Memo 2.3: Theoretical/Phenomenological Understanding

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1 Introduction

This memo seeks to briefly summarize the current theoretical understanding of the explosion mechanism and the observed homogeneity and diversity among different SNe Ia.

2 Homogeneity

As has been discussed elsewhere in this volume, observationally the first thing one notices about SNe Ia is that they form a nearly homogeneous class of objects (this is of course only true to 0th order). Theoretically the observed homogeneity is assumed to derive from the fact that white dwarfs explode at a unique mass, the Chandrasekhar mass (about 1.39 $M_\odot$). The explosion is thought to occur when an white dwarf in a close binary system accretes material from a companion at the proper accretion rate, so that it can grow to the Chandrasekhar mass. In the single-degenerate scenario, the accreted material is thought to be hydrogen (or possibly helium) which burns stably on the surface of the white dwarf to carbon and oxygen. When the Chandrasekhar mass is reached the carbon and oxygen fuel begins to fuse to form ^{56}Ni (the most tightly bound nucleus with equal numbers of neutrons and protons). The details of the explosion mechanism are exceedingly complicated involving turbulent burning and the possible transition of a sub-sonic burning front (a deflagration) to a super-sonic shock wave (a detonation). Such deflagration to detonation transitions have been observed in terrestrial burning fronts.

At present, fully 3-D turbulent explosion calculations are beyond the range of current computational resources, although some exploratory calculations have been performed (see Khokhlov 2001; Hillebrandt & Niemeyer 2000, and references therein). Therefore, the best studied theoretical models are 1-D, and have a variety of physical and numerical assumptions. Nevertheless, at least three models do a pretty good job of reproducing observed spectra and light curves. The standard deflagration model, W7 (Nomoto et al. 1984), has been studied extensively and two delayed detonation models: DD4 (Woosley 1991), and M36 (Höflich 1995), have also received some detailed theoretical scrutiny. It is fair to say that particularly the outer parts of a normal SN Ia should look similar to the outer parts of these models.

Because of the physical assumptions involved in performing these calculations, no definite statement can be made on the nature of the progenitor system, i.e., whether the progenitor system is single-degenerate or double degenerate. Based on some recent calculations, there tends to be a predilection in the general community in favor of the single degenerate scenario, because of worries that it would be hard to produce an explosion in the double degenerate scenario (due to electron capture Mochkovitch et al. 1997), and it is harder to produce the observed rate with only the double degenerate scenario (see Ruiz-Lapuente & Canal 2001, and references therein).

3 Comparison to Observations

Observations of supernovae are obtained in two complementary forms. Photometric observations measure the total brightness in a reasonably broad band filter as a function of time (to create the light curve in a particular bandpass). Spectroscopic observations measure the spectrum of the supernova at a particular time and a time series of spectroscopic observations can be thought of as producing a CAT-scan of the supernova (discussed elsewhere in this volume) since the spectrum forms at different layers in the supernova atmosphere at different times and one sees deeper into the supernova as the material expands due simply to geometrical dilution.

Photometry is both easier to obtain and to calibrate than is spectroscopy.

However, since there is more information inherently in spectroscopic observations from the viewpoint of desiring to compare like-to-like, spectroscopy is preferred. From a theoretical point of view it is very difficult to see how two objects could have identical spectroscopic evolution and have differing peak magnitudes.

Light curves also suffer from a fundamental degeneracy when relating them back to physical models. The rise to peak magnitude depends only on the combination

$$\tau_{\rm rise} \propto (\frac{\kappa^2 M^3}{E})^{1/4}$$

where κ is an effective mean opacity, M is the ejected mass, and E is the kinetic energy in the ejected material. Thus, one can obtain similar *bolometric* risetimes with differing values of κ, M, and E as long as the combination is preserved. However, the colors (comparisons of photometry in different bands) give important information about the nature of the supernova and information on extinction due to dust.

Nevertheless, from a theoretical viewpoint, having both photometry and spectroscopy is the most desirable way to be certain that one is comparing like-to-like.

Detailed spectroscopic calculations with the W7 model compared to SN 1994D show that the outer layers of W7 (unburned carbon and oxygen) seem to do a very good job of reproducing the early observations (Lentz et al. 2001a). This is not unique to model W7, (cf. M36 Höflich 1995), but however shows that real "normal" supernovae should have this property.

Normal supernovae are defined by the spectroscopic criterion of Branch et al. (1993) and are likely to be the most useful objects for precision cosmology. The dim, 91bg-like objects, and the brighter, 91T/99aa/00cx objects, may well be correctable by standard methods. Alternatively these peculiar events can be eliminated from the observational sample based on their photometric and/or spectroscopic characteristrics.

4 Diversity

While there is clearly more than one parameter for diversity in SNe Ia, the width/shape of the light curve has been most thoroughly studied. The light curve shape has been parameterized by the number of B magnitudes that the light curve declines by 15 days after maximum light, Δm_{15}, (Phillips

1993; Hamuy et al. 1996), the stretch parameter, s (Perlmutter et al. 1997), and by the deviation from a training set of templates, (Riess et al. 1996). Except for SN 2000cx, it appears that the peak magnitude can be well determined by knowing the light curve shape and the color $(B-V)$ at maximum light. The most likely explanation for this is that the effective value of κ varies between different supernovae (Khokhlov et al. 1993). This diversity is also seen spectroscopically, and is often described by the parameter $\mathcal{R}$(Si II) (see Figure 1 and Nugent et al. 1995). Further support for the explanation that the first order diversity is due to variations in the effective value of κ comes from the fact that the spectroscopic variation at maximum light can be well reproduced by varying the effective temperature (which then alters the opacities).

5 Higher Order Diversity

Hatano et al. (2000) have recently shown that there exists another parameter in the observed spectra of SNe Ia near maximum light, the velocity of the Si II line (see Figure 2 from Hatano et al. 2000). The high velocity SNe Ia of Figure 2 seem to be well reproduced by certain delayed detonation models that have higher density in the outer parts after the explosion (Lentz et al. 2001b). How this parameter correlates (or if it correlates at all) with peak luminosity is still unknown. It is likely that a better observed sample (from the Supernova Factory and SNAP) will shed light on the nature of the variations among different SNe Ia.

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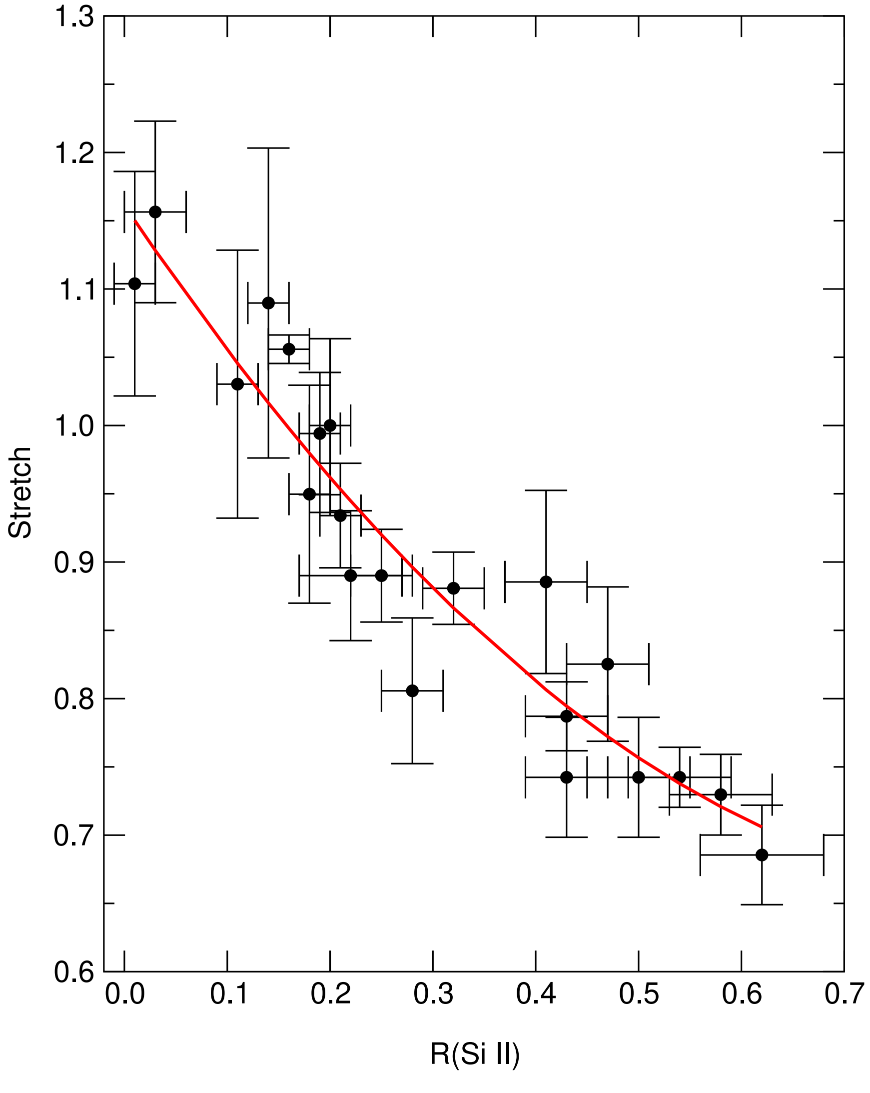

Figure 1: $\mathcal{R}$(Si II) parameter plotted against stretch. The correlation between these two distance independent variables is quite good. [Courtesy Peter Nugent, SCP]

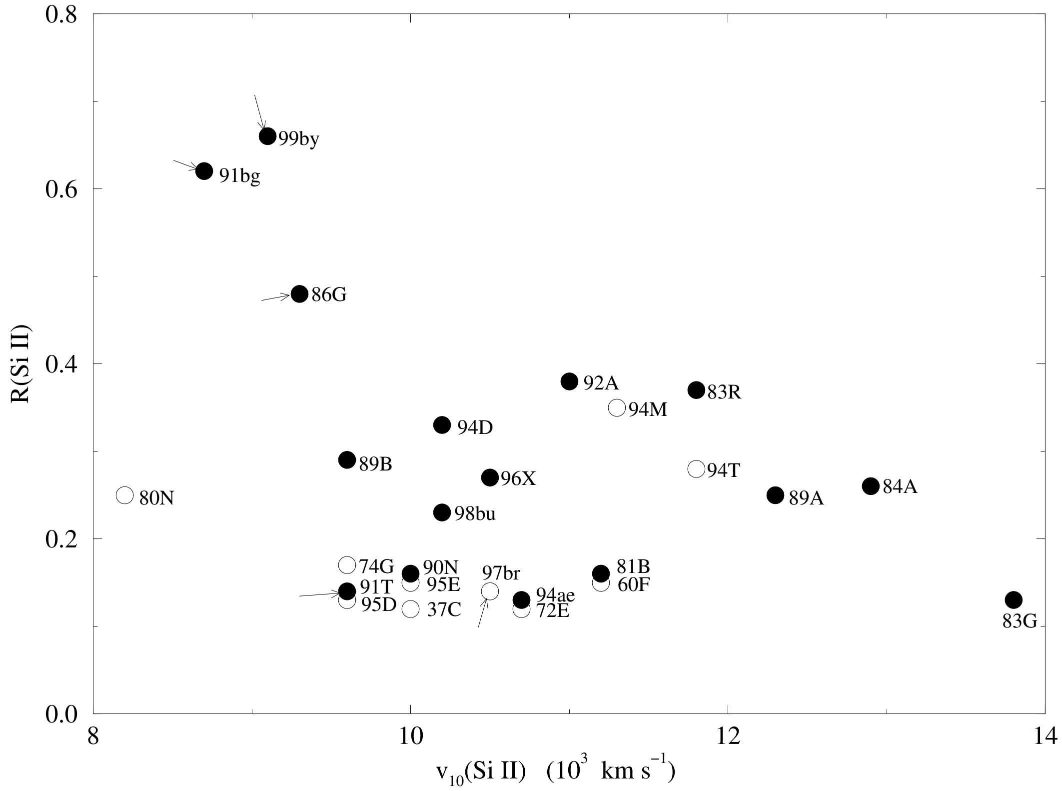

Figure 2: $\mathcal{R}$(Si II) parameter plotted against v_{10}(Si II), the Si II velocity 10 days after maximum. The arrows denote spectroscopically peculiar SNe Ia. The open circles mean that $\mathcal{R}$(Si II) has been obtained from a relation between Δm_{15} and $\mathcal{R}$(Si II). [From Hatano et al. (2000)].