Highlights of Astronomy, Volume 14
IAU XXVI General Assembly, 14-25 August 2006
Karel A. van der Hucht, ed.

doi:10.1017/S1743921307010769

On the road to consistent Type Ia supernova explosion models

Friedrich K. Röpke[1,2]

[1]Department of Astronomy and Astrophysics, University of California Santa Cruz,
1156 High Street, Santa Cruz, CA 95064, USA
[2]Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany
email: fritz@mpa-garching.mpg.de

Abstract. Keeping up with ever more detailed observations, Type Ia supernova (SN Ia) explosion models have seen a brisk development over the past years. The aim is to construct a self-consistent picture of the physical processes in order to gain the predictive power necessary to answer questions arising from the application of SNe Ia as cosmological distance indicators. We review recent developments in modeling these objects focusing on three-dimensional simulations.

Keywords. supernovae: general, hydrodynamics, methods: numerical

---

Despite the importance of SNe Ia for astrophysics and cosmology, a fully consistent description of the explosion mechanism is still lacking. Yet several ideas exist (Hillebrandt & Niemeyer 2000), and the interplay of modeling and observation has helped to shape a picture of the thermonuclear explosions of the progenitor C+O white dwarfs. Recent work has focused on modeling the single-degenerate Chandrasekhar-mass scenario. Here, the white dwarf commences nuclear burning as it approaches the limiting Chandrasekhar mass due to accretion from a non-degenerate binary companion. After about a century of convective carbon burning, a thermonuclear runaway leads to the formation of a flame near the star's center. It propagates outward giving rise to the explosion.

Hydrodynamically, two modes of flame propagation are admissible – a sub-sonic deflagration and a supersonic detonation. These two burning modes provide different options when building an explosion model. The signature of intermediate-mass elements in the spectra rules out a prompt detonation as a valid SN Ia model (Arnett 1969). Thus, the thermonuclear flame has to start out as a deflagration (Nomoto *et al.* 1976). Since laminar flame propagation is far too slow to explode the star, flame acceleration is the key issue of all models. The subsonic deflagration flame is subject to buoyancy and shear instabilities and strong turbulence is expected to be generated. The interaction of the flame propagation with turbulence provides an efficient way of accelerating its propagation.

This phenomenon has been studied in detail over the past years in elaborate three-dimensional numerical simulations (Reinecke *et al.* 2002; Gamezo *et al.* 2003; Röpke *et al.* 2005, 2006; Schmidt & Niemeyer 2006). In a Large Eddy Simulation approach, it is possible to implement a self-consistent model of the turbulent flame propagation (Reinecke *et al.* 1999). In such simulations, explosions were found that seem capable of reproducing gross features of observed SNe Ia (e.g., Blinnikov *et al.* 2006).

However, it seems unlikely that the turbulent deflagration model can cover the full sample of SNe Ia. The ultimate way of accelerating the thermonuclear burning would be a transition of the deflagration flame propagation mode to a supersonic detonation. The problems of this 'delayed detonation' model (Khokhlov 1991) arise from the unknown mechanism of the deflagration-to-detonation transition (DDT), and potentially from the fact that a detonation wave cannot cross ash regions (Maier & Niemeyer 2006).

Thus, it has to propagate around the complex deflagration structure and may not be capable of burning out pockets of fuel. Moreover, if ignited off-center, it has to compete with the expansion of the star, diluting the fuel, and may not reach the far side of the deflagration structure. These issues can be tested with multi-dimensional simulations parametrizing the DDT (Gamezo *et al.* 2005; Golombek & Niemeyer 2005).

Apart from the DDT, a major uncertainty of the explosion models is the configuration of the igniting flame. The ignition process is hard to address both analytically and numerically. Most of the simulations assumed a central ignition, but recent studies indicated that an asymmetric, off-center ignition may be possible (Kuhlen *et al.* 2006).

As a consequence, less material would be consumed and the nuclear energy release may not be sufficient to gravitationally unbind the white dwarf. A failure to explode the star results in gravitationally bound ashes erupting from the surface, sweeping around a core consisting of fuel and colliding on the far side of the star. Plewa *et al.* (2004) suggested that the compression of fuel in the collision region may be sufficient to trigger a detonation which would then burn the remaining fuel and give rise to a supernova explosion ('Gravitationally Confined Detonation' scenario). However, in a recent parameter study Röpke *et al.* (2007) showed that the conditions in the compressed region may not allow for a spontaneous detonation in realistic models. The bound configuration will then start to pulsate – a second chance to trigger a detonation that needs further investigation (Arnett & Livne 1994; Bravo & García-Senz 2006).

We conclude that the two major uncertainties in modeling SN Ia explosions – the DDT and the flame ignition – admit different scenarios that can be explored in large-scale three dimensional simulations. An evaluation of the scenarios needs to be carried out on the basis of comparison with observations (e.g., Kozma *et al.* 2005). At the same time, the physical processes underlying the DDT and the flame ignition need to be explored in separate numerical approaches.

References

Arnett, W. D. 1969, *Ap&SS*, 5, 180
Arnett, D., & Livne, E. 1994, *ApJ*, 427, 330
Blinnikov, S. I., Röpke, F. K., Sorokina, E. I., Gieseler, M., Reinecke, M., Travaglio, C., Hillebrandt, W. & Stritzinger, M. 2006, *A&A*, 453, 229
Bravo, E., & García-Senz, D. 2006, *ApJ* (Letters), 642, L157
Gamezo, V. N., Khokhlov, A. M., Oran, E. S., Chtchelkanova, A. Y. & Rosenberg, R. O. 2003, *Science*, 299, 77
Gamezo, V. N., Khokhlov, A. M. & Oran, E. S. 2005, *ApJ*, 623, 337
Golombek, I., & Niemeyer, J. C. 2005, *A&A*, 438, 611
Hillebrandt, W., & Niemeyer, J. C. 2000, *ARAA*, 38, 191
Khokhlov, A. M. 1991, *A&A*, 245, 114
Kozma, C., Fransson, C., Hillebrandt, W., Travaglio, C., Sollerman, J., Reinecke, M., Röpke, F. K., & Spyromilio, J. 2005, *A&A*, 437, 983
Kuhlen, M., Woosley, S. E., & Glatzmaier, G. A. 2006, *ApJ*, 640, 407
Maier, A., & Niemeyer, J. C. 2006, *A&A*, 451, 207
Nomoto, K., Sugimoto, D., & Neo, S. 1976, *Ap&SS* (Letters), 39, L37
Plewa, T., Calder, A. C. & Lamb, D. Q 2004, *ApJ*(Letters) , 612, L37
Reinecke, M., Hillebrandt, W., & Niemeyer, J. C. 2002, *A&A*, 391, 1167
Reinecke, M., Hillebrandt, W., Niemeyer, J. C., Klein, R., & Gröbl, A. 1999, *A&A*, 347, 724
Röpke, F. K., & Hillebrandt, W. 2005, *A&A*, 431, 635
Röpke, F. K., Hillebrandt, W., Niemeyer, J. C., & Woosley, S. E. 2006, *A&A*, 448, 1
Röpke, F. K., Woosley, S. E., & Hillebrandt, W. 2007, *ApJ*, 660, 1344
Schmidt, W., & Niemeyer, J. C. 2006, *A&A*, 446, 627