Signatures of Explosion Models for SN Ia & Cosmology

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Abstract. Based on detailed models for the progenitors, explosions, light curves (LCs) and spectra, we discuss signatures of thermonuclear explosions, and the implications for cosmology. Consistency is needed to link observables and explosion physics. SNe Ia most probably result from the explosion of a degenerate CO-White Dwarf (WD) close to the Chandrasekhar mass. There is strong evidence that most of the WD is burned with an extended outer layer of explosive C-burning products (O, Ne, Mg) and very little C remaining. Overall, the chemical structure is radially stratified. This leads to the currently favored delayed detonation model in which a phase of slow nuclear burning as a deflagration front is followed by a detonation phase. The importance of pre-conditioning became obvious. Within a unified scenario, spherical models allow to understand both the homogeneity and basic properties of LCs and spectra, and they allow to probe for their diversity which is a key for high precision cosmology by SNe Ia. We emphasize the relation between LC properties and spectra because, for local SNe Ia, the diversity becomes apparent the combination of spectra and LCs whereas, by enlarge, we have to for high-z objects. We show how we can actually probe the properties of the progenitor, its environment, and details of the explosion physics. We demonstrate the influence of the metallicity Z on the progenitors, explosion physics and the combined effect on light curves. By enlarge, a change of Z causes a shift of along the brightness decline relation because Z shifts the balance between 56Ni and non-radioactive isotopes but hardly changes the energetics or the 56Ni distribution. However, the diversity of the progenitors produces an intrinsic dispersion in B-V which may pose a problem for reddening corrections. We discuss the nature of subluminous SN1999by, and how it can be understood in the same framework as 'normal-bright' SNe Ia. At the example of SN200du, we show the influence of the progenitor system and distribution of isotopes on light curves. In both objects, we have seen clear evidence for some departure from sphericity probably due to circumstellar interaction and stellar rotation but the 3D signatures of deflagration fronts remain an elusive feature.

1. Explosions, Light Curves and Spectra

The last decade has witnessed an explosive growth of high-quality data for supernovae. Advances in computational methods provided new insights into the physics of the objects, and advances in cosmology. Both trends combined provided spectacular results not only for astronomy and the origin of elements but also for nuclear, high energy and particle physics, and cosmology. Further improvements and the quest for the nature of the dark energy requires an increased accuracy for distance determinations from 10% to about 2 to 3% (Weller & Albrecht 2001) making evolutionary effects with redshift a main concern, and a better understanding of the physics of SNe Ia a requirement. There is general
agreement that Type Ia Supernovae (SNe Ia) are the result of a thermonuclear explosion of a degenerate C/O white dwarf (WD) with a mass close to the Chandrasekhar limit. These scenarios allow to reproduce optical/infrared light curves (LC) and spectra of SNe Ia reasonably well. Nowadays, we understand the basic, observational features. SNe Ia appear rather homogeneous because nuclear physics determines the structure of the WD, the explosion, light curves and spectra: (1) the WD is supported by degenerate electron pressure, (2) the total energy production during the explosion is given by the release of thermonuclear energy, and (3) the light curves are powered by the radioactive decay of $^{56}\text{Ni}$ produced during the explosion. To first order, the outcome hardly depends on details of the physics, the scenario, or the progenitor ("stellar amnesia"). Homogeneity of SNe Ia does not (!) imply a unique scenario, and it took the revolution in observational methods with respect to time and wavelength coverage to reveal differences and expose the diversity of within SNe Ia. For recent reviews see Branch (1999) and Höflich et al. 2003).
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Figure 3. Influence of the metallicity Z on the B and V light curves for a progenitor star of 7 $M_{\odot}$ on the main sequence based on a delayed detonation model. For the progenitor, Z/O/Fe] is taken according to Argast et al. 2000.

Figure 4. Analysis of the subluminous SN1999by. We show IR-spectra at day 11 (upper left), the B and V light curves (right plots), and the chemical structure (lower panel). The explosion and evolution of the spectra are calculated self-consistently with the only free parameters being the initial structure of the exploding White Dwarf, and a parameterized description of the nuclear burning front. Without further tuning, the spectra and their evolution with time can be reproduced. Up to maximum light, the spectra are formed in layers of explosive C-burning, followed by the layers of incomplete Si burning. The long duration of these phases provides a lower limit for the initial WD mass which is close to the Chandrasekhar mass. Unburned material is restricted to the high velocity regime, i.e. the very outer layers. This strongly supports DD models for both the normal bright and subluminous SNe Ia.

A detailed discussion is well beyond the scope of this contribution. We want to illustrate some aspects and, for details, refer to the original publications.

- Consistency is required to link the observable and the progenitor system, progenitor and explosion physics. By the physical conditions, consistency is also demanded for the treatment of hydrodynamics, rate equations, and radiation transport (Fig.1). Density structures require detailed hydrodynamics, low densities cause strong non-LTE effects throughout the entire envelopes and the radiation field differs from a black body, chemical profiles are depth dependent, energy source and sink terms due to hydrodynamical effects and radioactive decays dominate throughout the photon decoupling region, and all physical properties are time-dependent because the energy diffusion time scales are comparable to the hydrodynamical expansion time scale (H"offlich, 1995). Our approach significantly reduces the number of free parameters, namely the initial structure of the progenitor, the accretion rate on the WD, and the description of the nuclear
Figure 5. High velocity CaII feature as tell-tail for interaction within the progenitor system. We show the CaII IR feature observed in SN 2003du on May 6th in comparison with theoretical models at about 15 days after the explosion (upper right), and its evolution with time (left). The calculations are based on a delayed detonation model which interacted with a nearby, shells of 0.02 $M_\odot$ and solar composition during the early phase of the explosion. The dominant signature of this interaction is the appearance of a persistent, secondary, high velocity Ca II feature. Without ongoing interaction, no H or He lines are detectable. Note that, even without a shell, a secondary Ca II feature can be seen for a period of 2 to 3 days during the phase when Ca III recombines to Ca II emphasizing the importance of a good time coverage for the observations. Nearby shells mainly change early time LCs (lower right) due to blocking by Thomson optical depth in the shell. In contrast, ongoing interaction will change the late time luminosities (from Gerardy et al. 2004).

burning front. The light curves and spectral evolution follow directly from the explosion model without any further tuning.

- The best current explosion scenario is the delayed detonation (DD) model (Khokhlov 1991). These models reproduce reasonable well the color evolution of optical and IR-LC, and the spectral evolution of both normal bright (Höflich 1995) and subluminous SNe (Fig. 4, Höflich et al. 2002) within a unified scenario. By enlarge, DD models produce radially stratified chemical structures for elements of explosive carbon, oxygen and Si burning in agreement with the observations from the optical and near IR (e.g. Fig. 4, Barbon et al. 1989, Wheeler et al. 1998, Marion et al. 2003) The brightness decline relation (Phillips 1993) can be understood as an opacity effect (Fig. 3, Höflich et al. 1996, Maeda et al. 2003) including the color evolution in B-V and the brightness range (Fig. 2 Höflich et al. 2002) by varying a single, free parameter for the amount of burning when the deflagration turns into a detonation which determines the pre-expansion of the WD. In spherical models, this quantity is often parameterized by a transition density $\rho_{tr}$. Other properties produce a dispersion. E.g. changes in the progenitor, i.e. in main sequence mass $M_{MS}$ and $Z$, alter the explosion energy and $^{56}$Ni mass, respectively, but, by enlarge, along the $M_V$($^{56}$Ni) and $\Delta M_V$(15d) relations (Höflich et al. 1998, 2001). However, the diversity in progenitors cause an intrinsic dispersion in B-V of 0.1 which, in practice, seriously hampers the corrections by interstellar reddening.
Figure 6. Late time IR-spectra a probe of the isotopic structure and its influence on the optical light curves. On the left, we give the NIR spectrum of the "Branch-normal" SN 2003du on Feb. 27, 2004 with Subaru, in comparison with the theoretical line profiles (solid thick line) based on a DD model with a central region consisting of non-radioactive iron group elements. In addition, the individual components of the forbidden [Fe II] transition at 1.644 $\mu$m are given for the original delayed detonation model (solid) and mixed chemistry (light) normalized to the maximum line flux (dotted) and the wings (dashed), respectively. Mixing of the inner iron-rich layers of $^{56}$Ni and stable isotopes (Fig. 4) is to be expected from current 3D models during the deflagration phase which is dominated by RT instabilities, and would produce round profiles which seem to be at odds with the observations. Possible explanations may be that small-scale, pre-existing velocity fields are important for the propagation of nuclear flames. On the right, the visual light curve and $(B-V)$ are given for the same delayed detonation model but with and without mixing of the inner layers. Differences in V and B-V are $\approx$0.2 and 0.05, respectively. In effect, mixing redistributes $^{56}$Ni from the outer to the inner layers which decreases the photospheric heating at about maximum light but increases the $\gamma$-trapping later on (from Höflich et al. 2004).

- The IR is a primary tool to study intermediate mass elements, and spectropolarimetry and line profiles allow to probe for 3-D signatures (Höflich 1991, Wang et al. 1997, Bowers et al. 1997, Wheeler et al. 1998, Howell et al. 2001, Höflich et al. 2002).
- Our models allow to study particular physics and relations to the properties of the progenitors in "isolation" such as signatures of the progenitor system (Fig. 5, Gerardy et al. 2004) and the distribution of neutron rich isotopes (Fig. 6, Höflich et al. 2004). In extensive studies, we investigated the influence of the central density of the WD, the ignition process, and metallicities (which are expected to change with time) (Höflich et al. 1998, 2001, Dominguez et al. 2002, see also Timmes et al. 2003). Pre-conditioning of the WD is a key to understand the diversity of SNeIa. Metallicity will effect the statistical sample because it changes the life times and radii of stars and, consequently, the binary system with mass overflow, and the physics of individual objects. A change of metallicity or progenitor MS mass effects both the progenitor evolution, WD structure and the observable LC shapes simultaneously, and the combined effect must be considered when comparing to observations. As can be seen from Fig. 3. The change of the initial Fe changes the core He burning during the stellar
Figure 7. Analysis of 3D effects in the subluminous SN1999by based on flux and polarization data. **Upper panel:** Comparison of the NIR spectrum on May 16 (left) with a spherical, subluminous delayed detonation model without and with mixing as expected from detailed 3-D deflagration models (Khokhlov, 2001) which does destroy any fit due to excitation of intermediate mass elements (S, Si), and the absorption by iron-group elements. **Lower, left panel:** Energy deposition by γ-rays at day 1 (left) and 23 (right) for a 3D deflagration model based on our full 3-D MC gamma ray transport. At about day 23, the energy deposition is not confined to the radioactive $^{56}Ni$ ruling out clumpiness as a solution to the excessive excitation of S and Si lines. **Lower, right panel:** Optical flux and polarization spectra at day 15 after the explosion for the subluminous 3-D delayed-detonation model in comparison with the SN1999by at about maximum light. In the observations, the polarization angle is constant indicating rotational symmetry of the envelope, and an axis ratio A/B of 1.17 (from Höflich et al. 2002, Höflich 2002, Howell et al. 2001).

evolution which determines the C/O ratio, whereas the $^{22}Ne$ directly effects the explosive nuclear burning by shifting the Nuclear Statistical Equilibrium slightly away from $^{56}Ni$. The former effect alters the energetics of the explosion (explosion energy) whereas the latter changes the energy gain by radioactive decay of $^{56}Ni$ which powers the LCs. For low metallicities, the influence of the energetics dominates the changes in the LC shape. It causes a change $\Delta t_{\text{rise}}$ of the rise-time for a given decline ratio and, thus, an offset $\Delta M$ in the brightness decline relation by $\Delta M \approx 0.1 \times \Delta(t_{\text{rise}})$.

These results do not (!) imply that all processes involved are spherical in nature but they are a result of the 'stellar amnesia' mentioned above, i.e. the properties depend mostly on integral quantities and basic nuclear physics. Despite the successes of spherical delayed detonation models, it becomes increasingly obvious that multidimensional effects are important towards a better understanding of SNe Ia.

- Asymmetries in a SN Ia may be present for a variety of reasons. Within the framework of the explosion of a massive WD, reasons and all seems to be realized. Reasons include instabilities in the burning front (Khokhlov 1995,
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2001, Reinecke et al. 2002 Gamezo et al. 2003), namely the deflagration phase, off-center detonations or the transitions from deflagration to detonation (Livne 1999), rapid rotation of the WD, and interaction with the accretion disk and the companion star. Whereas we have evidence for the existence of the latter effects, direct evidence is still elusive for the RT instabilities or, more precisely, such evidence has not been seen although it was expected (Figs. 4 & 6).

Both from the remnants and the lack of strong polarization in thermonuclear supernovae, limited scattering in brightness, we can conclude that the envelopes have rather small global deviations from spherical geometry of the order of 5 to 20%. For cosmology, deviations from sphericity will introduce a directional dependence of the luminosity of the order of about 4-6%.

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