The Extremes of Thermonuclear Supernovae

Stefan Taubenberger

Abstract The majority of thermonuclear explosions in the Universe seem to proceed in a rather standardised way, as explosions of carbon-oxygen (CO) white dwarfs in binary systems, leading to ‘normal’ Type Ia supernovae (SNe Ia). However, over the years a number of objects have been found which deviate from normal SNe Ia in their observational properties, and which require different and not seldom more extreme progenitor systems. While the ‘traditional’ classes of peculiar SNe Ia – luminous ‘91T-like’ and faint ‘91bg-like’ objects – have been known since the early 1990s, other classes of even more unusual transients have only been established 20 years later, fostered by the advent of new wide-field SN surveys such as the Palomar Transient Factory. These include the faint but slowly declining ‘02es-like’ SNe, ‘Ca-rich’ transients residing in the luminosity gap between classical novae and supernovae, extremely short-lived, fast-declining transients, and the very luminous so-called ‘super-Chandrasekhar’ SNe Ia. Not all of them are necessarily thermonuclear explosions, but there are good arguments in favour of a thermonuclear origin for most of them. The aim of this chapter is to provide an overview of the zoo of potentially thermonuclear transients, reviewing their observational characteristics and discussing possible explosion scenarios.

1 Introduction

The majority of Type Ia supernovae (SNe Ia) form a well-defined, spectroscopically homogeneous class. Their light curves show some variation, but largely form a one-parameter family in the sense that objects with broader light curves are intrinsically more luminous, a behaviour that allows for a standardisation of their luminosity,
making them valuable cosmic lighthouses. The parameter driving the light-curve width vs. peak luminosity relation is most likely the mass of radioactive $^{56}$Ni synthesised in the explosion, though there is growing evidence that a variation of the total ejecta mass may also be required (Stritzinger et al., 2006; Scalzo et al., 2014b).

However, next to these ‘well-behaved’ SNe Ia there are also several classes of weirdos, which are spectroscopically highly peculiar or do not obey the light-curve width vs. luminosity relationship of normal SNe Ia (e.g. Phillips, 1993; Phillips et al., 1999). Clearly, a one-parameter description is insufficient to categorise them, and it is very likely that most of them stem from somewhat different progenitor systems and have different underlying explosion mechanisms than normal SNe Ia. The link to the latter is that they are also believed to be thermonuclear explosions of WDs, based on the inferred nucleosynthesis or their occurrence in old stellar populations. However, some of them are clearly pushing the thermonuclear scenario to the limits. Fig. 1 introduces the main classes of these more or less extreme objects and highlights their location in the light-curve width vs. luminosity plane. With the exception of ‘SNe Iax’ and ‘SNe Ia-CSM’, all other highlighted classes are discussed below. Whenever relevant, a Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ is assumed.
Phase space of potentially thermonuclear transients. The absolute $B$-band magnitude at peak is plotted against the light-curve decline rate, expressed by the decline within 15 d from peak in the $B$ band, $\Delta m_{15}(B)$ (Phillips 1993). The different classes of objects discussed in this chapter are highlighted by different colours. Most of them are well separated from normal SNe Ia in this space, which shows that they are already peculiar based on light-curve properties alone. The only exception are 91T-like SNe, which overlap with the slow end of the distribution of normal SNe Ia, and whose peculiarities are almost exclusively of spectroscopic nature. References to individual SNe are provided in the respective sections.
2 91T-like SNe: spectroscopically distinct

91T-like SNe constitute a subclass of SNe Ia characterised by high peak luminosities and broad light curves, but especially by a peculiar pre-maximum spectroscopic evolution with Fe \textsc{iii} lines dominating the early spectra. After the formative and exceptionally well-characterised SN 1991T, a number of objects with very similar photometric and spectroscopic properties have been described in the literature. These include SN 1997br (Li et al. [1999]), SNe 1998ab, 1999dq (Jha et al. [2006]; Matheson et al. [2008]), LSQ12gdi (Scalzo et al. [2014a]) and several SNe from the Nearby Supernova Factory (Scalzo et al. [2012]; Taubenberger et al. [2013b]). Since SN 1991T itself is still the best-observed of its kind, the following discussion is focused on it, before transitional 99aa-like and rare 00cx-like SNe are presented in Sections 2.5 and 2.6.

2.1 Peak luminosity and light-curve properties

Photometry of SN 1991T has been provided by Filippenko et al. (1992a); Phillips et al. (1992); Schmidt et al. (1994); Lira et al. (1998); Altavilla et al. (2004). The SN shows slowly declining light curves, with $\Delta m_{15}(B) \sim 0.94$ (Phillips et al. [1999]). The overall morphology of the light curves resembles those of normal SNe Ia (Fig. 2a,b), and the secondary maxima in the near infrared are particularly bright (Hamuy et al. [1996]). The colour evolution is rather normal, the only exception being bluer pre-maximum $U - B$ colours than in most other SNe Ia (Lira et al. [1998]).

In the original studies (Filippenko et al. [1992a]; Phillips et al. [1992]; Ruiz-Lapuente et al. [1992]) there was quite some controversy about the absolute peak magnitudes of SN 1991T, which originated from uncertainties in the photometric calibration, distance of the SN, and extinction within the host galaxy. All authors agreed that SN 1991T was probably more luminous than average normal SNe Ia, but the estimated differences ranged from marginally significant 0.3 mag (Phillips et al. [1992]) to $\geq 1.1$ mag (Ruiz-Lapuente et al. [1992]). The corresponding $^{56}$Ni masses would be between 0.7 and $\geq 1.4$ M$_\odot$ (assuming a $^{56}$Ni production of 0.5 M$_\odot$ in a normal SN Ia), the latter being incompatible with all normally considered M$_{Ch}$- and sub-M$_{Ch}$ explosion models.

A better understanding of the extinction correction in SNe Ia based on their colours (Lira [1996]; Phillips et al. [1999]), new Cepheid-based distance estimates for the host galaxy (Saha et al. [2001]; Altavilla et al. [2004]) and sophisticated modelling of the SN light curves and spectra (Jeffery et al. [1992]; Mazzali et al. [1995]; Sasdelli et al. [2014]) have led to some convergence in the numbers, so that nowadays peak absolute magnitudes $\sim 0.4$--$0.5$ mag above average SNe Ia and $^{56}$Ni masses around 0.8 M$_\odot$ are favoured (Sasdelli et al. [2014]). This makes SN 1991T at best slightly overluminous with respect to the Phillips relation (Phillips [1993]; Phillips et al. [1999]), but consistent within the uncertainties, as can be seen from Fig. 1. Based on a larger SN Ia sample, Blondin et al. (2012) estimated that the class of 91T-like SNe...
Fig. 2 91T-like SNe in comparison to the normal SNe Ia 2003du (Stanishev et al., 2007) and 2011fe (Munari et al., 2013, Pereira et al., 2013, Taubenberger et al., 2013). a) $I$-band light curves. b) $B$-band light curves. c) Photospheric spectra. d) Nebular spectra. References for individual 91T-like SNe are provided in the main text.
is on average 0.2–0.3 mag more luminous than normal SNe Ia. 91T-like SNe are nowadays routinely included in cosmological SN Ia samples, though some authors have warned that they might introduce a systematic bias (e.g. Scalzo et al. 2012).

2.2 Spectroscopic properties

What really distinguishes SN 1991T and its siblings from other SNe Ia is their pre-maximum spectral evolution (Fig. 2c). Early-time optical spectra of normal SNe Ia, even of luminous and slowly declining ones, are dominated by lines of intermediate-mass elements (IMEs) such as Si II, S II, Ca II and Mg II (Branch et al. 1993). The Si II and Ca II lines, in particular, are often wide and deep, and ubiquitously show high-velocity absorptions associated with them (Mazzali et al. 2005). In SN 1991T, in contrast, IME lines are essentially absent a week before maximum light, and just start to emerge around peak brightness, never reaching the same intensity as in normal SNe Ia. Instead the early spectra are characterised by an almost featureless blue pseudo-continuum redward of \( \sim 5500 \) Å, a high near-UV flux, and two strong absorption features near 4250 and 4950 Å, which have been identified as Fe III multiplets \( \lambda 4404 \) and \( \lambda 5129 \) (Filippenko et al. 1992a; Ruiz-Lapuente et al. 1992; Jeffery et al. 1992). The strength of these lines requires high ionisation and a high Fe content in the outer layers of the SN ejecta, where line formation at those early epochs takes place (Jeffery et al. 1992; Ruiz-Lapuente et al. 1992; Mazzali et al. 1995; Sasdelli et al. 2014). For instance, Sasdelli et al. (2014) inferred mass fractions of \( \sim 3\% \) \(^{56}\)Ni and 1% stable Fe in SN 1991T above 13 000 km s\(^{-1}\).

Around maximum light IME lines start to emerge. Si II \( \lambda 6355 \) is clearly detected, but still weak compared to normal SNe Ia, and the same holds for S II and Ca II features. Si II \( \lambda 5972 \) remains virtually absent, placing SN 1991T in the shallow-silicon class following the classification scheme of Branch et al. (2006). The expansion velocity measured from the Si II \( \lambda 6355 \) line is relatively low, and its post-peak temporal evolution very flat, so that in the classification scheme of Benetti et al. (2005) SN 1991T – along with many normal SNe Ia – ends up in the low-velocity-gradient (LVG) group. Physically this may indicate that IMEs are confined to a relatively narrow region in velocity space around 10 000 km s\(^{-1}\).

The further spectroscopic evolution of SN 1991T very closely resembles that of normal SNe Ia, with spectra dominated by Fe II and Ca II lines during the weeks after maximum light. In fact, from post-maximum spectroscopy alone, 91T-like SNe can hardly be distinguished from normal SNe Ia. Nebular spectra of SN 1991T (Spyromilio et al. 1992; Gómez & López 1998; Silverman et al. 2012) reveal the usual [Fe II] and [Fe III] emission lines. The only difference is that these lines are slightly broader than in average normal SNe Ia, indicating that iron-group elements (IGEs) are distributed over a wide range in velocity.
2.3 Host galaxies and relative rates

91T-like SNe predominantly explode in late-type galaxies (Howell, 2001; Li et al., 2011), and are therefore likely associated with young stellar populations. Li et al. (2011) suggested that 91T-like SNe made up 9% of all SNe Ia in a volume-limited sub-sample of the Lick Observatory Supernova Search (LOSS), but given that LOSS targets mostly massive, star-forming galaxies, this estimate may be biased and the true rate of 91T-like SNe may be lower. Moreover, the 91T category of Li et al. also includes transitional, 99aa-like SNe (see Section 2.5). Silverman et al. (2012) estimated a much lower fraction of $\sim 2\%$ 91T/99aa-like SNe from the BSNIP spectroscopic SN Ia sample, with about half of them being genuine 91T-like objects. However, the BSNIP sample is also incomplete, and the estimates may suffer from observational biases. The same is true for the sample of Blondin et al. (2012), who found a fraction of 91T/99aa-like SNe of 5–6% among 462 SNe Ia.

2.4 Explosion scenarios

Viable explosion models for SN 1991T need to produce relatively large $^{56}\text{Ni}$ masses of $\gtrsim 0.8 \text{ M}_\odot$ and reproduce the spectroscopic peculiarities described above. Spectrum-synthesis calculations have been carried out for SN 1991T using codes with different levels of physical sophistication (Jeffery et al., 1992; Ruiz-Lapuente et al., 1992; Mazzali et al., 1995; Fisher et al., 1999; Sasdelli et al., 2014). All calculations agree in the need for a significant amount (a few percent) of IGEs – $^{56}\text{Ni}$ in particular – in outer layers, at velocities between $\sim 10,000$ and $20,000 \text{ km s}^{-1}$, to achieve the high ionisation and reproduce the Fe III absorption features observed at early phases when the interior of the SN ejecta is still optically thick. In fact, Ruiz-Lapuente et al. (1992) and Mazzali et al. (1995) modelled the early spectra of SN 1991T assuming almost pure iron-peak-element compositions, but Ruiz-Lapuente et al. admitted that their modelling was energetically not self-consistent, since complete burning to IGEs would lead to higher ejecta velocities than observed.

There are basically two ways to meet the requirement to enrich the outermost layers with $^{56}\text{Ni}$: either the $^{56}\text{Ni}$ has been produced in situ (i.e., in the outer layers of the exploding WD), or it has been produced further inside in high-density layers and mixed outward. In the early 1990s, normal SNe Ia were still widely believed to be pure deflagrations of Chandrasekhar-mass ($M_{\text{ch}}$-) WDs. The then still relatively new delayed-detonation model (Khokhlov, 1991), where an initial deflagration at some point transitions into a super-sonic detonation, was considered a promising scenario to explain SN 1991T. The hope was that the detonation may burn part of the outer mantle to IGEs (Ruiz-Lapuente et al., 1992; Mazzali et al., 1995). Modern three-dimensional simulations of delayed detonations with a self-consistent deflagration treatment do not confirm this behaviour. By the time the detonation sets on, the WD has had time to react to the heat released in the sub-sonic deflagration and expand.
This leads to lower densities in the outer layers, and the detonation front does not burn them to IGEs, but at most to IMEs (see e.g. Seitenzahl et al. 2013). What has instead been proposed recently (Fisher & Jumper, 2015) as a model that can lead to the inferred stratification inversion is a special variant of delayed-detonation models: a gravitationally-confined detonation (GCD; Plewa et al., 2004). In this scenario the IGEs in the outermost layers are not synthesised in situ by the detonation, but are the ashes of a strongly off-centre deflagration, which rise to the WD surface in a one-sided, buoyancy-driven plume. Owing to the weak deflagration, the WD is pre-expanded only little, and an ensuing detonation can burn most of the WD interior to $^{56}$Ni, leading to very luminous events (Fisher & Jumper, 2015). However, there is an ongoing debate whether a detonation is robustly initiated in such a scenario (e.g. Röpke et al. 2007), and it remains to be tested whether the spectroscopic and photometric display of this model match the observations of 91T-like SNe.

Another idea for the origin of $^{56}$Ni in the outer layers suggests 91T-like SNe to be the outcome of slightly sub-$M_{\odot}$ double-detonations, with $^{56}$Ni produced in the initial He-shell detonation on the WD surface (Filippenko et al., 1992a). Realistic simulations of this scenario (Fink et al. 2010; Kromer et al. 2010) have shown that indeed the most massive exploding sub-$M_{\odot}$ WDs can reach the peak luminosity of SN 1991T, and also produce $^{56}$Ni in the He-shell detonation. However, synthetic observables computed for these models show little similarity with SN 1991T: strong line blanketing suppresses almost the entire flux blueward of 4000 Å, the velocities especially of IMEs are too high, and the light curves rise and decline too rapidly. The latter two problems can most likely only be cured by increasing the total ejecta mass, which shows that there is almost no room for a sub-$M_{\odot}$ interpretation of 91T-like SNe.

Finally, Fisher et al. (1999) promoted a super-$M_{\odot}$ scenario for SN 1991T, based on the high luminosity and the large $^{56}$Ni mass required. However, with the latest $^{56}$Ni mass estimates of $\sim$0.7–0.9 $M_{\odot}$ (Scalzo et al. 2012; Sasdelli et al. 2014), a total mass in excess of $M_{\odot}$ may not be required. Based on a semi-analytic model with Bayesian priors, Scalzo et al. (2012) have shown that the light curve and kinetic structure of typical 91T-like SNe are compatible with a $M_{\odot}$ explosions.

### 2.5 99aa-like SNe: transitional objects

Whenever subclasses of SNe Ia are defined, the question arises on how distinct their properties really are. A clear-cut distinction from normal SNe Ia could lend support to an entirely different underlying progenitor system and explosion mechanism, whereas the presence of a continuity of objects with intermediate properties might rather favour a common explosion mechanism with just some variation in certain parameters. Objects with properties intermediate between 91T-like and normal SNe Ia have indeed been found: SN 1998es (Jha et al. 2006; Matheson et al. 2008), SN 1999aa (Krisiunas et al. 2000; Garavini et al. 2004; Jha et al. 2006;...
Matheson et al., 2008), and by now a number of objects akin to them. Silverman et al. (2012) have estimated the rate of 99aa-like SNe to be comparable to that of genuine 91T-like SNe.

Very early (∼ −10 d) spectra of SN 1999aa resemble those of SN 1991T in being Fe III-line dominated, and in their weakness of most IME lines. The difference to SN 1991T is that in SN 1999aa Ca II lines (especially H&K) are always prominent (Fig. 2c), and that SN 1999aa transitions to a normal SN-Ia-like appearance much earlier. Already a week before maximum light, Si II and S II lines start to be visible, and by maximum light the SN 1999aa spectrum is very similar to those of normal SNe Ia, with just a hint of the Fe III absorptions left. This may point at an Fe-enriched, highly ionised outer layer that is less massive and extended than in SN 1991T and becomes optically thin earlier. As in 91T-like SNe, the Si II λ6355 velocity measured in SN 1999aa shows little evolution from one week before to four weeks after peak brightness. Consequently, IMEs are probably confined to a narrow window in velocity space (Garavini et al., 2004).

Photometry shows that SN 1999aa is similarly luminous and slowly declining as SN 1991T, with Δm15(B) measurements ranging from 0.75 (Krisciunas et al., 2000) to 0.85 (Jha et al., 2006). 99aa-like SNe are routinely included in cosmological SN Ia samples.

2.6 00cx-like SNe: rare weirdos

The reason why SN 2000cx is discussed in the context of 91T-like SNe is its early-time spectroscopic appearance. Optical spectra of SN 2000cx are only available from 3 d prior to maximum light onwards, but at that time they are still dominated by Fe III lines (Fig. 2c), which are even more persistent than in SN 1991T and still detected at +15 d (Li et al., 2001b). Si II and S II lines are still weak in the earliest spectra, but grow significantly in strength within just a few days. It appears that SN 2000cx maintains a high ionisation and excitation in its ejecta for a longer time than most other SNe Ia. Multi-notched high-velocity components of Ca II H&K and the NIR triplet with velocities up to 20 000 km s⁻¹ are prominent even one week after maximum light (Thomas et al., 2004; Branch et al., 2004, see Fig. 2c), again not seen in other SNe Ia at similarly late epochs. The Si II λ6355 velocity evolution shows the same flat trend as in SN 1991T, but in SN 2000cx the measured velocity is 2000–3000 km s⁻¹ larger (Li et al., 2001b), hinting at an overall higher kinetic energy.

The photometry of SN 2000cx (Li et al., 2001b; Candia et al., 2003) provides no conclusive picture. The B-band decline is very slow [Δm15(B) = 0.93], similar to that of luminous 91T-like objects. However, the rise in the B-band, and also the rise and decline in all other bands reword of B, is relatively fast (Fig. 2b). The secondary peak in the NIR bands is not very pronounced, and the bolometric light curve is relatively narrow, all of which is reminiscent of mildly subluminous SNe Ia (Candia et al., 2003). Light-curve fitters fail to produce decent fits for SN 2000cx.
(Li et al., 2001b), and absolute magnitudes estimated by them cannot be trusted. Unfortunately, the distance to NGC 524, the host galaxy of SN 2000cx, is not well constrained, and it has therefore been debated whether SN 2000cx was overluminous, normal or even subluminous (Li et al., 2001b; Candia et al., 2003). The most recent calibrations actually suggest that the peak luminosity of SN 2000cx was similar to that of normal SNe Ia (Silverman et al., 2013).

00cx-like SNe seem to be extremely rare. In fact, with its peculiar properties SN 2000cx remained unique for more than a decade, and only recently a close twin of it has been found and discussed in the literature: SN 2013bh (Silverman et al., 2013). Despite the poor statistics, it is interesting that both SN 2000cx and SN 2013bh exploded in the very outskirts of their host galaxies, at projected distances of 25 and 18 kpc, respectively, from the host centres. SN 2013bh’s host is a star-forming galaxy, but at the location of the SN there is no sign of ongoing star formation, and the metallicity is likely to be low (Silverman et al., 2013). The latter is also true for SN 2000cx (Li et al., 2001b), which on top of this exploded in an S0 galaxy with overall low star-formation activity. Both SNe show no signs of host-galaxy interstellar Na D absorptions in their spectra, suggesting clean circumstellar environments (Patat et al., 2007; Silverman et al., 2013). All this might indicate that 00cx-like SNe stem from relatively old progenitors, in sharp contrast to 91T- and 99aa-like SNe.
3 91bg-like SNe: cool and subluminous

In 1991 the paradigm of SN Ia homogeneity changed drastically, since not only the luminous and spectroscopically unusual SN 1991T was discovered (see Section 2), but also the subluminous, fast-declining SN 1991bg (Filippenko et al., 1992b; Leibundgut et al., 1993; Turatto et al., 1996). SN 1991bg became the prototype of a whole class of objects, some of which have properties nearly identical to SN 1991bg, while others seem to bridge the gap to normal SNe Ia, and again others deviate in certain respects and are sometimes even more extreme than SN 1991bg itself. In the following we will first focus on SN 1991bg and its close twins, which include SNe 1997cn (Turatto et al., 1998; Jha et al., 2006), 1998de (Modjaz et al., 2001; Jha et al., 2006; Matheson et al., 2008), 1999by (Howell et al., 2001; Vinkó et al., 2001; Höflich et al., 2002; Garnavich et al., 2004; Silverman et al., 2012), 2005bl (Taubenberger et al., 2008), 2005ke (Hicken et al., 2009; Contreras et al., 2010; Blondin et al., 2012; Silverman et al., 2012; Patat et al., 2012), 2006bz (Hicken et al., 2009), and several other examples contained in the SN Ia samples of Hicken et al. (2009), Contreras et al. (2010), Ganeshalingam et al. (2010), Stritzinger et al. (2011), Blondin et al. (2012), and Silverman et al. (2012). In Sections 3.6 and 3.7 we will then discuss transitional 86G-like objects and the very subluminous and peculiar transient PTF 09dav, respectively.

3.1 Luminosity and colour evolution

The most obvious property of 91bg-like SNe is their significantly lower luminosity compared to normal SNe Ia. At peak they are 1.5–2.5 mag fainter in optical bands, reaching peak absolute magnitudes between $-16.7$ and $-17.7$ in $B$ (Taubenberger et al., 2008; Sullivan et al., 2011, see Fig. 1). With rather red maximum-light colours, $(B-V)_{\text{max}} \sim 0.5–0.6$ mag (Taubenberger et al., 2008), they are more reminiscent of stripped-envelope core-collapse SNe than normal SNe Ia, and while normal SNe Ia are reddest $\sim 30$ d after maximum light, 91bg-like SNe reach this point earlier, at $\sim +15$ d (Burns et al., 2014). Only a month or more after maximum light, during the Fe II-dominated phase, the colours of all SNe Ia converge to a common value (Lira, 1996).

At longer wavelengths, the luminosity differences are less pronounced. Wood-Vasey et al. (2008) found indistinguishable $JHK$ peak absolute magnitudes for normal and subluminous SNe. Kattner et al. (2012) instead suggested that there is a weak but significant trend of NIR peak absolute magnitudes with decline rate, and that 91bg-like SNe are fainter than normal SNe Ia also in $J$ and $H$, but only by about 0.5 mag. Finally, Krisciunas et al. (2009) concluded that there are two groups of fast-declining SNe Ia: transitional objects (Section 3.6) have NIR peak magnitudes indistinguishable from those of normal SNe Ia, whereas genuine 91bg-like objects are fainter than normal SNe Ia by 0.5–0.7 mag, confirming an earlier result
Fig. 3 91bg-like SNe in comparison to the normal SNe Ia 2003du (Stanishev et al., 2007) and 2011fe (Munari et al., 2013; Pereira et al., 2013). a) $I$-band light curves. b) $B$-band light curves. c) Photospheric spectra. d) Nebular spectra. References for individual 91bg-like SNe are provided in the main text.
The Extremes of Thermonuclear Supernovae

for SN 1999by by Garnavich et al. (2004). All these studies, however, are limited by the small number of 91bg-like SNe in the investigated samples.

The light curves of 91bg-like SNe show a fast decline from peak, reflected in a light-curve decline parameter \( \Delta m_{15}(B) \) of 1.8–2.1 [\( \Delta m_{15}(B) \approx 1.7 \) in normal SNe Ia]. From pre-maximum light curves rise times of 13 to 15 d have been estimated (Taubenberger et al., 2008), a few days shorter than those of normal SNe Ia (Fig. 3a,b). However, a simple time stretch is insufficient to map the light curves of 91bg-like SNe onto those of normal SNe Ia. First and foremost, 91bg-like SNe lack the secondary maxima in the NIR bands that are characteristic of normal SNe Ia (Fig. 3a). Instead, they show single peaks delayed by a few days with respect to that in \( B \) (Garnavich et al., 2004; González-Gaitán et al., 2014; Friedman et al., 2015).

The first peak in normal SNe Ia, in contrast, precedes those in bluer bands. Kasen (2006) and Blondin et al. (2015) suggested the occurrence of the secondary NIR peak in SNe Ia to be related to a recombination wave propagating through chemically stratified ejecta. The recombination of Fe\( \text{III} \) to Fe\( \text{II} \) would happen earlier in less luminous and cooler SNe, and in 91bg-like SNe this would cause the first and second NIR peaks to merge to form a single, slightly delayed maximum.

Starting at \( \Delta m_{15}(B) \sim 1.7 \), many quantities of SNe Ia such as colours and spectroscopic appearance (see below) show a steeper dependence on \( \Delta m_{15}(B) \) than at lower decline rates. This also holds for the peak luminosity, making 91bg-like SNe Ia fainter than predicted by the Phillips relation for the given \( \Delta m_{15}(B) \) (Garnavich et al., 2004; Taubenberger et al., 2008) see Fig. 1]. This deviation from the width–luminosity relation as calibrated with normal SNe Ia disqualifies 91bg-like SNe as useful cosmic distance indicators. However, since at higher redshift they are disfavoured by Malmquist bias anyway, they are unlikely to compromise SN Ia cosmology.

The inferred quasi-bolometric peak luminosities of 91bg-like SNe are at least a factor 2–3 below those of normal SNe Ia, and range from \( \log(L) = 42.1 \) to 42.4 (e.g. Taubenberger et al., 2008). The bolometric peak can be used to estimate the mass of \( {^{56}\text{Ni}} \) synthesised in an explosion. For 91bg-like SNe, \( {^{56}\text{Ni}} \) masses between \( \sim 0.05 \) and \( \sim 0.10 \, \text{M}_\odot \) (e.g. Mazzali et al., 1997; Sullivan et al., 2011) have been derived in this way. The late-time tail of bolometric light curves is sensitive to the \( {^{56}\text{Ni}} \) mass as well, but also to the degree of \( \gamma \)-ray and positron trapping. Normal SN Ia bolometric light curves can be reproduced assuming complete positron trapping, but increasing \( \gamma \)-ray losses owing to the expansion of the ejecta (e.g. Kerzendorf et al., 2014). There are indications that this scheme breaks down for 91bg-like SNe (Mazzali et al., 1997). Either there is increasing flux redistribution into bands not accounted for in the quasi-bolometric light curve, or positron trapping is incomplete, which would have important consequences for the magnetic-field configuration in the ejecta (Ruiz-Lapuente & Spruit, 1998), and might hint at an explosion mechanism different from normal SNe Ia.
3.2 Spectroscopic characteristics

The spectroscopic evolution of 91bg-like SNe largely resembles that of normal SNe Ia. Pre-maximum optical spectra are dominated mostly by intermediate-mass elements, but soon after maximum light they transition to being shaped by Fe and Co lines as the line-forming region recedes into the IGE-rich core of the ejecta (Fig. 3c). This transition happens earlier in 91bg-like SNe than in normal SNe Ia, but otherwise the similarities in the evolution indicate a comparable degree of chemical stratification in the ejecta. In particular, strong outward-mixing of IGEs is disfavoured by the Fe-poor early spectra.

However, looking in detail, a number of spectroscopic peculiarities in 91bg-like SNe become evident (Filippenko et al., 1992b; Leibundgut et al., 1993; Mazzali et al., 1997). In early-time spectra O I $\lambda$7774 and Ti II lines between 4000 and 4400 Å are unusually prominent, and the Ti lines increase in strength until a few days past peak brightness (Fig. 3c). C I lines have clearly been detected in NIR spectra (Höflich et al., 2002; Hsiao et al., 2015). C II lines more tentatively in optical spectra as late as a few days before maximum (Taubenberger et al., 2008; Blondin et al., 2012). Si II lines are pronounced, and Si II $\lambda$5972 is particularly strong (Nugent et al., 1995; Hachinger et al., 2008). The characteristic Si II ‘W’ feature, in contrast, appears less marked than in normal SNe Ia. Some of the observed peculiarities can be attributed to the comparatively low temperature and ionisation state of the ejecta (Mazzali et al., 1997; Hachinger et al., 2008, 2009), which leads to a higher abundance of neutral and singly ionised species and disfavours lines arising from highly excited states. However, it is unlikely that the temperature alone can explain all peculiarities. A truly higher abundance of oxygen is probably required (Hachinger et al., 2009), but also not unexpected in a subluminous SN with a low $^{56}$Ni mass and overall low burning efficiency. Whether or not an enhanced Ti abundance is needed is more controversial. It would also be much harder to explain from a nucleosynthesis perspective.

The ejecta velocities measured in 91bg-like SNe are on average lower, but not dramatically different from those in normal SNe Ia. Before maximum light the velocities estimated from Si II $\lambda$6355 are on the low side (but still within the range) of velocities observed in normal SNe Ia. After maximum light, however, when in low-velocity normal SNe Ia the Si II velocities settle at 9000–10 000 km s$^{-1}$, those in 91bg-like SNe keep decreasing, reaching typical values around 7000 km s$^{-1}$ (Taubenberger et al., 2008) by the time the Si II $\lambda$6355 line disappears because of blending with emerging Fe II emission. Up to now, no high-velocity features (HVFs; Mazzali et al., 2005) have ever been detected in 91bg-like SNe. Since the origin of HVFs in SNe Ia is still obscure, it is also unclear whether the absence of HVFs in 91bg-like SNe is related to their explosion mechanism or to their circumstellar environments.

Nebular ($\gtrsim$ 100 d) spectra of SNe 1991bg and 1999by are again rather unusual (Fig. 3d). While normal SNe Ia are characterised by a mix of broad [Fe II], [Fe III] and [Co III] emission lines at those phases, broad lines of doubly ionised species are absent in SNe 1991bg and 1999by. Their nebular spectra are dominated by broad
[Fe II] and [Ca II] λλ 7291, 7324 emission lines, indicative of a comparatively low ionisation throughout most of the ejecta. However, narrow [Fe III] and [Co III] emission lines (FWHM = 1000–2000 km s⁻¹) are superimposed on the underlying broad [Fe II] spectrum, and their relative strength increases with time (Turatto et al., 1996; Mazzali et al., 1997). Their width suggests that they originate exclusively from the innermost ejecta. Mazzali & Hachinger (2012) argued that the required high ionisation state in this innermost region could be explained by a low central density, as it is found in violent-merger explosion models (Pakmor et al., 2010).

Based on their fast light-curve decline and their strong Si II λ 5972 line, 91bg-like SNe belong to the class of CL (‘cool’) SNe in the Branch et al. classification scheme (Branch et al., 2006), and to the class of ‘FAINT’ SNe following Benetti et al. (2005). In fact, 91bg-like SNe form the cores of these groups, which encompass also transitional objects and some weirdos, and whose boundaries to other SN Ia classes are not sharp.

### 3.3 Polarimetry

Spectropolarimetric observations are available for SNe 1999by (Howell et al., 2001) and 2005ke (Patat et al., 2012), and reveal interesting differences to the polarisation signal observed in normal SNe Ia. The latter typically show very low continuum polarisation (<0.2%), indicating that the ejecta show no global deviation from a spherical shape. At the same time, strong line polarisation (up to 1%) is observed in Si II and Ca II lines in early-time spectra, pointing at significant compositional inhomogeneities in the outer layers (Wang et al., 2007). HFVs, in particular, are always strongly polarised. From this point of view it may not be surprising that in SNe 1999by and 2005ke line polarisation is among the weakest in SNe Ia (~0.4%; Howell et al., 2001; Wang et al., 2007; Patat et al., 2012): 91bg-like SNe do not show HFVs. What is really remarkable, however, is the relatively high continuum polarisation in SNe 1999by and 2005ke, which reaches and even exceeds 0.5% in the line-free region around 7000 Å (Howell et al., 2001; Patat et al., 2012). According to Patat et al., this could be explained by an oblate geometry with a global asymmetry at the 15% level. Suitable explosion models for 91bg-like SNe must be capable of producing that degree of asphericity.

### 3.4 Host galaxies and relative rates

In stark contrast to 91T-like SNe which explode almost exclusively in star-forming late-type galaxies (see Section 2.3), 91bg-like SNe are mostly found in massive elliptical or S0 galaxies with a star-formation rate below a few times 10⁻⁹ M⊙ yr⁻¹ (Howell, 2001; Neill et al., 2009; González-Gaitán et al., 2011). Only few 91bg-like SNe have been found in spiral galaxies, most prominently SN 1999by, which
exploded in the Sb galaxy NGC 2841. However, despite its morphological classification the spectral features of NGC 2841 are those of an elliptical galaxy (Gallagher et al., 2005).

Concerning the relative rate of 91bg-like SNe, discordant numbers have been quoted in the literature. Based on a volume-limited subsample of SNe discovered by LOSS, Li et al. (2011) estimated that 91bg-like SNe constitute 15% of all SNe Ia. Silverman et al. (2012) obtained a much lower fraction of 91bg-like SNe of ~6% of all SNe Ia on the basis of the Berkeley Supernova Ia Program (BSNIP) spectroscopic sample. Using only light-curve information, Ganeshalingam et al. (2010) derived a fraction of ~11% for a largely congruent sample of SNe. Finally, González-Gaitán et al. (2011) estimated that 7–9% of all local SNe Ia are 91bg-like. All these studies have different systematics, and all have a strong host-galaxy bias since they are based on samples discovered by targeted SN surveys. However, the biggest uncertainty in the rate comes from the demarcation of 91bg-like SNe, and the question whether transitional, 86G-like SNe (Section 3.6) are counted separately or not. Including transitional objects, the fraction of subluminous SNe Ia estimated by González-Gaitán et al. (2011) triples, from 7–9% to 22%. In magnitude-limited samples, 91bg-like SNe are strongly suppressed by Malmquist bias. Accordingly, Östman et al. (2011) and Foley et al. (2009) did not find any 91bg-like SNe Ia in their higher-redshift samples with mean $z$ of 0.17 and 0.35, respectively, and while González-Gaitán et al. (2011) did find several subluminous SNe Ia in the SNLS data set at $0.1 \lesssim z \lesssim 1.0$, with one exception they were all transitional objects.

### 3.5 Explosion scenarios

Promising explosion models for 91bg-like objects need to explain the main characteristics of these SNe, including the low $^{56}\text{Ni}$ masses, the rapidly declining light curves, the relatively high continuum polarisation and the particular chemical abundance structure. Spectral modelling carried out by Hachinger et al. (2009) revealed that the ejecta of 91bg-like SNe are chemically stratified, dominated by oxygen above $\sim 8000$ km s$^{-1}$ and by IMEs below. In particular, strong outward mixing of IGEs is not compatible with the spectroscopic display of 91bg-like SNe. This result basically rules out pure deflagrations (e.g. Fink et al., 2014, and references therein) as a possible explosion mechanism for 91bg-like objects, although the required low $^{56}\text{Ni}$ masses could be accomplished within this scenario. Delayed detonations (e.g. Seitenzahl et al., 2013, and references therein), on the other hand, retain a high level of chemical stratification, but fail to produce $^{56}\text{Ni}$ masses below $\sim 0.2–0.3 \, M_\odot$, not low enough for 91bg-like SNe. Taken together, 91bg-like objects are unlikely to originate from thermonuclear explosions in $M_{\text{Ch}}$ WDs.

Pakmor et al. (2010) presented a violent merger of two $0.9 \, M_\odot$ WDs, which produced about the right $^{56}\text{Ni}$ mass and spectroscopically provided a satisfactory match with 91bg-like objects. However, because of the large total ejecta mass of $1.8 \, M_\odot$ and the accordingly large optical depths for $\gamma$-rays and optical photons, the
light curve of that model was very broad and inconsistent with those of rapidly declining 91bg-like events. In fact, using an analytic light-curve model, Stritzinger et al. (2006) and Scalzo et al. (2014b) claimed significantly sub-$M_{\text{Ch}}$ progenitors for fast decliners.

Sub-$M_{\text{Ch}}$ explosions are typically realised as double detonations, where a first detonation in an accreted He shell on top of the WD triggers a second detonation in the CO core via converging shocks (Fink et al., 2010, and references therein). If the exploding WD is sufficiently lightweight, only small amounts of $^{56}\text{Ni}$ are produced. The main problem in the classical double-detonation models is the effect of the ashes of the He detonation: they are rich in IGEs and generate a lot of opacity in the outer layers, which is usually detrimental to the spectrum (Kromer et al., 2010). This effect might be mitigated or avoided by keeping the He-shell mass at a minimum, and by igniting the detonation dynamically through accretion-stream instabilities (Guillochon et al., 2010) or in the course of a violent merger (Pakmor et al., 2013). As a matter of fact, even the very-low-mass He shells natively present on top of virtually all CO WDs might be sufficient for these scenarios to work. However, the capability of these models to reproduce 91bg-like SNe still remains to be demonstrated.

3.6 $86\text{G}$-like SNe: half way between normal and 91bg-like SNe

Five years before SN 1991bg, the first peculiar SN Ia was discovered: SN 1986G in Centaurus A exhibited a low luminosity and unusually red colours (Phillips et al., 1987). However, since the SN was embedded in a dust lane, and showed prominent interstellar Na I D absorption lines in its spectra, it was not totally clear to which extent the observed peculiarities were intrinsic, or just caused by extinction and reddening along the line of sight. With a better handle on the extinction towards SN 1986G (Hough et al., 1987; Phillips et al., 1999), it has become clear that the SN is indeed intrinsically unusual, and seems to be a transitional object between normal and 91bg-like SNe. Several other 86G-like SNe have subsequently been studied, including SN 1998bp (Jha et al., 2006; Matheson et al., 2008), SN 2003gs (Krisciunas et al., 2009; Silverman et al., 2012) and iPTF 13ebh (Hsiao et al., 2015). They appear to be at least as frequent as the more extreme 91bg-like objects (González-Gaitán et al., 2011).

The light curves of 86G-like SNe decline rapidly [with a typical $\Delta m_{15}(B)$ around 1.8, see Fig. 1], and peak at magnitudes intermediate between those of normal and 91bg-like objects ($M_{B,\text{max}} \sim -18$, translating into $^{56}\text{Ni}$ masses of about 0.2 $M_{\odot}$). In NIR bands, 86G-like SNe do show double-peaked light curves, with the first peak preceding those in bluer bands, in analogy to normal SNe Ia. However, the secondary maxima are very weak, and occur soon after the first peaks. The $JHK$ peak magnitudes are brighter than in 91bg-like SNe, and align with those of normal SNe Ia, which have been proposed to be standard candles in the NIR (Wood-Vasey et al., 2008; Krisciunas et al., 2009; Kattner et al., 2012).
Spectroscopically, 86G-like SNe show again properties intermediate between normal and 91bg-like events. The Si II $\lambda$5972 line is as strong as in 91bg-like objects, but Ti II lines – while present – are considerably weaker, indicating an intermediate ionisation state (Fig. 3c). At nebular phases (Cristiani et al., 1992; Silverman et al., 2012), 86G-like objects show a high ionisation in a sufficiently large volume of the ejecta to produce broad [Fe III] emission (Fig. 3d), in contrast to the narrow [Fe III] emission seen in 91bg-like objects which arises exclusively from the innermost regions (Mazzali & Hachinger, 2012).

With their intermediate properties, 86G-like objects play a critical role for understanding whether subluminous SNe Ia are just the extreme tail of a single SN Ia population, or a distinct class of objects with different progenitors or explosion mechanisms.

### 3.7 PTF 09dav: simply the most subluminous 91bg-like event?

PTF 09dav (Sullivan et al., 2011) may or may not constitute the most extreme 91bg-like SN to date by quite a margin. Even though the eventual classification remains controversial, there are reasons to consider PTF 09dav a 91bg-like event. First of all, the light-curve morphology with a single peak in the I band and a rapid decline in all bands is very similar (Fig. 5a). Sullivan et al. (2011) estimated a $\Delta m_{15}(B)$ of 1.87 $\pm$ 0.06, well within the range observed in 91bg-like objects. The colours at maximum light are also the same as in 91bg-like SNe, with $(B-V)_{max} = 0.56$ mag, and the main spectroscopic features in form of prominent Ti II, Si II and O I lines are identical (Fig. 5c).

What makes PTF 09dav stand out from the crowd of 91bg-like objects is its extremely low luminosity. With a peak absolute B-band magnitude of about $-15.5$, it is $\sim 1.5$ mag fainter than other 91bg-like SNe, and $\sim 3.5$ mag fainter than normal SNe Ia (Fig. 1), leading to a $^{56}$Ni mass estimate of merely 0.019 M$_\odot$ (Sullivan et al., 2011).

The low luminosity goes hand in hand with a number of peculiarities in early-time spectra, which Sullivan et al. (2011) have analysed in detail. To start with, the derived expansion velocities are low, even by the standards of subluminous SNe Ia, reaching only $\sim 6000$ km s$^{-1}$ a few days after maximum light. Si II $\lambda$5972 is surprisingly weak, in spite of the apparently low temperature and ionisation of the ejecta. This might be explained by an overall low Si abundance, which would be in line with the complete absence of Si II lines in PTF 09dav. Instead, spectral modelling suggests the presence of a number of species that require low temperatures: Ti II, Mg I, Na I and Sc II. The Sc II detection, in particular, appears convincing, and is unprecedented in thermonuclear SNe, where the abundance of Sc is expected to be orders of magnitude below those of e.g. Ca, Ti and Cr (e.g. Seitenzahl et al., 2013). The tentative identification of Sr II lines – if correct – would be even more difficult to explain within a thermonuclear explosion scenario, as Sr is a classical s-process element. Interestingly, there is almost no Fe required to obtain a good fit. This is
especially true at more advanced phases (~2 weeks after maximum), when normal 91bg-like SNe start to be dominated by Fe II emission. Finally, a nebular spectrum of PTF09dav taken three months after maximum shows little else than strong, broad [Ca II] $\lambda\lambda 7291, 7324$ emission and weak, narrow H$\alpha$ (Fig. 5d). Fe emission lines, which dominate the nebular spectra of all other SNe Ia including 91bg-like objects, are entirely absent.

It may be doubted that all the observed spectroscopic peculiarities can be solely explained by a lower ejecta temperature (though this may indeed be an important factor). Instead, it appears likely that the nucleosynthesis in PTF09dav proceeded differently than in other SNe Ia, favouring elements between Ca and Cr at the expense of both classical IMEs such as Si and S, and classical IGEs such as Fe, Co and Ni. The consequence of this would be that the similarities of PTF09dav with 91bg-like SNe at early phases are mostly coincidental, that it likely had a different progenitor and explosion mechanism, and should not be regarded as a member of this group. We will come back to PTF09dav in the context of the so-called Ca-rich gap transients in Section 5 where we compare its properties with those of other low-luminosity SNe with predominant [Ca II] emission at late phases.
02es-like SNe: subluminous but slowly declining

With ‘02es-like SNe’ we refer to a group of objects which are not really extreme in any one photometric or spectroscopic property, but populate a region in SN Ia phase space that was long believed to be devoid of objects, and which lies far off the Phillips relation (Fig. 1).

The first observations of an 02es-like SN date back to the end of the 1990s, but more than 10 yr should pass before the first data were published. 02es-like SNe are hence the most recent addition to the zoo of thermonuclear transients. Actually, the group is so young that not even the term ‘02es-like SNe’ is well established in the literature, let alone a sharp membership definition. What is used here is a somewhat wider reading of the term compared to White et al. (2015), including also SNe that do not exhibit the same very low ejecta velocities as SN 2002es. With this definition the class encompasses SN 2002es itself and SN 1999bh (Li et al. 2001a; Ganeshalingam et al. 2012), SN 2010lp (Kromer et al. 2013, Taubenberger et al. 2013b), PTF 10ops (Maguire et al. 2011), iPTF 14atg (Cao et al. 2015; Kromer et al. 2016), PTF 10ujn and PTF 10acd b (White et al. 2015), and arguably SN 2006bt (Hicken et al. 2009; Ganeshalingam et al. 2010; Foley et al. 2010). White et al. (2015) have shown that 02es-like SNe are clearly distinct from SNe Iax in a number of key properties.

4.1 General evolution and diversity

The description of the observational characteristics of 02es-like SNe can be strongly abbreviated by referring to Section 3, where the spectroscopic and photometric properties of 91bg- and 86G-like SNe are presented. This is because 02es-like SNe behave very similarly to 91bg / 86G-like SNe in most respects, featuring cool ejecta with low ionisation and spectra with strong Si II (especially λ5972), O I and Ti II lines at early phases (Fig. 4c). The light-curve morphology with a single peak in the I band also resembles that of traditional subluminous SNe (Fig. 4a), and so do the relatively red colours \((B - V)_{\text{max}} = 0.2 \ldots 0.5\). The absolute magnitudes are faint, with \(M_{B,\text{max}}\) ranging from \(-17.6\) to \(-18.1\) for most of the objects, more similar to SN 1986G than to the fainter genuine 91bg-like SNe, but still significantly subluminous compared to normal SNe Ia. Through Arnett’s rule (Arnett 1982) or more sophisticated light-curve modelling, \(^{56}\text{Ni}\) masses around \(0.15 - 0.20\,\text{M}_\odot\) have been estimated (Maguire et al. 2011; Ganeshalingam et al. 2012; Kromer et al. 2013). Only SN 2006bt is an exception, peaking at \(M_B \approx -19\) and thus being almost as luminous as normal SNe Ia with a similar \(\Delta m_{15}(B)\) of about 1.1 (Foley et al. 2010; see Figs. 1 and 4).

What really distinguishes 02es-like objects from 91bg- and 86G-like SNe are their time scales. Their light-curve peaks are much wider, with longer rise times of 19–20 d (Maguire et al. 2011; Cao et al. 2015) and slower decline. In fact, with \(\Delta m_{15}(B)\) in the range 1.1 to 1.3, 02es-like SNe in this respect closely resemble
Fig. 4 02es-like SNe in comparison to the normal SNe Ia 2003du (Stanishev et al., 2007) and 2011fe (Munari et al., 2013; Pereira et al., 2013; Taubenberger et al., 2015), and the subluminous SN Ia 1991bg (Filippenko et al., 1992b; Leibundgut et al., 1993; Turatto et al., 1996, see also Section 3). a) $I$-band light curves. b) $B$-band light curves ($g$-band for PTF 10ops). c) Photospheric spectra. d) Nebular spectra. References for individual 02es-like SNe are provided in the main text.
normal SNe Ia, and are very different from 91bg-like objects with $\Delta m_{15}(B)$ between 1.8 and 2.0. The overall stretched light-curve peak is paralleled by a slower evolution of the SN colours, and by a later and more gentle transition from IME- to Fe II-dominated spectra.

A point in which the class of 02es-like SNe shows significant diversity are the ejecta velocities. Some objects like SN 2006bt or PTF 10ops show Si II λ6355 velocities at peak of $\sim 10000$ km s$^{-1}$ (Foley et al., 2010; Maguire et al., 2011), while SN 2002es and its closest siblings (SN 1999bh and PTF 10acdh) show Si II velocities between 6000 and 7000 km s$^{-1}$ (Ganeshalingam et al., 2012; White et al., 2015). With $\sim 8000$ km s$^{-1}$, iPTF 14atg takes an intermediate position (Cao et al., 2015).

### 4.2 Early UV spike in iPTF 14atg

Among all 02es-like SNe, iPTF 14atg is the only one which was discovered very soon after explosion, and which has an excellent coverage of the early light curve by ground-based and swift UV photometry. In the earliest photometric data points, up to $\sim 5$ d after the estimated instant of explosion, it shows a spike in the swift UV bands, which is also tentatively visible in the $u$ and $b$ bands (Cao et al., 2015). No excess is visible in redder bands, in particular in the $r$ band, even at an extremely early phase $\sim 1$ d after the explosion. A spectrum of iPTF 14atg taken $\sim 3$ d after explosion (Cao et al., 2015), during the UV spike, shows a blue continuum with only relatively weak, broad features which do not seem to match any of the lines seen later on. Without similarly early observations for other 02es-like SNe, it is unclear whether or not this behaviour is generic for this class of objects.

### 4.3 Nebular spectroscopy of SN 2010lp

A nebular spectrum of SN 2010lp (264 d after maximum; Taubenberger et al., 2013a) in most respects closely resembles spectra of 91bg-like SNe taken at similar phases (see Section 3.2), being dominated by broad [Fe II] and [Ca II] emission (Fig. 4d). No broad [Fe III] emission is visible, and the curious narrow ($\sim 2000$ km s$^{-1}$ FWHM) [Fe III] and [Co III] emission lines, which were detected in SNe 1991bg and 1999by and gave rise to speculations on a low central matter density (Mazzali & Hachinger, 2012), are totally absent in SN 2010lp. Instead, [O I] λλ6300,6364 emission is observed there (Taubenberger et al., 2013a), which is even more curious for a thermonuclear SN, as these lines are usually considered hallmark features of core-collapse explosions. The [O I] lines in SN 2010lp are similarly narrow as the [Fe III] lines in SN 1991bg and double-peaked, which suggests the emission to arise from a complexly shaped oxygen-rich region in the central parts of the ejecta. Again, it remains to be seen how generic this behaviour is among
02es-like SNe, although a low-S/N nebular spectrum of iPTF 14atg (Kromer et al., 2016) seems to show the same features as that of SN 2010lp.

4.4 Rapid fading of SN 2002es after one month

About 30 d after maximum, just before the expected settling on a radioactive tail, all optical light curves of SN 2002es start to fade rapidly (Ganeshalingam et al., 2012, see Fig. 4a,b). The enhanced decline lasts for at least 40 d (when the photometric follow-up ends). Between +30 and +70 d, SN 2002es fades by 3.5–4.5 mag in B, V, and R, about three times as much as a normal SN Ia in the same period. Qualitatively, the behaviour is similar to the decline observed in some ‘super-Chandrasekhar’ SNe Ia at somewhat later epochs (see Section 7), which there has been attributed to dust formation (Taubenberger et al., 2013b). Ganeshalingam et al. (2012) discussed several possible explanations, including dust formation, an IR catastrophe (Axelrod, 1980), γ-ray escape and a light-curve peak powered by shock breakout rather than radioactivity. γ-ray escape would require none of the γ-rays and only 30% of the positrons to be trapped at +70 d, which is nearly impossible if the trapping was still mostly complete at maximum light. Dust formation at such an early epoch would be unprecedented, and is disfavoured by the fact that the SN colours turn bluer once the light curve starts to drop. An IR catastrophe is theoretically predicted to occur after several hundred days when the ejecta have cooled down to 1000–2000 K (Axelrod, 1980), and has been confirmed at such a late epoch in SN 2011fe (Fransson & Jerkstrand, 2015). Given the spectroscopic evolution of SN 2002es, which continues to be similar to that of SN 1991bg, such a drastic change in the plasma state is strongly disfavoured. Finally, if the entire light-curve peak had merely been the result of shock breakout without any radioactive re-heating of the ejecta, a progenitor radius of ~15 R☉ would have been required. This is only feasible with an extended H envelope, but no H is observed in the spectra of SN 2002es. In summary, the rapid dimming of SN 2002es starting a month after maximum light remains a mystery. Other 02es-like SNe either do not have photometric coverage after +40 d (SN 1999bh, PTF 10ujn and PTF 10acdh), or do not show a similar drop as SN 2002es (SN 2006bt, SN 2010lp, PTF 10ops and iPTF 14atg).

4.5 Host galaxies and explosion environments

Similar to their 91bg-like cousins, 02es-like events have a tendency to explode preferentially but not exclusively in massive, early-type host galaxies with R-band absolute magnitudes between −19 and −22 (White et al., 2015). The explosion site of SN 2006bt was found at a large projected distance of 33.7 kpc from its elliptical host galaxy (Foley et al., 2010). PTF 10ops was even more extreme in this regard. Maguire et al. (2011) found no potential host galaxy in the surroundings
of PTF 10ops down to a limiting absolute magnitude of $-12$ in $R$, fainter than any known SN host. They concluded that PTF 10ops was most likely associated with a massive galaxy at a projected distance of 148 kpc, making this one of the most remote SNe discovered to date. Such extreme offsets are reminiscent of Ca-rich gap transients (Section 5), and impose strong constraints on the longevity of the progenitor systems.

4.6 Explosion models

Given the similarity between 02es-like and 91bg-like SNe, much of the model discussion from Section 3 applies here as well. In particular, pure-deflagration models are disfavoured because of the strong mixing in the ejecta, which is in conflict with the stratified ejecta required to produce 91bg-like spectra (Hachinger et al., 2009). The main differences in 02es-like SNe are their somewhat larger $^{56}\text{Ni}$ masses, meaning that the faintest $M_{\text{Ch}}$ delayed-detonation models are not necessarily excluded, and their broader light curves and partially lower velocities, which point at higher opacities and possibly a larger ejecta mass than in 91bg-like SNe.

Important constraints on progenitor systems and explosion models are provided by the early-time UV spike in iPTF 14atg. In principle, there are several ways to produce a short-lived early UV flash in SN explosions, including the presence of radioactive material close to the surface of the ejecta at negligible optical depth (Diehl et al., 2014), the breakout of the SN shock from the progenitor star (Piro et al., 2010; Rabinak et al., 2012; Nakar & Sari, 2012), and an interaction of the SN ejecta with circumstellar material (Raskin & Kasen, 2013) or a companion star (Kasen, 2010). Cao et al. (2015) discussed most of these scenarios in the context of iPTF 14atg, and concluded that except for ejecta–companion interaction all other models could be ruled out, suggesting that the progenitor of iPTF 14atg must have had a non-degenerate companion. However, as pointed out by Kromer et al. (2016), with respect to ejecta–CSM interaction, Cao et al. have only excluded a very specific CSM configuration, and neglect the possibilities of a more compact CSM with non-negligible optical depth in the shocked region (Raskin & Kasen, 2013) or a non-spherical CSM distribution.

A completely different approach to constrain the nature of 02es-like SNe concentrates on their spectroscopic similarity to 91bg-like SNe. Maguire et al. (2011) and Ganeshalingam et al. (2012) noted that a violent-merger model of two $0.9 \, M_\odot$ WDs by Pakmor et al. (2010) might be an attractive scenario for PTF 10ops and SN 2002es. This model, originally meant to explain 91bg-like SNe, has too slowly-declining light curves to provide a convincing fit to 91bg-like SNe, but for 02es-like SNe this property is beneficial. Kromer et al. (2013, 2016) presented revised versions of the model, i.e. mergers of a $0.9 \, M_\odot$ primary and a $0.76 \, M_\odot$ secondary at different metallicities. The slightly asymmetric mass configuration of these models leads to a higher $^{56}\text{Ni}$ production, and both the light curves and spectra provide excellent matches to those of the 02es-like SNe 2010lp and iPTF 14atg. Hav-
ing unburned oxygen near the centre of the ejecta, these models might also potentially reproduce the [O i] $\lambda\lambda 6300, 6364$ emission observed in the nebular spectra of SN 2010lp (Taubenberger et al., 2013a) and iPTF 14atg (Kromer et al., 2016).

Pakmor et al. (2013) finally suggested that both 91bg-like and 02es-like SNe might stem from violent mergers whose primary CO WDs have a thin He layer on the surface. This He layer could be dynamically ignited during the merger process and trigger a subsequent C detonation in the core. This scenario should work with He as well as CO WD companions. He WD companions might result in 91bg-like SNe, while the significantly more massive CO WD companions would lead to a higher total ejecta mass and might explain 02es-like SNe.
5 Ca-rich gap transients

Traditionally, the classification of SNe was exclusively based on spectroscopic properties near maximum light. However, over the years it has unsurprisingly turned out that maximum-light spectra are not sufficient to capture and categorise the full diversity of phenomena revealed by more and more advanced observational campaigns. As a consequence, additional classification criteria based on light curves or the late-time evolution were introduced, and attempts were made to group together objects that were believed to share the same progenitors and explosion mechanisms. The group of Ca-rich gap transients constitutes an extreme example of this approach, as the assignment to this group is not at all based on the early-time spectroscopic properties (which can be quite diverse), but mostly on ‘Ca-rich’ late-time spectra and a luminosity in the ‘gap’ between novae and ordinary supernovae (Kasliwal et al., 2012).

Ca-rich gap transients are one of the youngest SN classes. The first observations of such objects were carried out in the early 2000s (Filippenko et al., 2003), but it was only years later that Ca-rich gap transients were fully characterised as a separate class of objects (Perets et al., 2010; Kasliwal et al., 2012). Meanwhile, the ‘gap’ is no longer empty, and encompasses SN 2005E (Perets et al., 2010; Kasliwal et al., 2012), SN 2005cz (Kawabata et al., 2010; Perets et al., 2011b), PTF 09dav (Sullivan et al., 2011; Kasliwal et al., 2012), SN 2007ke, SN 2010et / PTF 10iuv and PTF 11bij (Kasliwal et al., 2012), SN 2012hn (Valenti et al., 2014), and a few other Ca-rich transients reported by Perets et al. (2010).

5.1 Light curves and peak luminosity

Classical novae have $R$-band absolute peak magnitudes between $-5$ and $-10$, classical SNe are (with the exception of a few low-luminosity SNe IIP) brighter than $-16$ at peak. The ‘gap’ between these two luminosity regimes has until recently been relatively devoid of transients, but the advent of new high-cadence wide-field surveys such as PTF, PanSTARRS or OGLE has populated this strip from two sides, with luminous novae and subluminous SNe. Ca-rich gap transients are characterised by peak magnitudes between $-14.0$ and $-16.5$ (Perets et al., 2010; Kasliwal et al., 2012), and thus fall on the bright end of the gap. The morphology of their light curves is similar to 91bg-like SNe (Section 3.1) or fast-evolving SNe Ib/c, with single peaks in the NIR bands, rise times of $9$–$15$ d, fast post-maximum decline and relatively red colours $(B-V)_{\text{max}} \sim 0.6$ mag (Fig. 5a,b).

Waldman et al. (2011) compared the bolometric light curve of SN 2005E (with a peak luminosity $\log(L_{\text{max}}) = 41.5$) to those of models featuring different compositions of radioactive species. It seems that a satisfactory fit can be obtained with a light curve powered exclusively by the $^{56}\text{Ni}$ decay chain, at least if the total ejecta mass is adjusted accordingly (which Waldman et al. did not do). In that case, a $^{56}\text{Ni}$ mass just below 0.01 $M_\odot$ would be required. Alternatively, the light curve of
Fig. 5 Ca-rich gap transients in comparison to the normal SNe Ia 2003du (Stanishev et al., 2007) and 2011fe (Munari et al., 2013; Pereira et al., 2013), the subluminous SN Ia 1991bg (Filippenko et al., 1992b; Leibundgut et al., 1993; Turatto et al., 1996, see also Section 3), and the stripped-envelope core-collapse SNe 1990U and 2004aw (Taubenberger et al., 2006). a) $I$-band light curves. b) $B$-band light curves ($g$-band for PTF09dav). c) Photospheric spectra. d) Nebular spectra. References for individual Ca-rich gap transients are provided in the main text.
SN 2005E could also be reproduced by a combination of mostly $^{48}\text{Cr}$, $^{52}\text{Fe}$ and $^{44}\text{Ti}$ decay, in which case, however, a ridiculously high $^{44}\text{Ti}$ mass in excess of 1 $M_\odot$ would be needed (Waldman et al. 2011; Kasliwal et al. 2012). Without a more precise knowledge of the ejecta mass, this degeneracy cannot be resolved easily. Finally, since the light curves of most Ca-rich gap transients look quite similar, the results obtained for SN 2005E are also applicable to other members of this class.

5.2 Spectroscopic characteristics

Since the group definition of Ca-rich gap transients is not based on early-time spectroscopic properties, it is not surprising to encounter some diversity among the group members. For most of them, however, a common scheme emerges. These objects are characterised by He-rich and H-free early-time spectra, formally leading to an SN Ib classification (Perets et al. 2010; Kasliwal et al. 2012). Indeed, their photospheric spectra bear strong similarity to those of stripped core-collapse SNe of Type Ib/c (Kawabata et al. 2010; Perets et al. 2010; Kasliwal et al. 2012; Valenti et al. 2014, see Fig. 5c), showing lines of He I, O I, Mg II, Ca II and maybe Si II, Ti II and Fe II, with photospheric velocities of 10 000–11 000 km s$^{-1}$ at maximum light. Ca-rich gap transients turn nebular very early, so that after 50–100 d the ejecta seem to be transparent. The spectra are then dominated by strong [Ca II] $\lambda\lambda$7291, 7324 emission (Fig. 5d). The Ca II NIR triplet and [O I] $\lambda\lambda$6300, 6364 are usually also detected but comparatively weak, and [Fe] emission lines are entirely absent. With these characteristics, Ca-rich gap transients are different from both SNe Ia and stripped core-collapse SNe during the nebular phase, but closer to core-collapse SNe (which show basically the same lines, just with stronger [O I]) than to SNe Ia with their Fe-dominated nebular spectra. The detection of [O I] emission, in particular, is normally considered a hallmark feature of core-collapse explosions. In fact, the spectroscopic evolution led Kawabata et al. (2010) to interpret SN 2005cz as a core-collapse explosion of a low-mass ($\sim$10 $M_\odot$), envelope-stripped star, in spite of its location in an elliptical galaxy. This, however, was before the class of Ca-rich transients had been fully established.

Following Arnett (1982), an ejecta mass of 0.25–0.41 $M_\odot$ and a kinetic energy of 4.4–7.2 $\times$ 10$^{50}$ erg have been estimated for SN 2005E on the basis of its early light curve and ejecta velocity (Perets et al. 2010). The same authors modelled a +62 d spectrum of SN 2005E with a nebular spectrum synthesis code to obtain an estimate of the total ejecta mass of 0.275 $M_\odot$, half of which would be Ca. Such a low total mass and such a large Ca fraction (about two orders of magnitude higher than in any other SN) were unprecedented. As a caveat it should be mentioned, however, that the +62 d spectrum was not fully nebular, and a continuum contribution was subtracted before the modelling, introducing considerable uncertainties in the derived numbers. Moreover, for the Arnett formalism, an assumption had to be made regarding the mean ejecta opacity. Choosing this to be the same as in normal SNe Ia led to the
quoted numbers, while a lower mean opacity would result in higher ejecta-mass and kinetic-energy estimates.

That the distinction between Ca-rich transients and faint SNe Ib/c is not always sharp is exemplified by SN 2012hn (Valenti et al., 2014). This SN had peak magnitudes similar to other Ca-rich transients, and was thus 1–2 mag fainter than normal SNe Ib/c. The flux below 5500 Å was strongly suppressed already at maximum light owing to Fe II, Ti II and Cr II line blanketing, and no He I lines were detected, so that the early-time spectra showed little resemblance to those of other Ca-rich gap transients (Fig 5c). However, [Ca II] emission started to emerge already at maximum light, and one month after peak [Ca II] and the Ca II NIR triplet were by far the strongest features in the spectrum. In a truly nebular spectrum taken 150 d after maximum, on the other hand, [O I] emission was almost equally prominent as [Ca II], and their ratio was not far from what is typically found in stripped core-collapse SNe (Fig. 5d). Valenti et al. (2014) estimated the ejecta mass to lie between \( \sim 0.7 \) and \( \sim 2.1 \) M\(_\odot\), with the large range of values being due to the fairly unconstrained mean ejecta opacity.

Finally, PTF 09dav was also very different from other Ca-rich transients (but also from SN 2012hn) at early phases. Sullivan et al. (2011) instead found similarities with 91bg-like SNe, but unusually low ejecta velocities and curious Sc II lines. A more in-depth discussion of the spectroscopic and photometric properties can be found in Section 3.7. Three months after maximum the spectrum of PTF 09dav has changed completely and is entirely dominated by broad [Ca II] emission, like those of more canonical Ca-rich gap transients (Kasliwal et al., 2012). However, again there are a few remarkable differences: [O I] emission is not detected at all in PTF 09dav, and the only feature not caused by Ca is a weak and relatively narrow H\( \alpha \) line, whose width suggests an origin in a shocked H-rich CSM. With an estimated ejecta mass of 0.36 M\(_\odot\) (Sullivan et al., 2011), PTF 09dav aligns well with the masses derived for other Ca-rich gap transients (Kasliwal et al., 2012).

### 5.3 Host galaxies and explosion environments

Up to this point, the reader may have wondered why a thermonuclear origin is favoured for Ca-rich gap transients by most authors, although the spectra and light curves bear stronger similarity to core-collapse SNe than to SNe Ia. One reason are certainly the rather low inferred ejecta masses which seem to be at odds with massive-star progenitors. The main reason, however, are the explosion sites of many of these objects.

Ca-rich transients have a high fraction of early-type galaxies among their hosts: about 50% of this still rather small sample of objects exploded in E or S0 galaxies (Perets et al., 2010; Kasliwal et al., 2012), to be compared to \( \sim 22\% \) of SNe Ia and at most \( \sim 1\% \) of core-collapse SNe (Li et al., 2011). The stellar populations of these E and S0 hosts are predominantly old, and even if there had been recent star formation in a few of the hosts so that some young, massive stars are present, they
are highly unlikely to be the progenitors of Ca-rich gap transients: if Ca-rich gap transients had massive progenitors, they should be much more frequently observed in actively star-forming galaxies, where those stars are by orders of magnitude more abundant.

The argument becomes even stronger when taking into account the locations of Ca-rich transients within their hosts. The distribution of explosion sites seems to be strongly skewed towards large galactocentric distances (Perets et al., 2010; Kasliwal et al., 2012; Yuan et al., 2013; Lyman et al., 2014). Projected distances between 20 and 40 kpc have been derived for several objects, and distances above 5 kpc are quite common. Yuan et al. (2013) have shown that for half of the Ca-rich transients essentially 100% of the host-galaxy K-band light is enclosed by isophotes passing through their locations.

There are two basic scenarios of how stars can end up at such remote locations: either they were formed in situ, or they were expelled from their hosts.

i) *In-situ formation.* Deep pre- and post-explosion images and spectra have been investigated for a number of Ca-rich gap transients at large projected distances. None of them shows any concentration of light (satellite galaxy, globular cluster, massive star, star-forming region) at the site of the explosion, to limiting absolute magnitudes between $-5.3$ and $-12.4$ (Van Dyk et al., 2003; Perets et al., 2010, 2011b; Kasliwal et al., 2012; Lyman et al., 2014). The deepest of these limits effectively rule out the presence of globular clusters (GCs) and all except for the very faintest known dwarf galaxies (Lyman et al., 2014). In fact, Yuan et al. (2013) have shown that the radial distribution of GCs would be in good agreement with that of Ca-rich gap transients, but yet they do not favour this scenario given the available detection limits. Any association of massive stars (Lyman et al., 2014) or ongoing star formation at the locations of Ca-rich transients can be excluded on safe grounds. Hence, if the progenitors of Ca-rich transients are really formed in situ, they must belong to a long-lived population of rather low-mass stars. Yuan et al. (2013) have suggested that the locations of Ca-rich transients could be consistent with relatively metal-poor, low-mass Halo stars, but Lyman et al. (2014) doubt any association with a genuine Halo population.

ii) *Runaway systems.* The alternative to in-situ formation are progenitor systems formed in more central regions of the hosts galaxies, and then kicked out by gravitational interaction with a supermassive black hole (SMBH; Foley, 2015) or as a consequence of a preceding supernova explosion (Lyman et al., 2014). Massive stars can be excluded as progenitors even in this case, since for realistic kick velocities of a few hundred km s$^{-1}$ the progenitors’ life times have to be close to 100 Myr to reach the locations of the most remote Ca-rich transients observed. Less massive single stars, on the other hand, do not explode, so binarity is probably a key property. Lyman et al. (2014) have pointed out strong parallels between Ca-rich transients and short-duration γ-ray bursts (SGRBs) in terms of host-galaxy morphologies and offsets from their hosts. These SGRBs are usually thought to be mergers of two neutron stars or a neutron star (NS) and a black hole, which received their kicks by the two preceding core-collapse explosions within the system.
5.4 Explosion models

Explosion scenarios for Ca-rich gap transients need to be compatible with the main characteristics of these objects as inferred from observations: a low mass of $^{56}$Ni, a probably rather low ejecta mass, a rapid spectroscopic and photometric evolution, a Ca-rich chemical composition (though the exact degree of enhancement is not yet robustly established), the presence of He, and their locations at sometimes very large distances from the centres of their hosts.

The spectra, which in most cases resemble SNe Ib at early phases and show strong [Ca II] next to weak [O I] lines at nebular epochs, might suggest a core-collapse origin of Ca-rich transients (Kawabata et al., 2010), but as explained in Section 5.3 this scenario is disfavoured by their locations far from other young, massive stars or star-forming regions. In the realm of thermonuclear explosions, on the other hand, it is very unlikely from a nucleosynthesis perspective that Ca-rich transients are deflagrations or detonations of CO WDs like normal SNe Ia. Neither the abundance of He and Ca, nor the paucity of Fe, Co and Ni could be explained with that scenario. Instead, more exotic models have to be invoked.

One scenario frequently discussed in the context of Ca-rich transients is the .Ia model (Bildsten et al., 2007; Shen et al., 2010; Waldman et al., 2011; Woosley & Kasen, 2011; Sim et al., 2012). Similar to the double-detonation model for normal SNe Ia, a detonation is ignited in an accreted or natively present He layer on the surface of a CO or ONe WD. The difference is that in the .Ia model the emergent shock wave fails to ignite the core. The mass of the He layer, and hence the ejecta mass, can range from a few times $0.01 \times M_{\odot}$ ($\sim 0.3 M_{\odot}$ (Shen et al., 2010; Waldman et al., 2011), in fair agreement with the numbers estimated for Ca-rich gap transients, though a bit on the low side. The nucleosynthesis in the He detonation mostly proceeds to Ca, Ti and Cr, with only a relatively small amount of lighter IMEs and Fe/Co/Ni produced, again in agreement with the inferred ejecta composition of Ca-rich transients. Light curves and spectra of .Ia models vary strongly with the initial setup, and are sensitive to both the mass of the He shell and that of the core of the WD (which affects the density of the He layer). An acceptable match to the bolometric light curves of Ca-rich transients can probably be obtained if these parameters are chosen accordingly. For instance, Waldman et al. (2011) found that the detonation of a $0.2 M_{\odot}$ He shell on top of a $0.45 M_{\odot}$ WD provides a good match to the bolometric peak of SN 2005E, but a somewhat too rapid decline. For the same initial conditions, Sim et al. (2012) obtained a slightly more complete nucleosynthesis, favouring the production of the short-lived $^{48}$Cr at the expense of $^{44}$Ti, resulting in a significantly brighter light-curve peak.

Sim et al. (2012) have also shown that in sufficiently low-mass WDs the ignition of a second detonation (either in the centre of the CO core via converging shocks or on the interface between the core and the He layer) does not enhance the production of $^{56}$Ni or other radioactive species by much, but leads to a significantly larger ejecta mass. The effect are explosions which are slightly more luminous at peak and have (at least for centrally ignited second detonations) broader light curves. This
possibility thus increases the parameter space for models to explain faint and (more or less) rapidly declining transients.

Another way to produce faint and rapidly-declining transients is an accretion-induced collapse (AIC) of a WD. Darbha et al. (2010) have shown that such events can eject about the right $^{56}\text{Ni}$ mass to reproduce the peak luminosity of Ca-rich gap transients, but that the total ejecta mass is very low, so that the ejecta velocities are too high, the light curve declines too rapidly and the ejecta composition does not match that inferred for Ca-rich transients. Darbha et al. (2010) speculated that a better match might be achieved by enshrouded AICs, where the Ni-dominated ejecta collide with surrounding unburned CO-rich material. The impact may trigger partial burning of C and O to IMEs, and the increased mass and opacity would decelerate the ejecta and slow down the light-curve evolution.

A completely different approach tries to constrain possible explosion scenarios for Ca-rich gap transients from their unusual locations. Lyman et al. (2014) proposed the progenitors of Ca-rich transients to most likely be runaway stars in binary systems. One of the constituents of the system would be a NS, which received a strong kick upon formation in a core-collapse SN. The other constituent would possibly be a WD. Based on calculations by Metzger (2012), NS–WD mergers would produce faint optical counterparts, whose peak luminosity and energetics would be in rough agreement with Ca-rich transients. However, the predicted Ca abundance is much lower than what Perets et al. (2010) inferred for SN 2005E, which is a potential shortcoming of this scenario. Moreover, it appears questionable if a binary system would remain bound in a core-collapse SN explosion where the newly formed NS receives a kick of several hundred km s$^{-1}$, required to reach the explosion sites of some Ca-rich transients tens of kpc away from the centres of their hosts.

Foley (2015) instead suggested the kicks to be caused by gravitational interaction with central SMBHs. They found that many host galaxies of Ca-rich transients show signs of recent mergers, so that they might host binary SMBHs, which should be effective in ejecting stellar systems. If a binary system of a CO and a He WD that would normally not merge within a Hubble time is not only ejected, but also hardened in the course of the ejection process, a CO-He WD merger might take place tens to hundreds of Myr later at a large galactocentric distance. While this scenario could nicely explain the unusual locations of Ca-rich transients, it remains to be shown that CO-He WD mergers would result in explosions with the same low luminosity, low inferred ejecta masses and unusual nucleosynthesis pattern as revealed by Ca-rich gap transients.
6 Are the fastest decliners thermonuclear SNe?

The objects that are the subject of this section are extremely few in number, and still show considerable diversity. Forcing them into one class would be pointless, and so this section is rather a collection of weird individuals that share a steep rise before and a tremendously rapid and deep decline after peak, and for which a thermonuclear origin seems to be at least an option.

6.1 SN 1885A – observations in the 19th century

SN 1885A in M31, also known as S Andromedae, was the closest and brightest SN visible from the northern hemisphere for centuries. Discovered independently on 1885 August 19 and 20 by Isaac Ward and Ernst Hartwig, respectively, and thereafter followed by many astronomers, it reached 6th magnitude at peak (see de Vaucouleurs & Corwin, 1985, for references to all historical reports). Had it been in an isolated position, it would have been a naked-eye target, but since it exploded at a projected distance of only 16 arcsec from the centre of M31 (Fesen et al., 1989), a small telescope or binoculars were needed to spot it. Lacking modern detector technology and even sufficiently fast photographic emulsions, the observations were performed visually, estimating the brightness and colour of the transient relative to those of other well-known stars. De Vaucouleurs and Corwin (1985) did an admirable job in carefully collecting, assessing and homogenising over 500 of these 100-year-old observations and converting them into a modern \( V \)-band light curve (Fig. 6b), \( B - V \) colour curve and spectroscopic information.

At the time of discovery, SN 1885A was only about a day before peak, and several non-detections before August 17 allow to constrain the rise time of the transient to be extremely short, a few days at most. At the distance of M31 and corrected for Galactic extinction, an observed peak magnitude of \( \sim 5.9 \) corresponds to an absolute \( V \)-band magnitude of about \( -18.7 \), so the transient was not faint at peak. After maximum light, SN 1885A declined by \( \sim 3.5 \) mag within the first month \( \Delta m_{15}(V) \approx 2.3 \) mag; de Vaucouleurs & Corwin (1985); van den Bergh (2002) before settling on a more gentle slope reminiscent of the \( ^{56}Co \) tail seen in other SNe. However, the transition between peak and tail is much more gradual than usual, casting some doubts on the correctness of the interpretation as a radioactivity-powered tail. The colour of SN 1885A was always red, but especially at early phases. A colour curve reconstructed by de Vaucouleurs & Corwin (1985) shows a \( B - V \) colour of \( \sim 1.3 \) mag at peak, which remains constant for \( \sim 20 \) d, and then turns bluer, reaching \( B - V \sim 0.9 \) mag at \(+30\) d. Such a colour evolution is unmatched by any other SN observed ever since. Verbal descriptions of spectroscopic properties and their evolution (de Vaucouleurs & Corwin, 1985) agree on the presence of a (quasi-)continuum with superimposed broad lines, which is typical for SNe. Balmer lines were not detected, but apart from that an unambiguous line identification on this basis seems difficult.
Fig. 6 Fast-declining transients in comparison to the normal SNe Ia 2003du (Stanishev et al., 2007) and 2011fe (Munari et al., 2013; Pereira et al., 2013), the subluminous SN Ia 1991bg (Filippenko et al., 1992b; Leibundgut et al., 1993; Turatto et al., 1996, see also Section 3), and the stripped-envelope core-collapse SN 2004aw (Taubenberger et al., 2006). a) I-band light curves. b) B-band light curves (V-band for SN 1885A). c) Photospheric spectra. d) The remnant of SN 1885A, seen in absorption against the bulge of M31 in near-UV lines of Ca II and Fe II. ©AAS. Reproduced with permission from Fesen et al. (2015). References for individual fast-declining transients are provided in the main text.
6.2 The remnant of SN 1885A

The remnant of SN 1885A was found by Fesen et al. (1989) through ground-based narrow-band near-UV imaging. The remnant appears as a little dark spot superimposed on the bulge of M31, at a projected distance of only $\sim 60$ pc from the centre of the galaxy. To be seen in absorption, it has to be on the near side of M31, back-lit by the bulge. All previous searches for emission lines, starting already with Walter Baade in the 1940s (Osterbrock, 2001), had failed. Subsequent HST imaging and spectroscopy of the remnant (Fesen et al., 1999, 2007, 2015; Hamilton & Fesen, 2000) allowed a much more detailed study of its size, composition and geometry. The remnant is still in free expansion, and has reached a diameter of 0.7–0.8 arcsec, implying an outer-edge ejecta velocity of $\sim 12,500$ km s$^{-1}$ (Fesen et al., 1999). The strongest absorption (down to $\sim 20\%$ transmission) is observed in the Ca II H&K resonance lines, where the remnant looks nearly spherical on global scales (Fesen et al., 1999, 2007, 2015, see Fig. 6d). Other detected absorption lines are from Ca I, Fe I and Fe II. In Ca I and Fe I, which trace the regions with the highest Ca and Fe abundances, the remnant appears slightly smaller than in Ca II and lopsided, indicating a radial ionisation gradient in the ejecta and an off-centre peak in the Ca and Fe distribution (Fesen et al., 2007). Fe II, on the other hand, shows a number of plumes or filaments (Fig. 6d), and is quite different from the other ions in its spatial distribution (Fesen et al., 2015).

The SN 1885A remnant has not been detected in X-rays. Adopting the ISM gas density in the bulge of M31 measured by Li et al. (2009) from diffuse X-ray emission, an $M_{\text{Ch}}$ SN Ia remnant should be orders of magnitude brighter than the observed limits (Perets et al., 2011a). Perets et al. therefore argued that either SN 1885A exploded in a local void, or the ejecta mass of the transient was much lower than that of a canonical $M_{\text{Ch}}$ SN Ia.

6.3 SN 1939B

Photometric data for SN 1939B have been compiled from historic sources by Leibundgut et al. (1991). The light curve of this SN is similarly narrow as that of SN 1885A, with a somewhat slower rise (de Vaucouleurs & Corwin, 1985) and an even slightly faster initial decline. Perets et al. (2011a) measured a $\Delta m_{15}(B)$ of 2.6. About two weeks after maximum, the light curve settles on a tail which is most likely $^{56}$Co-powered. The transition between peak and tail phase is much sharper than in SN 1885A, and more similar to what is observed in other Type I SNe. SN 1939B was probably even more luminous than SN 1885A, reaching $M_B \lesssim -19$ (Fig. 1). In a $+22$ d spectrum of SN 1939B published by Perets et al. (2011a), similarities with normal Type Ia and Ib/c SNe are evident below 5500 Å, but an unusual behaviour is seen above that wavelength. This might, however, be attributed to flux-calibration problems of the photographic spectrum.
6.4 SN 2002bj

The rise time of SN 2002bj is constrained to be less than one week by a non-detection 7 d before maximum down to a limiting magnitude 3.5 mag below peak (Poznanski et al., 2010). However, not only the rise but also the decline is very rapid, and steepening further after \( \sim 10 \) d. Within 18 d from maximum, SN 2002bj drops by 4.5 mag in the \( B \) band (Poznanski et al., 2010; see Fig. 6b), and Perets et al. (2011a) measured a remarkable \( \Delta m_{15}(B) \) of 3.2. There is no indication of a flattening of the light curves or a settling on a radioactive tail out to 20 d after maximum when the follow-up ends. Like SNe 1885A and 1939B, SN 2002bj features a rather high peak luminosity \( \log L_{BVRI} \approx 43.0 \) \( (M_B,_{\text{max}} \approx -19; \) Poznanski et al. 2010). Over 15–20 d after maximum light, there is only a mild colour evolution, and the \( B - V \) colour remains comparatively blue at \( \sim 0 \) mag.

Spectra of SN 2002bj have been obtained at 7 and 11 d after maximum (Poznanski et al., 2010). They show a blue continuum with numerous weak P-Cygni lines superimposed (Fig. 6c). Modelling the spectra, Poznanski et al. (2010) identified carbon, oxygen, IMEs and helium. \( \text{C}\text{II} \) lines are very prominent and the \( \text{HeI} \) detection is also unambiguous. \( \text{CaII} \) lines, in contrast, are very weak. No evidence was found for IGEs or hydrogen. With P-Cygni absorptions blueshifted by 4000 km s\(^{-1}\) the ejecta velocities are extraordinarily low. Finally, a polarisation spectrum showed no line polarisation exceeding 0.2%, indicating that composition asymmetries are small.

Applying Arnett’s rule (Arnett, 1982) and scaling relations to SN 2002bj, Poznanski et al. (2010) found numbers that were difficult to reconcile. Their estimate of the \( ^{56}\text{Ni} \) mass of 0.15–0.25 M\(_{\odot}\) equalled or exceeded that of the total ejecta mass of \( \sim 0.15 \) M\(_{\odot}\). Even if for the lower-limit \( ^{56}\text{Ni} \) mass of 0.15 M\(_{\odot}\) a direct contradiction could possibly be avoided, it would imply that the ejecta consist to 100% of \( ^{56}\text{Ni} \), which is inconsistent with the observed spectra which show IMEs but lack any evidence of IGEs. Moreover, for the estimated \( ^{56}\text{Ni} \) mass a much brighter light-curve tail would be expected. Poznanski et al. (2010) therefore speculated that an energy source other than \( ^{56}\text{Ni} \) decay is required to power the light curve of SN 2002bj, and suggested a contribution by \( ^{48}\text{Cr} \) decay as a possible solution.

6.5 SNe 2005ek and 2010X

With SNe 2005ek (Drout et al., 2013) and 2010X (Kasliwal et al., 2010) there are finally two SNe with sufficiently similar behaviour to be discussed together.

For SN 2010X no multi-band photometry is available around maximum light. The existing \( r \)-band light curve, however, is morphologically nearly identical to that of SN 2002bj. SN 2005ek also has very similar light curves, but with a slightly more linear decline right after peak (Fig. 6.a,b), and with extensive multi-band coverage during the first 15–20 d after maximum which allowed Drout et al. (2013) to measure a \( \Delta m_{15}(B) \) of 3.5. The rise times of SNe 2005ek and 2010X are not as
The Extremes of Thermonuclear Supernovae

tightly constrained as that of SN 2002bj, and could well be longer than 10 d. Like SN 2002bj, SNe 2005ek and 2010X show no flattening of their decline out to +17 d. For SN 2005ek, however, two late-time detections at +38 and +68 d prove the presence of a radioactive tail which likely starts around day 20. The optical colours of SN 2005ek are significantly redder than those of SN 2002bj, and show a stronger time evolution to the red (with $B - V$ rising from 0.2 mag at peak to 0.9 mag on day 15). What distinguishes SNe 2005ek and 2010X from the other SNe discussed in this section, however, is their significantly lower peak luminosity ($M_{R, \text{max}} \approx -17.3$ and $-17.0$, respectively).

The spectroscopic evolution of SNe 2005ek ($-1 \text{ to } +11 \text{ d}$; Drout et al. 2013) and 2010X ($-4 \text{ to } +34 \text{ d}$; Kasliwal et al. 2010) appears similar to those of normal stripped-envelope core-collapse SNe of Type Ic (Fig. 6c), with lines of $\text{O I}$, $\text{C II}$, $\text{Ca II}$, $\text{Na I}$, $\text{Mg II}$, $\text{Si II}$, $\text{Ti II}$ and $\text{Fe II}$ detected through spectral modelling (Drout et al., 2013; Kleiser & Kasen, 2014). The evolutionary time scales of the spectra are relatively fast, in line with the narrow light curves. In fact, Drout et al. (2013) noted slight flux excesses in a $+9 \text{ d}$ spectrum of SN 2005ek with respect to a synthetic fit, which might be attributed to emerging lines of $\text{[O I]} \lambda 5577$, $\text{[O I]} \lambda \lambda 6300, 6364$ and $\text{[Ca II]} \lambda \lambda 7291, 7324$. This would be one of the earliest detections of nebular emission in a SN of any type. In both SNe 'normal' ejecta velocities of about 8000–10 000 km s$^{-1}$ are measured a few days after maximum light, at least twice as high as in SN 2002bj. In general, despite the photometric similarities, spectroscopically SNe 2005ek and 2010X have little in common with SN 2002bj.

Estimates of $M_{\text{Ni}}$, $M_{\text{ej}}$ and $E_{\text{kin}}$ for SNe 2005ek and 2010X yield a much more consistent picture of low-mass and low-energy $^{56}$Ni-powered explosions than in the case of SN 2002bj, mainly due to the lower luminosities. For SN 2010X, Kasliwal et al. (2010) analytically derived a $^{56}$Ni mass of 0.02 $M_{\odot}$, a total ejecta mass of 0.16 $M_{\odot}$, and a kinetic energy of $\sim 1.5 \times 10^{50}$ erg. Spectral modelling of SN 2005ek provided satisfactory results for an ejecta mass of 0.3 $M_{\odot}$ and a kinetic energy of $2.5 \times 10^{50}$ erg (Drout et al., 2013).

6.6 Host galaxies and environments

While SNe 2002bj, 2005ek and 2010X exploded in spiral galaxies with presumably heterogeneous stellar populations (Poznanski et al. 2010; Kasliwal et al. 2010), SN 1939B was found in an elliptical galaxy and SN 1885A was associated with the bulge of M31 with a characteristic age of the stellar population of $\sim 10 \text{ Gyr}$ (Perets et al., 2011a). For Perets et al. this high fraction of occurrence in old stellar populations favours WDs as the progenitors for these SNe. For SNe 1885A and 1939B this is certainly correct. However, considering the diversity among the four objects discussed in this section, it is unclear whether this conclusion applies to SNe 2002bj, 2005ek and 2010X.
6.7 Explosion models

There are several approaches to constrain the explosion mechanism(s) underlying the group of rapidly declining Type I SNe discussed above. Fesen et al. (2015) tried to make use of the spatially resolved abundance structure of the SN 1885A remnant (Fig. 3c). Since the remnant is still expanding freely, the structure imprinted by the explosion is conserved, providing a spatially resolved image of the SN ejecta. From apparent plumes in the distribution of Fe II absorption, Fesen et al. infer the presence of a deflagration phase, and favour a delayed-detonation mechanism. However, the rapidly declining light curve of SN 1885A seems inconsistent with delayed-detonation explosions (e.g. Seitenzahl et al., 2013). Moreover, Perets et al. (2011a) argued that an $M_{\text{Ch}}$ explosion was probably difficult to reconcile with the observed X-ray limits for the remnant, supporting a sub-Chandrasekhar ejecta mass.

Other attempts to identify suitable explosion models revolve around ways to produce low ejecta masses, since most analytical estimates and numerical modelling of light curves and spectra suggest ejecta masses between 0.15 and 0.30 $M_{\odot}$ (Poznanski et al., 2010; Kasliwal et al., 2010; Drout et al., 2013). The first such model was invoked by Chevalier & Plait (1988), who found good agreement between a synthetic light curve for a He surface detonation of Woosley et al. (1986) and the observed light curve of SN 1885A. That model ejected 0.26 $M_{\odot}$ of material, 0.19 $M_{\odot}$ of which were $^{56}$Ni. Similarly, Poznanski et al. (2010) proposed a .Ia explosion model for SN 2002bj, i.e. a thermonuclear flash in a low-mass He shell on the surface of a WD (Bildsten et al., 2007; Shen et al., 2010). These flashes produce transients with peak absolute magnitudes between $-15$ and $-18$ and rise times $< 10 \text{ d}$ (Shen et al., 2010). Their rise is definitely fast enough to be compatible with SN 2002bj, but they are not quite luminous enough, and the decline of the light curves flattens out too early. The same conclusion was reached by Waldman et al. (2011), whose series of He surface detonations cover an even wider range of outcomes (but primarily extend to lower peak luminosities).

Another problematic aspect of .Ia SNe is their nucleosynthesis, as pointed out by Drout et al. (2013). The ejecta of .Ia SNe consist mostly of He and elements between Ca and Ni, but show very low abundances of C, O and IMEs such as Mg, Si and S, which have all been detected in the spectra of SNe 2002bj, 2005ek and 2010X, and according to spectral modelling of SN 2005ek (Drout et al., 2013) even dominate the ejecta by mass. Synthetic spectra for He detonations (Waldman et al., 2011; Sim et al., 2012), in contrast, are almost exclusively shaped by elements from Ca to Cr, and are very red even at early epochs owing to strong line blanketing at short wavelengths. Drout et al. (2013) therefore suggested that edge-lit double-detonations of low-mass WDs as presented by Sim et al. (2012) might provide a better match in terms of ejecta composition than pure He-shell detonations. However, as shown by Sim et al. (2012), the spectroscopic difference between edge-lit double detonations and pure He-shell detonations is marginal at least for their models, since the early spectra are always formed in the ashes of the He shell.

Drout et al. (2013) compared the light curve of SN 2005ek also to other thermonuclear models with low ejecta mass. They concluded that accretion-induced col-
lapse (e.g. [Darbha et al. 2010] and NS–NS mergers (e.g. [Metzger et al. 2010]) could be ruled out based on their low luminosities and extremely narrow light curves, but that WD–NS or WD–BH mergers (e.g. [Metzger 2012]) might be possible candidates, although also these models tend to be too faint.

However, also core-collapse models are being discussed as explanation for at least some of the objects in this section. Based on the spectroscopic similarity of SNe 2005ek and 2010X with SNe Ic such as SN 1994I, [Drout et al. 2013] proposed that the binary-interaction scenario for envelope stripping might also work for stars with an initial mass just slightly above the limit for iron core collapse. Indeed, [Tauris et al. 2015] studied close binary systems of a He star and an accreting NS, and found that these can lead to ultra-stripped core-collapse SNe with ejecta masses of just a few tenths of a solar mass. The low optical depth of the ejecta would then result in strong $\gamma$-ray leakage and short retention times for optical photons, both of which would help to explain the rapid decline of the light curves.

An alternative core-collapse scenario has been proposed by [Kleiser & Kasen 2014], and this is the only model so far that seems capable of reproducing the observed narrow light curves without the need for a small ejecta mass. The idea is that of a rather normal stripped-envelope core-collapse explosion with very little radioactive material. The peak light curve would be powered by the recombination of oxygen and other abundant elements initially ionised by the SN shock, in analogy to H recombination in SNe IIP. Once the ejecta have recombined and the stored energy is exhausted, the end of the oxygen-plateau phase is reached and the light curve drops rapidly. A small amount of radioactive material could then still produce a radioactive tail.
7 ‘Super-Chandrasekhar’ SNe Ia: the mass puzzle

For a long time there was general consensus that CO WDs explode at the very latest when approaching a mass of \(\sim 1.4 \, M_\odot\), known as the Chandrasekhar-mass stability limit. The \(M_{\text{Ch}}\) limit is very fundamental (Chandrasekhar, 1931), denoting the mass where the degeneracy pressure of the relativistic electron gas loses against the self-gravity of the WD, leading to a collapse. Even luminous 91T-like SNe (see Section 2) have been shown to be consistent with \(M_{\text{Ch}}\) progenitors (e.g. Stritzinger et al., 2006; Scalzo et al., 2014b). It was only during the past decade that a few objects were discovered whose enormous luminosities, broad light curves and moderately low ejecta velocities seemed to be in conflict with explosions of 1.4 \(M_\odot\) WDs and instead suggested larger ejecta masses. The explosions were therefore dubbed ‘super-Chandrasekhar’ SNe Ia.

As of now, the class of ‘super-Chandrasekhar’ objects is still small, including SNe 2003fg (Howell et al., 2006), 2004gu (Contreras et al., 2010), 2006gz (Hicken et al., 2007; Maeda et al., 2009), 2007if (Scalzo et al., 2010; Yuan et al., 2010; Childress et al., 2011; Taubenberger et al., 2013b), 2009dc (Yamanaka et al., 2009; Tanaka et al., 2010; Silverman et al., 2011; Taubenberger et al., 2011; 2013b; Hachinger et al., 2012) and SN 2012dn (Chakradhari et al., 2014; Parrent et al., 2016). SNe 2006gz and 2012dn have many properties in common with other ‘super-Chandrasekhar’ SNe Ia, but challenge any group definition based on the sheer luminosity owing to their comparatively moderate photometric properties.

7.1 Early-time light curves and peak luminosity

The overall light-curve morphology of ‘super-Chandrasekhar’ SNe Ia is quite similar to that of normal SNe Ia, with a smooth, rounded peak followed by a radioactive-tail phase. The main difference lies in the peak luminosity and the time scales of the light-curve rise and decline, but also certain colours show a characteristic evolution distinguishing ‘super-Chandrasekhar’ from ordinary SNe Ia. \(B\)-band peak absolute magnitudes typically lie between \(-19.5\) and \(-20.4\) (Hicken et al., 2007; Scalzo et al., 2010; see Figs. 1 and 7b), quasi-bolometric peak luminosities \(L_{\text{peak}}\) between 43.2 and 43.5, outshining average normal SNe Ia by a factor \(\sim 2\) (Taubenberger et al., 2011). The light curves evolve very slowly. For SN 2009dc, Silverman et al. (2011) reported a first detection on an image taken 21 d before \(B\)-band maximum, and estimated a rise time of 23 \(\pm\) 2 d, significantly longer than in normal SNe Ia (17–20 d; Conley et al., 2006; Hayden et al., 2010). Also the decline rates after peak are among the slowest ever observed for SNe Ia, with \(\Delta m_{15}(B)\) between 0.7 and 0.9.

Applying Arnett’s rule (Arnett, 1982) to the quasi-bolometric light-curve peaks of ‘super-Chandrasekhar’ SNe Ia leads to high \(^{56}\)Ni-mass estimates, not only because of the high luminosity, but also because of the long rise time. For SN 2009dc, Yamanaka et al. (2009), Silverman et al. (2011) and Taubenberger et al. (2011) find \(^{56}\)Ni masses of 1.8 \(\pm\) 0.5 \(M_\odot\), which by itself is at best marginally compatible with
Fig. 7 ‘Super-Chandrasekhar’ SNe Ia in comparison to the normal SNe Ia 2003du (Stanishev et al., 2007) and 2011fe (Munari et al., 2013; Pereira et al., 2013), the SN Iax 2005hk (Phillips et al., 2007; Silverman et al., 2012) and SN 1991T (Mazzali et al., 1995; Gómez & López, 1998; Lira et al., 1998; Altavilla et al., 2004; Silverman et al., 2012; see also Section 2). a) $I$-band light curves at early times. b) $B$-band light curves at early times. c) Late-time $B$-band light curves. d) Photospheric spectra. e) Nebular spectra. References for individual ‘super-Chandrasekhar’ SNe Ia are provided in the main text.
the Chandrasekhar mass of a non-rotating WD. If the ejecta are not entirely made up of $^{56}\text{Ni}$ (which they are not), there is no way to reconcile the peak light curve of SN 2009dc with the explosion of a $1.4\,M_\odot$ WD unless other energy sources help to power it. Scalzo et al. (2010) reached a similar conclusion for SN 2007if by fitting the peak and the tail of the light curve. They inferred a $^{56}\text{Ni}$ mass larger than $\sim 1.3\,M_\odot$ and a total ejecta mass in excess of $\sim 1.8\,M_\odot$ at $3\sigma$ confidence level, with most likely numbers of $M_{\text{Ni}} \approx 1.6\,M_\odot$ and $M_{\text{ej}} \approx 2.2\,M_\odot$.

Apart from high peak luminosities and broad light curves, ‘super-Chandrasekhar’ SNe Ia are characterised by an unusually high $U$-band and UV flux and blue UV – optical colours (Brown et al., 2014), at least compared to normal SNe Ia where that region is strongly suppressed due to heavy line blanketing by IGEs. The $V–I$ and $V–\text{NIR}$ colour evolution of ‘super-Chandrasekhar’ SNe Ia is also very different from normal SNe Ia, which is related to the fact that these objects do not show distinct secondary maxima in the $IJHK$ bands, but rather broad, delayed, plateau-like peaks (Taubenberger et al., 2011; Friedman et al., 2013, see Fig. 7b).

Most other SNe Ia, from luminous 91T-like objects to moderately subluminous 86G-like events, appear to be very good standard candles in the NIR (Wood-Vasey et al., 2008; Krisiunas et al., 2009; Kattner et al., 2012). ‘Super-Chandrasekhar’ SNe Ia defy this trend, being overluminous by $\sim 1$ mag also in these bands (Taubenberger et al., 2011). Similarly, they are apparently not good standardisable candles at optical wavelengths (Howell et al., 2006; Silverman et al., 2011; Taubenberger et al., 2011), being too luminous for their light-curve shape and thus lying systematically ‘above’ the Phillips relation (Phillips, 1993; Phillips et al., 1999).

All the characteristics described above apply without exception to SNe 2003fg, 2007if and 2009dc. SNe 2006gz and 2012dn share most of these properties, from a slow light-curve decline over a single-peaked, broad $I$-band light curve to unusually high UV luminosities (Hicken et al., 2007; Chakradhari et al., 2014; Brown et al., 2014). However, with peak absolute magnitudes $M_B \approx -19.5$ they are significantly fainter than other ‘super-Chandrasekhar’ SNe Ia, and in fact just marginally more luminous than normal SNe Ia.

### 7.2 Early-time spectroscopic properties

SNe 2003fg, 2006gz, 2009dc and 2012dn show pre-maximum spectra dominated by IMEs and unburned material, with lines of IGEs probably making some contribution below 5000 Å (Hicken et al., 2007; Silverman et al., 2011; Chakradhari et al., 2014; Parrent et al., 2016; see Fig. 7d). Ca II lines are weaker than in normal SNe Ia, C II and O I more prominent. C II $\lambda 6580$ and $\lambda 7234$, in particular, are unusually strong and persistent, being visible not only up to $\sim 10$ d before peak as in normal SNe Ia, but even two weeks after maximum (Silverman et al., 2011; Taubenberger et al., 2011; Chakradhari et al., 2014; Parrent et al., 2016). SN 2007if differs significantly from the rest, with early spectra dominated by a blue continuum with only weak Fe III and IME lines superimposed, suggesting a high ionisation
state similar to 91T-like SNe (Section 2). However, though weaker than in the other ‘super-Chandrasekhar’ SNe Ia, C II lines are also detected in SN 2007if, and similarly persistent even past maximum light (Scalzo et al. 2010; Yuan et al. 2010). All ‘super-Chandrasekhar’ SNe Ia show a very blue SED and a high UV flux in early spectra, indicating little line blanketing by IGEs.

High-velocity features have not been found in ‘super-Chandrasekhar’ SNe Ia even at the earliest epochs (Taubenberger et al. 2011), while they are very common in normal SNe Ia, at least in Ca II (Mazzali et al. 2005). But irrespective of the absence of high-velocity features, also the ‘photospheric’ velocities are moderate to low, ranging from 8000 to 12 000 km s\(^{-1}\) for Si II \(\lambda 6355\) and from 7500 to 10 000 km s\(^{-1}\) for C II \(\lambda 6580\) at maximum light (Hicken et al. 2007; Taubenberger et al. 2011; Chakradhari et al. 2014). These velocities imply a low kinetic energy per mass. Coupled with the large energy release from synthesising the amount of \(^{56}\text{Ni}\) inferred from the light-curve peak, this would necessitate a large ejecta mass, with a significant amount of unburned material left. For SN 2009dc, Taubenberger et al. (2011) estimated that a total ejecta mass close to 3 M\(_\odot\) would be required to keep the velocities as low as observed if really 1.5 M\(_\odot\) of \(^{56}\text{Ni}\) or more had been synthesised in the explosion.

About 2–4 weeks after maximum, as the photosphere recedes into the Fe core of the ejecta, the spectra of ‘super-Chandrasekhar’ SNe Ia become increasingly Fe II-dominated. The same transition takes place in all normal SNe Ia as well, but typically a bit earlier. During the following weeks the spectra of the moderate-velocity specimens of ‘super-Chandrasekhar’ SNe such as SNe 2007if and 2012dn are very similar to those of normal SNe Ia, while those of the low-velocity SN 2009dc resemble closely those of SNe Iax, with a wealth of resolved lines which are blended in normal SNe Ia (Fig. 7d).

For SN 2009dc a polarisation spectrum was recorded by Tanaka et al. (2010) a few days after maximum light. It showed no significant continuum polarisation (< 0.3%), indicating minimum deviations from spherical symmetry on global scales. Despite the lack of typically strongly polarised high-velocity features, a polarisation up to 0.7% was observed in lines of Si II and Ca II, which points at some inhomogeneities in the spatial distributions of those elements.

7.3 Evolution during the nebular phase

Some (but not all) ‘super-Chandrasekhar’ SNe Ia exhibit an enhanced fading after a certain point in time in all optical bands (Fig. 7f). In SN 2009dc, which has the best light-curve coverage of all ‘super-Chandrasekhar’ SNe Ia, the rapid dimming starts \(\sim\)200 d after maximum and lasts for at least 150 d, during which an additional fading by \(\sim 1.2\) mag is observed compared to the behaviour expected for a \(^{56}\text{Co}\)-decay powered light curve with increasing \(\gamma\)-ray losses (Silverman et al. 2011; Taubenberger et al. 2011). For SN 2006gz the light-curve coverage is limited, but one year after maximum the quasi-bolometric light curve is suppressed by \(\sim 2.5\) mag (Maeda...
making the SN even significantly less luminous than ordinary SNe Ia. SN 2012dn shows signs of an inflection point in the light curves as early as 70 d after maximum (Chakradhari et al., 2014), but no real late-time photometry has been published to date. SN 2007if, on the other hand, shows no unexpected dimming, and its light curve remains on the usual $^{56}$Co-decay tail out to one year after maximum (Taubenberger et al., 2013b).

The substantial dimming observed in SN 2006gz goes hand in hand with a strong suppression of the blue part of the spectrum (Maeda et al., 2009, see Fig. 7e). Taubenberger et al. (2013b) showed that both effects, the light-curve drop and the suppression of blue flux, can be consistently explained by additional reddening in SNe 2006gz and 2009dc at late times, and speculated that dust formation – though never seen in other thermonuclear SNe – might have taken place in these events at different phases in a carbon-rich shell outside the Fe core. They estimated that a dust mass of few times $10^{-4} M_\odot$ would be sufficient to explain the dimming observed in SN 2009dc.

Before the putative dust formation sets in, the bolometric light-curve tail can be used to estimate $^{56}$Ni and ejecta masses. Although the luminosity difference to normal SNe Ia during this phase is even larger than at peak, the $^{56}$Ni and ejecta masses derived from the tail are more modest. The reason is that the largest part of the increased luminosity during the tail phase does not come from a higher $^{56}$Ni mass, but from more efficient $\gamma$-ray trapping due to low ejecta velocities and hence high densities (Taubenberger et al., 2013b).

Spectra taken during the early nebular phase (100–200 d after peak) are available for SNe 2007if and 2009dc (Silverman et al., 2011; Taubenberger et al., 2011; Blondin et al., 2012) and show the same [Fe II], [Fe III] and [Co III] emission features as those of normal SNe Ia. However, as a consequence of the lower ejecta velocities, lines that are normally blended are partially resolved in SN 2009dc. One year after maximum, the spectra of ‘super-Chandrasekhar’ SNe Ia are still dominated by forbidden Fe lines, but the hallmark [Fe III] feature at 4700 Å is very weak (Silverman et al., 2011; Taubenberger et al., 2013b, see Fig. 7e). In normal SNe Ia the flux ratio between the [Fe III]-dominated 4700 Å feature and the [Fe II]-dominated 5200 Å feature lies between 1.3 and 1.8, in SNe 2007if and 2009dc between 1.0 and 1.1 (Taubenberger et al., 2013b). This points at a low ionisation state, probably related to high ejecta densities.

7.4 Host galaxies and explosion environments

‘Super-Chandrasekhar’ SNe show a tendency to explode in rather low-mass galaxies (Taubenberger et al., 2011), and those events that were found in more massive galaxies typically exploded in relatively remote locations. Taken together, this indicates that the metallicity at all explosion sites was probably low, and that low metallicity may in fact be a key ingredient in the progenitor evolution (Khan et al., 2011). SN 2007if, in particular, went off in an extreme dwarf galaxy ($M_g = -14.45$)
with the lowest oxygen abundance \(12 + \log(O/H) = 8.01\) of any spectroscopically measured SN Ia host galaxy \(\text{[Childress et al., 2011]}\). Hence, there might not only be a Malmquist, but also a metallicity bias favouring ‘super-Chandrasekhar’ SNe in high-z SN Ia samples, constituting a potential source of systematic error in SN Ia cosmology.

7.5 Explosion models

The initial idea to explain ‘super-Chandrasekhar’ SNe, promoted by \(\text{[Howell et al., 2006]}\), was that of a rapidly spinning WD whose limiting mass could quite significantly exceed 1.4 M\(\odot\) owing to the stabilising action of centrifugal forces \(\text{[Langer et al., 2000]}\). When a \(\sim 2\) M\(\odot\) WD explodes, so the theory went, it could produce the required 1.2–1.5 M\(\odot\) of \(^{56}\text{Ni}\). \(\text{Hachisu et al., 2012}\) even suggested, based on more refined binary evolution scenarios, that a heavily rotating WD could grow to 2.3–2.7 M\(\odot\) before exploding, setting the stage even for the most extreme ‘super-Chandrasekhar’ SNe 2007if and 2009dc. The presence of a strongly quantising magnetic field also may \(\text{[Das et al., 2013]}\) or may not \(\text{[Chamel et al., 2013]}\) be able to stabilise WDs up to such high masses. Finally, \(\text{[Hicken et al., 2007]}\) proposed that a WD merger would be an easier way for a WD to gain such a high mass than accretion in a single-degenerate scenario.

However, as shown by the explosion simulations for a rapidly rotating 2 M\(\odot\) WD by \(\text{Pfannes et al., 2010b,a}\), this model is probably not suited to explain ‘super-Chandrasekhar’ SNe Ia. It might well produce superluminous transients, but fails in terms of explosion energetics and nucleosynthesis. If the flame proceeds subsonically \(\text{[Pfannes et al., 2010b]}\), the differential rotation inhibits a flame propagation in the equatorial direction, and only 0.5 M\(\odot\) of IGEs are produced in total. Moreover, most of the ejecta mass below 3000 km s\(^{-1}\) is made up by unburned C and O, which is in clear conflict with the Fe-dominated nebular spectra of ‘super-Chandrasekhar’ SNe. If the flame instead propagates supersonically, the differential rotation is less of an obstacle, and a very powerful explosion emerges. In this ‘AWD3det’ model of \(\text{Pfannes et al., 2010a}\) 1.5 out of 2.0 M\(\odot\) of the progenitor are burned into \(^{56}\text{Ni}\), and only 0.08 M\(\odot\) in an equatorial torus remain unburned, most of it ending up above 12 000 km s\(^{-1}\). Spectrum-synthesis calculations by \(\text{Hachinger et al., 2012}\) have subsequently shown that the AWD3det model produces too high ejecta velocities and has way too much burned material at high velocity for being a good match with SN 2009dc which is characterised by low velocities.

The failure of the AWD3det model clearly shows that if the luminosity of SN 2009dc is to be generated by the decay of \(\gtrsim 1.5\) M\(\odot\) of \(^{56}\text{Ni}\), a total mass of \(\sim 3\) M\(\odot\) is required to keep the ejecta velocities sufficiently low, and most of the additional mass would have to remain unburned \(\text{[Hachinger et al., 2012]}\). However, \(\text{Taubenberger et al., 2013b}\) have shown that the 3 M\(\odot\) model of \(\text{Hachinger et al., 2012}\) would be inconsistent with the bolometric light curve of SN 2009dc during the radioactive tail (before dust formation occurs). The high mass and low ejecta
velocities would lead to very efficient $\gamma$-ray trapping, making the model light curve too bright by almost a factor 2 between 100 and 200 d. From this consideration, it actually appears that there is no $^{56}$Ni mass – ejecta mass combination that can consistently explain the peak luminosity, tail luminosity and ejecta velocities observed in SN 2009dc, at least without tremendous fine-tuning of the density profile or multi-dimensional effects.

A multi-dimensional effect that has been discussed quite early in the context of ‘super-Chandrasekhar’ SNe Ia is an explosion with an off-centre Ni distribution (Hillebrandt et al., 2007). These models exhibit lines of sight along which the peak luminosity is boosted, and others along which it is depressed. However, along the boosted lines of sight the peak is attained earlier and the post-maximum light curve declines faster than seen from other directions, in disagreement with observations of ‘super-Chandrasekhar’ SNe Ia. Also, there would be no effect on the light-curve tail, when the ejecta become optically thin, while in observed ‘super-Chandrasekhar’ SNe the luminosity during the tail is even more enhanced compared to normal SNe Ia than at peak.

A way out of this dilemma would be a scenario where the light curve is not entirely Ni-powered. The possibility of an enshrouded explosion along the lines of the ‘tamped detonations’ of Khokhlov et al. (1993), where the ejecta are decelerated by interaction with a surrounding circumstellar medium, was already discussed by Hicken et al. (2007), Scalzo et al. (2010) and Taubenberger et al. (2011). Hachinger et al. (2012) took this a step further by allowing for a contribution to the luminosity of SN 2009dc in the form of an underlying blackbody-like continuum in their spectral models, which led to superior fitting results. A potential problem with all interaction-aided models is that there are no clear interaction signatures in the light curves (sudden kinks or drops) and spectra (narrow or intermediate-width emission lines) of any ‘super-Chandrasekhar’ SN Ia. This could be achieved if the interaction phase is already over at the time of the first observations. There is no hydrogen observed in the spectra, so the surrounding material would have to be H-free. This excludes thermonuclear explosions of AGB-star cores (Taubenberger et al., 2011) or explosions of WDs within common envelopes, leaving mergers of CO WDs with a rather compact CO-rich CSM as a viable scenario (Hicken et al., 2007) Taubenberger et al. (2011, 2013b).

Motivated by the need to reproduce the tail light curve of SN 2009dc (see above), Taubenberger et al. (2013b) proposed an explosion of a 1.4 M$_\odot$ WD enshrouded by $\sim$0.6–0.7 M$_\odot$ of CO material (the debris of the former companion WD), with a $^{56}$Ni mass of $\sim$1.0 M$_\odot$. In this model, the ejecta velocities and the tail luminosity would match those of SN 2009dc, but the radioactively powered light curve alone falls short of reproducing the light-curve peak in optical bands. To that end, a significant boost would have to come from X-ray and UV photons emitted by the shock soon after explosion, which would have to be trapped, reprocessed to longer wavelengths and released on photon-diffusion time scales. Whether this mechanism can actually work, remains to be tested with detailed simulations. However, Taubenberger et al. (2013b) pointed out that several other peculiarities of ‘super-Chandrasekhar’ SNe might also be consistently explained within this scenario: the large amount of swept-
up carbon could give rise to the strong and persistent C II features, the high early-time UV luminosity may be the ‘afterglow’ of the shock emission, and the high density and carbon content in the shocked CSM region may provide favourable conditions for dust formation once these layers have cooled down sufficiently.

Acknowledgements

The author acknowledges support by project TRR 33 ‘The Dark Universe’ of the German Research Foundation (DFG), and thanks Markus Kromer and Suhail Dhawan for helpful discussions.

References

Altavilla, G., Fiorentino, G., Marconi, M., et al. 2004, MNRAS, 349, 1344
Arnett, W. D. 1982, ApJ, 253, 785
Axelrod, T. S. 1980, PhD thesis, University of California, Santa Cruz
Benetti, S., Cappellaro, E., Mazzali, P. A., et al. 2005, ApJ, 623, 1011
Bildsten, L., Shen, K. J., Weinberg, N. N., & Nelemans, G. 2007, ApJ, 662, L95
Blondin, S., Dessart, L., & Hillier, D. J. 2015, MNRAS, 448, 2766
Blondin, S., Matheson, T., Kirshner, R. P., et al. 2012, AJ, 143, 126
Branch, D., Fisher, A., & Nugent, P. 1993, AJ, 106, 2383
Branch, D., Thomas, R. C., Baron, E., et al. 2004, ApJ, 606, 413
Branch, D., Dang, L. C., Hall, N., et al. 2006, PASP, 118, 560
Brown, P. J., Kuin, P., Scalzo, R., et al. 2014, ApJ, 787, 29
Burns, C. R., Stritzinger, M., Phillips, M. M., et al. 2014, ApJ, 789, 32
Candia, P., Krisiucnas, K., Suntzeff, N. B., et al. 2003, PASP, 115, 277
Cao, Y., Kulkarni, S. R., Howell, D. A., et al. 2015, Nature, 521, 328
Chakradhri, N. K., Sahu, D. K., Srivastav, S., & Anupama, G. C. 2014, MNRAS, 443, 1663
Chamuel, N., Fantina, A. F., & Davis, P. J. 2013, Phys. Rev. D, 88, 081301
Chandrasekhar, S. 1931, ApJ, 74, 81
Chevalier, R. A., & Plait, P. C. 1988, ApJ, 331, L109
Childress, M., Aldering, G., Aragon, C., et al. 2011, ApJ, 733, 3
Conley, A., Howell, D. A., Howes, A., et al. 2006, AJ, 132, 1707
Contreras, C., Hamuy, M., Phillips, M. M., et al. 2010, AJ, 139, 519
Cristiani, S., Cappellaro, E., Turatto, M., et al. 1992, A&A, 259, 63
Durbha, S., Metzger, B. D., Quataert, E., et al. 2010, MNRAS, 409, 846
Dus, U., Mukhopadhyay, B., & Rao, A. R. 2013, ApJ, 767, L14
de Vaucouleurs, G., & Corwin, Jr., H. G. 1985, ApJ, 295, 287
Diehl, R., Siegert, T., Hillebrandt, W., et al. 2014, Science, 345, 1162
Drout, M. R., Soderberg, A. M., Mazzali, P. A., et al. 2013, ApJ, 774, 58
Fesen, R. A., Gerardy, C. L., McLin, K. M., & Hamilton, A. J. S. 1999, ApJ, 514, 195
Fesen, R. A., Höflich, P. A., & Hamilton, A. J. S. 2015, ApJ, 804, 140
Fesen, R. A., Höflich, P. A., Hamilton, A. J. S., et al. 2007, ApJ, 658, 396
Fesen, R. A., Saken, J. M., & Hamilton, A. J. S. 1989, ApJ, 341, L55
Filippenko, A. V., Chornock, R., Swift, B., et al. 2003, IAU Circ., 8159
Filippenko, A. V., Richmond, M. W., Matheson, T., et al. 1992a, ApJ, 384, L15
Filippenko, A. V., Richmond, M. W., Branch, D., et al. 1992b, AJ, 104, 1543
Leibundgut, B., Tamman, G. A., Cadonau, R., & Cerrito, D. 1991, A&AS, 89, 537
Leibundgut, B., Kirshner, R. P., Phillips, M. M., et al. 1993, AJ, 105, 301
Li, W., Filippenko, A. V., Trefers, R. R., et al. 2001a, ApJ, 546, 734
Li, W., Filippenko, A. V., Gates, E., et al. 2001b, PASP, 113, 1178
Li, W., Leaman, J., Chornock, R., et al. 2011, MNRAS, 412, 1441
Li, W. D., Qiu, Y. L., Qiao, Q. Y., et al. 1999, AJ, 117, 2709
Li, Z., Wang, Q. D., & Wakker, B. P. 2009, MNRAS, 397, 148
Lira, P. 1996, Master’s thesis, MS thesis. Univ. Chile (1996)
Lira, P., Suntzeff, N. B., Phillips, M. M., et al. 1998, AJ, 115, 234
Lyman, J. D., Levan, A. J., Church, R. P., Davies, M. B., & Tanvir, N. R. 2014, MNRAS, 444, 2157
Maeda, K., Kawabata, K., Li, W., et al. 2009, ApJ, 690, 1745
Maguire, K., Sullivan, M., Thomas, R. C., et al. 2011, MNRAS, 418, 747
Matheson, T., Kirshner, R. P., Challis, P., et al. 2008, AJ, 135, 1598
Mazzali, P. A., Chugai, N., Turatto, M., et al. 1997, MNRAS, 284, 151
Mazzali, P. A., Danziger, I. J., & Turatto, M. 1995, A&A, 297, 509
Mazzali, P. A., & Hachinger, S. 2012, MNRAS, 424, 2926
Mazzali, P. A., Benetti, S., Altavilla, G., et al. 2005, ApJ, 623, L37
Metzger, B. D. 2012, MNRAS, 419, 827
Metzger, B. D., Martínez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
Modjaz, M., Li, W., Filippenko, A. V., et al. 2001, PASP, 113, 308
Munari, U., Henden, A., Belligoli, R., et al. 2013, New Astronomy, 20, 30
Nakar, E., & Sari, R. 2012, ApJ, 747, 88
Neill, J. D., Sullivan, M., Howell, D. A., et al. 2009, ApJ, 707, 1449
Nugent, P., Phillips, M., Baron, E., Branch, D., & Haaschildt, P. 1995, ApJ, 455, L147
Osterbrock, D. E. 2001, Walter Baade: a life in astrophysics (Princeton University Press)
Östman, L., Nordin, J., Goobar, A., et al. 2011, A&A, 526, A28
Pakmor, R., Kromer, M., Röpke, F. K., et al. 2010, Nature, 463, 61
Pakmor, R., Kromer, M., Taubenberger, S., & Springel, V. 2013, ApJ, 770, L8
Parrent, J. T., Howell, D. A., Fesen, R. A., et al. 2016, MNRAS, 457, 3702
Patat, F., Höflich, P., Baade, D., et al. 2012, A&A, 545, A7
Patat, F., Chandra, P., Chevalier, R., et al. 2007, Science, 317, 924
Pereira, R., Thomas, R. C., Aldering, G., et al. 2013, A&A, 554, A27
Perets, H. B., Badenes, C., Arcavi, I., Simon, J. D., & Gal-yam, A. 2011a, ApJ, 730, 89
Perets, H. B., Gal-yam, A., Crockett, R. M., et al. 2011b, ApJ, 728, L36
Perets, H. B., Gal-Yam, A., Mazzali, P. A., et al. 2010, Nature, 465, 322
Pfannes, J. M. M., Niemeyer, J. C., & Schmidt, W. 2010a, A&A, 509, A75+
Pfannes, J. M. M., Niemeyer, J. C., Schmidt-W., & Klingenberg, C. 2010b, A&A, 509, A74+
Phillips, M. M. 1993, ApJ, 413, L105
Phillips, M. M., Lira, P., Suntzeff, N. B., et al. 1999, AJ, 118, 1766
Phillips, M. M., Wells, L. A., Suntzeff, N. B., et al. 1992, AJ, 103, 1632
Phillips, M. M., Phillips, A. C., Heathcote, S. R., et al. 1987, PASP, 99, 592
Phillips, M. M., Li, W., Frieman, J. A., et al. 2007, PASP, 119, 360
Piro, A. L., Chang, P., & Weinberg, N. N. 2010, ApJ, 708, 598
Plewa, T., Calder, A. C., & Lamb, D. Q. 2004, ApJ, 612, L37
Poznanski, D., Chornock, R., Nugent, P. E., et al. 2010, Science, 327, 58
Rabinak, I., Livne, E., & Waxman, E. 2012, ApJ, 757, 35
Raskin, C., & Kasen, D. 2013, ApJ, 772, 1
Röpke, F. K., Woosley, S. E., & Hillebrandt, W. 2007, ApJ, 660, 1344
Ruiz-Lapuente, P., Cappellaro, E., Turatto, M., et al. 1992, ApJ, 387, L33
Ruiz-Lapuente, P., & Spruit, H. C. 1998, ApJ, 500, 360
Saha, A., Sandage, A., Thim, F., et al. 2001, ApJ, 551, 973
Sasdelli, M., Mazzali, P. A., Pian, E., et al. 2014, MNRAS, 445, 711
Scalzo, R. A., Aldering, G., Antilogus, P., et al. 2010, ApJ, 713, 1073
—. 2012, ApJ, 757, 12
