SN Ia Diversity: Theory and Diagnostics

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Existing evidence of photometric and spectroscopic diversity among Type Ia supernovae is compared with the predictions from physical modeling of the explosions. Concerning light curves, changes in the central ignition density of massive ($M \simeq M_{Ch}$) C+O white dwarfs alone do not give appreciable variation. Spectroscopic diversity has been found in the nebular phase, the underluminous SN 1991bg providing an extreme case. A range of 0.4–0.8 $M_\odot$ of ^{56}Ni synthesized in the explosions is derived from the nebular spectra of a sample of SNe Ia. For SN 1991bg, however, a ^{56}Ni mass of $\sim$ 0.1 $M_\odot$ only is obtained. That leads us to explore models based on the detonation of low–mass WDs for this SN. Additionally, a nebular spectrum of SN 1991bg shows narrow Hα emission at the position of the SN. If this emission is confirmed against background contamination from the galaxy, it would be first evidence of a nondegenerate, H–rich companion in a SNIa.

1. Introduction

Type Ia supernovae (SNIa) are attributed to the thermonuclear explosion of C+O white dwarfs. Explosive ignition would be the outcome of accretion of matter from a close companion in a binary system and it would completely burn the star, leaving no bound remnant. In most models, explosive C burning starts at the center of the WD as a result of the increase in density and temperature induced by quasistatic mass growth. Explosive ignition densities (determined by the thermonuclear reaction rates in the strong–screening/pycnonuclear regime) always are $\rho_{ign} \gtrsim 2 \times 10^9 g\ cm^{-3}$, which means that the WD mass is $M \gtrsim 1.37 M_\odot$, thus very close to the Chandrasekhar mass for a ^{12}C+^{16}O mixture ($\simeq$ 1.45 $M_\odot$). The exact ignition density depends on the mass–accretion rate and also on the mass and temperature of the WD at the start of the accretion process (Hernanz *et al.* 1988), but the range of masses allowed by those models is very small ($\Delta M \lesssim 0.1 M_\odot$). This provides the main theoretical basis to the claim that SNIa explosions are very homogeneous and can thus be used as standard candles for extragalactic distance determinations.

In the "standard" model outlined above, one big unknown is the mechanism that propagates the burning from the center to most of the mass of the WD. Burning might propagate supersonically all the way from the center to the surface, as a *detonation* (Arnett 1969). It might also start subsonically and remain so until being quenched by the expansion of the star (driven by the pressure waves that run ahead of the burning front), as a *deflagration* (Nomoto, Thielemann & Yokoi 1984; Sutherland & Wheeler 1984; Woosley, Axelrod & Weaver 1984). Or, finally, it might start subsonically, as a deflagration, and at some point turn supersonic (*delayed detonation*: Khokhlov 1991; Woosley 1992). Complete detonation of massive ($M \simeq M_{Ch}$) C+O WDs would incinerate the whole star to Fe–peak elements (due to the overall high densities) and thus appears incompatible with the presence of lines of intermediate–mass elements (O through Ca) in the spectra obtained around maximum light (Woosley & Weaver 1986). Deflagrations can produce more admissible explosions, but since the propagation of burning depends on the development of hydrodynamic instabilities (in full 3–dimensions) there is currently no way to predict the velocities of the flame front (see, however, Arnett and Livne, this volume, for recent progress). Delayed detonations can also produce acceptable explosions (even with some advantage over pure deflagrations as to the nucleosynthesis of neutron-rich Fe–peak nuclides), but they add to the uncertainties of the initial, subsonic stage, that of the point where the burning becomes supersonic (delayed detonations induced by pulsation do not escape this, since the occurrence and characteristics of the pulsation depend on the velocities of the subsonic flame along the previous stage and the start of the detonation is hypothetical).

In the massive C+O WD model, the material accreted from the companion can, in principle, have any chemical composition but it has to be effectively incorporated into the degenerate core to make its central density grow. Lighter material (H, He) has thus to burn (nonexplosively) into C+O in the outer layers. One popular scheme avoids this restriction by having another, less massive C+O WD as the companion of the mass–accreting one (Iben & Tutukov 1984). The actual dearth of suitable systems in the Galaxy now casts strong doubts on this scheme (see Renzini, this volume) and it has renewed interest on the ones where the companion is nondegenerate and has a H–rich envelope (*symbiotic stars*, for instance).

Statistical arguments (Kenyon *et al.* 1993) seem to preclude massive WDs in symbiotics as the progenitors of most SNIa. Lower–mass WDs should thus also be considered. C+O WDs with masses significantly below M_{Ch} cannot be made to explode by quasistatic accretion, but they can do it if they are *dynamically* compressed. That can be achieved by shock waves originated by explosive burning of the outer layers. *He detonation* (either of the He accumulated from burning H or of that accreted from a He–rich companion) has been pointed out as a likely mechanism (Livne 1990; Livne & Glasner 1991; Woosley & Weaver 1993; see also Livne, this volume). It induces C detonation near the center of the low–mass C+O WDs. The difficulty encountered in the detonation of *massive* WDs no longer holds here, since at lower densities detonation leads to partial burning only and thus produces intermediate–mass elements as well as the Fe–peak ones. A much wider range of masses ($M \sim 0.5 - 1.3\ M_{\odot}$) can work in the detonation model, in contrast with the very narrow range of the "standard", massive WD model.

From the observational point of view, the claimed homogeneity of SNIa is also increasingly challenged. The light curves of different events span a sizeable range and there even seems to be a correlation between peak luminosity and the slope of the light curve after maximum (see Suntzeff, this volume). The recent SN 1991bg has been extremely underluminous (Filippenko *et al.* 1992a; Leibundgut *et al.* 1993; Phillips *et al.* 1993). Spectroscopic diversity is seen in the spectra around maximum (see Filippenko, this volume), and premaximum spectra of the superluminous SN 1991T (Filippenko *et al.* 1992b; Ruiz–Lapuente *et al.* 1992) significantly differ from those of the more "standard" SN 1990N (Leibundgut *et al.* 1991). Differences are also found between nebular spectra of diverse SNIa (Ruiz–Lapuente & Filippenko 1993), SN 1991bg being again an extreme case (Ruiz–Lapuente *et al.* 1993a). In the following we will outline the range of variability allowed by current models and also the diagnostics that can be obtained from modeling of the spectra (especially in the nebular phase) concerning the mass of the progenitors, the explosion mechanism, and also the nature of the companions of the exploding stars.

2. Models and Diagnostics

Let us consider first the range of variation in the observable characteristics of the explosions (peak luminosities, light–curve shapes, spectral evolution) allowed by the "standard", massive C+O WD model. As we have already pointed out, within its very narrow mass interval a sizeable range of explosive ignition densities is possible, depending on the initial mass of the WD, its temperature, and the accretion rate. It is $2-3 \times 10^9 g\ cm^{-3} \lesssim \rho_{ign} \lesssim 1.5 \times 10^{10} g\ cm^{-3}$ (Hernanz *et al.* 1988). The upper part of this range ($\rho_{ign} \gtrsim 8 - 8.5 \times 10^9 g\ cm^{-3}$), however, would probably lead to gravitational collapse rather than to thermonuclear explosion (Timmes & Woosley 1992, 1994; García *et al.* 1993). In the remaining density range, the dynamics, nucleosynthesis and light curves of explosions corresponding to different ignition densities and different explosion mechanisms (deflagrations and delayed detonations, with diverse prescriptions and parameters for the propagation of burning) has been systematically explored (Canal *et al.* 1991; Bravo *et al.* 1993). The conclusion is that, for a given mechanism and fixed prescription and parameters, variation in the ignition density alone, within the preceding range, gives almost constant peak luminosity and only minor variations in light curve shape and expansion velocity of the photospheric material.

Larger variations are of course possible if we allow changes in prescriptions and parameters within a given mechanism (in fact, both pure deflagrations and pure detonations are limiting cases of delayed detonations). The problem here is that we have no criterion to determine prescriptions and parameters from the characteristics of a given evolutionary scheme. Models of the light curves and spectra are, in principle, powerful diagnostic tools. Optical luminosities at any stage of SNe Ia depend on the amount of radioactive Ni (^{56}Ni) initially synthesized in the explosion, its distribution within the ejecta, on the total mass of the object, and on the velocity of the ejecta, all these factors entering in the fraction of energy deposited from γ–rays and positrons originated in the decay chain ^{56}Ni→^{56}Co→^{56}Fe. Optical spectra reveal the chemical composition of the material and its distribution in velocity space.

With the possible exception (to be discussed below) of SN 1991bg, no known SNIa light curve cannot be acceptably adjusted within the "standard" model if we allow significant variations of the explosion prescriptions and/or parameters from one explosion to another. Simultaneous measurements of optical magnitudes and γ–ray line fluxes can further restrict the models. In the case of SN 1991T, the lack of detection of the 847 keV line by COMPTEL, together with the measured apparent blue magnitude (m_B) at the same epoch has discarded many variations of the "standard" model (Ruiz–Lapuente *et al.* 1993b, see Höflich *et al.* 1993 for a discussion on the models proposed by these authors).

Photospheric spectra of SNe Ia have been calculated, up to now, mostly for deflagration models (Wheeler, Swartz & Harkness 1993; see Eastman, this volume, and Kirshner *et al.* 1993 for more recent developments). They have chiefly been compared with the spectra of the "standard" SNIa SN 1981B around maximum and the agreement is good. Premaximum spectra of the "normal" SN 1990N and of the "peculiar" SN 1991T have also been calculated from *ad hoc* modifications of the "standard" deflagration model W7 (Nomoto, Thielemann & Yokoi 1984). Jeffery *et al.* (1992), using a LTE procedure, find that SN 1990N might be consistent with the W7 model, except for the outer, higher–velocity material, and that the chemical composition of the outer layers of SN 1991T departs both from that of SN 1990N and from that predicted by the W7 model. From a NLTE analysis, Ruiz–Lapuente *et al.* (1992) conclude that the premaximum spectra of

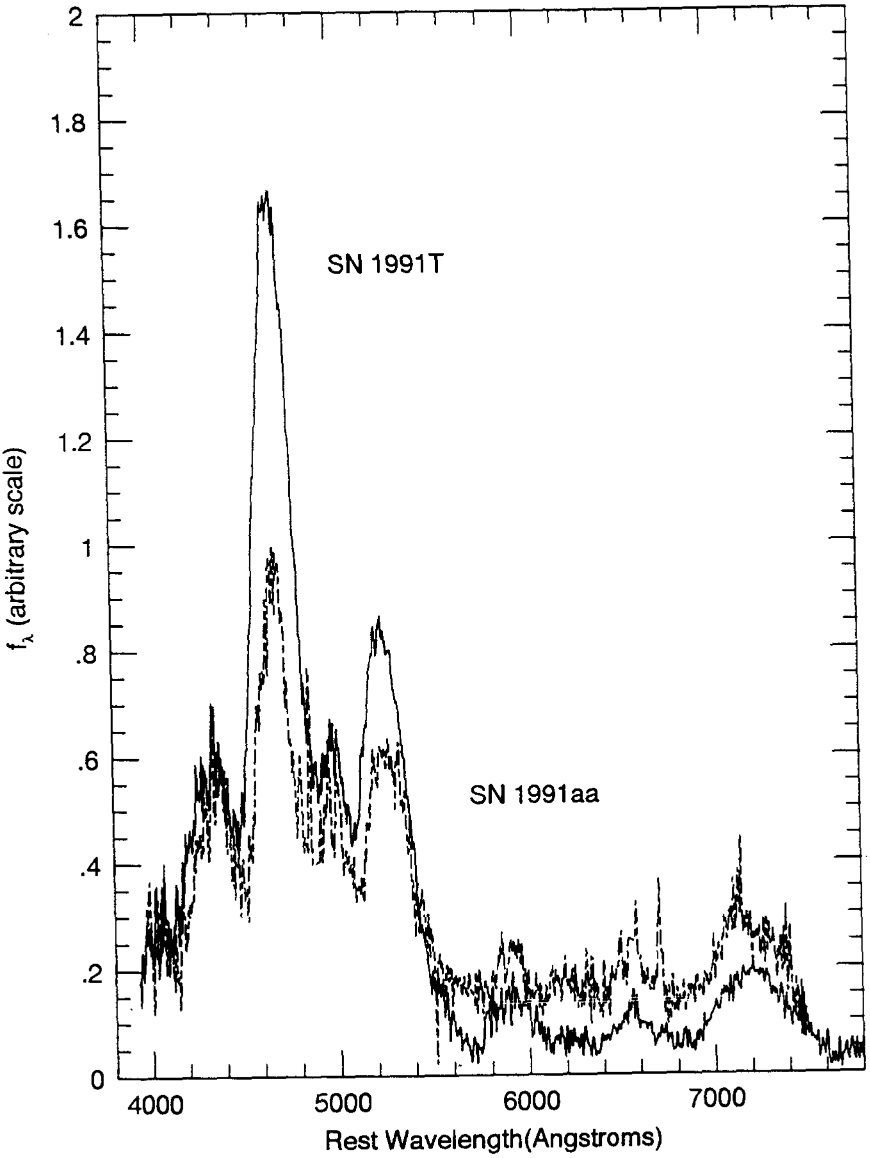

FIGURE 1. Comparison of a nebular spectrum of SN 1991T in NGC 4527 and the nebular spectrum of SN 1991aa in an anonymous galaxy corresponding to a similar phase (around 270 days and 250 days after explosion respectively). The spectra show broader [FeIII], [FeII] and [CoIII] features and a higher emissivity at around 4600 Å in SN 1991T than in SN 1991aa. We found that the electron temperature in SN 1991T seems to be higher than in SN 1991aa by more than 1000 K (see Ruiz-Lapuente and Filippenko 1993). The spectra have been shifted to agree in the flux scale.

SN 1991T are consistent with a composition made of ^{56}Ni and its decay products ^{56}Co and ^{56}Fe in the outermost layer.

Moreover, Ruiz–Lapuente & Filippenko (1993) find, from the nebular spectra, that the Co+Fe core of SN 1991T extends up to higher velocities than in other SNe Ia observed in their late stages. In Fig. 1 we compare spectra of SN 1991T and SN 1991aa corresponding to a similar phase. Nebular spectra of SNe Ia were first modelled by Axelrod (1980) and Meyerott (1980), based on a Fe+Co composition, and compared with SN 1972E. Among more recent observations of SNe Ia at the nebular phase, differences have been found. Modeling of the spectra (Ruiz–Lapuente & Lucy 1992; Ruiz–Lapuente & Filippenko 1993, Ruiz-Lapuente *et al.* 1993a) points to variable amounts of ^{56}Ni in the Fe-peak core being synthesized in the corresponding explosions: SN 1986G would have produced a low amount (around 0.4 $M_\odot$) and SN 1991T the largest amount of the sample (0.7–0.8 $M_\odot$); SN 1991aa and SN 1972E would have synthesized intermediate amounts (0.5–0.6 $M_\odot$). The lowest tail of the ^{56}Ni production is held so far by SN 1991bg which according to our analysis (Ruiz-Lapuente *et al.* 1993a) would have produced an amount of ^{56}Ni similar to that synthesized in SNe II.

Concerning the nature of the companion of the exploding WD, there are possible diagnostics for the cases in which the companion has a H–rich envelope. In particular, Chugai (1986) predicted that the fraction of the envelope stripped by the explosion would appear as low–velocity material in the nebular spectrum of the SN. This has been confirmed by 2–D hydrodynamical simulations (Livne, Tuchman & Wheeler 1992). The very underluminous SN 1991bg could have provided the first example of it (Ruiz–Lapuente *et al.* 1993a).

SN 1991bg, besides being clearly underluminous at all observed epochs showed by the shape of its light curve and by the early transition to the nebular phase of its spectra signs of having synthesized a small amount of ^{56}Ni, and also of having only a small mass of material on top of the radioactive region (Filippenko *et al.* 1992b; Leibundgut *et al.* 1993). In Fig. 2 we show a nebular spectrum obtained 212 days after explosion. A preliminary analysis (Figure 2a, dotted line) indicated a lower electron temperature and a smaller width of the Fe lines than in "normal" SNIa. That also pointed to a very small initial ^{56}Ni mass ($\lesssim 0.1 - 0.2 M_\odot$). The spectrum cannot be fitted with a pure Fe–peak composition, but requires mixing of intermediate–mass elements with the decay products of ^{56}Ni. All this could be consistent with detonation of a small–mass C+O WD. To check it, we have calculated the spectrum of a detonated C+O WD of 0.65 $M_\odot$. It is also shown in Fig. 2 (Figure 2b, dotted line).

An important point is the feature around 6,570 Å, which would correspond to *Hα emission* at low velocity. This result, if confirmed by a thorough checking against possible galactic Hα emission at the position of the SN, would be the first clear evidence of a nondegenerate, H–rich companion in a SNIa.

3. Discussion

The explosion of massive C+O WDs by variations of the deflagration/delayed detonation mechanisms seems to account rather well for the light curves and spectra of the SNe Ia. However, this agreement may not be unique since models of explosions of less massive C+O WDs have not yet been checked through extensive spectral and light curve calculations. SN 1991bg now poses a new problem to the standard model, since it might be indicating that low–mass C+O WDs can explode as SNIa. Such explosion may occur as C detonation of the core induced by He detonation in the outer layers, with the He resulting from burning of H accreted from a nondegenerate companion (testing the spectral effects of the He left after the detonation in the outer shell needs further consideration). Contribution from low-mass, H-accreting WDs in symbiotics to the SNIa population might also meet the statistical requirements that seem hard to be fulfilled by massive WDs and/or double degenerates.

Detonation of C+O WDs in the mass range 0.6–1.2 $M_\odot$ would synthesize from extremely low amounts of ^{56}Ni ($\simeq$ 0.01 $M_\odot$) up to $\simeq$ 1.1 $M_\odot$ (Woosley & Weaver 1994; Ruiz-Lapuente *et al.* 1993a; when comparing the yields in the two references, it should be noted that in the second one the mass of the accreted He layer is implicitly included in the total mass of the core). That would largely encompass the range inferred from observed SNIa luminosities, from SN 1991bg up to SN 1991T. There is a gap between SN 1991bg and events such as SN 1986G, but it might perhaps be partially filled by recent estimates of the luminosity of Tycho's SN (van den Bergh 1993).

The singular characteristics of SN 1991bg might also be fitted by other models. Nomoto (this volume) suggests that, in a merging double degenerate system the more massive WD could collapse after accreting 0.2–0.4 $M_\odot$ while the rest of the less massive WD forms an envelope of $\sim$ 0.6 $M_\odot$. A neutron star would result, $\sim$ 0.1 $M_\odot$ of ^{56}Ni would be synthesized at the bottom of the envelope, and the latter would be ejected with a total kinetic energy $\sim 10^{51}$ erg. On the other hand, some pulsating delayed detonation models of massive WDs can equally produce only small amounts of ^{56}Ni (Höflich *et al.*, this volume). Accurate modeling of the light curves and spectra of the different models is thus required. Detection of events similar to SN 1991bg would greatly contribute to clarify the issue.

The possibility that SNIa cover a significant range of peak luminosities does not preclude their use for extragalactic distance determinations. It only means that measurements of distances to individual supernovae, based on adequate models, should be preferred to the classical "standard candle" assumption.

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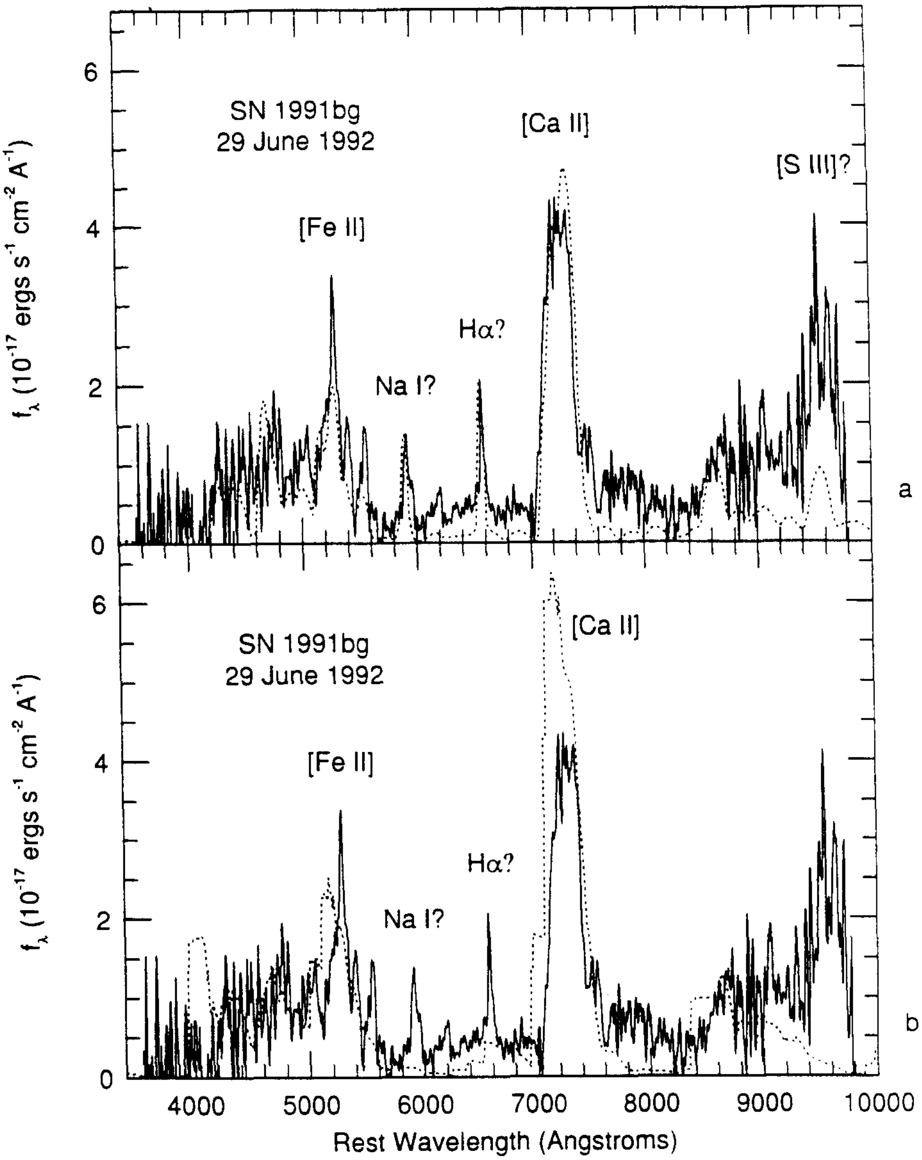

FIGURE 2. (*a*) The nebular spectrum of SN 1991bg 212 days after explosion (solid line), and a synthetic spectrum (dotted line) from a preliminary model (see Ruiz-Lapuente *et al.* 1993a). Slow moving H has been included to test the plausibility of the Hα identification. (*b*) The nebular spectrum of SN 1991bg 212 days after explosion (solid line), and calculated spectrum of a detonation model of a C+O WD of 0.65 $M_\odot$ for the same epoch (dotted line).