Modeling Type Ia supernovae with explosions in white dwarfs near and below the Chandrasekhar mass

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The progenitor evolution and the explosion mechanism of Type Ia supernovae remain unexplained. Nonetheless, substantial progress has been made over the past years with three-dimensional hydrodynamic simulations of different scenarios. Here, we review some recent work pertaining to the leading paradigms of modeling: thermonuclear explosions of white dwarf stars near and below the Chandrasekhar mass limit. We discuss implications of the different explosion channels and their predictions of observables.

Keywords: Type Ia supernovae, thermonuclear explosions, white dwarf stars, numerical simulations

1. Introduction

Despite substantial progress in theoretical modeling and numerical simulations over the past years,[1] our understanding of the physical mechanism of Type Ia supernovae remains incomplete. This has two main reasons. (i) The progenitor systems from which these explosions arise have not been identified, and therefore the initial conditions for the explosion simulations are uncertain. (ii) Modeling the explosion stage itself is a severe multi-scale multi-physics challenge and relies on assumptions and approximations. Some of these approximations could be mitigated with multi-dimensional hydrodynamical simulations. They form a cornerstone of a consistent modeling pipeline that follows a progenitor model over explosion and nucleosynthesis to the formation of observables. By avoiding tunable parameters, such a modeling pipeline facilitates a direct comparison of model predictions with astronomical data.

This allows for conclusions to be drawn on the validity of the assumed progenitor scenarios. In the following, we describe the application of this modeling pipeline to two different explosion scenarios.

2. Explosion models

Ignoring the fascinating but complex and still enigmatic evolution of progenitor systems of Type Ia supernovae, the main question to simulations is how to set up the state of the white dwarf at the onset of explosion. The two fundamental choices, a configuration close to the limit of stability, the Chandrasekhar mass, and a white dwarf below that mass limit, imply different explosion scenarios.[2] The compact structure of a near-Chandrasekhar mass object causes high densities of the material ahead of the thermonuclear burning front[3] if it propagates as a supersonic detonation. The products of such an explosion, almost exclusively iron group elements, are inconsistent with observations of Type Ia supernova. To produce the required intermediate mass elements detected in their spectra, burning has to start out as a subsonic deflagration in a white dwarf close to the Chandrasekhar mass. After some time of pre-expansion of the star, the burning front may turn into a supersonic detonation. In a sub-Chandrasekhar mass white dwarf, in contrast, the densities are lower and allow for the required intermediate-mass elements to be produced in a detonation.

For both scenarios, the actual ignition of the burning remains uncertain and is difficult to resolve in multidimensional hydrodynamic simulations.[4] Therefore, simulations often start out with an assumption on the triggering of the explosive burning.

3. Near-Chandrasekhar mass explosions

Sets of simulations have been carried out to test the impact of initial parameters on the outcome of explosions in near-Chandrasekhar mass white dwarf stars. Testing the ignition configuration[5] revealed that the number and spatial distribution of ignition sparks is the most important parameter for the strength of the deflagration. Few and asymmetrically distributed sparks lead to an incomplete disruption of the white dwarf. With very many ignition kernels (that are less likely to be realized in nature[4,6]), a complete unbinding of the star becomes possible, but the mass of ^{56}Ni produced is too low to explain the brighness of normal Type Ia supernovae. A detonation may form later and enhance the thermonuclear burning,[7] but here we restrict our discussion to cases where the flame propagation remains subsonic throughout.

Pure deflagrations in near-Chandrasekhar mass white dwarfs have been discussed as a model for the subclass of Type Iax supernovae.[8] An open question, however, remains: Can deflagrations in Chandrasekhar-mass white dwarfs cover the entire range of objects in this class, including the very faint events? To explore this, we have carried out an extended systematic study of three-dimensional hydrodynamic explosion simulations[9] varying the distance of single-spark ignitions from the stellar center, but also other parameters such as the central density of the white dwarf at the onset of explosion, its metallicity, its carbon mass fraction, and its rotation state. This suite of models shows that it it well possible to decrease the ^{56}Ni production and thus the brightness of the modeled events to values that would match the faintest members of the Type Iax supernova class. However, inconsistencies were discovered, too. The faint events evolve to quickly in brightness. All models fall onto a strong correlation between the produced ^{56}Ni mass and the total eject mass. This correlation does not match observations and none of the initial parameters was able to perturb it significantly. For the brighter models, however, reasonable matches with observations were found. Previous claims of chemically layered ejecta structures[10] based on the "abundance tomography" method contradict the picture of Type Iax supernovae originating from deflagrations in Chandrasekhar-mass white dwarfs. Because of the intrinsic instabilities of subsonic flame propagation, such a scenario would predict well-mixed ejecta. Recent forward-modeling,[11] however, finds that the predictions of such models may still be consistent with observations.

Improvements in explosion modeling and – in particular – in the treatment of non local thermodynamic equilibrium (NLTE) effects in the radiation transfer calculations are needed to settle the question of whether deflagrations in Chandrasekhar-mass white dwarfs can explain at least the brighter Type Iax supernovae. Given the failure to model the faint events in this framework, it seems possible that not all members of the observationally-defined class of Type Iax supernovae pertain to the same physical explosion mechanism.

4. Sub-Chandrasekhar mass explosions

Explosions of white dwarf stars below the Chandrasekhar mass are an appealing model because they seem to reproduce important observational trends.[12] The question, however, is how such inert objects trigger a detonation. A classical model is that of double detonations: A helium shell is accreted on top of a carbon-oxygen white dwarf. Once massive enough, it triggers a shell detonation that initiates a secondary detonation of the carbon-oxygen core. If the helium shell is not too massive, its products do not strongly impact the observables and the match with data from normal Type Ia supernovae improves.[13–16]

We have recently explored the mechanism of triggering of the secondary core detonation and the impact of the shell detonation products on predicted observables in an extended sequence of three-dimensional hydrodynamic simulations.[17–19] This study identifies different possibilities for the core detonation initiation depending on the mass of the helium shell and the carbon-oxygen core. Although a reasonable match is obtained in the predicted observables with observational data, some shortcomings remain. These include too red spectra and too wide variations of the lightcurve width-luminosity relation with viewing angle. Some of these deficiencies can be attributed to approximations in the treatment of NLTE effects in radiation transport,[16] but the mismatches may also call into question the explosion model itself.

5. Imprints on nucleosynthesis yields

Apart from comparing to optical observables, another approach to discriminate between and assess the validity of Type Ia supernova explosion models is by their imprints on the nucleosynthesis yields.[20] An important difference between near- and sub-Chandrasekhar mass explosion models is the production of manganese.[21] In explosive carbon burning, it can only be produced in (super-)solar ratio to iron if the densities are sufficiently high to allow for normal freeze-out from nuclear statistical equilibrium. This is the case for explosive burning in the cores of Chandrasekhar-mass white dwarfs. Alpha-rich freezeout, as occurring at lower densities in explosions of sub-Chandrasekhar mass objects, destroys the mother nucleus of ^{55}Mn, ^{55}Co, by proton captures. This produces additional ^{56}Ni at the expense of manganese. Therefore, it was concluded that a substantial fraction of Type Ia supernovae has to originate from the Chandrasekhar-mass explosion channel so that these objects can drive the manganese-over-iron trend in galactic chemical evolution towards the solar value. Our new double-detonation sub-Chandrasekhar mass explosion models,[19,20] however, show that additional manganese can be produced in the helium shell detonation. This lowers the fraction of Chandrasekhar-mass models needed to explain the galactic chemical evolution of manganese.

6. Conclusions

Three-dimensional hydrodynamic simulations help to avoid tunable parameters in the modeling of different explosion scenarios for Type Ia supernovae. The optical observables derived from such models via nucleosynthesis postprocessing[22] and radiative transfer calculations can be exposed directly to observational data. For the time being, however, the discriminative power of this approach is insufficient to identify a valid model for normal Type Ia supernovae. All considered scenarios have some advantages and some shortcomings. The reason may simply be that the correct scenario has not yet been found. Sub-Chandrasekhar mass explosions are a promising model, but in the double detonation mechanism they still fail to match some important observational properties of Type Ia supernovae. Similar explosions can, however, also be triggered by mergers of two white dwarfs.[23–26]

A similar situation is encountered with deflagrations in near-Chandrasekhar mass white dwarf stars. While this model looks promising for explaining brighter members of the Type Iax supernova class, its fainter end cannot be reproduced.

To ultimately settle the question of the origin of Type Ia supernovae, constant improvement is required in the explosion modeling as well as in the treatment of radiative transfer predicting the optical observables. Alternative observables that may help to discriminate between models include the nucleosynthesis yields discussed here, but also spectropolarimetry data,[27–29] the search for surviving companion stars in the double degenerate progenitor model[30] and imprints of different explosion scenarios on the forming supernova remnants.[31,32]

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