brightness is made especially difficult by the non-linear sensitivity of the photographic emulsion. A significant improvement in the accuracy of the photometry can be made by using CCD detectors, where the linear nature of the detector allows for much better background subtraction and photometric accuracies.

In this contribution, I will focus on recent results based on CCD photometric and spectroscopic data to explore the homogeneity and inhomogeneity of Type Ia explosions. It is less my goal to discuss the utility of Type Ia supernovae as standard candles, and more to offer a new perspective on the physical evolution of Type Ia explosions as revealed from the new high-quality data. It is my hope that a fresh look based on the new CCD data on these extremely well-studied objects will lead the discussion in this conference to new directions of understanding the underlying physical event.

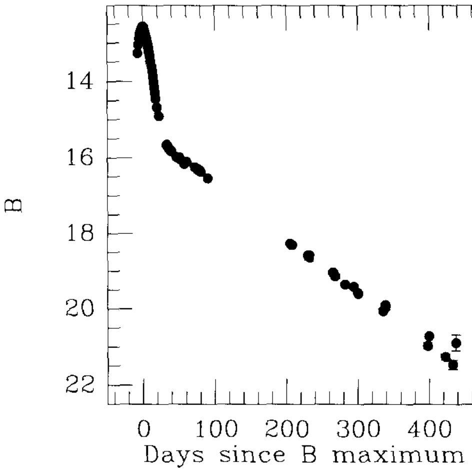

FIGURE 1. B magnitude light curve for the Type Ia SN1992A in NGC 1380

2. A Template Event: SN1992A

SN1992A was a Type Ia supernova discovered by Liller (1992) on 11.2 Jan 1992 (UT) in NGC 1380, an S0 galaxy in the Fornax cluster. Our initial observations showed that this was a typical Type Ia caught well before maximum. Its location in the periphery of the galaxy implied low reddening (an $E(B-V)$ reddening of 0.00 was estimated by Kirshner, *et al.* 1993) and very low galaxy background, making this an easy object to follow to faint magnitudes. Staff astronomers at CTIO immediately began an intensive $UBV(RI)_{KC}$ photometric and spectrophotometric study of the evolution of the object. A parallel effort to monitor the SN with HST and IUE (Kirshner, *et al.* 1993) was made by the HST SINS project group based at CfA.

In Figure 1 I present the B light curve from 92A through day 450 as an example of the quality of the data. No error bars are plotted if the errors are smaller than the symbol size. These data are based on CCD frames taken primarily at the CTIO 0.9m telescope. The data were calibrated relative to field stars in the frame, which were measured on ten photometric nights. Great care was made to measure the color terms of the filter/CCD photometric system to ensure that all the data are on a uniform photometric system. The color terms are averages of typically 5-10 nights of photometric solutions.

The B magnitude evolution in Figure 1 is quite typical for a Type Ia supernova. The SN was caught six days before B maximum which occurred on 19.0 Jan 1992 at B=12.56. The $(B-V)$ color at B maximum was 0.00 ± 0.02. The supernova passed through the photospheric phase and entered the optically thin "exponential tail" phase about 36 ± 2 days past B maximum. The exponential tail has an e-folding time of 76.8 ± 0.5 days and is extremely linear (in magnitudes) from day 36 to 450.

Our perception of the simplicity of the evolution of Type Ia events may be something of a historical accident since almost all light curves have been measured in blue light. The evolution in other colors is not as simple. In Figure 2 I present the $UBV(RI)_{KC}$ evolution of 92A from days –6 to +100. Whereas the UB light curves fall rapidly from maximum until about day 36 and then enter the exponential tail, the $V(RI)_{KC}$ light curves are much more complicated. The I_{KC} light curve reaches a secondary maximum around day 23, and both V and R_{KC} have associated inflection points at the same time. A secondary maximum similar to that seen in the I_{KC} light curve has been seen in the near-infrared by Elias, *et al.* (1985). Since there is evidence of a correlated inflection

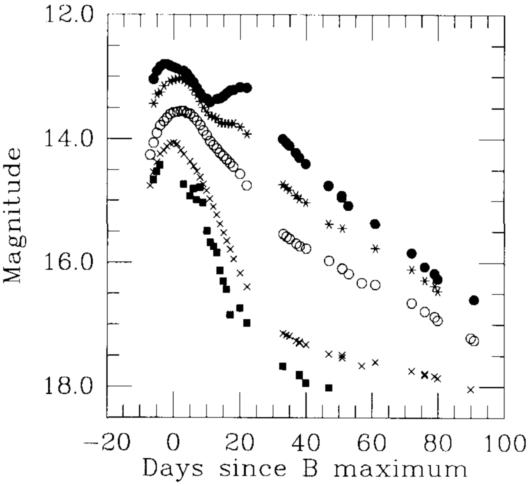

FIGURE 2. $UBV(RI)_{KC}$ evolution of SN1992A. The order of the curves is *IRVBU* from top to bottom. For presentation, the *R* curve was shifted by +0.5 mag, the *V* curve by +1.0 mag, etc.

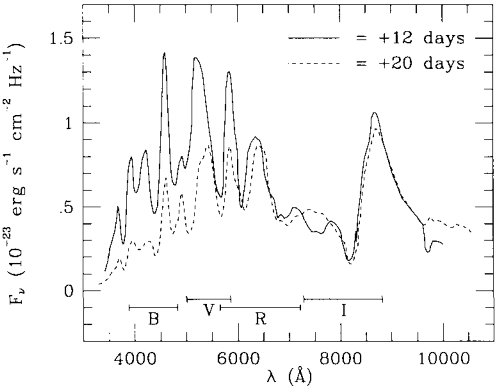

FIGURE 3. Spectrophotometry of SN1972E from Kirshner, *et al.* (1973). The two spectra were observed +12 days (solid line) and +20 days (dashed line) past *B* maximum.

from *V* out to *K*, it would be very difficult to explain this behavior simply as the variation of spectral features: instead, it seems that there is a redistribution of flux from the ultraviolet and blue to redder wavelengths. This redistribution can be best studied with spectrophotometry, but unfortunately, the published spectrophotometric coverage of Type Ia supernovae from days 0 to 30 that extends beyond 7000Å is almost non-existent. The best study to date is still the rather old Kirshner, *et al.* (1973) work on 72E. In Figure 3 I present two spectra from 72E taken on days 12 and 20. There are no obvious large changes in spectral features: rather, the evolution seems to be due to a general decrease in flux in the blue compared to the region redward of 6000Å.

Figure 2 also shows that the time of maximum light is quite different in the different bandpasses. One can see the well-known delay of the time of *V* maximum with respect to *B* maximum: in 92A the delay is $\sim 2.2 \pm 0.5$ days. The R_{KC} peaks at the same time as *V*, but the I_{KC} evolution near maximum is very complicated and apparently peaks at about 2.5 days *before* *B* maximum. The final peculiarity in the $V(RI)_{KC}$ light curves is that they only begin to fall at the e-folding rate of the *B* light curve after day ~ 100.

In Figure 4 I compare 92A with some other well-observed supernovae by shifting all the light curves to the same maxima in a given color, but with the time relative to the

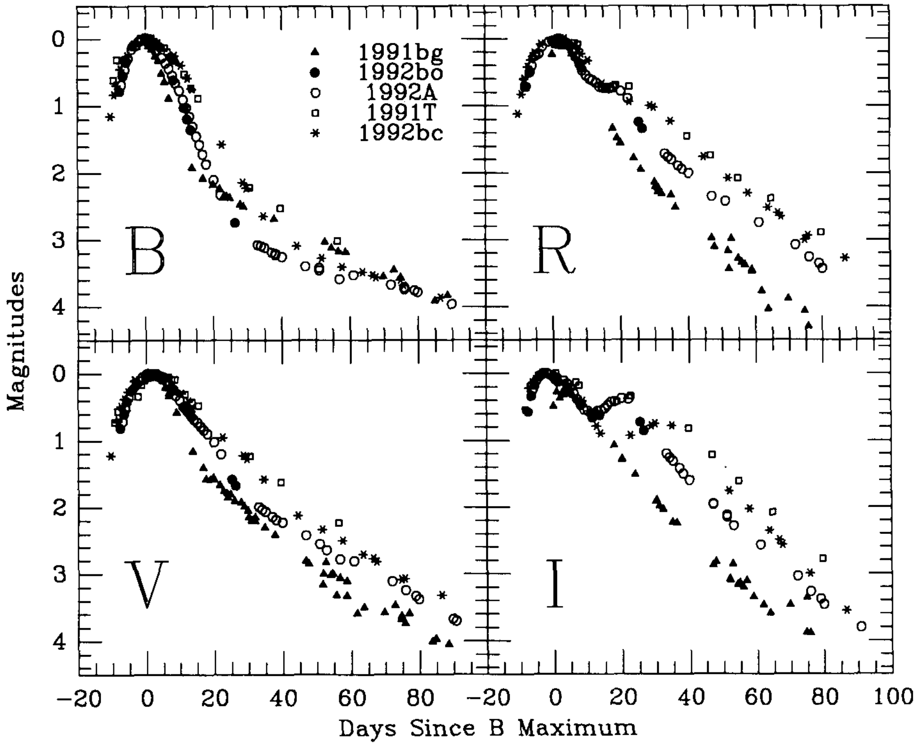

FIGURE 4. *BV* (left panel) and $(RI)_{KC}$ (right panel) evolution of bright Type Ia

time of B maxima. The comparison in the I_{KC} band is particularly difficult since the I_{KC} evolution near maximum light is quite variable among different supernovae. In the case of 91bg, I have aligned the light curve at day five. This figure reveals spectacular variations in light curve types, especially in the redder colors where most of the flux is produced. One gets the feeling from these diagrams that had the historical data been taken in the I_{KC} band rather than B, questions about the homogeneity of Type Ia events would have been raised much earlier.

The inhomogeneity of Type Ia light curves has been noted by many astronomers but the variations can be seen much more clearly in the CCD photometry. The most obvious variation in the B light curve is the "speed" of evolution away from maximum. A simple parameter β was invented by Pskovskii (1967) to describe this effect: Phillips (1993) has provided a similar but numerically more robust parameter Δm_{15} which is the difference in B magnitude between B maximum and 15 days after maximum. It can be seen in the data plotted in Figure 4 that Type Ia supernovae can differ by more than 1 magnitude in B at 15 days after maximum. Evidently "fast" supernovae such as 91bg both rise to maximum and fall from maximum in B more quickly than "slow" supernovae such as 91T or 92bc. Similar behavior is seen in V in Figure 4, but the differences in the evolutionary speed near maximum light seem to be less than in B.

The evolution from 20 to 100 days (when the B light curve is on the exponential tail) is dramatically variable in Type Ia supernovae, especially in the redder colors. While there is no clear trend in B evolution past day 25 as a function of Δm_{15}, in $V(RI)_{KC}$ the fast supernovae are clearly fainter. The spread in I_{KC} is as large as 2 magnitudes around day 50!

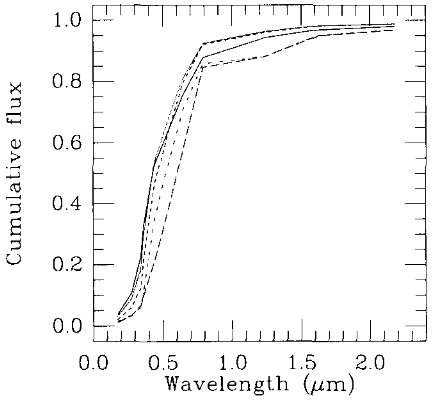

FIGURE 5. Cumulative flux distributions for SN1992A for days −6 to 80. At 3000Å the curves from top to bottom correspond to days −6, 0, 5, 20, and 77.

3. Bolometric light curves for Type Ia supernovae

A common assumption in past papers on the evolution of Type Ia supernovae was that the luminosity evolution of the supernova in some way mimicked the B evolution. From Figure 4 one can see that this is not a valid assumption. Recent careful modeling of the luminosity evolution of these supernovae has produced predicted BV colors based on the convolution of the appropriate filter bandpass and the predicted monochromatic fluxes. Given the uncertain nature of the monochromatic opacities (Harkness 1991), it is important to turn this problem around and try to predict the bolometric luminosity evolution based on the observed colors. The bolometric luminosity, calculated from the observed colors, is often called the "uvoir" bolometric luminosity to emphasize that it represents only the thermalized fraction of the total luminosity, and does not account for the energy escaping directly as gamma rays. Leibundgut & Pinto (1992) give a particularly clear discussion of the energy deposition rates in Type Ia supernovae where they show that by day 25, more than half the energy from the radioactive decay of ^{56}Co is freely escaping the supernova nebula.

To calculate the bolometric luminosity, we not only need $UBV(RI)_{KC}$ photometry, but also estimates of the ultraviolet fluxes below 3000Å and the near-infrared JHK colors. If dust forms at later epochs, mid-infrared colors also would also be needed. While there is no evidence to date which implies that dust forms in Type Ia events, there are so few infrared studies of Type Ia supernovae that one should not rule out the possibility. HST and IUE ultraviolet spectrophotometry for 90N and 92A through day 80 has been published by Kirshner *et al.* (1993), and the ultraviolet evolution, insofar as these SN are typical, is well established. The average JHK evolution based on a number of SN has been published by Elias *et al.* (1985). It is obvious, however, that there is variation among supernovae in the near-infrared, and a much larger survey of the IR evolution of supernovae is long overdue.

In Figure 5 I present the cumulative distribution of flux for 92A from day −6 to day 80. The space ultraviolet fluxes are taken from the Kirshner *et al.* (1993) work, and the infrared photometry is estimated from the average curve given in Elias *et al.* (1985) scaled to a single JHK measurement from ESO on day 4.5. This figure shows that the bolometric light curve is dominated by the optical flux. Even the earliest data at day −6 show that the flux below the optical window is only ~15% of the total and by day 5 it is well below 10%. Similarly the near-infrared adds at most ~10% to the total flux at early times and no more than about ~15% by day 80. The final bolometric light curve for 92A

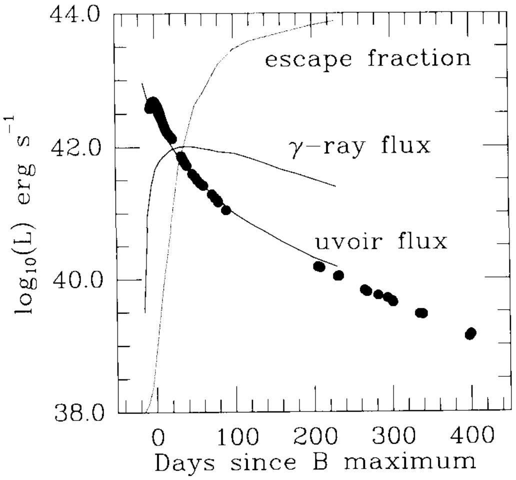

FIGURE 6. "Uvoir" bolometric light curve for SN1992A. The theoretical curves are from Leibundgut & Pinto 1992. The curve "γ" refers to the escaping γ-ray flux. The curve "uvoir flux" refers to the fraction of the γ-ray flux absorbed by the supernova nebula and re-radiated. The escape fraction of γ-rays is plotted with 0 at the bottom and 1 at the top. The theoretical curves have been shifted by $\Delta t = -20$ days, and the model fluxes reduced by 0.7 dex.

is given in Figure 6. For the data through day 100, I have included the HST ultraviolet fluxes in the calculation and the near-infrared fluxes from the scaled Elias *et al.* (1985) curve. For the data past day 100 we only have B to I_{KC} magnitudes. To calculate the late-time bolometric luminosity, I have estimated a "bolometric correction" based on the 92A data from days 75-90 where I have compared the total uvoir flux to that from the B to I_{KC} integration. This correction of 0.24 dex was added to the B to I_{KC} integration.

The bolometric luminosity plotted in Figure 6 has some unusual features. The maximum luminosity is ~42.65 dex, which is significantly less than a "standard model" of an exploding CO white dwarf at the Chandrasekhar mass which predict values closer to 43.3 dex (Arnett, *et al.* 1985). Either the distance scale chosen is grossly in error (the distances are based on the scales by Tonry using the surface brightness fluctuation [SBF] method, or Jacoby and collaborators based on the brightness distribution of planetary nebulae [PNLF]: see Jacoby *et al.* 1992 for a complete discussion of the distance scale problem) or this Type Ia supernova is underluminous with respect to the standard model. The other curious aspect of the bolometric evolution is the inflection in the light curve around day 20. It should not be surprising that the flux integration has not removed the inflection seen in the optical and near-infrared light curves since the inflection is seen in all colors redder than the B band. No model to date has predicted any inflection at this time in the light curve.

I have performed a similar calculation for 91T, 89B, and 91bg for the data through day 120 which is plotted in Figure 7. The 91bg curve is my preliminary estimate: Alain Porter will be publishing a more definitive curve including important new near-infrared photometry that was not available at the time of this article. The distance moduli and reddenings were taken from Phillips (1993). While one may disagree with the scale of the adopted distances, the internal agreement of the SBF and PNLF distance estimates of 5% (Jacoby *et al.* 1992) implies the *relative* distance scales are quite accurate. In Figure 7 one sees that there must be a range in a factor of 10 in the luminosities of Type Ia supernovae. Based on this data and a number of other bright supernovae, Phillips (1993) has shown that the spread in luminosities is well-correlated with the Δm_{15} parameter, in

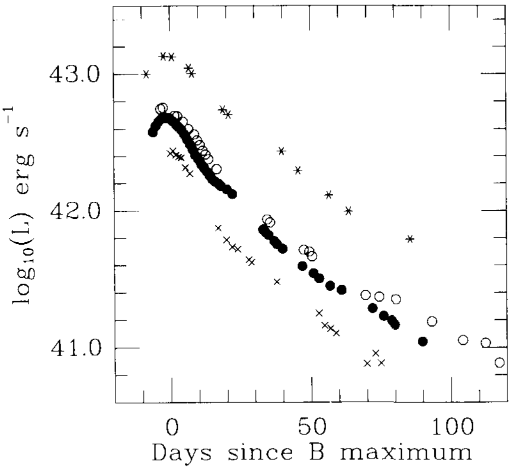

FIGURE 7. "Uvoir" bolometric light curves for (top to bottom) 91T, 89B, 92A, and 91bg

that "slow" supernovae such as 91T are more luminous than "fast" ones like 91bg or 86G. The relative luminosities also correlate well with spectral feature of SiII and TiII seen at maximum light (Phillips, private communication). The strong correlations between the intrinsic luminosities at maximum light and either the photometric or spectrographic characteristics around maximum light mean that is may well be possible that the intrinsic luminosity differences among Type Ia supernovae can be corrected to a "standard" Type Ia event.

The final question perhaps is "Are the majority of Type Ia supernovae homogeneous in luminosity near maximum light, except for a few peculiar ones like 91bg and 86G?" A number of authors, such as Branch & Tammann (1992) and Sandage & Tammann (1993) argue that in a sample of historical supernovae observed with photographic plates, peculiar supernovae are either rare or not important since sub-luminous supernovae will be less likely to be discovered in magnitude limited samples. It is curious however, that only recently have "peculiar" supernovae been accepted as a real phenomenon because of the high quality of the photometric CCD data. Why have almost all the peculiar events been discovered in the last 10 years with CCD photometry? The true incidence of peculiar events, or perhaps more realistically, of a range in luminosities, will only be measured through a systematic analysis of a flux-limited supernova search. A range in luminosity will be seen both as a steepening away from a slope of 5 (due to a Malmquist bias) and a real scatter in the maximum magnitude versus $\log_{10}(z)$ Hubble diagram. To this end, it is interesting to note that the Calán/CTIO survey for supernovae has discovered one supernova (92bo) out of a sample of 7 which appears to be underluminous by 0.8 in B and also has characteristically "fast" photometric behavior (Maza, *et al.* 1994 in preparation).

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