New Cosmological Data and the Values of the Fundamental Parameters
IAU Symposium, Vol. 201, 2005
Anthony Lasenby and Althea Wilkinson, eds.

The Rise Time of the Normal Type Ia SN 1990N

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Abstract. The earliest spectrum available of a well-observed, local type Ia SN, the UV-optical spectrum of SN 1990N obtained 14 days before B maximum, was modelled with a Monte Carlo code in order to determine its epoch and consequently the rise time from explosion to B max, which is important for fitting template light curves. If a standard density distribution and composition for the SN ejecta are used, and the Cepheid distance modulus to the host galaxy, NGC4639 in the Virgo cluster, $\mu = 32.0$, is adopted, the spectrum is best reproduced for an epoch $t = 5.5 \pm 1$ days, implying for the SN a rise time of 19.5 ± 1 days. For a shorter μ, t is smaller, but for a T-F distance $\mu = 31.4$ the solution is not consistent.

1. Introduction

The characteristic shape of their light curve is used to calibrate Type Ia Supernovae (SNe Ia) and to use them as cosmological standard candles. Phillips (1993) showed that brighter SNe Ia decline more slowly than dimmer ones.

Riess et al. (1995) introduced a more sophisticated method based on the entire shape of the early light curve, which allows the SN maximum brightness to be determined by comparison with a set of template light curves of objects whose distance is assumed to be known. This technique has been applied to distant SNe to derive cosmological parameters (Riess et al. 1998).

Using an alternative, but essentially similar approach, Perlmutter et al. (1997) used the 'stretch', namely the relative width of the light curve at $t = t(Max) + 15$ days, to normalise the SN brightness. This method introduces the rising part of the light curve, which is largely undersampled for most SNe Ia.

Theory suggests that the rise time t_r scales with the decline rate (Arnett 1996, p.455). For local SNe, $t_r = 19.5 \pm 0.2$ days (Riess et al. 1999b). However, Reiss et al. (1999a) suggested that t_r decreases with redshift, and that for distant SNe $t_r \sim 17$ days. This may be indicative of evolutionary effects.

It is therefore important to determine t_r. While data at very early epochs are not available, and since the results of synthtetic light curve calculations depend on assumptions made about the details of the explosion, we adopt a different approach: spectroscopic dating. Using our Monte Carlo code (Mazzali & Lucy 1993, Lucy 1999, Mazzali 2000) we modelled the earliest available well-observed spectrum of a local SN Ia: the UV (IUE)–optical spectrum of SN 1990N taken on 26 June 1990, 14 days before B maximum (Leibundgut et al. 1991).

2. Dating a SN spectrum

The early-time spectrum of a SN Ia consists of P-Cygni lines superposed on a pseudo-continuum, which is really due to line opacity. The P-Cygni absorptions form near the photosphere, and their blue-shift tracks the photospheric velocity v_{ph} closely. With time the photosphere recedes to lower velocity regions in the homologously expanding ejecta, and the lines drift slowly redwards. Which lines are present in the spectrum and their strength depends on the temperature. The basic relations are: $L = 4\pi R_{ph}^2 \sigma_B T_*^4$ and $R_{ph} = v_{ph} t$.

If we know the luminosity L (which implies we know the distance d) and measure v_{ph} from the line shift, there is one best value of the epoch t for which L and the photospheric radius R_{ph} give the best temperature T_* so that the spectrum can be reproduced. However, d is not usually known. A different combination of L and t can give the same T_* using the correct v_{ph}. Therefore, it is apparently not possible to determine t unless d is known, and viceversa.

However, since the density in the ejecta is a steep function of radius ($\rho \sim r^{-7}$, Nomoto et al. 1984), the same v_{ph} falls at different densities for different values of t. This results in different line strengths and in synthetic spectra with different properties, offering a way out of the indetermination of the problem.

3. Calculations for SN 1990N

We computed models on a grid of distances and epochs. We chose three values for the distance modulus to NGC 4639: a 'short', Tully-Fisher distance $\mu = 31.4$ ($d = 19.1$Mpc, Pierce 1994); a 'long,' Cepheid distance $\mu = 32.0$ ($d = 25.1$Mpc, Sandage et al. 1996); and an intermediate value, $\mu = 31.7$ ($d = 21.9$Mpc). We chose values of t between 3 and 7 days, i.e. risetimes of 17 to 21 days. This covers the likely range of possibilities (SN 1990N was discovered on 23 June 1990, 17 days before B maximum). The fractional variation of the epoch in our grid (more than a factor 2) is much larger than that of the distance (30%). For each value of μ and t we tried to obtain a best fit model (i.e. one with the correct temperature) by varying L and v_{ph}. We adopted $E(B-V) = 0.0$.

We used a W7 density structure (Branch et al. 1985) and abundances appropriate for the outer part of a SN Ia ejecta, where O and Si dominate. The consistence between the value of v_{ph} and the near-photospheric abundances is an important diagnostics. Another diagnostics is the radiation dilution factor W. This should be about 0.5 near the photosphere, but it can be smaller if v_{ph} is selected too large and not enough matter is present. On the other hand, if v_{ph} is too small and the photosphere is too deep W can be much larger than 0.5.

For $\mu = 31.4$ the flux is reproduced for $L = 1.2\ 10^{42}$erg. The spectrum is rather blue, requiring $T_* \sim 10^4$K. For $t = 5$, 6 or 7 days v_{ph} is small, and most lines are too red. Also, the photosphere is too deep, as indicated by the very large value of W, and the Si and Fe lines are much too strong. For smaller epochs a reasonable value of R_{ph} is achieved with higher v_{ph}. Both $t = 3$ and

$t = 4$d yield reasonable spectra, but the small epoch means that the density is rather high, and so W is again too large. The best estimate of the epoch at this distance is $t = 3.5 \pm 1$ days (a conservative error estimate). However, the fact that in all models $W > 1$ suggests that R_{ph} is always too small. Because this is the consequence of the small L, this distance is likely to be too small.

If $\mu = 31.7$, $L = 1.8 10^{42}$erg. The correct T_* is reached for $v_{ph} = 9000$km s^{-1} if $t = 7$d, and for $v_{ph} = 12250$ km s^{-1} if $t = 6$d. In both cases the velocity is small, and the Si and Fe lines are too strong. For $t = 5$d $v_{ph} = 16000$ km s^{-1}, and for $t = 4$d $v_{ph} = 14000$ km s^{-1}, which are reasonable values. For $t = 5$d W is large and the lines too deep. The $t = 4$d spectrum has a reasonable $W = 0.64$, and appropriate mass fractions for O (0.5), Si (0.2) and the Fe-group (0.1). Strong Si III lines may indicate that T_* is somewhat too high. Finally, for $t = 3$d, $v_{ph} = 17000$ km s^{-1} is required. This is the highest v_{ph} which can be used with the W7 density structure at this epoch. The ejecta mass above v_{ph} is only 0.03 $M_\odot$, and even at 3 days the density at this velocity is low and the spectral lines are very shallow. The best estimate of the epoch for this distance is then $t = 4.5 \pm 1$ days.

The required luminosity for a distance $\mu = 32.0$ is $L = 2.3\ 10^{42}$erg. Once again the smallest epoch, $t = 3$d, is ruled out because even the maximum allowed value $v_{ph} = 17000$ km s^{-1}, gives too hot a spectrum. At the opposite end, for $t = 7$d $v_{ph} = 13000$ km s^{-1} is rather small, and the Si and Fe lines are too strong. For the other values, $t = 4$, 5 or 6 days, reasonable fits can be found. The synthetic spectrum for $t = 4$d requires $v_{ph} = 17000$ km s^{-1}as for $t = 3$d. Therefore the densities are lower, and although the synthetic spectrum is reasonable some of the synthetic lines are too shallow, indicating that there is not enough material to form lines as strong as those observed. The spectrum for $t = 6$ d is probably still a bit too hot, as shown by the strong lines of Si III. The best spectrum is definitely that obtained for $t = 5$d. This was computed for $v_{ph} = 15750$km s^{-1}, and it has $T_* = 9100$K and $W = 0.54$. The best estimate of the epoch for this distance is then $t = 5.5 \pm 1$ days.

4. Conclusions

The epoch of an early SN spectrum can be determined to ±1 day for a given distance. For a very early spectrum, a difference of just one day in the assumed epoch results in a large change of the parameters (v_{ph}, abundances) required to obtain a good fit. These parameters can become incompatible with the observations. If a later spectrum is used, the uncertainty on the epoch is larger.

We can exploit some of the properties of the computation to select among different distances. In the particular case of SN 1990N, $\mu = 31.4$ appears to be small. In this case, in fact, L and R_{ph} are small, and W is large. Our best estimate is $\mu = 32.0$ and $t = 5.5 \pm 1$ days. A good fit using these parameters is obtained for $v_{ph} = 15200$km s^{-1} and abundances O=0.60, Si=0.10 by mass, yielding $T_* = 8900$K, $W = 0.57$ (Fig.1). The Cepheid distance is therefore an acceptable value, although a somewhat smaller distance is also reasonable.

This result implies for SN 1990N a risetime $t_r = 19.5 \pm 1$ days, which is in agreement with observational values. Since SN 1990N had rather a small $\Delta m_{15}(B)$ for a 'normal' SN Ia, it was probably on the bright side. It may be

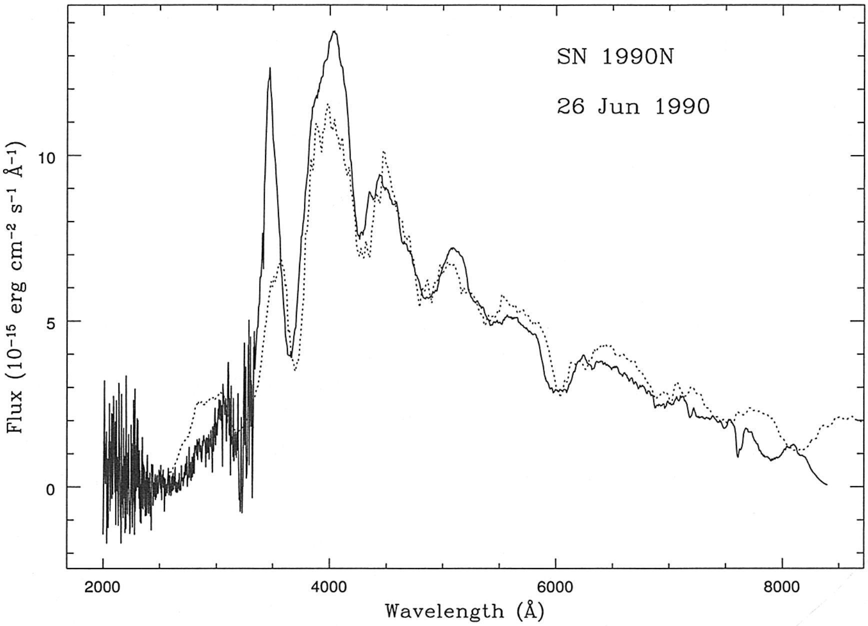

Figure 1. The −14d UV-optical spectrum of SN 1990N (solid line) compared to the synthetic spectrum for $\mu = 32.0$ and $t = 5.5$ days.

expected that t_r for dimmer objects having larger $\Delta m_{15}(B)$ is somewhat smaller. It will be interesting to verify this whenever very early spectra become available.

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