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Progenitors of Type Ia Supernovae

R. Kotak

Queen's University Belfast

Abstract. I briefly review what is known about thermonuclear (Type Ia) supernovae and their progenitors from an observational perspective.

1. Introduction

In spite of over a century of supernova (SN) research, and nearly a decade of employing Type Ia SNe as standardizable candles – leading to the unexpected result that the expansion of the universe is accelerating (Riess et al. 1998; Perlmutter et al. 1999) – the nature of the progenitor system of thermonuclear SNe continues to elude us. As I attempt to describe in the following sections, this is not due to want of trying, and probably signifies a gap or a flaw in our understanding of these remarkable events.

Quite aside from the fact that Type Ia SNe are used as relative distance indicators, compounding the urgency of identifying the progenitors, it is essential to do so for a number of other equally compelling reasons including some of the following (see also Branch et al. 1995; Livio 2000): (i) SNe of both the core-collapse and thermonuclear variety represent the end-point of single and binary stellar evolution. Direct identification of the progenitor system – or initial boundary condition – would provide much-needed constraints to stellar evolution models; a possible alternative could invoke the observed SN Ia rate (when reliable rates become available) as a function of environment and redshift, and forcing population synthesis models to match these; (ii) stellar evolution and feedback from SNe in the form of nucleosynthetic, kinetic, and radiative output are crucial for modelling galaxy evolution; (iii) the initial conditions (e.g. density) in the core are crucial for understanding when and where the explosion is triggered, and how the burning front proceeds throughout the star – these depend critically on the nature of the progenitor, although environmental effects (e.g. metallicity) probably also play a role. Last, but by no means least, we must be able to quantify how all of the above vary with cosmic epoch.

In what follows, I first discuss the scenarios for production of Type Ia SNe, followed by an inexhaustive review of their observational properties. I then describe recent exciting results, and end with some thoughts on future directions for Type Ia research.

2. The Standard Model

Hoyle & Fowler (1960) proposed a model for the explosion of stars in which the electron-degenerate stellar core underwent thermonuclear burning which could trigger an explosion, disrupting the entire star in the process. This mechanism seemed to hold on energetic grounds. Today, there is general consensus (on theoretical grounds) that Type Ia SNe result from the thermonuclear explosion of a carbon-oxygen white dwarf that has grown to the Chandrasekhar mass ($\sim 1.4\,M_\odot$) (Whelan & Iben 1973) by accreting material from a close binary companion. A donor star is essential as the white dwarf mass distribution function peaks sharply at about $0.6\,M_\odot$ (e.g. Homeier et al. 1998) and needs to accrete material to grow to $1.4\,M_\odot$.

Furthermore, the explosion itself is triggered in the centre, or slightly off-centre, and the burning front propagates inside-out. The hypothesis that the light curves are powered by the deposition of energy into the SN ejecta from the gamma-ray photons and positrons resulting from the radioactive decay of freshly-synthesized ^{56}Ni (Truran et al. 1967; Colgate & McKee 1969) in the chain ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe, has been observationally substantiated.

The plethora of binary systems that might lead to the thermonuclear explosion of the primary (i.e. the white dwarf) can be broadly divided into the single- and double-degenerate categories (see Branch et al. 1995, for a detailed review). In the former, the non-degenerate donor star could be a main-sequence star, red giant, or a subgiant, and accretion could proceed via Roche-lobe overflow or a wind from the donor. In the latter, the donor star is another white dwarf or subdwarf (Iben & Tutukov 1984; Webbink 1984), and mass transfer might occur via an accretion disk, or coalescence. The combined mass of the binary system must exceed $1.4\,M_\odot$ and the orbital period must be short enough for the system to merge within a Hubble time by emission of gravitational radiation (see also section 4.1.). A major problem that faces this scenario (and most others), is that of growing the white dwarf to the Chandrasekhar limit.

Several variants of the standard model have also been proposed (e.g. as described in Branch et al. 1995). These include low-mass accreting He white dwarfs (Iben & Tutukov 1984) which might explode following the ignition of He in the core. However, the resulting SN ejecta would be dominated by He and ^{56}Ni, which is at odds with the observed spectra (Nomoto & Sugimoto 1977). Accreting O-Ne-Mg white dwarfs are another possibility – these arise from stars with progenitor masses near $10\,M_\odot$. However, Nomoto & Kondo (1991) suggest that upon reaching the Chandrasekhar mass, these are likely to undergo accretion-induced collapse to a neutron star, thereby avoiding explosion.

Other interesting variants include explosions that occur at sub- or super-Chandrasekhar masses. While the explosion of a white dwarf below the Chandrasekhar mass would alleviate the problem of accreting and retaining a large amount of material, and might account for the so-called sub-luminous Type Ia SNe, e.g. SN 1991bg-like objects (e.g. Leibundgut et al. 1993), current models are unable to reproduce the observed species at the observed velocities (Livne & Arnett 1995). The possibility of super-Chandrasekhar white dwarfs was considered over four decades ago (Ostriker & Bodenheimer 1968). More recent modelling, with updated physics has rekindled this idea (Uenishi et al. 2003; Yoon & Langer 2005). Differential rotation of the white dwarf can result in stable configurations up to $\sim 4\,M_\odot$. Intriguingly, there might be some evidence that explosions from super-Chandrasekhar mass white dwarfs may have been discovered (Section 6.). However, this channel is unlikely to account for the bulk of Type Ia SNe.

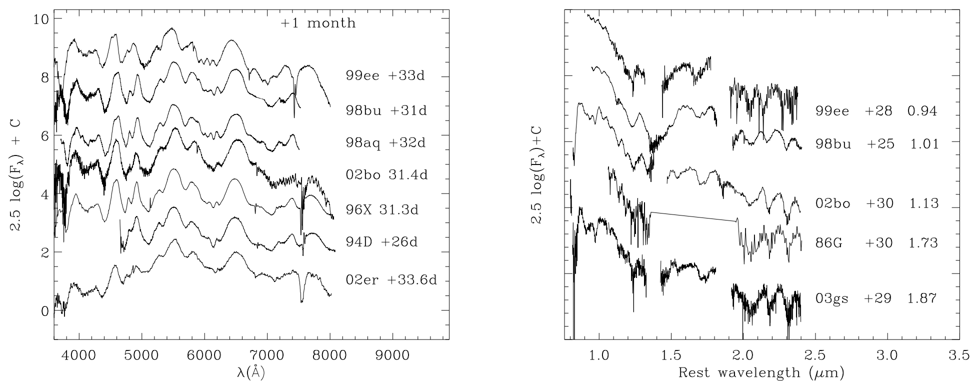

Figure 1. Optical (left) and near-IR spectra (right) at about a month post-maximum light, showing the persistent similarity. The infrared spectra are ordered by the light curve decline-rate parameter (Δm_{15} indicated next to the epoch in days) with the slowest-decliner being SN 1999ee and the fastest one being SN 2003gs. Data taken from Kotak et al. (2005) and references therein.

3. The Observed Properties of Type Ia SNe

Type Ia SNe are classified on the basis of spectroscopic features at optical wavelengths, namely the presence of a strong P Cygni-type feature at $\sim$6150 Å which is attributed to blue-shifted SiII λ6347,6371 Å, and the absence of features due to hydrogen (Pskovskii 1969) or helium. The homogeneity in the spectra (see Fig. 1) and light curves has been pointed out by several authors (e.g. Branch & Tammann 1992; Leibundgut et al. 1991; Hamuy et al. 1996) and has been used as an argument in support of a common underlying mechanism. Branch (1998) summarises the correlations that have been observed between light curve shapes and colours, peak magnitude, and spectral line strengths and velocities. Remarkably, Type Ia SNe can be ordered in explosion strength, with the stronger explosions being more luminous, bluer, having a slowly-declining light curve, and faster ejecta velocities than the dimmer events. This one-parameter sequence is directly linked to the amount of ^{56}Ni produced in the explosion, which controls the peak luminosity and temperature. This has recently been called into question (e.g. Benetti et al. 2004). Li et al. (2001) report a high intrinsic peculiarity rate of 36$\pm$9 % in a distance-limited sample of Type Ia SNe. “Peculiarity” is defined as in Branch et al. (1993) i.e. a SN is defined to be peculiar if the strength and type of spectroscopic features observed are genuinely different from those SNe considered to be normal (e.g. SN 1989B; Barbon et al. 1990) and cannot be simply attributed to differences in expansion velocity. Li et al. (2001) suggest that such a high peculiarity rate may point to different progenitor systems. However, Branch (2001) argues the exact opposite. This issue will almost certainly be settled in the coming years with the next generation of surveys.

4. Where is the Hydrogen?

Given the zoo of possible configurations of the progenitor binary system in the single-degenerate scenario, several authors have argued in its favour, the most recent of these being Parthasarathy et al. (2007) who speculate that most – if not all – Type Ia SNe must arise in this way. While candidate progenitor systems are observed to exist e.g symbiotic systems (e.g. Munari & Renzini et al. 1992) and recurrent novae (e.g. Hachisu et al. 1999), the biggest weakness of this scenario is the persistent lack (but see Section 6. below) of observational signatures of accreted material i.e. hydrogen or helium in the overwhelming majority of Type Ia SNe. Furthermore, all models to date that have considered the impact of the SN explosion on the donor star, predict significant quantities of material (mostly hydrogen or helium) stripped from the companion star. A dedicated attempt to detect circumstellar hydrogen soon after the explosion was made by Cumming et al. (1996). Assuming a wind speed of $10\,\mathrm{kms^{-1}}$, they place an upper limit on the mass-loss rate of the progenitor star of $\sim 1.5 \times 10^{-5} \mathrm{M_{\odot} yr^{-1}}$ (see Fig. 2).

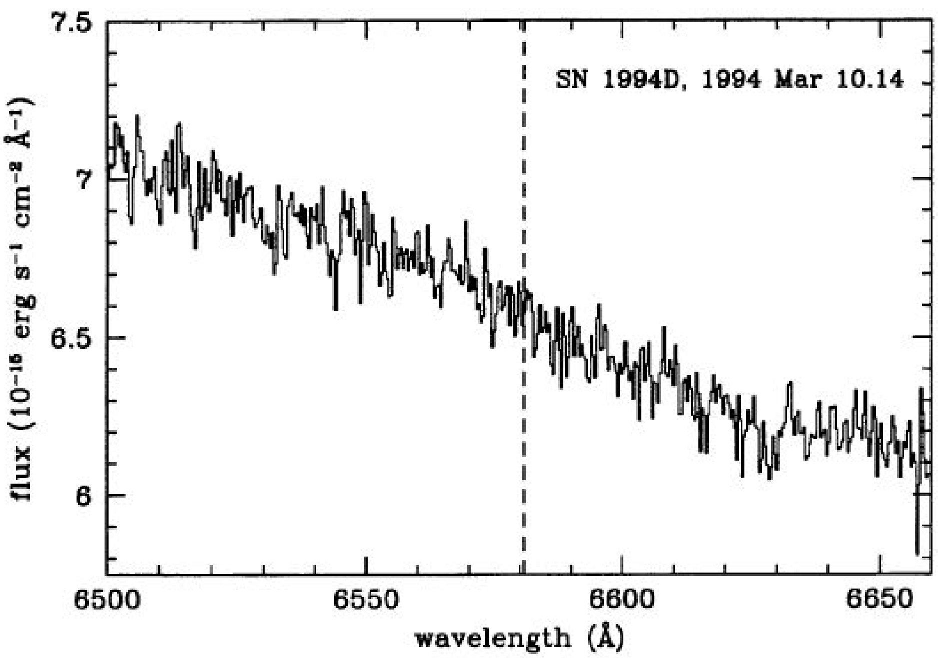

Figure 2. Portion of the high-resolution spectrum of the normal Type Ia SN 1994D taken 10 d before maximum light. The dashed line shows the expected position of Hα in the restframe of the host galaxy. Taken from Cumming et al. (1996).

Marietta et al. (2000) present detailed 2-D calculations for three different hydrogen-rich companion stars (main-sequence, subgiant, and red giant), and attempt to quantify the mass stripped from the companion and its distribution in velocity and solid angle. For all cases, there is substantial stripping, and up to 0.54 $M_\odot$ in the red giant case, with typical velocities in the $< 1000\,\mathrm{kms}^{-1}$ regime i.e. significantly slower than typical ejecta velocities of $10{,}000\,\mathrm{kms}^{-1}$. This means that the highest chance of detecting this entrained material would be at very late epochs when the ejecta are optically thin. Mattila et al. (2005) and Leonard (2007) attempted to detect evidence of stripped material via high-resolution spectroscopy of the Hα region. No Hα was detected. While there are potential caveats attached to the interpretation of these results, further modelling is required.

4.1. The Double-Degenerate Channel

Support for the double-degenerate channel has waxed and waned over the years. If the double-degenerate channel were responsible for the majority of Type Ia events, then the lack of observed hydrogen would be neatly accounted for as the most common type of white dwarfs (DA) have very thin ($\lesssim 10^{-4} M_\odot$) superficial layers of hydrogen, which would not leave any observable trace upon explosion. On the theoretical side, double-degenerate systems are a natural outcome of binary stellar evolution (Iben & Tutukov 1984; Iben & Livio 1993). Indeed, many double-white dwarf systems have been found (e.g. Maxted & Marsh 1999), including two white dwarf – subdwarf systems that are good candidates for this channel (Koen et al. 1998; Maxted et al. 2000). However, massive, tight, white dwarf – white dwarf pairs have not been found in sufficient numbers. Napiwotzki (2003) conducted a survey of over 1000 white dwarfs to search for such systems; one candidate has been identified. Although it is observationally challenging to search for these systems, many problems remain on the theoretical front e.g. it is difficult to envisage why a very large fraction of mergers would result in a very similar amount of ^{56}Ni being produced. While a satisfactory explanation for the absence of observed accreted material is still lacking, the double-degenerate scenario will have to be revisited on both theoretical and observational grounds.

5. Multi-Wavelength Observations of Type Ia SNe

While most SN research has been traditionally carried out at optical wavelengths, advances in technology have meant that wavelength regions which were previously inaccessible to SN research are now no longer so, thus providing a host of new diagnostics. Also, very late-time (post-1 yr) optical and near-infrared spectroscopy has become possible for the nearby events (e.g Bowers et al. 1997; Motohara et al. 2006). At these phases, the SN ejecta are nearly transparent and can provide unique insights into the earliest phases of the explosion, providing an opportunity to confront state-of-the-art explosion models.

5.1. Radio and X-ray Observations

For all single-degenerate scenarios, one expects the presence of hydrogen (or possibly helium) in the circumstellar environment of the SN. Detecting this circumstellar material and determining its amount, extent, density, outflow velocity etc. would provide us with a means to indirectly infer the nature of the underlying progenitor system.

Radio observations are, in principle, an excellent probe of the pre-SN evolution. Radio emission from SNe arises from synchrotron emission due to the shock-interaction between the fast-moving ejecta and the slow-moving circumstellar matter (Chevalier 1982; Sramek et al. 1984). Boffi & Branch (1995) considered the radio emission arising from a symbiotic system i.e. a white dwarf – red giant binary. From radio observations taken at a week before maximum light. Eck et al. (1995) ruled out a symbiotic progenitor for the nearby Type Ia SN 1986G as no radio source coincident with SN 1986G was detected at 2 or 6 cm. Recently, Panagia et al. (2006) presented a sample of 27 Type Ia SNe that have been observed using the VLA. None were detected. They derive a 2σ upper limit assuming a steady mass-loss rate of $\sim 7 \times 10^{-6} - 3 \times 10^{-8} M_{\odot} yr^{-1}$. They argue that their findings strongly disfavour the symbiotic channel. However, Hughes et al. (2007) point out that although the above radio flux limits support a low-density circumstellar environment around Type Ia SNe, the radio limits themselves rely on uncertain empirical calibrations and parameterizations relevant for Type Ib/c (i.e. core-collapse) SNe. Meanwhile, the non-detection of Hα emission by Leonard (2007) could still be consistent with widely-separated symbiotic systems.

Until 2006, there was no report of X-ray emission from a Type Ia SN. X-ray emission would be expected to arise due to the interaction between the fast-moving SN ejecta and the dense material presumably arising from the wind of the progenitor star. Immler et al. (2006) presented a study of the early-time UV and X-ray behaviour of eight Type Ia SNe observed with the *Swift* satellite, and claim a 3-3.6σ tentative X-ray detection of the Type Ia SN 2005ke; they use the X-ray luminosity to infer a mass-loss rate of the progenitor star of $\sim 3 \times 10^{-6} M_{\odot} yr^{-1}$ for an assumed wind velocity of 10 kms^{-1}. However, a recent X-ray study of 4 Type Ia SN by Hughes et al. (2007) includes the same *Swift* data as Immler et al. (2006) augmented by data from the *Chandra X-ray Observatory* at a later epoch. They do not detect SN 2005ke at either epoch, refuting the Immler et al. (2006) claim.

5.2. Near- and Mid-Infrared Observations

Several authors have highlighted the diagnostic potential of spectral features in the near-infrared region (e.g. Wheeler et al. 1998). Early-time observations can provide a particularly powerful diagnostic of the dynamic model because they probe different depths at the same epoch within the exploded white dwarf through the strongly variable line-blanketing opacity. For instance, the Ca II 1.15 μm line can be used to determine the velocity at which complete burning to nickel stops; the depth of the 1.2μm deficit provides a temperature diagnostic for the silicon layers; the MgII λ1.09, 1.68 μm lines indicate the boundary between explosive carbon and oxygen burning, and can be used to constrain the amount of unburned material (Marion et al. 2003). Furthermore, the large number of lines in the optical/uv regions, coupled with the strong Doppler-broadening (several thousand kms^{-1}) can make line profiles difficult to measure. Strong extinction effects often introduce additional error. In contrast, the near-IR has fewer lines and reduced sensitivity to extinction uncertainty, allowing firm line identification and accurate measurement of line strength and evolution.

An exciting development has been the first detection (see Fig. 3 of a Type Ia SN at mid-infrared wavelengths (Gerardy et al. 2007). The spectrum of SN 2005df shows strong fine-structure lines, while the line-profiles indicate

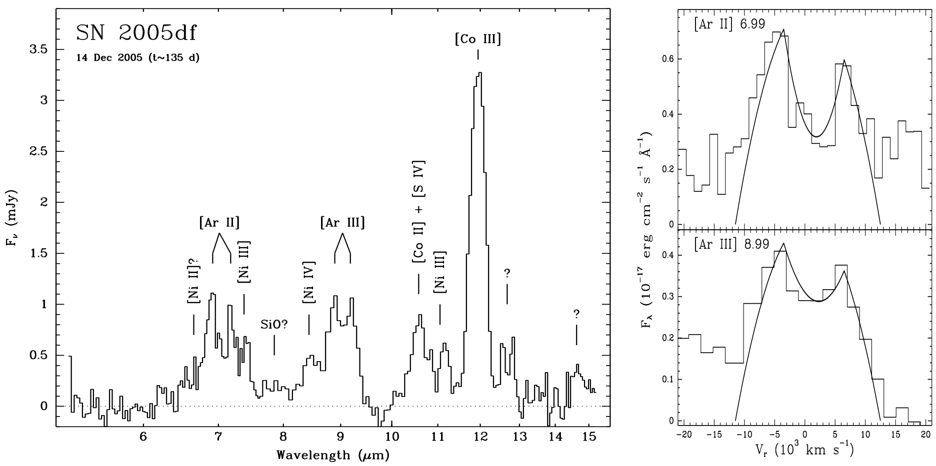

Figure 3. Left: The observed mid-infrared spectrum of the Type Ia SN 2005df at ∼135 d. Wavelengths are shown as vacuum coordinates in the observer's frame. The observed line width is determined by the expansion velocity of the species. Right: Detail of the observed Ar line profiles compared with calculated emission-line profiles. The double-peaked profile is best modelled by a pole-on prolate emission geometry with an off-center spherical hole near the middle. Taken from Gerardy et al. (2007).

that the ejecta is chemically-stratified which is broadly consistent with delayed-detonation models. Intriguingly, the Ar lines at 6.99 and 8.99 μm show a two-pronged emission profile (Fig. 3) indicating that the distribution of Ar deviates significantly from spherical symmetry. Interestingly, SN 2005df is a sub-luminous event and produced only 0.13-0.22 $M_\odot$ of ^{56}Ni.

The last few years have witnessed a substantial growth in the near-IR coverage of Type Ia SNe at all epochs (e.g. Motohara et al. 2006; Stanishev et al. 2007, Kotak et al. in preparation), and the mid-infrared database is also set to increase several-fold. However, progress in modelling these multi-wavelength, multi-epoch spectra needs to be made.

6. Extreme Supernovae

In recent years, there has been a marked rise in the number of 'peculiar' or extreme SNe reported. Two events that have forced us to question the standard model are highlighted below.

6.1. SN 2002ic

The discovery of SN 2002ic (Hamuy et al. 2003) was a turning point. SN 2002ic showed typical characteristics of a Type Ia SN at early times, but with strong and persistent Hα emission. Remarkably, after 60 d it changed into the spectral form of a Type IIn SN (i.e. a SN with narrow emission lines). High-resolution spectroscopy resolved the narrow Hα component revealing a P Cygni-like profile and measured a velocity of $\sim$100 kms^{-1} (see Fig. 4). The detection of a P Cygni

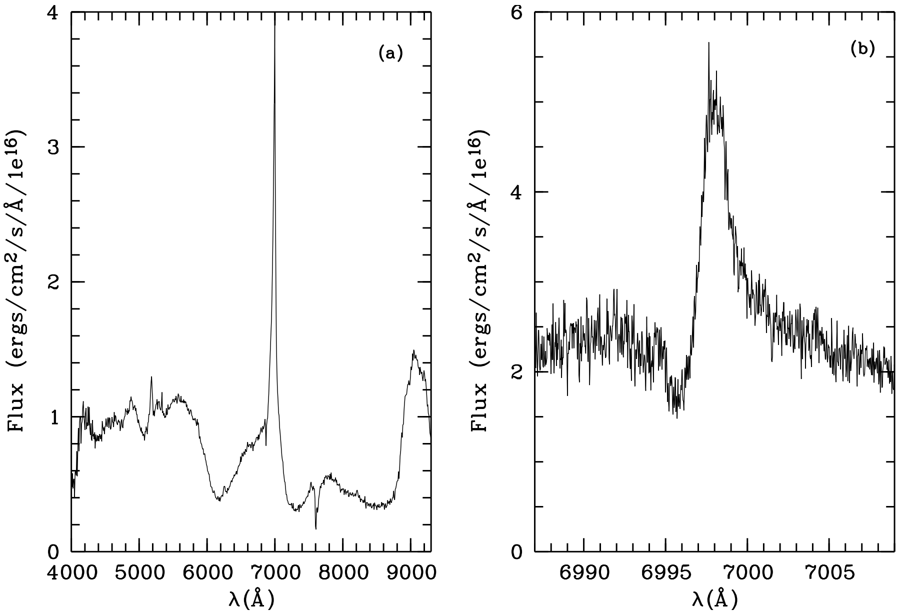

Figure 4. (a) Low resolution Subaru spectrum of SN 2002ic at +222 d (Deng et al. 2004) showing features due to Ca, O, Fe, in addition to strong Hα emission. (b) High resolution VLT spectrum centred on Hα (rest-frame, +256 d) which is clearly resolved into a P Cygni profile, providing evidence for a slowly expanding ($100\,\mathrm{kms}^{-1}$) undisturbed progenitor wind (Kotak et al. 2004).

profile implies that the SN shock is evolving in a slowly-expanding ($100\,\mathrm{kms}^{-1}$) dense medium, very likely the progenitor wind (Kotak et al. 2004).

Meanwhile, on the basis of spectropolarimetry data, Wang et al. (2004) reported that the hydrogen-rich matter was highly aspherically distributed, and suggested that this SN might have exploded in a dense, clumpy, disk-like environment. SN 2002ic went on to produce another surprise: K-band measurements at about 300 d post-explosion, yielded $K \sim +18$. At the distance of SN 2002ic ($z \sim 0.0667$), this corresponds to a huge K-band luminosity - more than a *hundred* times that of a typical Type Ia SN at the same epoch! Kotak et al. (2004) argue that the source of the IR emission is an infrared echo due to pre-existing dust in the circumstellar medium.

Not surprisingly, half-a-dozen scenarios were put forward in a short time in an attempt to pin down the progenitor of this remarkable SN. These range from single star Type 1.5 SN scenarios (Iben & Renzini 1983; Hamuy et al. 2003) to single-degenerate channels (e.g. Kotak et al. 2004; Wood-Vasey & Sokoloski 2006) to support for the double-degenerate channel (Livio & Riess 2003), and even a core-collapse scenario (Benetti et al. 2006). Unfortunately none of the above are able to explain all aspects of the observed behaviour in an uncontrived fashion.

6.2. SN 2003fg

Recently, Howell et al. (2006) reported the discovery of SN 2003fg ($z = 0.2440$) which is over a factor of two brighter than the median, thus deviating significantly from the luminosity-light curve width relation. In order to reproduce the observed luminosity, Howell et al. (2006) argue that $\sim 1.3\,\mathrm{M}_{\odot}$ of ^{56}Ni would be required, implying that the mass of the progenitor must have been above the Chandrasekhar limit. Such SNe, or less extreme versions thereof, may be a potential source of concern in high-redshift Type Ia SN samples. However, Hillebrandt et al. (2007) argue that a Chandrasekhar-mass off-centre explosion resulting in a highly asymmetric distribution of radioactive material ($\gtrsim 0.9\,\mathrm{M}_{\odot}$) might mimic a super-Chandrasekhar mass explosion. This scenario requires observation from a preferred viewing angle, thus predicting such events to be rare. The very recent report (Hicken et al. 2007) of another possibly super-Chandrasekhar mass explosion raises interesting questions.

7. Future Prospects

There has been unrelenting effort both on the theoretical and observational fronts to pin down the nature of the progenitor systems of Type Ia SNe. The problem is complex. On the observational side, as sample sizes increase with ever-more ambitious surveys, and high-quality multi-wavelength, multi-epoch data become available, ever more stringent criteria will have to be met by theoretical advances. This surely means that very exciting times lie ahead!

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