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Review

Modeling Type Ia supernova explosions

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ABSTRACT

Despite their astrophysical significance – as a major contributor to cosmic nucleosynthesis and as distance indicators in observational cosmology – Type Ia supernovae lack theoretical explanation. Not only is the explosion mechanism complex due to the interaction of (potentially turbulent) hydrodynamics and nuclear reactions, but even the initial conditions for the explosion are unknown. Various progenitor scenarios have been proposed. After summarizing some general aspects of Type Ia supernova modeling, recent simulations of our group are discussed. With a sequence of modeling starting (in some cases) from the progenitor evolution and following the explosion hydrodynamics and nucleosynthesis we connect to the formation of the observables through radiation transport in the ejecta cloud. This allows us to analyze several models and to compare their outcomes with observations. While pure deflagrations of Chandrasekhar-mass white dwarfs and violent mergers of two white dwarfs lead to peculiar events (that may, however, find their correspondence in the observed sample of SNe Ia), only delayed detonations in Chandrasekhar-mass white dwarfs or sub-Chandrasekhar-mass explosions remain promising candidates for explaining normal Type Ia supernovae.

1. Classification of supernovae

Supernovae are dramatic cosmic explosions that have attracted the interest of the astrophysical community because of their importance for many research fields including the dynamical and chemical evolution of galaxies, the formation of compact objects, the synthesis of heavy elements and the mapping of the geometry of the Universe. Although they are all extremely luminous transient events that brighten and fade on timescales of days to weeks, supernovae vary significantly in their properties. The *astronomical classification* distinguishes two main types based on their spectra: in Type I supernovae no hydrogen lines are seen in the spectrum while Type II supernovae (making up about 57% of all supernovae [1]) show strong hydrogen features. A further sub-division of Type I is made according to a strong silicon line that is seen in Type Ia objects (about 24% of all supernovae [1]) at peak luminosity but is absent in Type Ib/c (about 19% of all supernovae [1]).

The goal of supernova modeling is to understand the physical mechanism of these events. The *astronomical* classification scheme has no direct link to the underlying physics and, therefore, a first step is to establish an astro*physical* classification.

All kinds of supernovae are associated with cataclysmic explosions at the end of stellar evolution. A fundamental question in modeling the physical mechanism of these events (and thus a good basis for a physical classification) is the source of the explosion energy. From the observations, the kinetic energy of the ejecta is estimated as $\sim 10^{51}$ erg. If the exploding object is a star, only two energy sources are sufficient to power such an explosion. About 10^{53} erg of gravitational binding

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energy is released in the collapse to a neutron star – certainly sufficient to power a supernova. Such a collapse to a neutron star (or perhaps to a black hole in some cases) is believed to drive all kinds of supernovae except for Type Ia – see [2]. Here, the alternative energy source is tapped: the nuclear energy of the stellar material. This energy can be liberated in a thermonuclear explosion. Because neither hydrogen nor helium is observed in the spectra of these objects, the most promising class of stars that could explode as Type Ia supernovae (SNe Ia) is white dwarfs (WDs). In the degenerate matter WDs, explosive thermonuclear burning is possible. Although WDs consisting of oxygen and neon may also explode in a supernova, the more common event is believed to be the explosion of a carbon–oxygen WD. Under the conditions encountered here, thermonuclear burning will reach nuclear statistical equilibrium in large fractions of the star and ^{56}Ni will be the dominant burning product. The Chandrasekhar mass ($\sim$1.4 $M_{\odot}$) poses the upper limit of the stability of a WD. Burning this mass of carbon–oxygen material to ^{56}Ni releases about 2×10^{51} erg and thus can power a SN Ia. This scenario at the same time answers the question of why SNe Ia are bright events observable for days, weeks, and months. If the brightness were due to thermal emission, a rapid decline would be expected given the huge kinetic energy of the ejecta and the associated cooling by expansion. The ^{56}Ni produced in the explosion provides an explanation for why the supernova stays bright for a long time: it decays radioactively to ^{56}Co and subsequently to ^{56}Fe (with respective half-lives of 6 and 77 days) releasing gamma rays and positrons that heat the ejecta and and give rise to the bright optical display we observe from SNe Ia [3,4].

In summary, this provides a *physical* classification of supernovae as stellar explosions due to thermonuclear combustion or gravitational collapse. While Type Ia supernovae fall into the first category, all other classes (except for exotic events such as pair-instability supernovae) are attributed to gravitational collapses of stellar cores.

2. Astrophysical significance

The study of SNe Ia in particular has two motivations. First, SN Ia explosions leave their imprint on the interstellar medium. As energetic explosions they drive shock waves into their environments and thus can contribute to the dynamical evolution of galaxies. Moreover, they produce iron group elements (IGEs) in large amounts (predominantly ^{56}Fe from the decay of ^{56}Ni) and distribute it into their surroundings. This makes them the dominant source of iron in the cosmic cycle of matter. It is also possible that they produce p-process elements in significant amounts [5–7].

Second, SNe Ia have been established over the last 15 years as one of the most important tools in observational cosmology. Initially, this was motivated by the apparent homogeneity of this class of objects. If the intrinsic brightness of the supernova is known, the luminosity distance can be inferred from measuring its apparent magnitude. The measurements carried out in the late 1990s [8,9] gave rise to our current cosmological standard model. They established the notion of an *accelerated* expansion of the Universe. Its cause is parametrized as a "dark" component dominating the energy density today, but the nature of this enigmatic form of energy is unclear. SNe Ia can help to shed light on this question and this makes them an important probe of fundamental physics [10]. Beyond proving the acceleration of cosmic expansion, they provide one of the most promising ways to test dark energy models. Their particular strength lies in the fact that they probe the geometry of the Universe directly. It is therefore possible to reconstruct its expansion history without any assumption on the energy contents. Not even the validity of the Einstein equations has to be assumed. This model-independent reconstruction of the Hubble function $H(z)$ depending on redshift z (e.g. [11]) is a powerful method to discriminate between dark energy models and scrutinize them by exposure to astronomical data. Conventional approaches try to fit supernova data to an assumed ΛCDM cosmology. Most dark energy models, however, are set up in such a way that they fit the global parameters of such a model. Model-independent reconstructions offer a way to break this degeneracy. When comparing $H(z)$ as obtained from current SN Ia samples to the expansion histories predicted by various dark energy models, clear differences are seen. Some parametrizations are clearly inconsistent with the supernova data. As an example, $H(z)$ as obtained from the Union2 SN Ia sample is compared with mDGP models [12,13] in Fig. 1. With the upcoming SN Ia surveys a more detailed evaluation of dark energy models is feasible and model-independent analysis methods are a promising tool for this task.

The application of SNe Ia as distance indicators in observational cosmology rests on the implicit assumption of knowing the intrinsic luminosity of these events. Evidently, SNe Ia are not standard candles. There is considerable variation in the properties of "normal" events and the number of observed outliers and peculiar sub-classes keeps growing. For the normal events, a calibration is possible [16,17] that renders them the best distance indicators out to redshifts $\sim$1. But still, the accuracy needs to be improved for making progress in validating dark energy models. Moreover, the calibration method has been established on the basis of a set of nearby SNe Ia and there is no guarantee that it works equally well at large distances. Systematics, evolutionary effects, and correlations of the brightnesses of the events with properties of the surrounding material are key questions that cannot be answered by observations alone. Clearly, a sound theoretical understanding of the physical mechanism of SNe Ia is mandatory to increase confidence in SN Ia cosmology.

3. SN Ia fundamentals

The basics of SN Ia theory rest on a number of assumptions, some of which are hard to prove. Most observations originate from the cloud of ejecta in a phase several days after the actual explosion. Emission in the optical range is observed that is attributed to the heating of the ejecta by gamma rays and positrons. Therefore all information we have on the evolution of the progenitor system and the details of the explosion mechanism is indirect. The goal of SN Ia theory is therefore to construct a plausible explosion scenario that is in agreement with the observations.

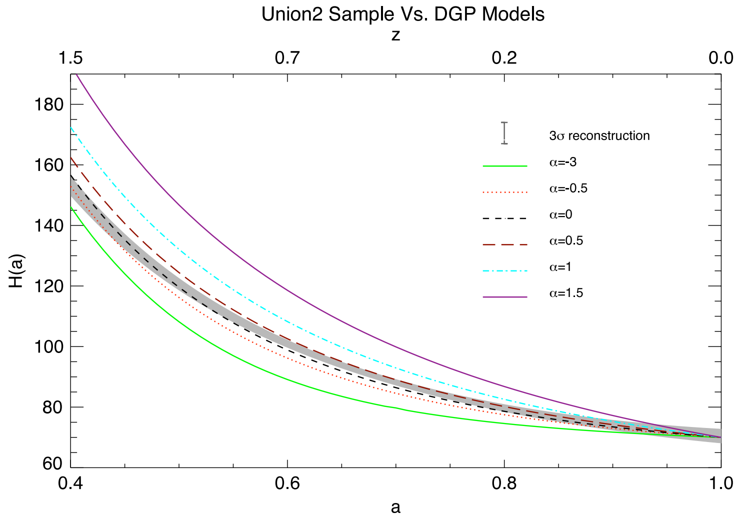

Fig. 1. Reconstructed expansion history of the Universe from the Union2 supernova sample (with 3σ error bars) compared to mDGP models with different choices of the parameter α (from [14]). For $\alpha = 0$ the ΛCDM model is recovered while $\alpha = 1$ corresponds to the original DGP model [15].

It is widely agreed that SNe Ia originate from thermonuclear explosions of white dwarf (WD) stars [18] consisting of carbon and oxygen (although oxygen–neon WDs might also contribute to the SN Ia sample). Traditionally, the assumed homogeneity of SNe Ia was taken as an indication that the explosions should proceed in similar ways in nearly identical progenitors for all events. A characteristic mass that is suggestive here is the Chandrasekhar mass – the limit of stability of the progenitor WD – and this led to a preference for Chandrasekhar-mass explosion models over the last decades (e.g. [19]). The notion of homogeneity, however, is challenged by recent observations and Chandrasekhar-mass scenarios as the only explanation for SNe Ia have to be critically reconsidered. Allowing for a diversity of progenitor WDs raises the question of whether a typical mass of produced ^{56}Ni exists that explains normal SNe Ia (about 0.5–0.6 $M_\odot$ in the Chandrasekhar-mass scenario, [20]). Moreover, if different progenitor channels and explosion mechanisms contribute to SNe Ia it seems unlikely that they all should match the solar isotopic pattern in the iron group. All this weakens the constraints on models that were taken for granted before.

The challenges to SN Ia theory are therefore to determine which progenitor channels and explosion scenarios can contribute to SNe Ia. Does one model account for the full diversity of events observed? Given the peculiar events and the wide span of characteristics seen in contemporary surveys this seems unlikely. One approach to tackle these questions is forward modeling. Starting out from an assumed progenitor, the explosion is followed by hydrodynamic simulations from which observables are derived that can be compared directly to observations. A complementary approach is to predict the frequency of different progenitor systems and to compare it to the observed rate of SNe Ia (or subclasses thereof). In all approaches, however, it is important to model the ingredients by carefully avoiding tunable parameters. Only this guarantees sufficient predictive power of the observables derived from the models to assess the validity of different scenarios. For the explosion modeling, which will be the focus here, this implies multi-dimensional treatment of the hydrodynamics.

Single WDs are the end stages of stellar evolution of intermediate-mass and low-mass stars and, as such, they are inert objects. The Fermi pressure of the degenerate electrons stabilizes them against gravitational collapse. Given this everlasting stability for an isolated WD, something further is needed to explain how they reach the point at which an explosion triggers. Either an evolution of the WD properties to reach conditions for spontaneous self-ignition or external compression of the material is necessary. Setting aside more exotic scenarios, it is clear that in order to introduce the required dynamics, the progenitor has to be one component of an interacting binary system. There has been much speculation on the nature of the companion star (see, e.g., [2] for a review). For the explosion, however, the critical question is whether it triggers spontaneously as a result of the high densities reached when the WD approaches the Chandrasekhar mass because of mass accretion from the companion, or due to "external" phenomena, e.g. dynamic instabilities in the accretion stream [21], or detonations in the accreted layer of material. In the first case, a long-lasting stable accretion is required as WDs are usually formed much below the Chandrasekhar mass. In the explosion, the mass of the fuel is then fixed to $\sim$1.4 $M_\odot$. This is not necessarily the case in the second scenario. Instabilities in the progenitor evolution may trigger the WD explosion before the Chandrasekhar mass is reached. Consequently, from the perspective of the explosion mechanism, the fundamental distinction is into *Chandrasekhar-mass models* and *non-Chandrasekhar-mass models.*

4. Chandrasekhar-mass Explosion Models

In the Chandrasekhar-mass explosion model, a carbon–oxygen (C + O) WD approaches the Chandrasekhar limit by accreting matter from a binary companion. This companion can, in principle, be another carbon–oxygen WD (for which, however, long-lasting stable accretion may be difficult to arrange), or, in the more commonly discussed scenario, a normal star. While in the first case carbon–oxygen material is accreted directly, in the latter scenario hydrogen- or helium-rich matter is accumulated on top of the C + O WD and burns hydrostatically into carbon and oxygen. In both cases, the accretion leads to a steady increase in the WD mass. Close to the Chandrasekhar limit, the central density reaches values above 10^9 g cm^{-3} and carbon fusion reactions set in. This, however, is not yet the onset of the actual supernova explosion but leads to a century of convective carbon burning. Here, the burning stays non-explosive since the energy released in the reactions is carried outwards from the WD's center by convective motions. The convective flow is highly turbulent and difficult to model [22,23]. Due to gradual increase of the background temperature, small temperature fluctuations near the center of the WD finally reach conditions for a thermonuclear runaway that ignites a burning front. The number of ignition sparks and their distribution is not known, but will have significant impact on the explosion characteristics. In this sense, the ''initial conditions'' for Chandrasekhar-mass explosion scenarios are poorly known.

Once ignited, the burning front propagates from the center of the WD outwards burning the initial C + O material into heavier elements. The dominant species in the nuclear ash is ^{56}Ni which by its radioactive decay makes the event bright.

A Chandrasekhar-mass model where accretion proceeds from a normal star can, in principle be assessed by the imprint it should leave on the ejecta. As the explosion wave runs over the star, some of its outer envelope (consisting mainly of hydrogen) should be stripped off [24]. Recent simulations [25], however, show that the mass of H expected to be mixed in the ejecta does not disagree with current observations, provided the companion is a main-sequence star.

4.1. Modeling the combustion front

To first order, the composition of the burning products depends on the fuel density ahead of the combustion front. For the highest densities prevailing at the stellar core at the onset of the explosion, burning is complete and proceeds to nuclear statistical equilibrium (NSE). Ultimately, iron group elements are produced here. At lower fuel densities, incomplete burning leads to the synthesis of intermediate-mass elements (IMEs), such as Si, Ca, Mg, and S. Even lower fuel densities allow for conversion of carbon to oxygen, and below a certain threshold burning ceases. All burning stages are reached subsequently in the explosion of a Chandrasekhar-mass WD because the burning starts out from the dense center of the star and propagates towards the lower density material near the surface while expanding and diluting the stellar matter due to the nuclear energy release.

Due to the extreme sensitivity of the carbon fusion rate to temperature and the high conductivity of the electron-degenerate material, burning proceeds in microscopically thin fronts which are sometimes called flames in analogy to terrestrial chemical combustion. Typically, the thickness of such flames is of the order of 10^{-1}–1 cm, while the radius of a Chandrasekhar-mass WD is about 2,000 km. Seen from the scale of the exploding WD, it is therefore appropriate to model the combustion wave as a discontinuity that separates the fuel from the ashes.

In this discontinuity approximation, two distinct modes of flame propagation can be identified as the only possibilities admissible by the laws of hydrodynamics. In subsonic *deflagrations*, the flame is mediated by thermal conduction while it is driven by shock waves in supersonic *detonations*.

4.2. Pure detonations

A pure detonation of a Chandrasekhar-mass WD was the first model for a SN Ia explosion tested in numerical simulations [26]. As a model for SNe Ia, however, it is rejected. Once a detonation is triggered, it burns the entire WD at supersonic velocities. Thus, no causal contact is established over the detonation wave between the energy release in the ashes and the fuel ahead of it. Therefore burning proceeds at the high initial densities. In a Chandrasekhar-mass WD, the stellar material has densities above 10^7 g cm^{-3} almost out to the edge of the star. At these densities, NSE is reached in the detonation and ultimately iron group elements are produced. Therefore the model lacks the IMEs that are prominently seen in the spectra of SNe Ia.

4.3. Pure (turbulent) deflagrations

In a Chandrasekhar-mass WD, sufficient amounts of IMEs are can only be synthesized if the fuel material is not burned at the densities set by hydrostatic equilibrium. To bring the material ahead of the flame out of equilibrium causal contact over the flame is necessary and thus a subsonic flame propagation as a deflagration is required. Here, the energy release behind the flame leads to a pre-expansion of the fuel ahead of the flame. Burning then partially takes place at low enough densities to produce IMEs in significant amounts.

A laminar deflagration flame, however, propagates too slowly (with Mach numbers of about 10^{-2}, [27]) to catch up with the expansion of the star. Thus, only little material is burned before the density falls below the burning threshold. This problem is resolved by noting that deflagrations are not laminar when propagating from the center of the WD outwards. An inverse density stratification in the gravitational field of the star is created that leads to buoyancy instabilities. On large scales, the non-linear regime of the Rayleigh–Taylor instability leads to the formation of hot and light burning bubbles that raise into the cold and dense fuel. At the interfaces, strong shear flows emerge that reach Reynolds numbers as high as 10^{14}. Consequently, strong turbulence is generated near the flame. Large turbulent eddies decay to smaller ones and this establishes a turbulent cascade spanning about 12 orders of magnitude in scale space. In a wide sub-range of this cascade,

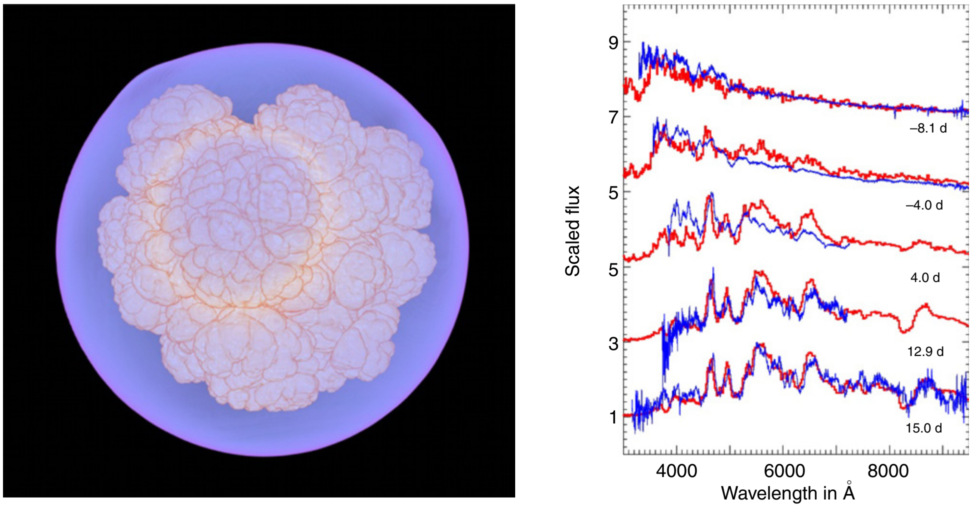

Fig. 2. Pure deflagration in a Chandrasekhar-mass C + O WD: snapshot of the flame propagation 1.0 s after ignition in multiple sparks around the star's center (left). The wrinkled deflagration flame is shown as the light isosurface inside the exploding WD (indicated by density rendering). In the plot on the right, *preliminary* predictions for spectra resulting from this event are given. The model spectra in red are compared to observations of SN 2005hk in blue. Note that this comparison does not reach the same quality as the others shown in this article. Only a scaled flux is plotted; the absolute magnitudes do not match. Moreover, no reddening correction was applied to the spectra of SN 2005hk. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the flame interacts with the turbulent eddies on various scales. They drag the flame around and lead to a dramatic increase in flame surface area. This effect enhances the effective burning rate strongly and accelerates the flame far beyond the laminar flame speed. Thanks to this interaction with turbulence, a deflagration is able to successfully explode a WD star [28–30]

The numerical representation of the thin flame front itself and of the flame–turbulence interaction requires special techniques. In our grid-based hydrodynamic SN Ia code LEAFS, the flame is treated as a discontinuity and its propagation is tracked with the level-set method [31]. The unresolved internal structure of the flame is irrelevant for its propagation as its speed is determined solely by the turbulent velocity fluctuations. Because the full turbulent cascade cannot be resolved in numerical simulations, turbulence is accounted for by a subgrid-scale model [32,33].

A prototypical example of a simulation modeling turbulent deflagration in a Chandrasekhar-mass WD is shown in Fig. 2. Initially, the deflagration flame is ignited in multiple sparks around the center of the WD [34] (note that off-center ignitions lead to different results [35]). The model produces 0.32 $M_\odot$ of ^{56}Ni – a value that is typical for centrally ignited turbulent deflagrations, but insufficient for the explanation of normal SNe Ia. The large-scale buoyancy instabilities lead to strong mixing of the chemical composition of the ejecta which is not observed in normal SNe Ia [36,37]. Thus, such simulations show that only a faint, low energy, peculiar event can be expected to result from pure turbulent deflagrations in Chandrasekhar-mass WDs.

In order to test this hypothesis with radiation transfer calculations, the chemical composition of the ejecta has to be known in more detail than provided by the hydrodynamical explosion simulations. Here, only a minimal treatment of the nuclear reactions based on five species is employed that is sufficient to model the dynamically relevant energy release. Details of the nuclear reactions are inferred in a postprocessing step based on Lagrangian tracer particles advected with the flow in the hydrodynamical simulation [38,39]. The results of this nuclear postprocessing step are mapped into our radiative transfer code ARTIS [40]. Although the mapping procedure is non-trivial and still preliminary, the derived spectra (see right plot of Fig. 2) qualitatively resemble those observed for the SN Ia subclass of 2002cx-like events (of which SN 2005hk is used as an example here). This supports the idea that this subclass can be explained by deflagrations in WDs [41].

4.4. Delayed detonations

Pure deflagrations in Chandrasekhar-mass WDs clearly fail to reproduce normal SNe Ia. For those objects, stronger burning is required that leads to a more energetic explosion and an enhanced ^{56}Ni production is needed to account for the brightness of normal SNe Ia. Moreover, less mixing and a pronounced layer of intermediate-mass elements in the outer layers of the ejecta is expected to give results in better agreement with the observations [42].

In the Chandrasekhar-mass model, an enhancement of the burning is possible only if the flame strongly accelerates. This cannot be expected to result from turbulence (which would at the same time mix the ejecta in an unfavorable way). A transition to a detonation seems to be the only viable possibility. The *delayed detonation* scenario [43,44] assumes a transition of the flame propagation mode by the Zel'dovich gradient mechanism [45]. As opposed to the pure detonations discussed in Section 4.2, the material is not burned at the high initial densities in the delayed detonation scenario. Here, the detonation propagates through a pre-expanded star that is brought out of hydrostatic equilibrium by the preceding deflagration

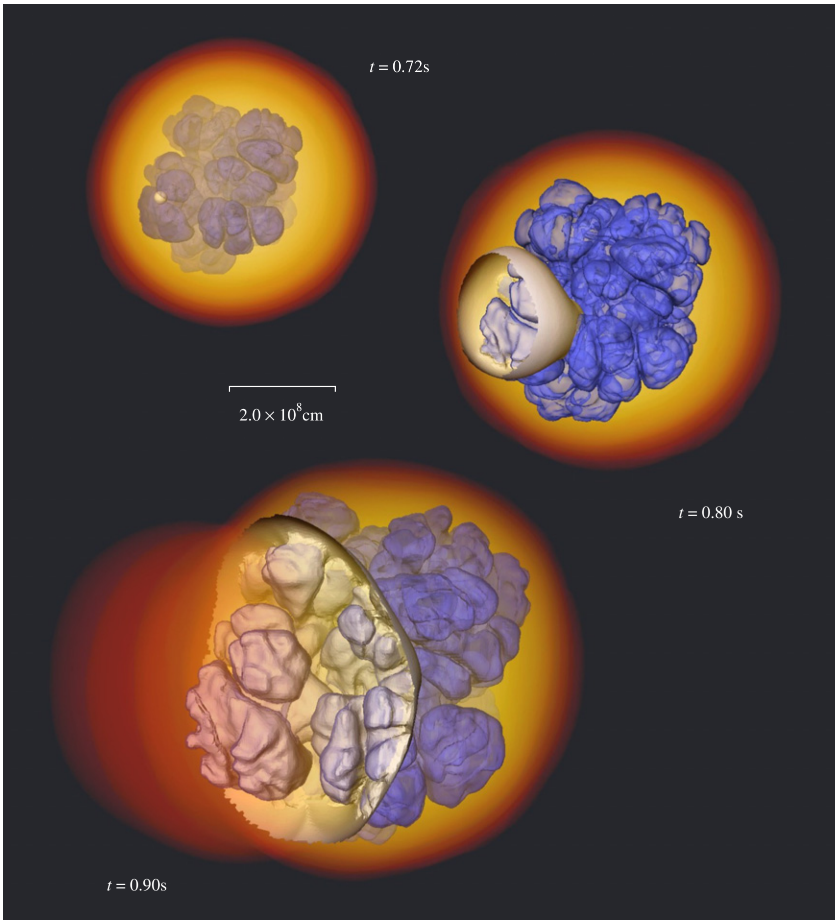

Fig. 3. Delayed detonation (from [52]). At $t = 0.72$ s the detonation (shown as the white isosurface) triggers. Subsequently it burns the remaining fuel wrapping around the ashes left behind from the initial deflagration.

phase. Thus, the detonation can produce a layer of intermediate-mass elements that encompasses almost all of the outer ejecta [46,47].

An open question, however, is whether or not such deflagration-to-detonation transitions (DDTs) occur in SNe Ia. Recent studies [48–50] indicate that they may be possible. Numerical simulations have been carried out in which the DDTs are parametrized. In one-dimensional models [51], a pre-defined transition density is assumed. Multi-dimensional simulations, however, allow for a physically better motivated parametrization taking into account the strength of turbulent velocity fluctuations. The triggering and propagation of the detonation is illustrated in Fig. 3 with snapshots from a three-dimensional delayed detonation simulation.

Light curves and spectra predicted from these events [53] match the observations reasonably well and even qualitatively reproduce the width–luminosity relation [17] that is used to calibrate SNe Ia as distance indicators in cosmology. With the chosen parametrization of the DDT, the models reproduce the range of luminosities observed for normal SNe Ia. Thus, the delayed detonation scenario holds promise for explaining the main characteristics of these events [54,46,47,55,56]. A potential problem for this scenario, however, is that some population synthesis studies predict too few realizations of progenitor systems able to form a Chandrasekhar-mass WD to be compatible with the observed rate of normal SNe Ia [57]. Moreover, the X-ray flux observed from elliptical galaxies is too low to allow for a sufficiently high number of hydrogen-accreting progenitors [58].

5. Non-Chandrasekhar-mass explosion models

5.1. He-accreting double-detonation sub-Chandrasekhar-mass models

In sub-Chandrasekhar double-detonation models, a C + O WD accretes helium from a binary companion (which may be a He-rich normal star or a He WD). Above the C + O core, a He layer builds up and when it becomes sufficiently massive, a detonation triggers by compression. This detonation burns the He layer and drives a shock wave into the core. If strong

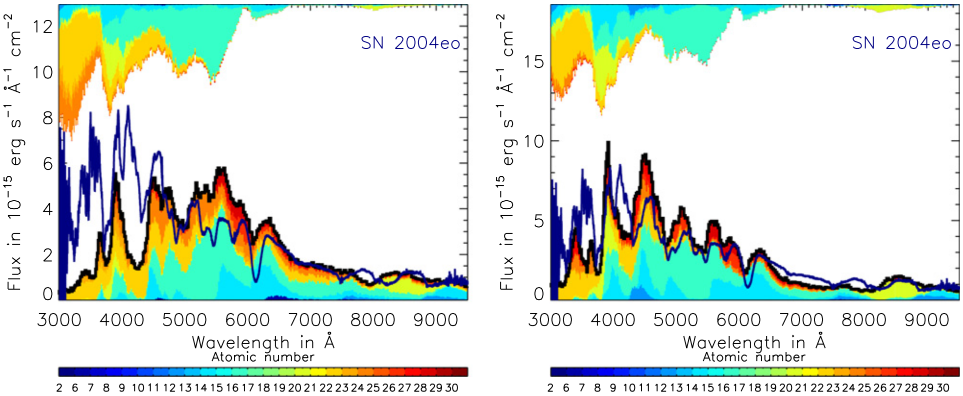

Fig. 4. Synthetic spectra around *B*-band maximum from a sub-$M_{\rm Ch}$ mass model ($M_{\rm core} = 1.025\,{\rm M}_\odot$, $M_{\rm shell} = 0.055\,{\rm M}_\odot$) compared to a spectrum from SN 2004eo at 3 days before *B*-band maximum. Left: pure He shell, right: He shell with 33% C admixture.

enough, the shock wave may initiate a secondary detonation in the C + O core (either at the interface between the core and the He shell or at the center of the core). Such sub-Chandrasekhar-mass models were studied in the 1990s [59,60] but have subsequently received little attention. Given the concerns raised by population synthesis calculations for Chandrasekhar-mass models, however, a reconsideration seems appropriate in the light of the significant improvements in simulation techniques since the first studies. From a population synthesis point of view, sub-Chandrasekhar-mass scenarios could perhaps even account for the bulk of normal SNe Ia [61].

Recent multi-dimensional simulations show that once the He shell detonates, the initiation of a core detonation is a very robust phenomenon. It is relatively independent of the He shell ignition geometry [62]. As in previous one-dimensional models, however, the nucleosynthesis expected from the detonation of a massive He shell above a C + O core is inconsistent with the observations [63–65]. This is mainly due to the fact that previous models predicted a substantial ^{56}Ni production in this layer. Recently, models with larger core masses (around $M_\odot$) have been studied – these have the advantage that a thin He shell may trigger a detonation [66]. Although the He shell detonation then does not produce significant amounts of ^{56}Ni, other iron-group isotopes are still synthesized [67] in multi-dimensional simulations (but see [68] for one-dimensional models still producing a significant ^{56}Ni fraction in the He shell ashes). In particular, absorption by Cr and Ti leads to strong flux redistribution towards the red parts of the spectrum making the models inconsistent with observations (see left plot of Fig. 4). This problem may be avoided if the He shell is polluted by carbon [65], for instance by instabilities in the accretion or by He burning prior to the onset of the detonation. A carbon enrichment reduces the mass number of alpha elements that can be synthesized and with a ∼33% admixture, the spectrum agrees much better with the observations (see right plot of Fig. 4).

Is the sub-Chandrasekhar-mass scenario a viable alternative to the delayed detonation model for explaining normal SNe Ia? If the effects of the He shell detonation products on the observables are neglected by considering toy models in which bare C + O cores were artificially detonated, the characteristics (and variations) of the observed sample of normal SNe Ia can be reproduced very well [69]. The strengths of the scenario are that it is not in conflict with predictions from population synthesis and that it provides a very simple, fundamental, and robust reason for the variability in brightness of normal SNe Ia: the mass of the exploding WD. Moreover, it also allows for a direct link of the supernova explosion models to progenitor properties, which is obscured in the Chandrasekhar-mass model. There, the progenitor properties are expected to have an impact on the ignition mechanism, but this effect is not theoretically understood.

5.2. Violent WD–WD mergers

A scenario for SNe Ia that is favored in some population synthesis calculations [57] is the merger of two carbon–oxygen white dwarfs [70,71]. WD binaries do exist in large numbers and they are in principle bound to merge due to the emission of gravitational waves; although in many cases the timescale for this to happen exceeds the Hubble time.

If the masses of the WDs are unequal, the merger proceeds in a very asymmetric way. The lighter star is disrupted by tidal forces and may form an accretion disk around the heavier companion. Such WD–WD mergers are not expected to lead to thermonuclear explosions but rather to the formation of a neutron star by burning from an initial C + O WD to an oxygen–neon WD and subsequent gravitational collapse [72]. The parameter space for WD–WD mergers, however, is rich and has not been fully explored.

A special case is the merger of nearly equal mass WDs. Due to the symmetry in the initial setup, a break-up of the lighter star is avoided. Instead, the stars merge violently within a few orbits. In the *violent merger scenario* [73], this leads to a thermonuclear explosion.

This scenario has been studied in numerical simulations using a modified version of the Smoothed Particle Hydrodynamics code Gadget [74]. During the inspiral, the two WDs are heavily deformed due to tidal interaction and finally plunge into each other. The inspiral and merger for two WDs of 0.9 $M_\odot$ each is shown in Fig. 5. When the two masses first

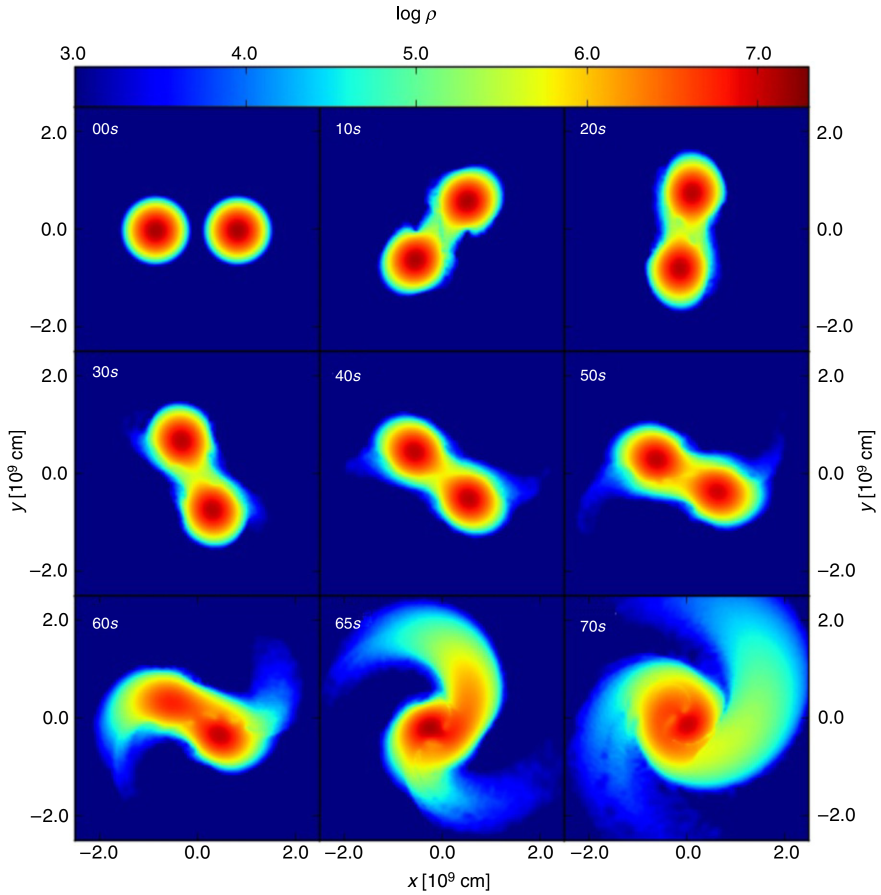

Fig. 5. Inspiral and merger of two 0.9 $M_\odot$ WDs.

touch, temperatures above 2.8×10^9 K are reached in material of $\rho = 3.8 \times 10^6$ g cm^{-3}. These conditions can be sufficient to trigger a detonation [75]. Since the formation of a detonation wave is not resolvable in our simulations, a detonation is *assumed* to trigger. We follow its propagation over the merged object by means of our grid-based hydrodynamic supernova code LEAFS. In this process, the merged object is completely disrupted. Given the masses of the two initial WDs, the total mass of the ejecta is above the Chandrasekhar mass. In contrast to the widespread assumption that super-Chandrasekhar-mass explosions were bright events, the ensuing event is in fact a faint supernova. Only very little mass has densities above the threshold for IGE production before being burned by the detonation. The amount of produced ^{56}Ni (powering the optical display by its radioactive decay) is only about 0.1 $M_\odot$. Light curves derived from the explosion model with the radiative transfer code ARTIS [40] are shown in Fig. 6. They are much fainter than the light curves of normal SNe Ia but compare favorably to those of SN 1991bg-like objects. For this sub-class of SNe Ia no theoretical model was previously available. *Violent WD–WD mergers* seem a promising option to explain them [73].

6. Conclusion

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 are analyzed in a model-independent way.

Nonetheless, the theoretical understanding of SNe Ia is still an open question. Although fundamental aspects of models (e.g. that SNe Ia arise from thermonuclear explosions of C + O WDs in binary systems) seem compelling, a level of accuracy is required from the models that challenges astrophysical theory and numerical modeling. Besides the complex explosion mechanism, the lack of observations of the progenitor systems is a serious obstacle to astrophysical modeling. 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.

Apart from pure detonations of Chandrasekhar-mass WDs it is difficult to rule out any of the explosion scenarios discussed here (pure turbulent deflagrations, delayed detonations, sub-Chandrasekhar-mass models, and violent mergers of two WDs)

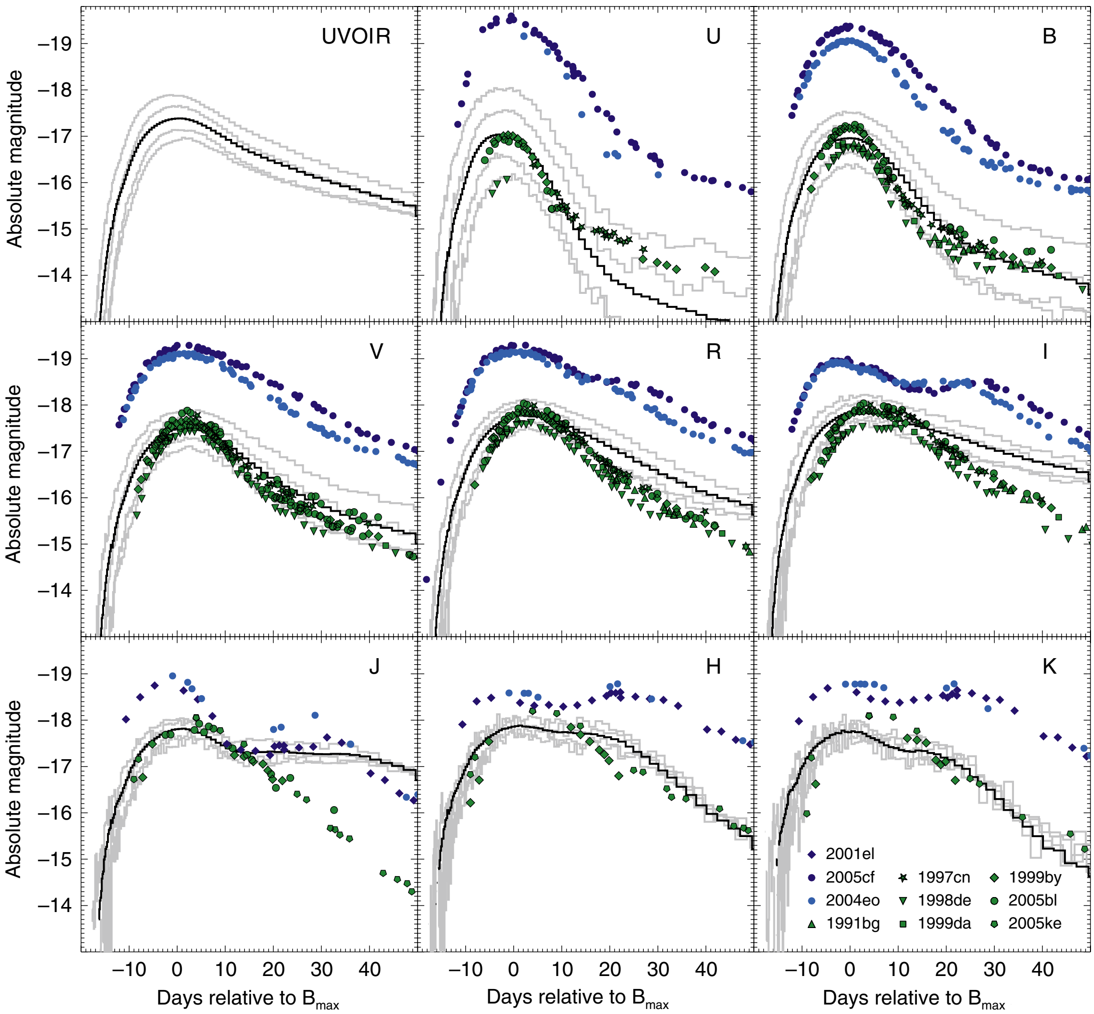

Fig. 6. Light curves predicted from the simulation of a violent merger of two 0.9 $M_{\odot}$ WDs. For each band, the gray light curves correspond to different viewing angles and the black curve represents the angle-average. For comparison, data from normal and sub-luminous SNe Ia are shown.

based on the predicted observables, although none of them matches the observations perfectly. This could imply that all the scenarios are indeed realized in Nature. However, it is also apparent that the observables around peak brightness are rather insensitive to the 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.

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