Memo 2.2.2: OBSERVATIONAL DIVERSITY AMONG TYPE Ia SUPERNOVAE

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The observational homogeneity of Type Ia Supernovae (SNe Ia) is impressive but not perfect. During the 1990s, much improved data made it possible to look seriously at the observational diversity. This, and associated ways to refine the use of SNe Ia as distance indicators, are the subjects of this memo. A much more extensive but not quite as up to date discussion of these issues, with relevant figures, can be found in a review article (Branch 1998). The status of our theoretical understanding of the diversity is discussed in Memo 2.3.

OBSERVATIONAL PROPERTIES OF NORMAL SNe Ia

The optical light curve (brightness versus time) of a normal SN Ia consists of an early rise and fall (the early peak) that lasts about 40 days, followed by a slowly fading tail. At maximum light the blue and visual absolute magnitudes at maximum light are $M_B \simeq M_V \simeq -19.4$, and the blue–minus–visual color index $B - V \simeq 0.0$ is roughly like that of a 10,000 K blackbody.

The spectral development closely conforms to a standard pattern. During the early "photospheric" phase the spectrum consists of a thermal continuum with broad line profiles superimposed. The "P–Cygni" type line profiles, consisting of unshifted emission peaks and blueshifted absorption troughs, are characteristic of spectral features forming in expanding atmospheres. Around the time of maximum light the most prominent features are produced by permitted transitions of Si II, Ca II, S II, O I, and Mg II. The characteristic widths and blueshifts of the features indicate that the line–forming layers expand at about 10,000 km s^{-1}. Blends of permitted Fe II P Cygni lines develop shortly after maximum light, and these gradually are replaced by collisionally–excited forbidden emission lines of iron and cobalt ions during the later "nebular" phase on the light–curve tail.

A ONE–DIMENSIONAL SEQUENCE OF SNe Ia

The discovery in 1991 of two conspicuously deviant SNe Ia motivated the splitting of the type into a majority subsample of "normals" and a minority of 'peculiars" (Branch, Fisher, & Nugent 1993). The most obvious peculiarity of SN 1991T was the presence in its early spectra of strong lines of Fe III rather than the lower–excitation lines of normal SNe Ia, indicating a higher than normal temperature. In addition, the light curve was mildly broader and brighter than normal. SN 1991T was an usually powerful SN Ia. At the other extreme, the spectrum of SN 1991bg contained low–excitation blends of Ti II lines in addition to the usual SN Ia features, indicating a subnormal temperature. Its light curve was narrower and dimmer than normal. SN 1991bg was an unusually weak SN Ia.

SNe Ia can be arranged in a one–dimensional sequence ranging from the peculiar powerful SN 1991T–like events through the normals to the peculiar weak SN 1991bg–likes. The first modern indication of this was provided by Phillips (1993), who confirmed a previous suspicion of Pskovskii that the peak luminosities of SNe Ia correlate with their immediate post–peak light–curve decline rates. More generally, a correlation between peak brightness and light–curve shape has been found to hold no matter whether the light–curve shape is quantified by means of the Δm_{15} parameter of Phillips (the decline in magnitudes of the B–band light curve during the first 15 days after maximum light), by the light–curve stretch parameter s of Perlmutter et al. (1999; the factor by which the shape of the light–curve peak is scaled in time to conform to a standard template), or by the more complex training–set MLCS (multi–color light curve shape) technique of Riess et al. (1998). Brighter SNe Ia have broader light curves.

Close examination of SN Ia spectra reveals that they too can be arranged in a one–dimensional sequence, and that the spectroscopic sequence parallels the light–curve sequence. Various ways of quantifying the spectroscopic diversity have been explored. The best known is the the $R(Si\ II)$ parameter of Nugent et al. (1995), which refers to the ratio of the depths of a neighboring pair of absorption features near 5800 and 6100 Å and has been shown to correlate well with the Δm_{15} parameter and the peak luminosity.

SN Ia properties also are correlated with the nature of their parent galaxies. Younger stellar populations have a statistical tendency to produce brighter SNe Ia (Hamuy et al. 2000).

The concept of a one–dimensional sequence of SNe Ia ranging from those having high–excitation spectra, slow light curves, high luminosities, and a tendency to come from younger stellar populations, to those having low–excitation spectra, fast light curves, low luminosities, and a tendency to come from older populations, is a useful one. A recent development that supports this view is the discovery by Li et al. (2000) that SN 1999aa (and some others like it) has observational properties that appear to fill the gap between the peculiar SN 1991T and the normal events. Similarly, Garnavich et al. (2001) present data on the well observed SN 1991bg–like event SN 1999by that support the view that these peculiar weak events form a smooth extension of the sequence of normal SNe Ia.

A one–dimensional sequence of SNe Ia is not, however, the whole story.

AT LEAST TWO DIMENSIONS

The observational diversity among SNe Ia cannot be entirely captured by a one–dimensional sequence. The clearest evidence is spectroscopic. SNe Ia having similar values of the $R(Si\ II)$ parameter show a substantial range of expansion velocities (Hatano et al. 2000) as inferred from the blueshift of the absorption produced by Si II λ6355. Figure 1 illustrates the spectroscopic diversity of spectra obtained about a week before maximum light. As the figure shows, SN 1984A had an exceptionally high expansion velocity, even though its $R(Si\ II)$ value was typical for a SN Ia. A plot of $R(Si\ II)$ against an expansion velocity parameter, for a sample of SNe Ia, appears in Memo 2.3.

Unfortunately, with present data it is difficult to determine how peak absolute magnitude correlates with expansion velocity, because reliable absolute magnitudes are available mainly for SNe Ia out in the Hubble flow where the relative distances are given to high accuracy by the redshifts while good spectra are available mainly for SNe Ia that are less distant and therefore observationally bright.

A very recent development is that the extremely well observed SN 2000cx turns out to be a strikingly peculiar SN Ia (Li et al. 2001). It had some of the characteristics of SN 1991T–like events, such as Fe III lines and a slow post–peak light–curve decline, but in other respects including a rapid rise to maximum brightness and an unusual color evolution, it was not like SN 1991T at all.

The available data are good enough to show that the SN Ia diversity is multi–dimensional but not extensive enough to tell us a great deal more than that. The "supernova factory" (Memo 2.2.3) is expected to provide the data to remedy this situation.

HIGH–REDSHIFT SNe Ia

The main concern about using high–redshift (high-z) SNe Ia for cosmology is the possibility that SN Ia "evolution" — systematic differences between the properties of local and high–z SNe Ia — could cause erroneous distances to be inferred for the high–z events. The data on high–z SNe Ia are of course not of the same quality as the best data on local SNe Ia; in particular, better spectra are needed. So far, systematic differences between the local and high–z events have not been found, either spectroscopically (Coil et al. 2000) or photometrically. In particular, the distributions of colors at maximum light and light–curve stretch factors for the two samples are very similar (Perlmutter et al. 1999; Goldhaber 2001). An apparent absence of SN 1991T–like events at high–z may or may not prove to be real (Li et al. 2000).

SNe Ia as STANDARDIZED CANDLES

Vaughan et al. (1995) proposed that a simple $B-V$ color cut, to simultaneosly eliminate SNe Ia that are highly reddened and extinguished by dust as well as those that are intrinsically red and subluminous, would yield a sample of nearly standard candles. Hamuy et al. (1996) found that using a color cut of $B-V<0.2$ to eliminate 3 of the 29 events in their sample of well observed SNe Ia in the Hubble flow produced absolute magnitude dispersions of only $\sigma(M_B)=0.24$ and $\sigma(M_V)=0.22$ (see the upper panel of Figure 2). And not all of this small dispersion is intrinsic to the supernovae. A color cut makes a very good start toward standard candles.

The most frequently used method to further standardize the peak absolute magnitudes of SNe Ia has been to rely on a correlation between absolute magnitude and some measure of light–curve shape (Riess et al. 1998; Perlmutter et al. 1999; Phillips et al. 1999). The amount of optical extinction is estimated from the observed colors on the assumption that the interstellar extinction law — the relation between the degree of reddening and the amount of optical extinction — is universal. These single–parameter photometric methods standardize SNe Ia well enough to give distances to within a dispersion of less than 10 percent. As shown by the bottom panel of Figure 2, when Δm_{15} is used to standardize the 26 non–red events of the SN Ia sample of Hamuy et al. (1996), $\sigma(M_V)$ reduces to only 0.14.

Two–parameter photometric luminosity corrections also have been introduced (Tripp & Branch 1999; Parodi et al. 2000). These do not distinguish between reddening by dust in the parent galaxies and intrinsic color differences among SNe Ia, but they do standardize SNe Ia luminosities to with the quoted observational errors.

Drell et al. (2000) pointed out that the application of different single–parameter light–curve standardization techniques gives different distances for individual high–z SNe Ia, and warned that this may be a sign of evolutionary effects that could produce spurious evidence for a cosmological constant. However, Leibundgut (2000) found that the same thing happens for the local sample. The problem may be due to the use of single–parameter corrections for multi–dimensional SNe Ia and/or to differences in allowing for extinction in the parent galaxies, rather than evolution.

It seems inevitable that there should be some evolutionary differences among the local and high–z samples, but as has been pointed out by many authors, the ranges in the ages and metallicities of the progenitors of local SNe Ia are so wide that there is no reason to expect to see SNe Ia at high–z that have no local counterparts. The best defense against distance errors due to evolution will be to have so much good data on both local and high–z SNe Ia that we can afford to be scrupulous about comparing only like with like. Events in one sample that don't have counterparts in the other (however interesting they may be physically) don't have to be used for distance determinations. Then we will be reying on SNe Ia that have the same spectroscopic and photometric characteristics to have the same absolute magnitude. This seems reasonable.

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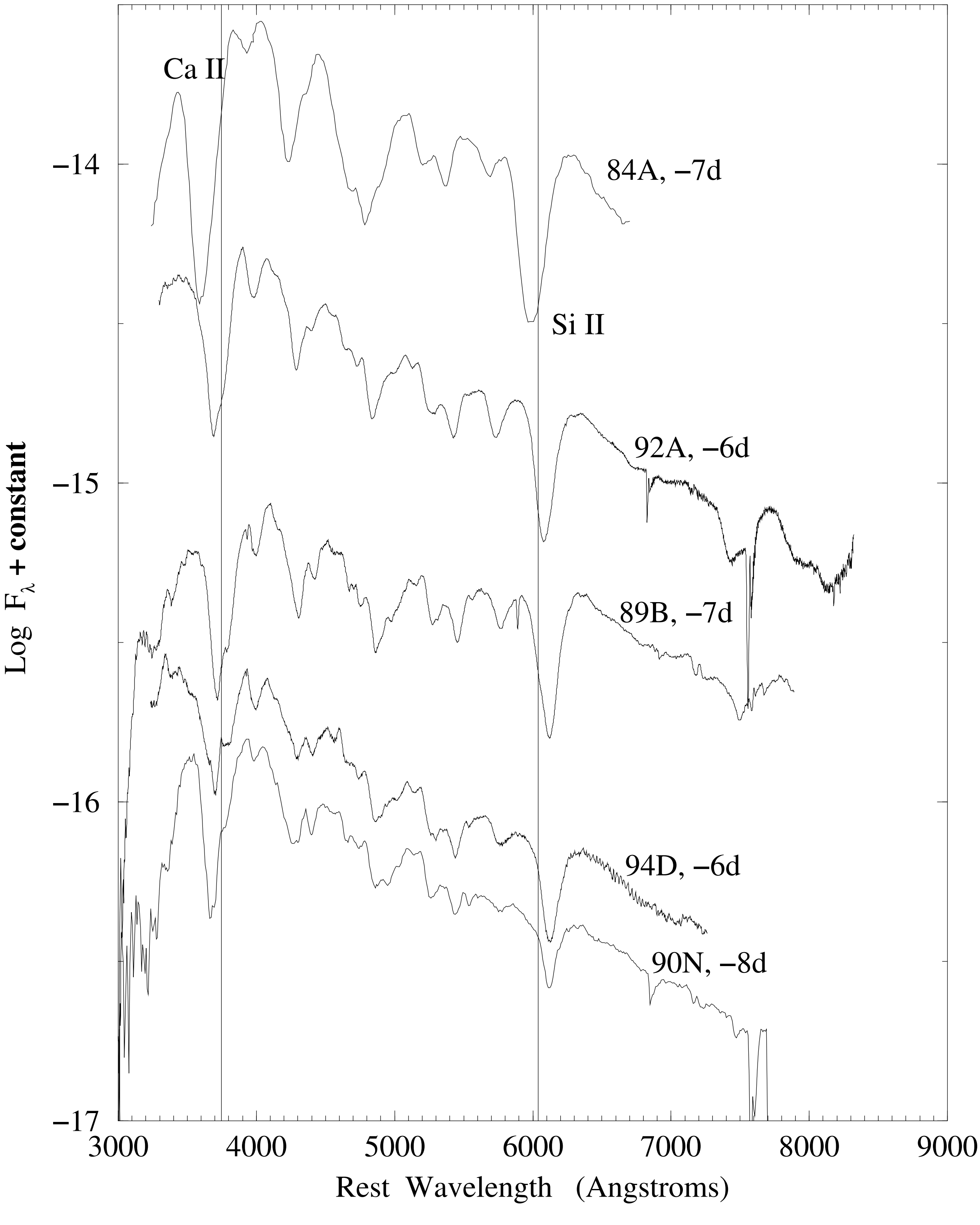

Figure 1: Spectra of 5 SNe Ia about a week before maximum light are arranged in decreasing order of expansion velocity. The vertical lines are blueshifted by 15,000 km s^{-1} with respect to Ca II λ3945 (the H&K blend) and Si II λ6355. From Hatano et al. 2000.

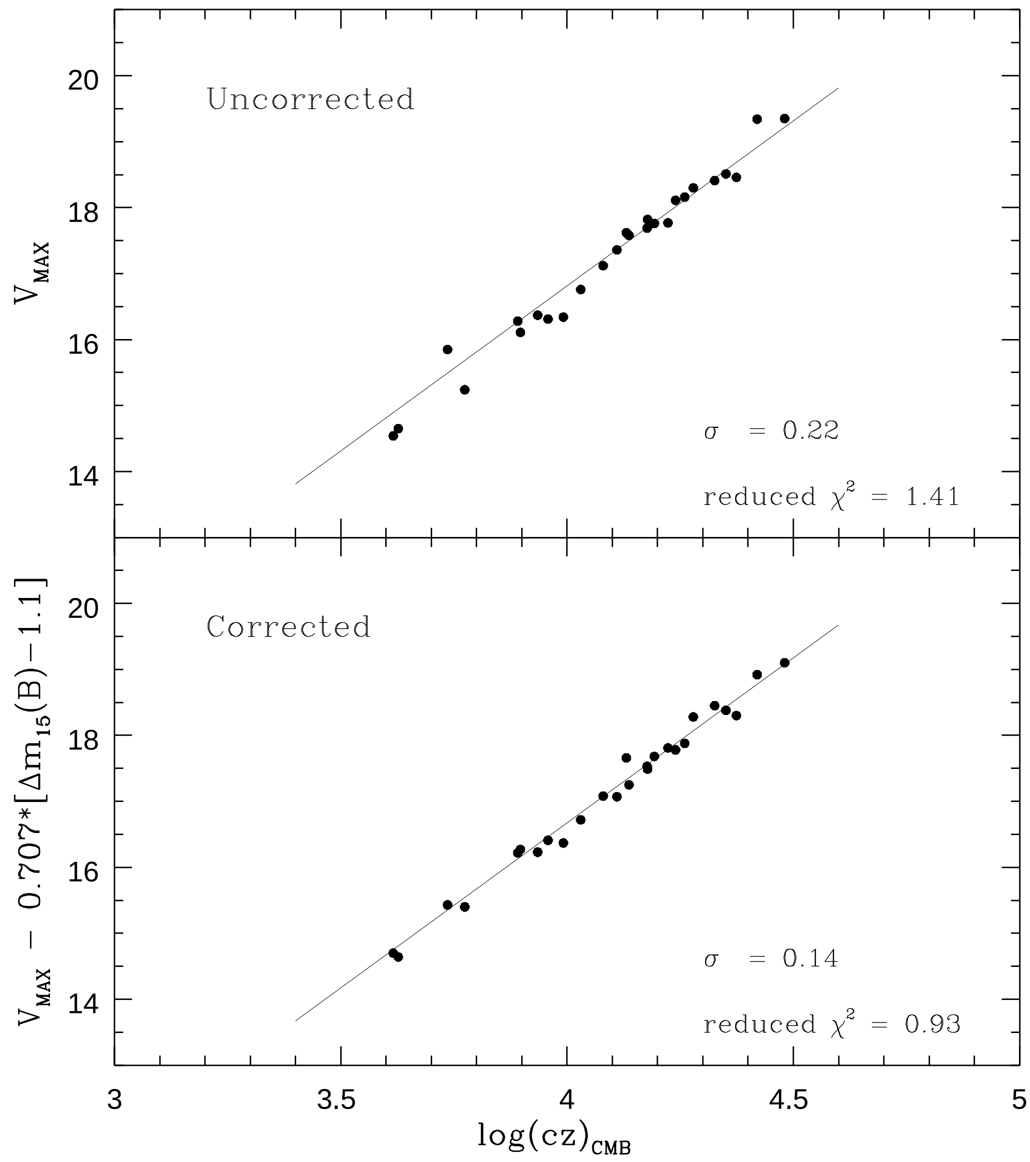

Figure 2: The Hubble diagram for 26 non–red SNe Ia. Ideal standard candles would fall on the solid line. In the upper panel, SNe Ia are treated as standard candles with no correction for extinction in the parent galaxies. In the lower panel, the SNe Ia are standardized by means of the Δm_{15} parameter. From Hamuy et al. (1996).