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Simulating the observed diversity of Type Ia supernovae

Introducing a model data base

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Abstract. Despite the importance of Type Ia supernovae (SNe Ia) for modern astrophysics, their detailed mechanism is still not fully understood. In this contribution, we present recent findings from numerical explosion models in the context of the observed diversity of SNe Ia and we discuss how these models can help to shed light on the explosion mechanism and the progenitor stars of SNe Ia. In addition, we introduce the Heidelberg Supernova Model Archive (HESMA), a new online data base where we provide integrated isotopic abundances and radially averaged ejecta profiles and synthetic observables for a wide range of state-of-the-art explosion models.

Key words. supernovae: general – methods: numerical – hydrodynamics – radiative transfer – nuclear reactions, nucleosynthesis, abundances

1. Introduction

Type Ia supernovae (SNe Ia) are characterised by prominent absorption features of Si II and the absence of H features in their maximum-light spectra (e.g., Filippenko 1997). An empirical relation between their peak brightness and light-curve width (Phillips 1993) makes them standardisable candles. Combined with their large intrinsic luminosity this makes them important tools for cosmological distance measurements (Riess et al. 1998; Perlmutter et al. 1999).

There is a wide consensus that SNe Ia originate from thermonuclear explosions of carbon–oxygen (CO) white dwarfs (WD) in interacting binary systems (Hoyle & Fowler 1960) and that their light curves are powered by the radioactive decay of ^{56}Ni and its daughter nucleus ^{56}Co (Colgate & McKee 1969). However, the actual progenitor stars are still elusive (e.g., Maoz et al. 2014, for a review) and details of the explosion mechanism not fully understood (e.g., Hillebrandt & Niemeyer 2000).

In the absence of direct progenitor detections, theoretical models are one promising way to further our understanding of SNe Ia. To this end, we have developed a suite of numerical codes for a detailed simulation of the thermonuclear burning, nucleosynthesis processes and the propagation of radiation through the resulting explosion ejecta in SNe Ia. Employing this simulation pipeline to explore the predictions of various progenitors scenarios and explosion mechanisms in the context of observed SN Ia properties allows us to derive constraints on certain scenarios (see e.g., Röpke et al. 2012).

In this contribution, we briefly present simulations for various progenitor models and discuss their properties in the context of the observed diversity of SNe Ia (Sections 2-4). In Section 5, we introduce the Heidelberg Supernova Model Archive, which provides isotopic abundances and synthetic observables for a large variety of explosion models to the community.

2. Chandrasekhar-mass models

In the canonical model of SNe Ia, a CO WD accretes H-rich material from a companion star (an evolved main-sequence star or a red giant, Whelan & Iben 1973). When it nears the Chandrasekhar stability limit (M_{Ch}) pycnonuclear reactions ignite in the WD core. After a simmering phase that lasts for several hundred years a thermonuclear runaway occurs in the electron degenerate WD matter (see e.g., Hillebrandt & Niemeyer 2000, for a detailed description). The thermonuclear burning can either proceed as a subsonic deflagration (mediated by thermal conduction) or as a shock-driven, supersonic detonation.

For a M_{Ch} WD the initial density is so high (a few times $10^9\,\mathrm{g\,cm^{-3}}$) that a detonation yields only iron-group elements (IGEs), excluding this channel for SNe Ia since their spectra indicate the presence of significant amounts of intermediate-mass elements (IMEs, e.g., Si, S, Ca) in the ejecta (Arnett 1969). In contrast, in a deflagration the WD can react to the energy release from the burning and expands. This, in turn, decreases the burning efficiency. Recent 3D models indicate that deflagrations yield at most $\sim 0.4\,\mathrm{M}_\odot$ of ^{56}Ni (Fink et al. 2014), which falls short to explain the peak brightness of the bulk of normal SNe Ia (observations indicate the need of $\sim 0.5 - 0.6\,\mathrm{M}_\odot$ of ^{56}Ni to power their peak brightness Scalzo et al. 2014). However, it has been shown that weak deflagrations that fail to completely unbind the progenitor WD explain the observed properties of a peculiar sub-class of faint SNe Ia, the so called Type Iax supernovae (e.g., Jordan et al. 2012; Kromer et al. 2013a; Magee et al. 2016).

One way to produce normal SNe Ia from M_{Ch} WDs is the delayed detonation scenario. Here, the burning starts as a deflagration, which allows the WD to expand before the burning mode switches to a detonation. This may happen either by a spontaneous deflagration-to-detonation transition (DDT, e.g., Khokhlov 1991; Seitenzahl et al. 2013), or the convergence of macroscopic fluid flows like in the gravitationally-confined detonation model (GCD, e.g., Plewa et al. 2004; Seitenzahl et al. 2016). In particular 1D DDT models have been very successful in explaining the observed properties of normal SNe Ia in the past (e.g., Höflich & Khokhlov 1996; Blondin et al. 2013). However, recent 3D DDT models have problems to reproduce the observed colours and the light-curve width-luminosity relation of SNe Ia (Sim et al. 2013). The reason for this seems to be turbulent mixing during the initial deflagration phase that produces ejecta with significant amounts of stable IGEs outside the ^{56}Ni region. In contrast, in 1D models turbulence is suppressed, leading to a concentration of stable IGEs in the centre of the ejecta.

3. Sub-Chandrasekhar-mass models

If a sub-Chandrasekhar-mass CO WD accretes He from a companion star (either a He-rich donor or a He WD), a detonation may be triggered in the accumulated He layer when the right conditions are met (Taam 1980; Shen et al. 2010). In this case, an ensuing detonation of the underlying sub-M_{Ch} CO core seems to be almost unavoidable (Fink et al. 2007; Moll & Woosley 2013). This so called double detonation mechanism (Iben et al. 1987) has the potential to produce a wide range of ^{56}Ni masses (e.g., Fink et al. 2010; Woosley & Kasen 2011) that covers faint and normally bright SNe Ia. The amount of ^{56}Ni produced is thereby directly proportional to the initial mass

Table 1. Overview of simulations presently available in HESMA.

Progenitor	Explosion mechanism	Number	Source
sub-M_{Ch} CO	double detonation	12	Fink et al. (2010); Kromer et al. (2010); Sim et al. (2012)
sub-M_{Ch} CO	core detonation	7	Sim et al. (2010); Marquardt et al. (2015)
sub-M_{Ch} CO	shell detonation	2	Sim et al. (2012)
sub-M_{Ch} ONe	core detonation	5	Marquardt et al. (2015)
M_{Ch} CO	deflagration	14	Kromer et al. (2013a); Fink et al. (2014)
M_{Ch} CO	spontaneous DDT	20	Seitenzahl et al. (2013); Sim et al. (2013); Ohlmann et al. (2014)
M_{Ch} CO	GCD	1	Seitenzahl et al. (2016)
M_{Ch} hybrid	deflagration	1	Kromer et al. (2015)
CO+CO merger	detonation	4	Pakmor et al. (2010, 2012b); Kromer et al. (2013b, 2016)
super-M_{Ch} CO	various	5	Fink (2010); Hillebrandt et al. (2013)

of the WD. However, IGE-rich burning ashes of the He shell detonation leave characteristic imprints on synthetic spectra that are not in agreement with the observed spectra of SNe Ia (e.g., Höflich & Khokhlov 1996; Kromer et al. 2010).

The final burning products of the He shell detonation depend very sensitively on the initial conditions in that shell. For example, an admixture of C nuclei to the He shell can suppress the production of IGEs leading to much better agreement with the observed properties of SNe Ia (Kromer et al. 2010). In the limit of bare sub-M_{Ch} CO WDs, studied by Shigeyama et al. (1992) and Sim et al. (2010), centrally ignited detonations qualitatively reproduce observed trends of normal SNe Ia like the light curve width–luminosity relation and the evolution of the Si line ratio from faint to bright SNe Ia. Lower mass sub-M_{Ch} WDs that produce only $\sim 0.1\,\mathrm{M}_{\odot}$ of ^{56}Ni may be good candidates to explain the sub-luminous 1991bg-like SNe Ia (Hachinger et al. 2009).

4. Violent mergers

Another progenitor channel for SNe Ia presents the merger of two CO WDs that together exceed the Chandrasekhar mass limit (Webbink 1984). From a theoretical point of view, however, this channel was heavily debated for a long time, since many simulations had shown that WD mergers undergo an accretion induced collapse rather than a thermonuclear explosion (e.g., Nomoto & Iben 1985; Saio & Nomoto 2004; Shen et al. 2012). All these simulations assumed that the lower mass WD is disrupted and then slowly accreted onto the primary (i.e., more massive) WD.

More recent simulations (e.g., Pakmor et al. 2011, 2013; Tanikawa et al. 2015) indicate that a detonation may form when the two WDs come in contact and the secondary WD is still intact. In this violent merger scenario the system is disrupted by a thermonuclear explosion. Since the mass of the primary WD is below M_{Ch} at the time of explosion, the violent merger scenario is basically a sub-M_{Ch} explosion scenario (even if the total ejecta mass can be larger than M_{Ch}, if the secondary WD is disrupted by the explosion). The violent merger scenario inherits all the positive properties of detonations of bare sub-M_{Ch} CO WDs. In particular, it can cover a wide range of peak brightness and the flux spectra qualitatively match those of observed SNe Ia (Pakmor et al. 2012b; Moll et al. 2014). However, the interaction of the ejecta with the secondary WD introduce strong asymmetries leading to significant continuum polarisation in the spectra, which is not observed in normal SNe Ia (Bulla et al. 2016).

Nonetheless, violent mergers with lower mass primaries (~0.9 $\mathrm{M}_\odot$) show remarkably similar observables to a group of slowly-evolving faint SNe Ia similar to SN 2002es (Kromer et al. 2013b, 2016). It will be interesting to obtain spectropolarimetry for a future event of this class to see whether a violent merger model is compatible.

5. Heidelberg Supernova Model Archive (HESMA)

Following repeated requests by the community for nucleosynthetic yields, ejecta profiles and synthetic observables of our explosion models, we have decided to set up a public model archive, the Heidelberg Supernova Model Archive (HESMA)[1]. We hope this facilitates further work, e.g., in galactic chemical evolution and the interpretation of observed SN spectra.

Currently, the archive comprises about 70 (multi-)dimensional explosion models from the SN Ia group formerly based at the Max Planck Institute for Astrophysics in Garching (MPA) and now spread to Heidelberg, Belfast and Canberra. The models cover a wide range of progenitor scenarios and explosion mechanisms. For an overview of the included models see Table 1. A graphical representation of a subset of the models is shown in Figure 1.

All the explosion simulations were performed with the hydrodynamics code LEAFS (Reinecke et al. 2002). Simulations of the merging process in the violent merger scenario were conducted using GADGET (Pakmor et al. 2012a). Detailed isotopic abundances were obtained from nucleosynthesis calculations employing a large 384-isotope network on thermodynamic trajectories of tracer particles (Travaglio et al. 2004). Finally, synthetic observables were derived with the Monte Carlo radiative transfer code ARTIS (Kromer & Sim 2009).

In HESMA, we provide integrated isotopic abundances as well as radially averaged density and isotopic abundance profiles of the explosion ejecta after they achieved homologous expansion. We also offer angle-averaged UVOIR bolometric light curves and gamma-ray and optical spetral time series. Bolometric light curves are tabulated from ~ 6 to 80 d past explosion. Gamma-ray spectra for selected models are available from ~ 6 to 100 d past explosion. Optical ($\lambda \in [3500, 9500]$ Å) spectral time series are available from ~ 6 to 40 d past explosion and will also be ingested to the Weizmann Interactive Supernova data Repository (WISeREP, Yaron & Gal-Yam 2012).

6. Conclusions

We presented a brief overview of a variety of state-of-the-art explosion models of CO WDs and discussed their properties in the context of the observed diversity of SNe Ia.

We also introduced HESMA, the Heidelberg Supernova Model Archive that comprises data for about 70 models on the hydrodynamical structure of the ejecta, on nucleosynthetic abundances as well as on synthetic observables: bolometric light curves and spectral time series in the optical and gamma rays.

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[1] `https://hesma.h-its.org`

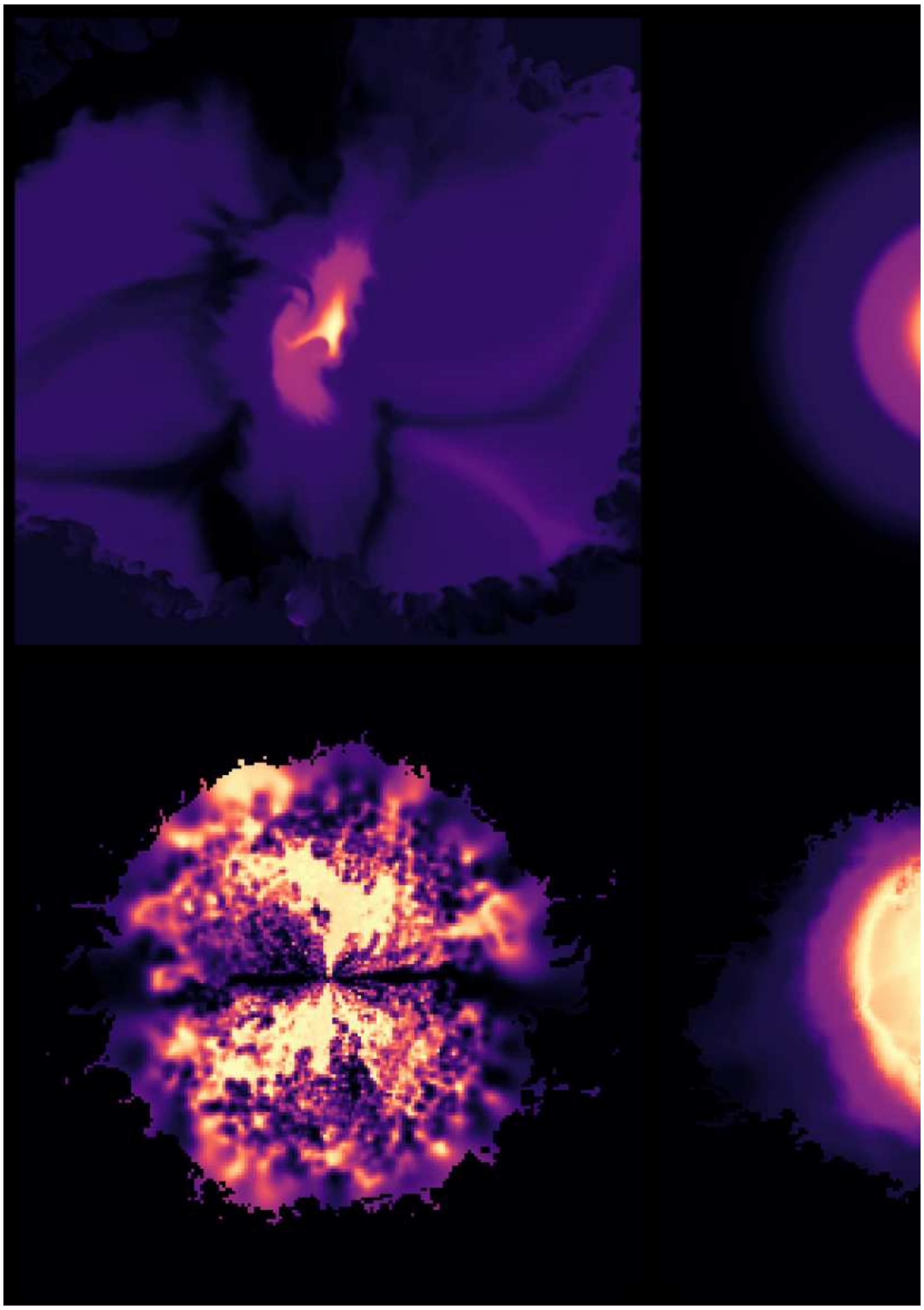

Fig. 1. Displayed are slices of the mean atomic number at the end of the hydrodynamics simulation for a variety of models from HESMA. The top row shows Chandrasekhar-mass explosions (from left to right: deflagration, delayed detonation and gravitationally confined detonation), the middle row shows explosions of a sub-Chandrasekhar-mass primary WD (from left to right: violent merger, pure detonation, double detonation), and the bottom row shows super-Chandrasekhar-mass explosions (from left to right: deflagration, delayed detonation, detonation).

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