Type Ia Supernovae: Energetics, Neutronization and Nucleosynthesis

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Abstract. The utility of Type Ia supernovae, not simply as probes of the distance scale but also as a means of constraining the properties of dark energy, demands a significant improvement in theoretical predictions of their properties in outburst. To this end, we have given substantial effort to quantifying the energetics and nucleosynthesis properties of deflagration fronts in the interiors of the putative carbon-oxygen white dwarf progenitors of Type Ia thermonuclear supernovae. We briefly review some essential features of our flame model and its properties in this paper and discuss its implications both for our multidimensional numerical simulations of SNe Ia and for nucleosynthesis (specifically ^{56}Ni production) in SNe Ia and Galactic chemical evolution.

Key Words

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INTRODUCTION

The inference drawn from studies of the cosmological distance scale - including the use of Type Ia supernovae as distance indicators - that the rate of expansion of the Universe is increasing, has generated greatly increased interest and activity in Type Ia supernova science. SNe Ia provide a particularly useful tool to probe and calibrate the distance scale as a consequence both of their high intrinsic brightness at maximum ($10^8 - 10^{10}$ L$_\odot$) and of the identification of a correlation (Phillips 1993) between the peak luminosity and the breadth of the light curve (*brighter is broader or less luminous supernovae decline from maximum more rapidly*).

The standard model for Type Ia supernovae consists of the thermonuclear incineration of a carbon-oxygen (CO) white dwarf star at the critical (Chandrasekhar) mass. It is generally believed that the realization of a mass 1.4 M$_\odot$ must occur as a consequence of the transfer of matter (accretion) from a binary companion. The question of the nature of the Type Ia progenitor system(s) remains one of the critical unsolved problems in SNe Ia research. After some $\sim$ 1000 years of nuclear smoldering, thermonuclear ignition

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occurs at or near the center and complete incineration of the CO white dwarf ensues within approximately two seconds. Thermonuclear burning for conditions of $Y_e \approx 0.5$ yields significant production of iron-peak nuclei, in particular ^{56}Ni (Truran, Arnett, & Cameron 1967), which powers the light curve. The need for accurate predictions of the "nickel mass" demands a careful treatment of the nuclear energetics, the degree of neutronization, and associated nucleosynthesis. In subsequent sections we will first provide an overview of the current status of Type Ia supernova models, then a brief summary of the critical features of our flame model, and finally a discussion of their implications for nucleosynthesis and Galactic chemical evolution.

MODELING SNE IA: WHERE DO WE STAND?

As noted above, in the context of the standard model we understand SNe Ia to involve the thermonuclear incineration of a Chandrasekhar mass carbon-oxygen (CO) white dwarf (Hoyle & Fowler 1960). We fully understand that a pure detonation (Arnett 1969; Hansen & Wheeler 1969), which yields iron-peak nuclei only (Arnett, Truran, & Woosley 1971), cannot be appropriate, since it fails to explain the concentrations of intermediate mass nuclei in SNe Ia ejecta (Branch *et al.* 1981).

Early sub-sonic flame evolution yields pre-expansion of the white dwarf and insures that the outer regions are not burned to ^{56}Ni, but rather produce such 'intermediate mass nuclei' as magnesium, silicon, and calcium (Thielemann, Nomoto, & Yokoi 1986). The flame must start out as a deflagration but ultimately approach sound speed (e.g. like the W7 model of Nomoto *et al.* (1984)), in order to be consistent with the observed velocities of intermediate mass nuclei in supernova spectra. The emphasis in many recent large scale multi-dimensional simulations has then been on 2D and 3D simulations of the deflagration phase (Calder *et al.* 2003; Hillebrandt & Roepke 2005; Gamezo, Khokhlov, & Oran 2005; Livne, Asida, & Hoeflich 2005; Roepke, Woosley, & Hillebrandt 2006; Calder *et al.* 2007) and on considerations as to how this might possibly lead to detonation.

Calder *et al.* (2004) reported the identification of a possible new SNe Ia explosion mechanism. They found that large-scale 3D simulations indicated that an off-center ignition creates a hot bubble of material that rises rapidly to the surface of the white dwarf. As the bubble breaks through the surface, hot material flows across the surface of the white dwarf star at high velocity, pushing material from the surface layers of the star ahead of it (Plewa *et al.* 2004). They anticipated that the convergence of the flow at the opposite point on the surface of the star can yield compression that raises the temperature and density of the matter to the point where a detonation might be triggered. In this scenario, pre-expansion of the star occurs both during the rise of the bubble to the surface and in the period during which the bubble flows about the surface, such that when detonation is achieved the density of the star has decreased sufficiently to insure that intermediate mass nuclei as well as ^{56}Ni and associated iron peak nuclei are produced.

The detailed energetics of the deflagration and the post-flame nuclear evolution of the white dwarf matter are critical factors - particularly for consideration of bubble evolution - which must be calculated accurately to provide realistic determinations of: (1) the total energy release; (2) the distribution of nucleosynthesis products in the ejecta; (3) the degree of neutronization of the ejected matter; and thus (4) the mass of ^{56}Ni ejected (and peak luminosity). This has motivated the considerable efforts to calibrate our flame model which are described below.

FLAME MODEL

Hydrodynamic simulations of deflagrations in thermonuclear (Type Ia) supernovae require the development and application of a realistic flame model - one which captures the underlying energetics, timescales, and compositional changes associated with this evolution. Our flame model builds upon and extends the advection-diffusion-reaction (ADR) model of Khokhlov (1991a, b; see also Vladimirova *et al.* 2006), with the inclusion of multiple burning stages and a reactive nuclear statistical equilibrium (NSE) post-flame state appropriate for simulations of CO deflagrations. We have calibrated this model with the use of self-heating reaction network calculations that utilize current compilations of the rates of thermonuclear reactions (Rauscher & Thielemann 2000) and of weak interactions (Langanke & Martinez-Pinedo 2001) and include the effects of screening and of Coulomb equation of state corrections to detailed balance (NSE) in a self-consistent manner.

For the range of density appropriate to our white dwarf initial model, our self-heating calculations establish the temperature-density conditions in the immediate aftermath of flame ignition. For these conditions, burning to NSE typically leaves a significant fraction of the available nuclear binding energy untapped. We call attention to the fact that the burning of equal masses of ^{12}C (6.78 MeV/amu) and ^{16}O (7.98 MeV/amu) to equal masses of ^{4}He (7.07 MeV/amu) and ^{56}Ni (8.64 MeV/amu) (in nuclear statistical equilibrium at high temperatures) yields effectively zero nuclear energy release. This is shown in our Figure 1, in which are plotted contours in the temperature-density plane of binding energy per nucleon, q, in MeV/amu, for the NSE state with Y_e=0.5. The dotted line corresponds to a two component NSE consisting of equal mass fractions of ^{4}He and ^{56}Ni. The final temperature achieved in our self-heating calculations is plotted here as a function of density (dot-dashed line). This stored energy is subsequently released in the post-flame evolution to a ^{56}Ni dominated NSE with expansion and neutronization. Its effects are most pronounced when considering the consequences of off-center ignition. This work is reported in the paper by Calder *et al.* (2007).

Further efforts to treat properly the nuclear energy release in Type Ia supernovae (Townsley *et al.* 2007) are now completed. This effort has implemented a state-of-the-art, efficient, accurate model of the nuclear burning both in the diffusive flame and after its passage, during the deflagration of a white dwarf star in a Type Ia supernova. Such a model is essential for using computer simulations of the explosion to understand systematic trends in the brightness of these events which are being heavily used to probe the expansion history of the universe. This has resulted in significantly improved modeling of both the strong and weak nuclear interaction physics necessary to follow the early phases of the explosion, and to enable high-quality nucleosynthesis studies to be accomplished simultaneously with detailed hydrodynamic study of Ia explosion mechanisms. Among other things, during the course of this work, we successfully matched a screened

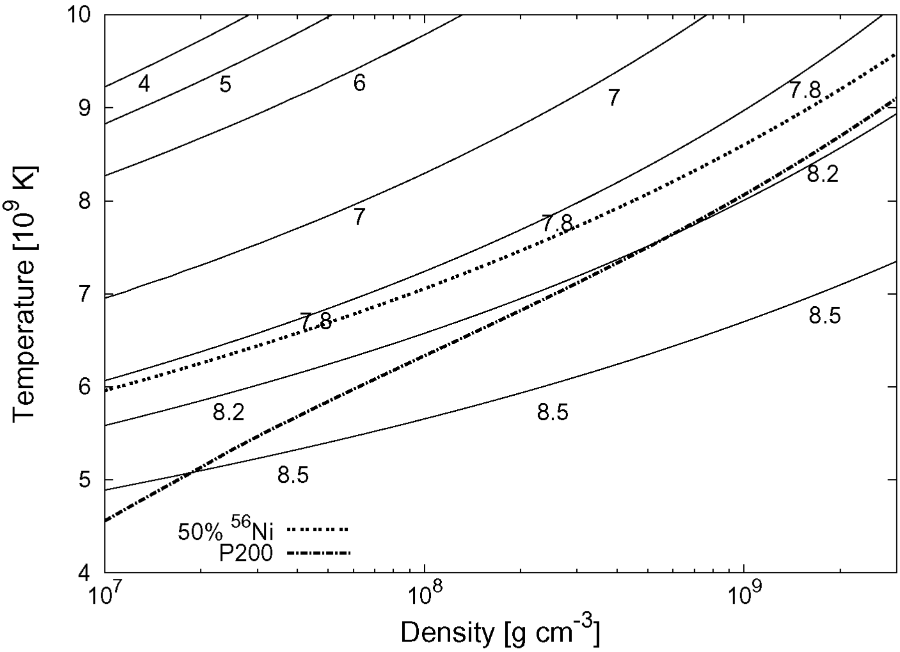

FIGURE 1. Contours of binding energy per nucleon, q, in MeV per nucleon, for the NSE state with $Y_e = 0.5$. Also shown as a function of density is the final temperature reached (dot-dashed line) by the 200 nuclide self-heating network calculation starting from an equal mixture of C and O by mass and burning to NSE. The line of 50% ^{56}Ni mass fraction (dotted line) in a two-component NSE (^{4}He and ^{56}Ni) indicates the temperature above which light particles dominate.

nuclear network calculation and a coulomb-corrected nuclear statistical equilibrium calculation, to insure a proper and accurate treatment of the nuclear network calculations approaching NSE at high temperatures and densities. The effects of the inclusion of a proper treatment of screening are reflected in the temperatures achieved in NSE shown in Figure 2.

NEUTRONIZATION, NUCLEOSYNTHESIS AND SNE IA PEAK LUMINOSITIES

The use of Type Ia supernovae as distance indicators utilizes the robustness of the Phillips relation, which correlates the peak luminosity with the breadth of the light curve. There is nevertheless a significant range in peak luminosity of SNe Ia events which we would like to better understand. Given that the peak luminosity is proportional to the mass of ^{56}Ni produced in the explosion, the observed broad range of peak luminosity imposes important clues to and constraints upon theoretical models for SNe Ia.

There are two factors which significantly impact the production of ^{56}Ni in SNe Ia

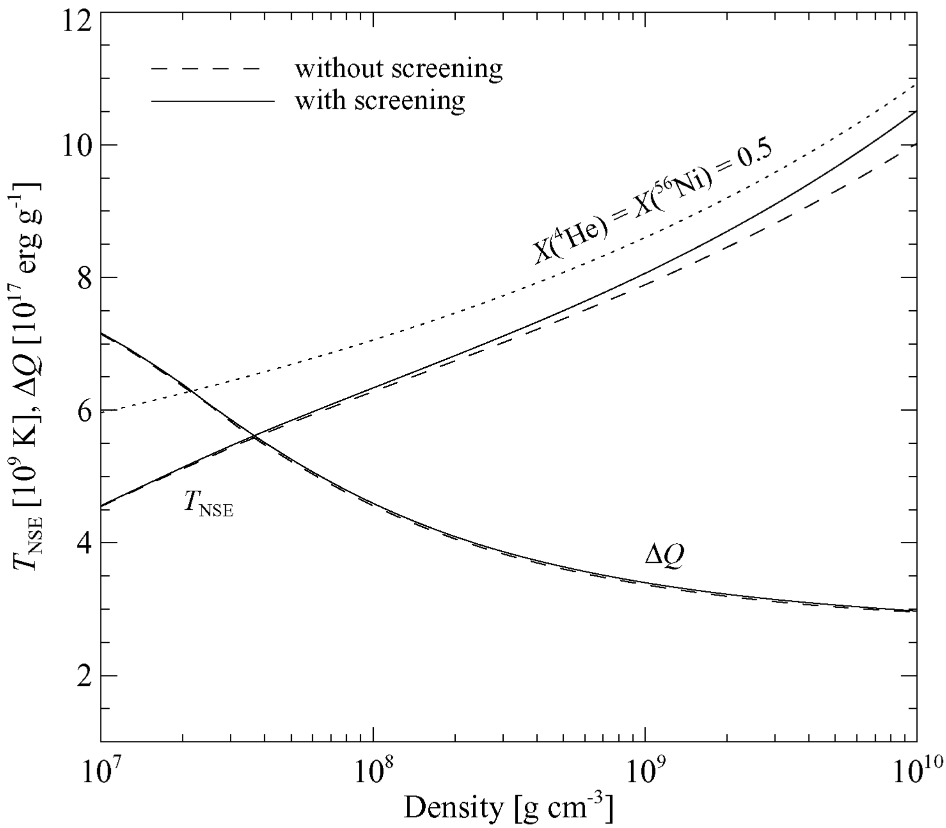

FIGURE 2. Energy released and NSE temperature for burning C/O as functions of density of the fuel for isochoric self-heating calculations with (solid lines) and without (dashed lines) electron screening and Coulomb corrections. For comparison, the contour corresponding to the condition (for $Y_e = 0.5$) that the nuclear statistical equilibrium consists of equal parts by mass of ^{4}He and ^{56}Ni is shown (dotted line). Note the divergence of the T_{NSE} curves when electron screening and Coulomb corrections are not appropriately accounted for. For example, at $\rho \gtrsim 2.0$ g cm^{-3}, neglect of electron screening artificially lowers the temperature of the NSE ashes.

events: (1) the degree of neutronization of the core matter; and (2) the extent to which "pre-expansion" proceeds during the deflagration phase - prior to the (presumed) onset of detonation. In this regard, we note that nearly all one-dimensional Chandrasekhar mass models of Type Ia supernovae (see, e.g. Nomoto *et al.* 1984; Iwamoto *et al.* 1999) produce most of their ^{56}Ni in a nuclear statistical equilibrium environment between mass shells $\sim$0.2 $M_\odot$ and $\sim$0.8 $M_\odot$. In this regime, weak interactions proceed on timescales exceeding the timescale for disruption of the white dwarf by a burning front. In contrast, at the higher densities characterizing the innermost regions $M \lesssim 0.2$ $M_\odot$, electron captures effect significant neutronization favoring the production of neutron-rich isotopes - e.g. ^{54}Fe, ^{56}Fe, ^{58}Ni - at the expense of ^{56}Ni. Note here that in the outermost regions 0.8 $M_\odot < M < 1.4\ M_\odot$ in these models, due to pre-expansion, the main nuclear burning products are intermediate mass nuclei like ^{16}O, ^{24}Mg, ^{28}Si, and ^{40}Ca. We note also that electron captures and neutronization can influence the energetics sufficiently that their effects on the hydrodynamic evolution must be included.

Timmes, Brown, & Truran (2003) have also noted that neutron excess can also be a direct consequence of the initial composition, e.g.: CNO hydrogen burning converts all initial CNO isotopes to ^{14}N following which helium burning converts the ^{14}N to ^{22}Ne via $^{14}N(\alpha,\gamma)^{18}F$, $^{18}F(e^+,\nu)^{18}O$, $^{18}O(\alpha,\gamma)^{22}Ne$. For a star of primordial Solar composition, this yields ~2.5 percent ^{22}Ne, but this can reach 5-10 percent for high metallicity populations and thereby impact SNe Ia brightness. This proton deficit results in more stable elements being produced at the expense of ^{56}Ni. The most dramatic effects of neutronization are, however, those realized in the inner core.

It is the sensitivity of the peak luminosities of Type Ia supernovae that has motivated our more careful study of nuclear energetics and the evolution of the core composition. Indeed, following flame passage, the NSE state continues to evolve due to both: (1) large scale fluid motions which change the temperature and density; and (2) electron captures which yield a more neutron-rich NSE state, lower electron degeneracy pressure, and alter the composition of the matter processed under these conditions. Modeling of these effects is critical as well to the effective use of tracer particles to capture a high fidelity recording of the temperature-density history for nucleosynthesis calculations.

SUMMARY

Both the observed characteristics of Type Ia supernovae in outburst and multidimensional theoretical simulations of these events inform us that there exists a strong dependence of the peak luminosity on the details of the nuclear energetics and composition. In this paper we have identified the manner in which we treat the flame energetics (Calder *et al.* 2007; Townsley *et al.* 2007). We emphasize the significance of a proper treatment of flame energetics and neutronization which impacts, among other things: the buoyancy of rising bubbles; the products of nucleosynthesis in the deep core (where e.g. W7 overproduces ^{54}Fe relative to ^{56}Fe); and the resulting SNe Ia light curves. This work provides the basis for our ongoing simulations of the deflagration phase of Type Ia flame evolution, leading in our models to a 'gravitationally confined detonation' event (Jordan *et al.* 2007).

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