ON THE MECHANISM OF TYPE Ia SUPERNOVAE

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ABSTRACT

Type Ia supernovae (SNe Ia) are one of the major tools to determine the cosmological parameters. Utilizing them as distance indicators, it is possible to geometrically survey the universe. To this end, the intrinsic scatter in the luminosities of these events needs to be calibrated using empirical relations between observables. A theoretical explanation for these relations is still lacking and can only be provided by a sound understanding of the mechanism of SNe Ia. Recently there has been significant progress in modeling SNe Ia. We report on numerical simulations of the explosion process, compare the results with observations of nearby SNe Ia, and discuss current uncertainties of the models. The presented simulations shed some light on the origin of the diversity of SNe Ia. Such simulations will pave the way towards an understanding of SN Ia diversities and correlations of their properties and ultimately provide a tool to validate the cosmological implications of SN Ia distance measurements.

Key words: type Ia supernovae; numerical simulations; hydrodynamics; turbulence; radiative transport; cosmology.

1. INTRODUCTION

Almost 80 years after Einstein’s attempts to derive a cosmological model from his theory of General Relativity, subsequently introducing and discarding the cosmological constant, two cosmological surveys (Riess et al., 1998; Perlmutter et al., 1999) of the universe based on distance measurements of type Ia supernovae (SNe Ia) revolutionized the cosmological paradigm. They found that the Universe is currently in a phase of accelerated expansion. This revived the discussion of the cosmological constant. Independent determinations of cosmological parameters based on anisotropies in the Cosmic Microwave Background radiations and on large-scale galaxy surveys provided independent confirmation of the SN Ia measurements.

Yet the question of the applicability of SNe Ia as distance indicators is still not satisfactory answered. SNe Ia are remarkably uniform events by astrophysical standards, but evidently no standard candles. Only the calibration of the distance measurements according to empirical correlations between observables provides the necessary accuracy for the determination of cosmological parameters. A firm theoretical reasoning of such correlations is, however, still lacking.

It is still an open question whether the accelerated expansion of the Universe is caused by a simple cosmological constant or some more complicated constituent. Therefore one of the most fascinating problems of cosmology is to determine the equation of state of this “Dark Energy” component. SNe Ia may be a suitable tool for this task, but the accuracy of measurements required here can only be reached if systematical errors that may arise from calibration of the distance measurements are under control. A sound understanding of the physical mechanism of SNe Ia is inevitable in this project.

This poses a great challenge to SNe Ia theory since it requires self-consistent parameter-free modeling so that the predictive power of the models is sufficient to tackle questions of the origin of diversities and correlations.

Consequently, as a first step, an astrophysical model has to be built and implemented into a numerical simulation code. As will be explained below, the nature of relevant physical effects requires three-dimensional simulations. This approach is notably different from earlier one-dimensional SN Ia models which parametrized physical effects and therefore could be tuned to fit the observational data. Although this approach provided valuable hints to underlying physical effects, it cannot be used to constrain the correlations. Three-dimensional models have been implemented over the past years by different groups on the basis of different assumptions (e.g. Hillebrandt et al., 2000; Reinecke et al., 2002b; Gamezo et al., 2003; Calder et al., 2004). Most of them led to viable explosions and the task is now to compare the results of these simulations with observations of nearby SNe Ia. Once a model matching the observational requirements has been established, it can be used to ex-
explore the diversity arising from variations of physical parameters as suggested by progenitor evolution and environmental effects. The results of such a survey should then be analyzed to identify correlations in the characteristics. This may eventually provide a theoretical basis for distance measurement calibrations and a handle on possible systematical errors in those.

2. ASTROPHYSICAL MODEL

2.1. Progenitor evolution and ignition

The cornerstones of the astrophysical model of SNe Ia are set by two fundamental characteristics of these events. Evidently, SNe Ia belong to the most energetic cosmic explosions. For a short period of time they can outshine an entire galaxy consisting of tens of billions of stars. Assuming SNe Ia originate form single stellar objects, only their gravitational binding energy, released in a collapse towards a compact object, or its nuclear energy, released in explosive reactions, come into consideration as possible energy sources. In the particular case of SNe Ia no compact object is found in the remnant excluding the first possibility. The fact that no hydrogen is found in the spectra of SNe Ia provides a strong hint that the object undergoing the nuclear explosion may be a white dwarf (WD) star consisting of carbon and oxygen.

A simple WD, however, is an inert object and thus the only way to introduce the necessary dynamics into the system is to assume it to be part of a binary system. Here the WD accretes matter – in the favored scenario from a non-degenerate companion – until it approaches the Chandrasekhar mass (the maximum mass that is supported against gravitational collapse by the pressure of the degenerate electrons). At this point, the density at the center of the WD increases rapidly so that fusion of carbon ignites. This gives rise to a stage of convective burning at the center of the WD outwards and to determine the composition and the distribution of the burning products in the ejected material.

2.2. Flame propagation and explosion

The goal of SN Ia explosion models is to follow the propagation of the thermonuclear flame from its ignition near the center of the WD outwards and to determine the composition and the distribution of the burning products in the ejected material.

In principle, hydrodynamics allows for two different modes of flame propagation. One is the subsonic deflagration in which the flame is mediated by the thermal conduction of the degenerate electron gas and the other is a supersonic detonation in which the flame is driven by shock waves. Already the first attempts to simulate SNe Ia (Arnett 1969) revealed that a prompt detonation cannot explain these events since the full star would be incinerated with sound speed. All material would then be burnt at high densities and converted to iron group elements. Observed spectra of SNe Ia, however, clearly show indication for significant amounts of intermediate mass elements (like Si, Ca, S ...) in the ejecta. These can only be produced in the burning at lower densities and therefore the material needs to expand prior to incineration. This is provided if the flame propagation starts out as a slow deflagration. A laminar deflagration front, however, propagates too slowly to release sufficient energy to explode the WD star.

Thus, a key feature of a viable SN Ia model is the way of flame acceleration. For this, two effects are conceivable.

Firstly, the flame propagation from the center of the star outwards is buoyancy unstable, since it leaves behind light and hot ashes below the dense fuel – a density stratification inverse to the gravitational acceleration. In its non-linear stage, the Rayleigh-Taylor instability leads to the formation of mushroom-shaped burning bubbles raising into the fuel. The Reynolds number typical for this situation is as high as $10^{14}$. Clearly, shear (Kelvin-Helmholtz) instabilities at the interfaces of these bubbles will generate turbulent eddies which then decay to smaller scales forming a turbulent energy cascade. The flame will interact with these eddies down to the Gibson-scale at which the turbulent velocity fluctuations become comparable to the laminar flame speed. This interaction corrugates the flame increasing its surface and consequently enhances the net burning rate. Thus, the flame is significantly accelerated and three-dimensional simulations (e.g. Hillebrandt et al. 2004, Reinecke et al. 2002, Gamezo et al. 2003) show that this effect may indeed lead to an explosion of the WD. In this deflagration model, SN Ia explosions are a problem of turbulent combustion.

Secondly, a transition of the flame propagation mode from subsonic deflagration to supersonic detonation could provide an additional enhancement of the burning. However, a mechanism providing such a transition in a SN Ia explosion could not be found yet and is therefore hypothetical. It can only be introduced at hoc into a SN Ia model and is therefore free parameter – an effect that one would rather avoid in order to maintain the predictive
power of the model.

We will thus focus on the pure deflagration model in the following. After outlining the numerical implementation in Sect. 3 we will thus discuss the results from simulations and the question to which degree they meet observable constraints in Sect. 4.

3. NUMERICAL IMPLEMENTATION

3.1. Relevant scales

The numerical implementation of a deflagration SN Ia model is significantly complicated by the wide range of relevant length scales involved in the problem. From the radius of the WD star (∼2000 km at the onset of the explosion and expanding in the process) it reaches down to the flame width and the Kolmogorov scale at which the turbulent energy is dissipated – both well below one centimeter. Simulations capturing the entire star reach resolutions around one kilometer while the Gibson scale is of the order of 10^4 cm at the beginning of the explosion and decreases steadily.

For large-scale SN Ia simulations this has three consequences.

1. It is not possible to fully resolve the interaction of the flame with turbulence. Therefore modeling of the effects on unresolved scales is necessary.

2. The internal flame structure cannot be resolved. Complementary small scale simulations in one or more dimensions are required here.

3. Assumptions about the flame properties at unresolved scales (e.g. stability below the Gibson scale) have to be validated in separate small-scale simulations.

3.2. Numerical techniques

As obvious from the consideration of the relevant scales, a suitable approach to implement a SNe Ia deflagration model on scales of the WD is that of a Large Eddy Simulation (LES). It captures the effects of turbulent phenomena at the largest scales where energy is fed into the turbulent cascade and models turbulence on unresolved scales. The numerical techniques forming the foundation of the implementation of a deflagration SN Ia model described here are described in Reinecke et al. (1999b), Röpke (2005), Schmidt et al. (2005), and Niemeyer & Hillebrandt (1995).

The hydrodynamics on the resolved scales is modeled in a finite volume approach. It is based on the PROMETHEUS implementation (Fryxell et al. 1989) of the piecewise parabolic method (Colella & Woodward 1984).

As a consequence of 1 of the enumeration above, a subgrid-scale model is applied to account for turbulent effects on unresolved scales. Some older simulations follow the implementation suggested by Niemeyer & Hillebrandt (1995), while one recent highly resolved run applied the updated modeling approach of Schmidt et al. (2005).

According to 2 from above, the flame representation has to follow a modeling approach. Seen from the scales of the WD star, it appears as a sharp discontinuity separating the fuel from the ashes. A suitable numerical method to follow the evolution of such an interface is the level set technique introduced to SN Ia modeling by Reinecke et al. (1999a).

In such an implementation, the flame propagation speed needs to be prescribed. This is, however, not an arbitrary quantity in our modeling framework. For turbulent combustion in the flamelet regime, which applies to the burning in major parts of SN Ia explosions, it is given by the turbulent velocity fluctuations. These are determined by the subgrid-scale turbulence model.

Nuclear reactions are implemented in the simplified approach proposed by Reinecke et al. (2002a). The progenitor material is composed of 12C and 16O. At high fuel densities nuclear burning terminates in nuclear statistical equilibrium represented by a mixture of 56Ni and α-particles. Once the fuel density drops below 5.25 × 10^7 g cm^−3 burning will become incomplete and intermediate mass elements (represented by 24Mg) are produced. The respective differences in nuclear binding energy is released which provides sufficient accuracy to model the dynamics of the explosion.

However, in order to derive synthetic spectra and light curves from models, the accurate distribution of different chemical species in the ejecta needs to be determined. This is achieved in a postprocessing step which makes use of the temperature and density evolution recorded by tracer particles advected in the hydrodynamical explosion simulation. On the basis of this data, the details of the nuclear reactions in the ashes are reconstructed employing an extended nuclear reaction network (Travaglio et al. 2004).

4. SIMULATIONS VS. OBSERVATIONS

4.1. Explosion models and global characteristics

We will now review the status of deflagration SN Ia modeling with particular emphasis on the question how the results of such simulations compare with observations. Due to recent progress in such simulations, a direct comparison with details of observations of nearby SNe Ia has come into reach.
One requirement to reliably derive observables from simulations is that the evolution of the models be followed to the stage of homologous expansion. In this hydrodynamically relaxed situation, the velocity of the ejected material is proportional to its radius. The implementation of a moving computational grid on which the simulations are carried out facilitated the long-term evolution of expanding SN Ia models (Röpke, 2005).

Due to the high computational expenses, most three-dimensional simulations comprised only one spatial octant of the WD star, assuming mirror symmetry to the other octants. However, only full-star setups (such as presented by Röpke & Hillebrandt (2005)) allow to study asymmetry effects. On the basis of spectropolarimetry observations of several SNe Ia (e.g. Wang et al. 2003), these are expected to occur in at least some explosions. Röpke & Hillebrandt (2005) showed, that such asymmetries arise exclusively from asymmetries in the flame ignition conditions and not from large-scale instabilities and resulting preferred modes in the flow patterns. Therefore, fixing a symmetric initial flame shape and studying the influence of other physical parameters on single-octant explosion models is a valid approach.

The propagation of the thermonuclear flame through the WD is shown in Fig. 1. The snapshots are taken from a recent high-resolution simulation in which the flame was ignited in multiple sparks around the center of the star (cf. the left part of Fig. 1). It agrees with the expectations in the astrophysical scenario outlined in Sect. 2.2. After ignition, the Rayleigh-Taylor instability leads to the formation of mushroom-shaped burning bubbles on large scales which are subsequently superposed by smaller modes of the instability. The resulting flow quickly becomes turbulent and the flame is being corrugated. This is apparent in the second snapshot of Fig. 1. In this turbulent burning mode, the flame propagates through most parts of the star (cf. the third snapshot in Fig. 1). A powerful explosion of the WD star results in this simulation.

Figure 1. Snapshots from a high-resolved SN Ia simulation starting from a multi-spot ignition scenario. The logarithm of the density is volume rendered indicating the extend of the WD star and the isosurface corresponds to the thermonuclear flame.

Naturally, the question arises if the outcome of simulations as the one described above meets the observational constraints. Such constraints arise from the global characteristics derived from observations, observed light curves, and spectra taken from nearby SNe Ia.

The global characteristics derived from SN Ia observations state that a valid explosion model should release around $10^{51}$ erg of energy and produce $\sim 0.4 \ldots 0.7 M_\odot$ of $^{56}$Ni in the nuclear burning. However, there exists a large diversity in the observations ranging from the class of sub-luminous SNe Ia (like SN 1991bg) to super-luminous events (e.g. SN 1991T). Our deflagration models started with a multi-spot ignition setup typically possess $7 \ldots 8 \times 10^{50}$ erg of asymptotic kinetic energy of the ejecta. They produce around $0.4 M_\odot$ of $^{56}$Ni. Thus they fall into the range of observational expectations, but in the current stage do not account for the more energetic SNe Ia.

4.2. Lightcurves

A further requirement is that synthetic lightcurves agree with observed ones. These are sensitive to the energy release, the $^{56}$Ni production, as well as to the distribution of elements in the ejecta. In Fig. 2 we compare synthetic light curves derived from the $2.2.2$ simulation (Röpke et al. 2005) with observations of SN 1994D. The multi-band light curve of this model was calculated using the STELLA code of Blinnikov et al. (1998) and Blinnikov & Sorokina (2000).

The distance to SN 1994D is still controversial. We have assumed the distance modulus 30.4 from Drenkhahn & Richtler (1999).

The model produced 0.3 $M_\odot$ of $^{56}$Ni, although observations require a bit higher $^{56}$Ni mass ($\sim 0.4 M_\odot$) for the assumed distance. There is generally very good agreement in the B and V bands near peak luminosities and in
Figure 2. Synthetic light curves derived from model 2.2.2 of Röpke et al. (2005) (solid curves) compared with observed light curves from SN 1994D.

The decline rate 20 days after the peak which is most important for cosmological applications of type Ia supernovae.

4.3. Spectra

A much harder test for the models is posed by the comparison of synthetic with observed spectra since these depend on details in the composition of the ejected material.

Nebular spectra provide a means of studying the central parts of the ejecta, since they are taken at epochs where these have become transparent due to expansion. Thus they explore the “heart of the explosion” and are a valuable tool to study details of the physical processes involved in the explosion stage. Unfortunately, only one single synthetic late time spectrum is available from our deflagration SN Ia models (Kozma et al., 2005). It was derived from a run that was intended to test the implementation of the moving grid and is not believed to provide a realistic SN Ia model. The flame was ignited in an axisymmetric shape where a sphere around the center of the WD star was perturbed by a toroidal structure of large wavelength and amplitude. This artificial and simple initial flame shape gives reason to not expect a good agreement between model and observation. However, as shown in Fig. 3 the broad iron features of the observed spectra are qualitatively reproduced. An inconsistency of the model with the observed nebular spectra is the appearance of a pronounced oxygen line at 6300 Å. Both features of the synthetic spectrum share a common origin. The broad iron lines are caused by NSE material that is transported in the uprising plumes of ashes and thus distributed in velocity space. At the same time strong downdrafts carry unburnt material towards the center of the WD.

The disagreement may in part be attributed to the simplicity of the explosion model. Its highly symmetric initial flame shape with large imprinted perturbations favor a pronounced evolution of large-scale Rayleigh-Taylor features. To answer the question whether the unburnt material at low velocities is a generic problem in the deflagration model of SNe Ia, the high-resolved simulations mentioned above was carried out. The finer structure of the turbulent flame in this simulation together with improved flame modeling led to a better burnout of the downdrafts. Much less unburnt material is found at low velocities in this model.

A powerful diagnostic tool to compare SN Ia models with observations is provided by the abundance tomography presented by Stehle et al. (2005). It makes use of spectra taken from SN 2002bo with an extraordinary good time coverage. Fitting this sequence of data with synthetic spectra unveils the composition of the ejecta in velocity space slice by slice, since the photosphere moves gradually inwards with the expansion of the remnant. This abundance tomography of the ejecta can be compared with results of our three-dimensional models, when averaged over the angles. Qualitatively, the mixed composition of the ejecta found by Stehle et al. (2005) is reproduced by deflagration SN Ia models in a natural way since these predict a distribution of burnt material with the rising bubbles. A problem was, however, that older predicted large unburnt material fractions in the central parts of the ejecta in disagreement with the results of Stehle et al. (2005). Our recent high-resolved simulation cures this problem by clearly reproducing the iron-group dominance in the low-velocity ejecta. The results are currently being analyzed and seem promising for matching the observations.

Figure 3. Synthetic nebular spectrum compared with observations (from Kozma et al. 2005).
Table 1. Variation of initial parameters in SN Ia explosion models.

| Parameter | range of variation | effect on $^{56}$Ni production | effect on total energy |
|-----------|--------------------|---------------------------------|-----------------------|
| $X(^{12}$C) | [0.30,0.62] | $\leq 2\%$ | $\sim 14\%$ |
| $\rho_c$ [10$^9$ g/cm$^3$] | [1.0,2.6] | $\sim 6\%$ | $\sim 17\%$ |
| $Z[Z_\odot]$ | [0.5,3.0] | $\sim 20\%$ | none |

5. DIVERSITY AND CORRELATIONS

The recent developments in the deflagration SN Ia explosion modeling outlined in the previous section seem to indicate that such a model is capable of reproducing the main features of observed objects. They do not rule out the alternative of a delayed detonation. The success of the pure deflagration model, however, may be taken as evidence that this stage provides at least a major contribution to the explosion process and general properties will not be changed much by a hypothetical deflagration-to-detonation transition.

It is therefore an important question to ask how such a model behaves under variation of physical parameters. Does it reproduce the observed diversity of SNe Ia? Are correlations between observables evident in the results?

Unfortunately, three-dimensional deflagration models of SNe Ia as described above are computationally expensive. To moderate these expenses, simplified setups may be used to study effects of physical parameters on the explosion models. Such an approach was recently taken by Röpke et al. (2005) and resulted in the first systematic study of progenitor parameters in three-dimensional models. The basis of this study was a single-octant setup with moderate (yet numerically converged) resolution. However, the lack in resolution did not allow a reasonable multi-spot ignition scenario and thus only weak explosions could be expected. It is therefore not possible to set the absolute scale of effects in this approach, but trends can clearly be identified.

The parameters chosen for the study were the WD’s carbon-to-oxygen ratio, its central density at ignition and its $^{22}$Ne mass fraction resulting from the metallicity of the progenitor. All parameters were varied independently to study the individual effects on the explosion process. In a realistic scenario, however, these parameters are interrelated by the evolution of the progenitor binary system. The results of this survey are given in Tab. 1.

A variation of the carbon-to-oxygen ratio effects the energy production in the burning due to the differences in the binding energies of these two nuclei. Counterintuitively, this results in no significant change in the $^{56}$Ni production. Röpke & Hillebrandt (2004) explained this effect by the fact that the potentially higher energy release in carbon-rich models is buffered by a higher $\alpha$-particle fraction in the NSE and only released when burning is already incomplete.

Models with lower central densities show a delayed flame evolution and consequently a lower and delayed energy production. This is due to the fact that the flame experiences a lower gravitational acceleration in these models resulting in decreased turbulence generation. Therefore less $^{56}$Ni is produced in these models. This effect is even more pronounced due to the fact that in low-density WDs less material is present at sufficient densities to be potentially burnt to NSE. A counteractive effect is expected at higher densities. Here, electron captures will become important favoring neutron-rich isotopes over $^{56}$Ni in the NSE. The dynamical effects of electron captures are, however, not yet implemented in our explosion model and therefore the current survey is restricted to relatively low central densities.

The metallicity of the progenitor star results in a certain $^{22}$Ne mass fraction in the WD. This is an isotope with neutron excess and therefore again favors the production of neutron-rich species over $^{56}$Ni in the NSE. Our results confirm the analytic prediction by Timmes et al. (2003) and agree with Travaglio et al. (2003). The metallicity parameter, however, has no effect on the explosion dynamics and the energy production in our models.

To determine the effects of these variations on observables, synthetic light curves were derived from all models (an example is shown in Fig. 2). From these, the peak luminosities and decline rates (in magnitudes 15 days after maximum; $\Delta m_{15}$), were determined. The pioneering work by Phillips (1993) established the relation between the peak luminosity and $\Delta m_{15}$ as one of the primary tools to calibrate cosmological SN Ia distance measurements. The so-called Phillips relation quantifies the decrease of $\Delta m_{15}$ for brighter SNe Ia.

The results from our models are compared with the relation given by Phillips et al. (1999) in Fig. 4. Obviously, the absolute magnitude of the Phillips et al. (1999) relation is not met by our set of models (cf. the upper panel of Fig. 4). Moreover, the range of scatter in $\Delta m_{15}$ is much narrower than that of the set of observations used by Phillips et al. (1999). The trend of our models is not clear. They are best fit by a line with a slope consistent with the Phillips et al. (1999) relation. It is, however, obvious, that a better agreement cannot be expected given the fact, that the parameters in our survey were chosen independently. A consistent stellar evolution would pick a sub-sample of our set of models and it will be investigated in forthcoming studies whether this will be in agreement with the Phillips relation.

Nonetheless, with our set of models, the question can be answered, which parameter dominates the slope in the direction of dimmer events for faster decline rates. The varied parameters are coded by different line styles in the lower panel of Fig. 4. Clearly, the progenitor’s metallic-
basis of comparison of these results with observations, the conclusion is drawn, that pure deflagration models are at least capable of reproducing the gross features of observed SNe Ia.

Such models therefore can be applied to study the origin of the diversity of SNe Ia. In a first systematic survey of initial parameters of three-dimensional models, the effects of the WD’s carbon-to-oxygen ratio, its central density and the progenitor’s metallicity on the explosion process were analyzed. Although this was only possible on the basis of simplified and therefore weakly exploding models, clear trends could be identified.

From this set of models, synthetic light curves were derived. The relation between the peak-luminosities and the decline rates of the light curves were found to be consistent with the slope predicted by Phillips et al. (1999). Due to the simplicity of the applied models, the absolute magnitude of effects could not be predicted.

Forthcoming studies will focus on the questions how a realistic stellar evolution of the progenitor interrelates the effects. A second important question is whether the range of scatter predicted by the observations can be reproduced with more elaborate models. Although it captures main aspects of observations, it may be possible that the applied SN Ia model is still incomplete and additional physical effects (like delayed detonations) need to be taken into account.

6. CONCLUSIONS

We discussed the mechanism of SN Ia explosions and reviewed the common astrophysical scenarios applied to explain these events. The implementation of such models into numerical simulations was described focusing on the pure deflagration model for SNe Ia. Subsequently, recent progress in numerical simulations was reported. On the

Figure 4. Peak luminosity vs. decline rate of the light curve in the B band (diamonds correspond to SN Ia explosion models). Compared with original relation by Phillips et al. (1999) (dashed curve) and shifted relation (solid curve) in the top panel.

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