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Nucleosynthesis in Highly Off-Center Detonation Models of Type Ia Supernovae

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Type Ia supernovae (SNe Ia) are commonly believed to be the thermonuclear incineration of accreting carbon-oxygen (C/O) white dwarfs. Observational evidence suggests that if a white dwarf explodes in a SN Ia some sort of detonation must take place. Several scenarios have been proposed as to how this detonation may actually occur, but the exact mechanism remains elusive. Using the FLASH code we have performed simulations, in two dimensions, of edge-lit core detonation in white dwarfs. Detailed yields, resulting from the explosive burning of the C/O plasma in these models, are examined using post-processing of tracer particles through a 532-nuclide reaction network. The reaction network includes strong as well as electroweak interactions. Results indicate that since the detonation is initiated at a point near the surface, there is a gradient in the thermal expansion timescale with polar angle. This leads to differential abundances across the explosion of, e.g., elemental Ni in the regions that did not proceed to a nuclear statistical equilibrium (NSE) composition. Observations of remnants could potentially test for such gradients.

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1. Introduction

There is a general belief that the SNe Ia are the thermonuclear incineration of a C/O white dwarf that has increased in mass through accretion [for a review, see 1], however a full understanding of the details of the ignition and explosion remains elusive. Two promising candidates for the SNe Ia explosion mechanism are the gravitationally confined detonation (GCD) model [2], and the sub-Chandrasekhar model.

In the GCD model carbon deflagration starts at a small off center point. This results in a buoyant flame bubble that quickly rises to the surface burning only a small fraction of the star during its travel [e.g. 3]. The bubble bursts through the surface layer but the material is largely confined to the surface of the white dwarf by gravity. As material continues to flow out of the star a strong surface flow forms. When the surface flow converges at the antipode of the break out point a detonation is thought to be induced by shock compressional heating [4, 5]. In the sub-Chandrasekhar model a layer of helium is deposited on the surface of a white dwarf. The Helium layer detonates resulting in a shock wave traveling around the surface of the white dwarf. Similar to the GCD scenario, when the shock wave converges at the antipode, a detonation is thought to be triggered at the edge of the carbon oxygen core [6, 7, 8, 9].

In this contribution, we report on work in progress to calculate nucleosynthetic yields in edge lit detonations where very little of the star is burned beforehand. We compute a shift in the center of mass of each element from carbon to germanium. We briefly describe how we calculate the abundances of the elements produced in a SN Ia and then summarize our results. Our central conclusion is that a highly off center detonation results in a non-spherically symmetric distribution of abundances. We conclude by briefly describing some implications of our findings.

2. Simulation

For the model discussed in this contribution we initiate a detonation in the surface layer of a $1.365 M_{\odot}$ white dwarf that has an isothermal temperature profile with a temperature, $T = 1.5 \times 10^7$ K. The white dwarf has also been expanded according to its fundamental radial-pulsation mode so that the central density is $10^8\ \mathrm{g\,cm^{-3}}$. This expansion reproduces a white dwarf similar to one at the onset of detonation in a GCD scenario [10]. The detonation is initiated by heating a spherical volume ~ 4 km in radius within the surface layer of the expanded white dwarf where the density is $10^7\ \mathrm{g\,cm^{-3}}$. The reactive-hydrodynamic simulation of the explosion was conducted using the FLASH code [11]. The code framework and the included physics is identical to that described in [10], and an effective adaptive mesh refinement resolution of 1 km is used. This model was run in 2-D cylindrical geometry with the detonation lit on the axis in order to properly reproduce the hydrodynamics. Detailed yields are calculated by post processing Lagrangian tracer particles included in the explosion calculation and are the primary focus of this contribution. We recorded the time history of $\sim 10^4$ particles which were initialized to evenly sample the initial mass of the white dwarf.

Our reaction network incorporates 532 nuclides. We use the reaction rates from the Joint Institute for Nuclear Astrophysics REACLIB Database[1] [12, and references therein]; the light-element

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[1] http://groups.nscl.msu.edu/jina/reaclib/db/

rates are mostly experimental and are from compilations such as [13] and [14]. Weak reaction rates are taken from [15] and [16]. Screening is incorporated using the formalism of Graboske et al. [17].

3. Results

We now present the results of our reaction network calculations for a highly off-center detonation in a SN Ia. We find that the detonation accelerates material in the direction that it is propagating. This results in material in the detonated hemisphere being first accelerated towards the stellar center before being turned around by pressure forces and expanding outward. Material in the detonated hemisphere is accelerated to lower velocities overall compared to material in the opposite hemisphere. Since material at a given radius on opposite sides of the star is accelerated to different velocities, material on the side opposite of where the detonation was initiated ends up at a lower density. This difference in expansion results in a different thermal history for material on opposite sides of the star and hence different nucleosynthesis.

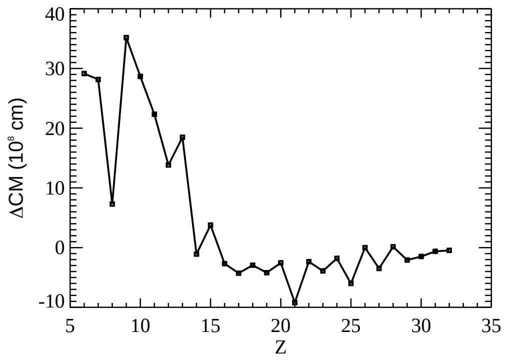

Figure 1: The shift in the center of mass of the elements from carbon to germanium at the end of our simulation. For reference the detonation was initiated at $\sim +2 \times 10^8$ cm on the vertical axis.

This difference in nucleosynthesis results in a number of nuclides exhibiting a gradient in abundance throughout the stellar remnant. We determined this by calculating the center of mass for a given element. Suppose a tracer particle i has a mass fraction $X_i(Z)$ of element Z the particles position is given by vector r_i, then the center of mass for a given elemental distribution, $r_{cm}(Z)$, is given by the equation

$$r_{cm}(Z) = \left(\sum_i X_i(Z) r_i \right) / \left(\sum_i X_i(Z) \right) . \tag{3.1}$$

Due to the symmetrical nature of our model the displacement of the center of mass for any element is along the y axis. Figure 1 shows the displacement of the center of mass for elements between C and Ge. These numbers are correct for the end of our simulation where strong reactions have frozen out and homologous expansion has been reached. Some of the isotopes making these elements, ^{56}Ni for Ni for example, decays so Figure 1 evolves with time. Notice, elements lighter than Si have their mass distributed more towards the location where the detonation was initiated. Elements heavier than Si are, for the most part, distributed away from where the detonation was initiated. These elements also display an odd-even pattern where odd Z nuclei are predominantly distributed farther away from the start of the detonation than their even Z counterparts.

4. Discussion

Having computed the distribution of elements in a highly off-center detonation we now ask if such an effect could be observable. It is currently unclear how much of an observable effect this asymmetry will have. Light curves and spectra need to be generated to test the observational signature in detail. A series of synthetic spectra generated over a range of time allows for direct comparison with observed supernovae. Kasen et al. [18] attempted to calculate the spectral signatures of GCD by considering ejecta interacting with an extended atmosphere. Their ejecta were calculated from a 1-D model and therefore were spherically symmetric and lack a compositional gradient. When revisiting the problem in 2-D the nucleosynthesis was done approximately and for only 13 elements [19]. Even if any compositional effects are obscured, we conjecture, the spectra will show some dependence on observing angle since the side of the remnant that expands at higher velocities will also be at a lower density making it more transparent at earlier times. The surface flow, which consists partly of deflagration ash, was excluded from our present model and needs to be considered. The surface flow might have its own spectral signature such as the presence of a high-velocity calcium absorber [18] and should be compared with the underlying compositional gradient. In a forthcoming publication, we will extend our discussion to include a detailed comparison of our work with other detonation scenarios.

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