Final Report for FG02-08ER41570

Making the Standard Candle: A study of how the progenitor white dwarf modulates the peak luminosity of type Ia supernovae

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1 Progress toward the Research Goals

The goals of the proposed research as stated in the proposal were

- Build a suite of one-dimensional initial models of different metallicities and central densities.
- Using the improved flame capturing scheme, simulate the explosion of a white dwarf with embedded Lagrangian tracer particles, and post-process the thermal histories of the tracers to reconstruct the nucleosynthesis of the explosion.
- Survey the effects of a changing progenitor metallicity on the isotopic yields. Of particular interest is 1) whether the linear relation between the mass of ^{56}Ni synthesized and the progenitor metallicity is moderated by the effect of electron captures in the core; and 2) how a varying central density alters the relation between metallicity and ^{56}Ni mass.
- Using these results, examine how the observed metallicity distribution would affect the brightness distribution of SNe Ia and the isotopic ratios about the Fe-peak.

The collaboration was funded under awards to Stony Brook University (DE-FG02-07ER41516, $78,516), Michigan State University (DE-FG02-08ER41570, $30,249), and Arizona State University (DE-FG02-08ER41565, $29,564). The work described in this report was performed with a collaborator, Dean Townsley, at the University of Arizona. In brief, we made progress toward the goals stated above by developing much of the computational technology necessary for the simulations. While we have not fully met the goals, the funding enable the collaboration to continue, served to train two students, and enabled the development of the simulation code required for the simulations that will meet these goals.

2 Accomplishments

Investigator Timmes collaborated with investigator Brown and MSU graduate student David Chamulak to study how reactions during the pre-explosive convective burning reduced the electron abundance of the white dwarf. In addition to the intrinsic electron fraction, Y_e, set by the composition of the progenitor white dwarf, during the simmering a small fraction ($\approx$ few %) of the ^{12}C is consumed. Protons produced via the $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$ capture onto ^{12}C making ^{13}N, which then electron captures to ^{13}C. This, along with the reaction $^{23}\mathrm{Na}(e^-,\nu)^{23}\mathrm{Ne}$, decreases Y_e. There are roughly 2 electron captures for every 6 ^{12}C nuclei consumed, giving $dY_e/dY_{12} \approx \frac{1}{3}$ (Fig. 1).

Using a self-heating reaction network, they demonstrated that electron captures on ^{13}N consume approximately one electron for every 6 ^{12}C nuclei consumed. This work confirms the findings of Piro and Bildsten [2], who studied this effect independently. As a result, there is a maximum electron abundance in the white dwarf at the time of the explosion, and this maximum is set by the amount of carbon consumed prior to ignition. This neutronization is sufficient to obscure a correlation between peak brightness and metalicity for progenitors with sub-solar metalicity. A paper on this finding has been submitted [1]. Funding from this award was specifically used in calculating

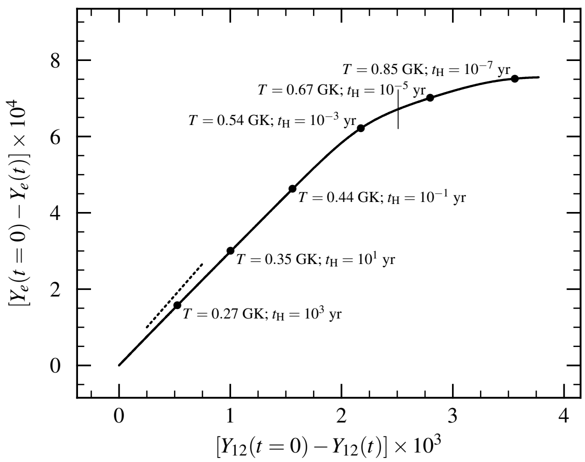

Figure 1: The change in electron abundance, $Y_e(t = 0) - Y_e(t)$, as a function of carbon consumed, $Y_{12}(t = 0) - Y_{12}(t)$. The break in the slope, at $Y_{12}(0) - Y_{12} \approx 2 \times 10^{-3}$, occurs when the heating timescale $t_H = C_P/\varepsilon$ becomes less than the timescale for electron capture onto ^{23}Na, which is ≈ 2700 s at $\rho = 3.0 \times 10^9\ \mathrm{g\,cm^{-3}}$. We indicate this point with the thin vertical line. To guide the eye, the short dotted line indicates a slope of $\frac{1}{3}$. From [1].

the effective heating rate per ^{12}C + ^{12}C reaction from the reaction chain described above. This calculation included a new determination of the $^{13}\mathrm{N}(e^-, \nu_e)^{13}\mathrm{C}$ rate [3].

Investigator Calder and students Aaron Jackson and Brendan Krueger performed suites of two-dimensional simulations investigating the role of physical parameters on the explosion dynamics. The suite consists of one-dimensional parametrized progenitor white dwarf models with multiple two-dimensional realizations drawn from each. As described in Townsley et al. [4], each progenitor produces several unique realizations, with each seeded by a random number used to generate a unique power spectrum of spherical harmonics ($12 \leq \ell \leq 16$). The spectra are used as initial perturbations to the "match head" in the center of the progenitor star. The collaboration investigated the role of metalicity and central density of the progenitor on the explosion outcome.

Collaborator Townsley refined a protocol for particle post-processing which can be used to treat both material burned by the flame and the detonation. This necessitates the use of ancillary information from the flame propagation and burning model in the simulation beyond simple processing of the density-temperature Lagrangian history. Also, tools for efficient reconstruction of particle histories from saved snapshot files were developed to interface with post-processing tools. Particle selection was explored and sets of representative test tracks were isolated and characterized for rigorous testing during continued development. Townsley subjected this technology to a battery of Verification and Validation tests and is in the process of producing a manuscript on this effort.

3 Cost Status

The funds provided to all institutions were spent or encumbered by the end of the performance period and there was no carry-over.

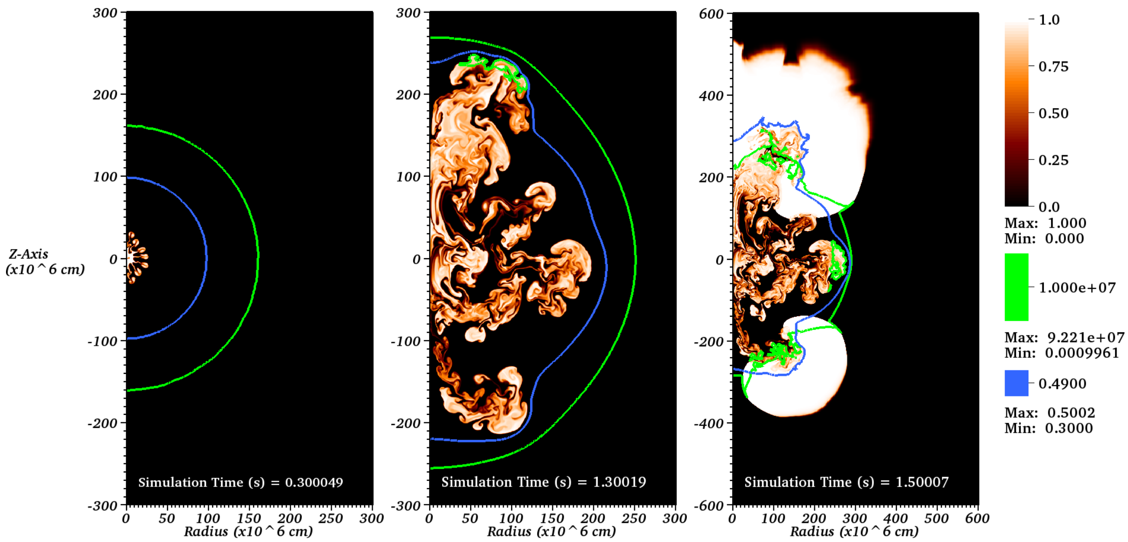

Figure 2: Images from a two-dimensional thermonuclear supernova simulation from a neutronized core progenitor. The left panel shows the development of fluid instabilities during the early deflagration phase, the center panel shows the configuration just prior to the first detonation, and the right panel shows the configuration with two distinct detonations consuming the star. Shown in color scale is the reaction progress variable which evolves from 0 to 1 and contours of $\rho = 10^7 \mathrm{g\,cm^{-3}}$ (green) and where the initial $X_{^{12}C} = 0.49$ (blue). The latter, initially inner, contour indicates the separation between the neutronized core and the higher-C surface layers. Note that the scale on the right panel is twice that of the first two.

4 Schedule

The performance period has ended and as the funding program ended, the schedule ends with this report. We are delighted to report, however, that while work continues funded by other sources, the goals outlined in the proposal were obtained. The collaboration developed products and technology for the research as outlined below and will utilize this technology in future research.

5 Products and Technology

5.1 Training of Students

Two students, Brenden Krueger and Aaron Jackson, attended *Stellar Death and Supernovae*, a conference held at the Kavli Institute for Theoretical Physics, UCSB, August 17-21, 2009. The students presented work in a poster.

In addition, although it was after the performance period for these grants, the two students, Brenden Krueger and Aaron Jackson, presented results from this effort at the 215th meeting of the American Astronomical Society, January 3-7, 2010. Each student presented a poster.

This award partially supported research by MSU graduate student David Chamulak on nucleosynthesis in surface detonation models. David presented a poster at the KITP conference *Stellar Death and Supernovae.* In addition, this work supported MSU graduate student Chris Richardson, who studied analytically how the speed of a multi-stage flame is affected when the timescale for the second reaction becomes much larger than the igniting one.

5.2 Collaboration Travel

- Calder traveled to the University of Chicago January 7-8, 2009 to work with collaborators.
- Calder and two students, Brendan Krueger and Aaron Jackson, traveled to the University of Arizona, Tucson, AZ, January 13-16, 2009 to work with collaborator Townsley.
- Calder, Krueger, and Jackson, with Townsley, traveled from the University of Arizona to Arizona State, Tempe, AZ, January 15, 2009, to work with Investigator Timmes.
- The collaboration traveled to the conference *Stellar Death and Supernovae*, at the Kavli Institute for Theoretical Physics, UCSB, August 17-21, 2009. The collaboration presented the results of research supported by these grants at the conference and were able to work together.

5.3 Publications During Performance Period

Refereed:

- *Evaluating Systematic Dependencies of Type Ia Supernovae: The Influence of Central Density*, B.K. Krueger, A.P. Jackson, A.C. Calder, D. M. Townsley, E.F. Brown, and F.X. Timmes, 2012, Astrophys. Jour., **757**, 175.

- *Evaluating Systematic Dependencies of Type Ia Supernovae: The Influence of Deflagration to Detonation Density.* A. P. Jackson, A. C. Calder,. D. M. Townsley, D. A. Chamulak, E. F. Brown, and F. X. Timmes, 2010, Astrophys. Jour., **720**, 00

- *Evaluating Systematic Dependencies of Type Ia Supernovae: The Influence of Progenitor* ^{22}Ne *Content on Dynamics*, D. Townsley, A. P. Jackson, A. C. Calder, D. A. Chamulak, Brown, E. F., & F. X. Timmes 2009, Astrophys. Jour.,**701**, 1582

5.4 Technology

The technology developed during the performance period is the simulation code with continued improvement to the three-stage energetics treatment that is capable both of accounting for the presence of ^{22}Ne in the fuel and for a spatially inhomogeneous fuel abundance. Developed technology also includes the routines for post-processing density and temperature histories from Lagrangian tracer particles.

In addition, and important technology developed during the course of these grants is the statistical framework for the study of systematic effect in type Ia supernova explosions Townsley et al. [4]. This technology is the foundation on which the collaboration will build years of research into type Ia supernovae to address issues like quantifying the intrinsic scatter of these events and exploring systematic effects.

References

[1] David A. Chamulak, Edward F. Brown, Francis X. Timmes, and Kimberly Dupczak. The reduction of the electron abundance during the pre-explosion simmering in white dwarf supernovae. *ApJ*, 677:160, 2008.

[2] Anthony L. Piro and Lars Bildsten. Neutronization during type Ia supernovae simmering. *ApJ*, 673:1009, February 2008.

[3] R. G. T. Zegers, E. F. Brown, H. Akimune, S. M. Austin, A. M. van den Berg, B. A. Brown, David A. Chamulak, Y. Fujita, S. Galès, M. N. Harakeh, H. Hashimoto, R. Hayami, G. W. Hitt, M. Itoh, T. Kawabata, K. Kawase, M. Kinoshita, K. Nakanishi, S. Nakayama, S. Okamura, Y. Shimbara, M. Uchida, H. Ueno, T. Yamagata, and M. Yosoi. Gamow-Teller strength for the analog transitions to the first $T = 1/2$, $J^{\pi} = 3/2^{-}$ states in ^{13}C and ^{13}N and the implications for type Ia supernovae. *Phys. Rev. C*, 77(2):024307, February 2008.

[4] D. M. Townsley, A. P. Jackson, A. C. Calder, D. A. Chamulak, E. F. Brown, and F. X. Timmes. Evaluating systematic dependencies of type Ia supernovae: The influence of progenitor ne22 content on dynamics. *ApJ*, 701:1582, August 2009.