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The Progenitor Systems of Thermonuclear Supernovae

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Despite the importance of Type Ia supernovae for modern astrophysics, their detailed explosion mechanism is still not fully understood. In this article, we present recent findings from numerical models in the context of their observed diversity and we discuss how these models can help to shed light on the explosion mechanism and to identify their progenitor systems. It is shown that the models have considerable predictive power and they can aid the identification of sources of systematic errors when used as distance indicators for cosmology.

1 Introduction

Type Ia supernovae (SNe Ia) are of paramount importance for cosmology. After calibration they are reliable cosmic-distance indicators and they are widely used to determine the expansion history and the energy content of the universe. However, a complete understanding of their explosion is still lacking. We do not know for sure what their progenitors are and, moreover, observations have revealed that even different progenitor channels may be necessary to match their observed spectral and photometric diversity (see, e.g. Hillebrandt *et al.*[1] for a recent review).

These findings are the sources of major systematic uncertainties in using SNe Ia distances (as determined from their apparent luminosity). For instance, if there are different kinds of progenitors with somewhat different luminosity and a relative rate changing with time this will lead to wrong (average) distances. Similarly, a potentially important effect that may modify the luminosity-distance relationship is the chemical composition of the progenitor star which also may change with time.

Here, we give a progress report on a project, started by us several years ago, with the objective to contribute to the understanding of SNe Ia by developing a theoretical framework consistent with prototypical observed explosions, but also capable of reproducing their observed diversity. In the sections which follow we discuss, both, recent explosion models and some of their predictions for observable properties.

2 Explosion Models

2.1 Pure Deflagrations in CO White Dwarfs

The most popular progenitor model for the average type Ia supernova is a massive white dwarf, consisting of carbon and oxygen, which approaches the Chandrasekhar mass ($M_{Chan} \simeq 1.4\ M_\odot$) by a yet unknown mechanism, presumably accretion from a companion star, and is disrupted by a thermonuclear explosion (see, e.g., Hillebrandt & Niemeyer[2] for a review). At high densities explosive carbon burning mostly produces radioactive ^{56}Ni. At lower densities intermediate-mass nuclei, like Ca and Si, are produced. These elements give rise to the typical observed spectra of SNe Ia.

Here, we present the results of a series of 3D full-star pure deflagration explosions (i.e., explosion models which do not assume a deflagration-to-detonation transition at some later phase) of Chandrasekhar-mass CO white dwarfs. In contrast to previous simulations, they were done with a gravity solver based on a FFT-solver for the Poisson equation rather than the monopole approximation, designed to work efficiently with the non-uniform grid spacing and the parallelisation approach of our combustion hydrodynamics code. This is important since the strongly anisotropic ignition configurations suggested by state-of-the-art simulations of the convective phase preceding the thermonuclear runaway[3] will lead to density distributions significantly diverging from a spherically-symmetric morphology.

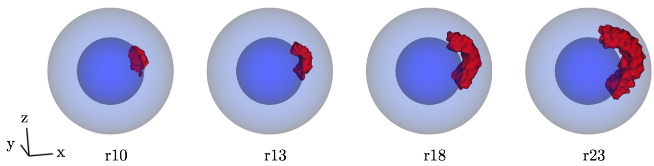

Figure 1. Initial flame configuration (red surface) for the simulations performed in the present section. The blue spheres correspond to white dwarf radii of 40 km and 75 km. The models are labelled according to the equivalent radius of a sphere of the same volume.

In particular, a sequence of initial models was constructed, ranging from a point-like ignition region towards larger coherent structures (see Fig. 1). Since all of them are located between 40 and 75 km off the centre of the white dwarf, the deflagration flame rises to the surface due to buoyancy before it can propagate through the centre. Consequently, the explosions evolve very asymmetric and are due to the weak ignition and the subsequent low nuclear energy release not able to burn the white dwarf completely, thus giving rise to a bound remnant of more than one solar mass and strongly supersolar metallicity.

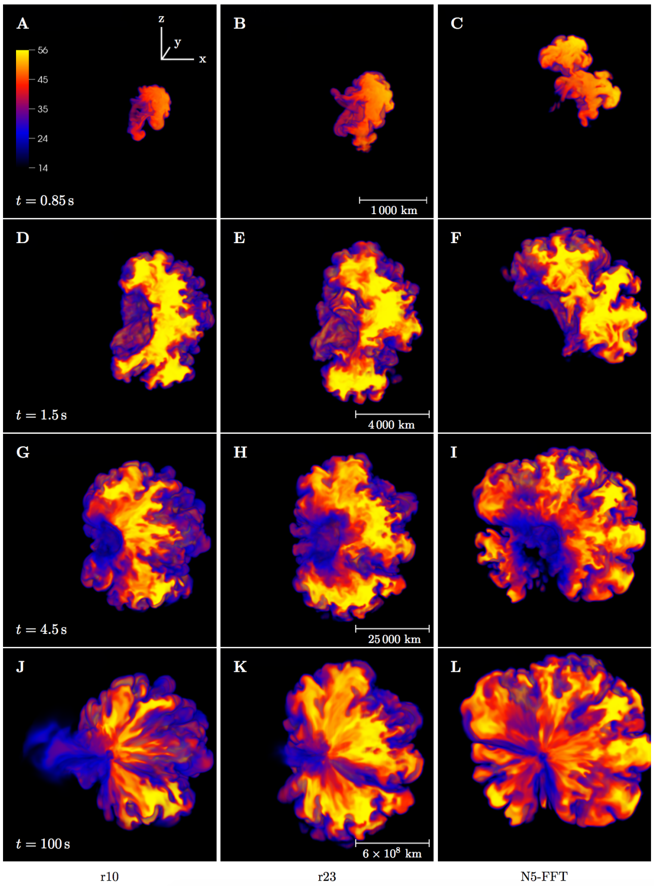

Figure 2. Volume renderings of the burnt material for three models (r10, r23, N5-FFT, from left to right), at four different times (0.85 s, 1.5 s, 4.5 s and 100 s, from top to bottom). The colours indicate the mean atomic number. Yellow denotes iron-group elements, purple intermediate-mass elements and blue fuel-rich material that is slightly polluted with ashes (see also the colour bar in panel A).

Fig. 2 shows the flame evolution on the basis of 3D volume renderings of a sub set of our models at different explosion stages, revealing strong mixing in the course of the turbulent burning. Additionally, the more symmetric N5 model from Kromer *et al.*[4] and Fink *et al.*[5] is re-calculated using the new FFT solver, to allow comparison to the earlier results. Owing to the asymmetric evolution, the surviving remnant receives a noticeable natal kick. It turns out that due to the new solver the corresponding recoil velocities are significantly increased against the values found by previous simulations.

Synthetic light curves from radiative transfer calculations for one particular model are shown in Fig. 3. The light curves show a noticeable viewing-angle dependency due to the asymmetric shape of the ejecta that is preserved until well into the homologous expansion phase. Compared to SN 2005hk, a typical member of the peculiar SN 2002cx-like class of Type Ia supernovae our light curves are about a magnitude fainter, offering the possibility

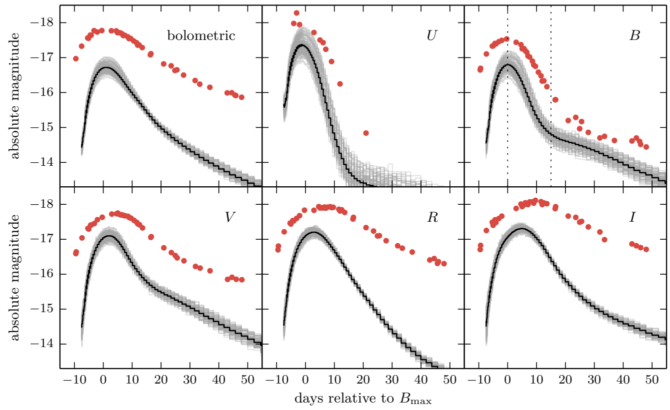

Figure 3. Synthetic light curves for the r23 model in different colour bands. The grey curves depict the light curves from 100 different viewing angles whereas the black curve illustrates the angle-averaged values. For comparison, observed light curves of SN 2005hk[7], a typical SN 2002cx-like object, are plotted as red circles.

to explain some of the fainter objects of the class of 2002cx-like SNe.

2.2 White Dwarf Mergers

Double degenerate systems of two CO white dwarfs are currently one of the most promising candidates to explain the progenitor systems of SNe Ia. However, it is still debated how they explode and if they can reproduce the observed properties of normal SNe Ia.

The introduction of violent mergers[6], in which dynamical interaction between the two WDs during the merger when the secondary WD is destroyed ignites a carbon detonation on the surface of the primary WD, provided the first plausible explosion scenario for a merger of two CO WDs. Moreover, explosions from violent mergers are able to explain many of the observed features of normal SNe Ia[8–10].

However, it is unclear how reliable ignition really is in this scenario and violent mergers also showed significant differences compared to observed events. In particular, their synthetic lightcurves seem to systematically decay too slowly compared to observations, most likely because the total mass of the ejecta (which is significantly above the Chandrasekhar-mass because both WDs are burned) is too large[11]. In addition the synthetic polarisation signal is too strong, indicating that the ejecta are more asymmetric than in nature[12].

To remedy these problems, Pakmor *et al.*[13] proposed an alternative ignition scenario in which dynamical accretion from the secondary WD on the primary WD ignites a thin helium shell on top of the primary. A detonation then burns the helium shell on the primary and sends a shockwave into its CO core that ignites a carbon detonation when it converges into a single point in the core, similar to double detonation scenarios[14]. Because ignition happens before the actual merger, the secondary WD may survive the explosion which can lower the ejecta mass significantly and reduce the asymmetry of the ejecta.

We ran the first explosion simulations with radiation transport postprocessing for this new explosion scenario. Fig. 4 compares the density structure and the composition of the ejecta (this work) and the old violent merger model[8]. The most obvious difference is in

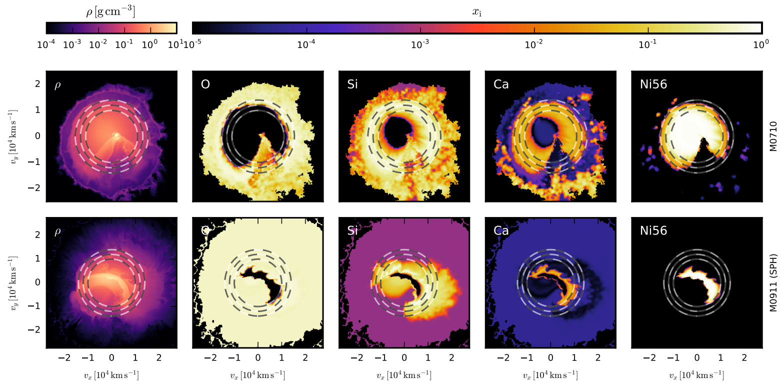

Figure 4. Density structure and composition of the ejecta of the helium-ignited CO-WD binary (top row, new) and the violent merger of two CO WDs (bottom row, from Pakmor *et al.*[8]). The ejecta are shown 100 s after ignition when the ejecta are expanding homologously. The compositions are obtained from postprocessing Lagrangian tracer particles whose density and temperature trajectories were recorded during the simulations. The dashed lines denote circles of constant velocity at 10^4 km/s, 1.2×10^4 km/s, and 1.4×10^4 km/s.

the asymmetry of the ejecta. The new explosion scenario leads to a rather spherical ejecta structure that only has a cone-like feature at the solid angle pointing to the secondary at the time of ignition. In contrast, the ejecta of a violent merger are far from spherical, caused by the strong interaction of the ashes of the primary and the secondary WDs. For the same reason, the new scenario does not show any oxygen in the centre of the ejecta, that is prominent in the violent mergers model.

Note also, that similarly to traditional double detonation models[15] the ashes of the helium shell of the primary WD contain significant amounts of iron group elements. Even though this helium shell only contains $10^{-2}\,\mathrm{M}_\odot$ of material, iron group elements have such a large opacity that the ashes of the shell have an imprint on the observables. There is also a strong difference in the time scales between the two models. Owing to a lower ejecta mass, the new model peaks several days earlier and fades more rapidly.

3 Probing the Geometry of SN Ia Explosions

A crucial uncertainty in our understanding of SNe Ia concerns the observed diversity among normal SNe Ia, which needs to be understood to reduce systematical errors in their use as cosmological distance indicators. Often, a significant part of this diversity is attributed to geometry effects[16]. Geometry also provides a clear discriminant between certain explosion models. For example, the best-studied scenario, the Chandrasekhar mass delayed-detonation model[17,18], predicts that the ejecta can be quasi-spherical on large scales but have complex substructure in both density and composition. In contrast, e.g. some simulations of violent white dwarf mergers[8] predict departures from spherical symmetry on large angular scales.

Our synthetic spectropolarimetry calculations reveal that the violent merger of a 1.1 and 0.9 $\mathrm{M}_\odot$ WD binary system is too asymmetric to explain the low polarisation levels commonly observed in normal Type Ia supernovae[12]. Furthermore, we have calculated syn-

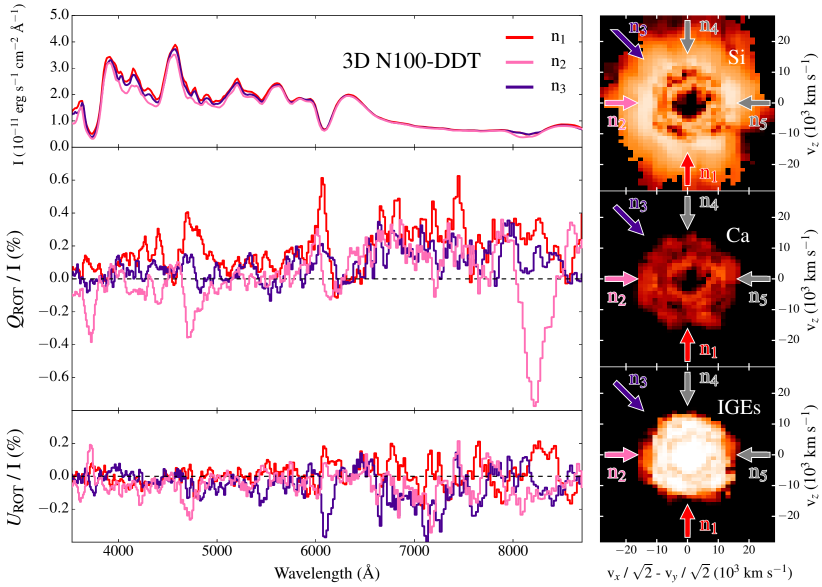

Figure 5. *Left-hand panels.* Flux (top) and polarisation Q_{ROT} (middle) spectra extracted for the prototypical delayed-detonation model at 17 d after explosion ($B-$band maximum light) along the n_1, n_2 and n_3 orientations. Polarisation U_{ROT} spectra are reported in the bottom panel and reflect deviations from a single-axis geometry. Polarisation spectra are Savitzky-Golay filtered using a first-order polynomial and a window of 3 pixels ($\sim$ 50 Å) for clarity. The model flux is given for a distance of 1 Mpc. *Right-hand panels.* Orientations of five observers selected for the model ($n_1 - n_5$) with respect to the ejecta composition. The mass fractions of silicon (top), calcium (middle) and IGEs (bottom) are displayed. White colours indicate a large mass fraction, dark colours a low mass fraction. Adopted from Bulla *et al.*[19].

thetic polarimetry for two alternative explosion scenarios[19]: the sub-Chandrasekhar-mass double-detonation and the Chandrasekhar-mass delayed-detonation model. Specifically, we studied two-dimensional double-detonation models and three-dimensional delayed-detonation models. An example for the calculations of a delayed-detonation model is shown in Fig. 5. For both models, we find modest polarisation levels ($<$ 1 per cent). Polarisation in the continuum peaks at $\sim 0.1-0.3$ per cent and decreases after maximum light, in excellent agreement with spectropolarimetric data of normal Type Ia supernovae. Higher degrees of polarisation are found across individual spectral lines. In particular, the synthetic Si II λ6355 profiles are polarised at levels that match remarkably well the values observed in normal Type Ia supernovae, while the low degrees of polarisation predicted in the O I λ7774 region are consistent with the non-detection of this feature in current data.

We conclude that both the sub-Chandrasekhar-mass double-detonation and the Chandrasekhar-mass delayed-detonation model can reproduce many of the characteristics of both flux and polarisation spectra for well-studied Type Ia supernovae. However, the two models considered in our study cannot account for the unusually high level of polarisation observed in extreme cases such as SN 2004dt.

4 Conclusions

Type Ia supernovae remain an important tool for observational cosmology. The measurement of cosmic distances based on these objects holds promise to constrain dark energy models – in particular, if the data is analysed in a model-independent way.

Nonetheless, the theoretical understanding of SNe Ia is still an open question. Although fundamental scenarios (thermonuclear explosions of CO WDs in binary systems) are compelling, a level of realism is required from the models that challenges astrophysical theory and numerical modelling. Numerous scenarios have been proposed over the last decades. To clarify which of these contribute to the observed SN Ia sample we follow the explosion, nucleosynthesis, and radiative transfer in a pipeline of simulations. This allows for a direct comparison of predictions with observations.

However, it is difficult to rule out any of the explosion scenarios discussed so far based on their predicted observables, although none of them matches the observations perfectly. This could imply that all the scenarios are indeed realised in nature in some way. However, it is also conceivable that the observables around peak brightness are rather insensitive to details of the explosion mechanism as they originate from the outer layers of the ejecta. To break this degeneracy, the comparison between models and observations has to be extended. In particular nebular spectra and spectropolarimetry data seem promising to provide complementary information.

As a service to the astrophysical community, we have set up the Heidelberg Supernova Model Archive (HESMA), publicly available at `https://hesma.h-its.org`. HESMA currently includes data on about 70 Type Ia supernova explosion models covering a wide range of progenitor scenarios and explosion mechanisms of Type Ia supernovae[20].

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