

TYPE Ia SUPERNOVA EXPLOSION: GRAVITATIONALLY CONFINED DETONATION

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Received 2004 May 4; accepted 2004 July 13; published 2004 August 5

ABSTRACT

We present a new mechanism for Type Ia supernova explosions in massive white dwarfs. The scenario follows from relaxing assumptions of symmetry and involves a detonation born near the stellar surface. The explosion begins with an essentially central ignition of a deflagration that results in the formation of a buoyancy-driven bubble of hot material that reaches the stellar surface at supersonic speeds. The bubble breakout laterally accelerates fuel-rich outer stellar layers. This material, confined by gravity to the white dwarf, races along the stellar surface and is focused at the location opposite to the point of the bubble breakout. These streams of nuclear fuel carry enough mass and energy to trigger a detonation just above the stellar surface that will incinerate the white dwarf and result in an energetic explosion. The stellar expansion following the deflagration redistributes mass in a way that ensures production of intermediate-mass and iron group elements with ejecta having a strongly layered structure and a mild amount of asymmetry following from the early deflagration phase. This asymmetry, combined with the amount of stellar expansion determined by details of the evolution (principally the energetics of deflagration, timing of detonation, and structure of the progenitor), can be expected to create a family of mildly diverse Type Ia supernova explosions.

Subject headings: hydrodynamics — instabilities — stars: interiors — supernovae: general — white dwarfs

1. INTRODUCTION

Type Ia supernovae are one class of luminous stellar explosions predominantly occurring in old stellar environments such as elliptical galaxies. The ejecta of these objects are rich in intermediate-mass and iron group elements. Explaining the nature of these objects is critical for understanding galactic chemical evolution (Truran & Cameron 1971). These supernovae also are the key component of one method used to determine the history of the universe and probe the origin of dark energy (Sandage & Tammann 1993; Perlmutter et al. 1999; Tonry et al. 2003; Knop et al. 2003).

Despite decades of effort, these events remain an unsolved mystery. Current ideas about the Type Ia explosion mechanism follow from the original work of Arnett, Nomoto, and Khokhlov (Arnett 1969; Nomoto et al. 1976; Khokhlov 1991), who pioneered deflagrating and detonating models following the idea (proposed by Hoyle & Fowler 1960) of massive white dwarfs as the core component of Type Ia supernovae. Scenarios include white dwarf detonations (Arnett 1969; Nomoto 1982), coalescing white dwarf pairs (Webbink 1984; Iben & Tutokov 1984), deflagrations or delayed detonations of massive white dwarfs (Nomoto et al. 1984; Khokhlov 1991; Yamaoka et al. 1992; Arnett & Livne 1994a), and collapse in a strong gravitational field (Wilson & Mathews 2004). None of these scenarios accounts for all the observed features of Type Ia supernovae. Some models produce energetic explosions but fail to explain the observed ejecta compositions, while others successfully produce the observed chemically stratified ejecta but require including ad hoc physics.

In this Letter, we present a new mechanism for Type Ia supernova explosions that naturally produces the desired fea-

tures of these types of models. Our model begins with the essentially central ignition of a deflagration in the core of a Chandrasekhar-mass white dwarf and results in a detonation born at the surface that will incinerate the star and produce a vigorous explosion.

2. NUMERICAL MODEL

The simulations presented here were performed with the adaptive mesh refinement hydrodynamics code FLASH (Fryxell et al. 2000). The numerical scheme includes self-gravity solved using a multipole expansion. We found that to properly account for asymmetries in the mass distribution and ensure momentum conservation, the expansion requires at least three multipole moments. The simulations reported here used 10 moments. The evolution of the deflagration front was computed with a flame capturing scheme and energy release accounting for carbon, magnesium, and silicon burning (Khokhlov 2001). In the regions not overrun by the deflagration, we used the iso7 nuclear network (Timmes et al. 2000). This hybrid approach allowed us to follow the evolution of the deflagration front and account for nuclear burning not associated with the deflagration (i.e., to capture a possible transition to detonation). The rest of the physics modules were identical to those of our previous study (Calder et al. 2004).

The computational domain was a two-dimensional region in cylindrical geometry from $-16,384$ to $16,384$ km in the z -direction and extending up to $16,384$ km in radius. We employed outflow-only boundary conditions; along the symmetry axis at $r = 0$ we used a reflecting boundary condition. The adaptive mesh allowed for a maximum local resolution of 8 km (corresponding to an effective grid size of 2048×4096). The simulation was executed at a Courant number of 0.6 with the time step limited to a maximum of 4×10^{-4} s. The progenitor was a 1.36 solar mass isothermal white dwarf composed of equal amounts of carbon and oxygen with a temperature of 3×10^7 K. The model was mapped to the computational grid following the procedure employed in Calder et al. (2004). The nuclear flame was initiated as a small spherical region of burned material in hydrostatic equilibrium with its surroundings.

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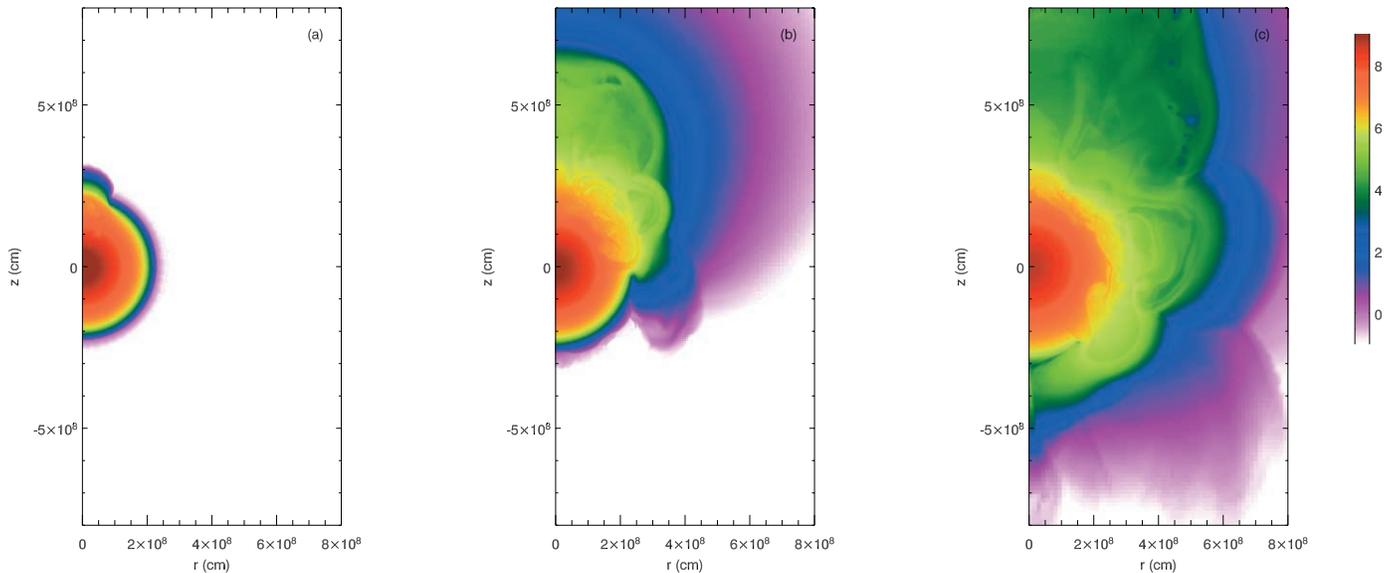


FIG. 1.—Evolution of the white dwarf following an essentially central ignition. Density in log-scale is shown for the innermost approximately one-sixth of the simulation domain. (a) Bubble breakout ($t = 0.9$ s). The material is expelled radially, and the high pressure of the burned bubble material produces a lateral acceleration of the outer layers of the star. (b) Bubble material expands above the star as the fuel-rich surface layers reach the equator in their race across the stellar surface ($t = 1.4$ s). Note that most of the surface layers are closely confined to the star. (c) Focusing of the fuel-rich streams just prior to the detonation ($t = 1.9$ s). Note the presence of the dense conical region stretching down along the symmetry axis beginning at $(r, z) = (0, -3 \times 10^8)$ cm.

The ignition region centered at $(r, z) = (0, 12.5)$ km had a radius of 50 km.

3. RESULTS

Figure 1 depicts the density evolution from the point of bubble breakout. The rapid ascent of the bubble toward the stellar surface accelerates the material above the bubble. This piston-like behavior results in the formation of a bulge filled with high-pressure, high-momentum material. During breakout, bubble material is expelled mostly radially, while the high pressure of the burned material accelerates the surface layers laterally (Fig. 1a). This fuel races along the stellar surface, followed by magnesium-rich ash. Both remain gravitationally confined to a ≈ 1000 km layer (Fig. 1b). At $t \approx 1.8$ s, this flood converges at the point opposite to the bubble breakout location, forming a conical compressed region bounded by the shock. This structure stretches down the symmetry axis beginning at $z \approx -3 \times 10^8$ cm (Fig. 1c).

At this time, conditions in the shocked region approach the detonation regime. By $t = 1.85$ s, material upstream of the confluence region has a density of $\approx 10^4$ g cm $^{-3}$ and moves at a velocity of 9500 km s $^{-1}$. Downstream of the shock, the density of the nuclear fuel is $\approx 5 \times 10^4$ g cm $^{-3}$ and the temperature reaches $\approx 1.4 \times 10^9$ K. Because of a mild density gradient present in the flooding material (Fig. 2a), the postshock density slowly increases with time while the temperature remains relatively constant. At $t \approx 1.93$ s, the postshock conditions are suitable for igniting the nuclear fuel: the density exceeds 1.7×10^6 g cm $^{-3}$, and the temperature is $\approx 2.2 \times 10^9$ K. The detonation point can be seen as a slightly overpressured region located near the symmetry axis at $(r, z) \approx (0, -3.35 \times 10^8)$ cm (Fig. 2b). We note that the analysis of the mass required for a successful detonation by Arnett & Livne (1994b) does not apply because the detonation is triggered behind the shock in the region confined (unable to expand) and fed by the incoming fuel flow.

The detonation wave born above the stellar radius will sweep

through the star, which underwent a substantial evolution from the moment of the ignition of the deflagration. During its ascent, the bubble displaced about 5% of the stellar mass. This mass displacement, combined with the pressure wave caused by nuclear energy release, leads to expansion of the star. Thermal expansion is present from the onset of the deflagration, with that part of the star nearest the deflagration experiencing relatively stronger thermal expansion. The global evolution of the stellar matter is, however, primarily in response to the softening of the gravitational potential caused by mass displacement. This expansion is mostly radial and becomes effective only after bubble breakout.

Figure 3 illustrates the evolution of density showing the amount of mass in several density intervals. The material with density greater than 1×10^8 g cm $^{-3}$ will undergo burning to iron peak elements, while material with density below 3×10^7 g cm $^{-3}$ will burn into intermediate-mass elements. Note that there is almost no stellar expansion prior to the breakout ($t \leq 0.9$ s). The breakout is followed by relatively fast expansion of the densest material ($\rho > 1 \times 10^9$ g cm $^{-3}$) and then by uniform expansion (identified by a simultaneous increase in the expansion rates at $t \approx 1.2$ s). This process continues until the ignition of the detonation, with the most rapid expansion at densities between 1×10^7 and 1×10^8 g cm $^{-3}$. At the time of detonation the amount of mass at the densities characteristic for production of intermediate-mass elements, $\rho < 3 \times 10^7$ g cm $^{-3}$, is $0.35 M_{\odot}$. The amount of mass at densities above 1×10^8 g cm $^{-3}$, required for production of the iron peak elements, is $0.71 M_{\odot}$.

4. DISCUSSION AND CONCLUSIONS

We presented a gravitationally confined detonation (GCD) mechanism for Type Ia supernova explosions. The components of the GCD scenario are a rising deflagrating bubble expelling a small amount of stellar matter, the associated stellar expansion caused by the shallower potential well, the flood of stellar material across the surface following the bubble breakout, and

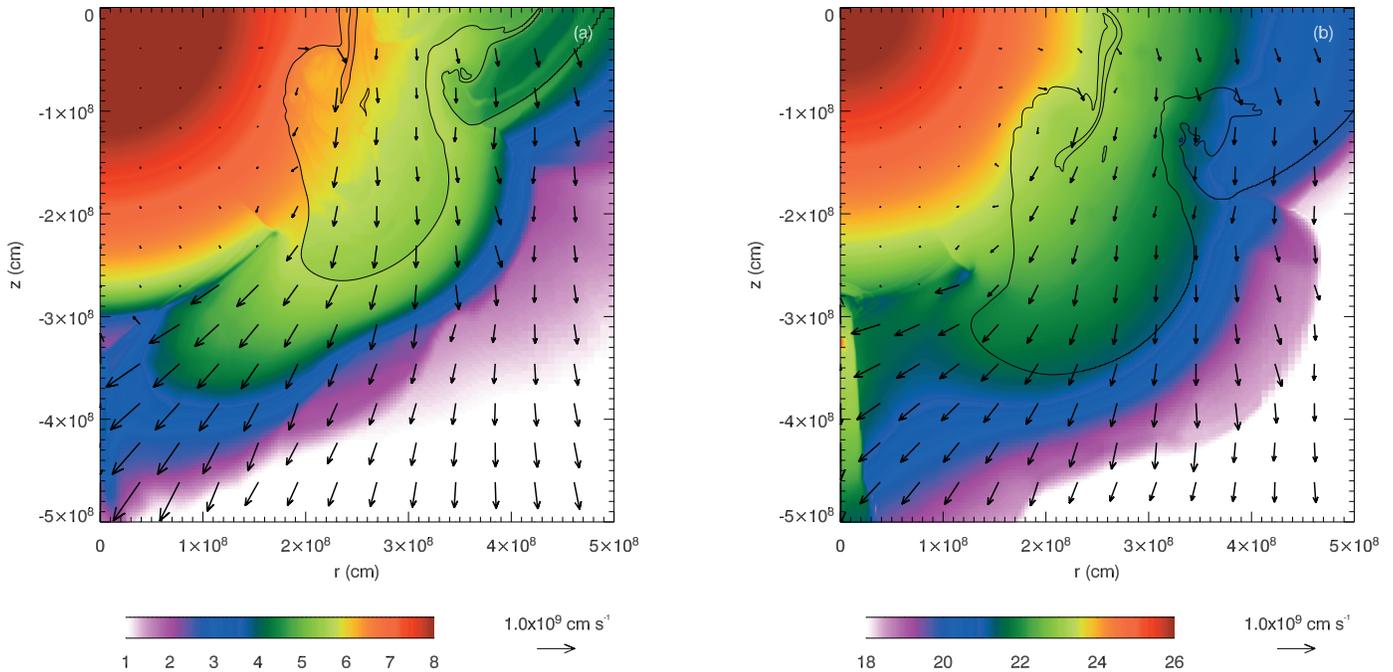


FIG. 2.—Evolution of the surface flood across the lower half of the star. (a) Density in log-scale at $t = 1.85$ s. Note the density gradient in the stream of fast-moving material. The interior of the star remains highly radially symmetric; only relatively low-density regions are perturbed by the surface flow. (b) Pressure in log-scale at the ignition of the detonation ($t = 2.005$ s). The ignition point can be seen as a small overpressured region located near the symmetry axis at $(r, z) \approx (0, -3.25 \times 10^8)$ cm. The shock wave preceding the bubble material is located in the low-density stellar layers near $(r, z) \approx (1.1 \times 10^8, -2.4 \times 10^8)$ cm. The contour marks the position of the advancing front of nuclear ash. Vectors show the velocity field; the velocity can be determined by comparing the length of the vectors with the length of the fiducial vector ($1 \times 10^9 \text{ cm s}^{-1}$).

a detonation in a gravitationally confined environment. This chain of events follows a deflagration born very close to the white dwarf center. Such an essentially central ignition is more probable than the idealized conditions adopted in standard deflagration or delayed detonation models, primarily because the central region of the star is convective. Such initial conditions also seem more probable than the far-off-center ignition considered by Niemeyer et al. (1996). This type of ignition results

in a rising deflagrating bubble accelerated by buoyancy to supersonic speeds. The transonic phase of the evolution is accompanied by the formation of a bow shock ahead of the bubble that compresses and heats the nuclear fuel. Our attempts to associate this region with a transition to detonation failed because the shock is too weak. This result is independent of the details of the flame evolution because the bubble rise is controlled by buoyancy, which depends only on the density jump across the flame front. We discovered, however, that the flood of the expelled surface layers following the bubble breakout remains confined to the surface, races around the star, and is ultimately focused into a hot, compressed, high-density region located just above the stellar surface. Conditions in this region satisfy the criteria necessary for a detonation.

Stellar expansion in the GCD mechanism is a natural consequence of the essentially central ignition of a deflagration. The flame displaces mass, which softens the gravitational potential well leading to an expansion of the star. The expansion will slow on a timescale comparable to the sound crossing time of the white dwarf as the star approaches a new equilibrium. Therefore, we expect that at still later times, if not for the fact that the detonation will completely disrupt the star, the initial expansion would be followed by contraction of stellar material and the star would oscillate.

Because of this preexpansion, the detonation front will encounter densities similar to those found in models where preexpansion results from a centrally ignited large-scale deflagration (Reinecke et al. 2002; Gamezo et al. 2003). The estimate of nucleosynthetic yield for intermediate-mass (iron peak) elements is a lower (upper) limit in view of the fact that the stellar expansion continues after the moment of the detonation. Determining the final yield, however, requires simulating the detonation. The actual conditions across the detonation wave,

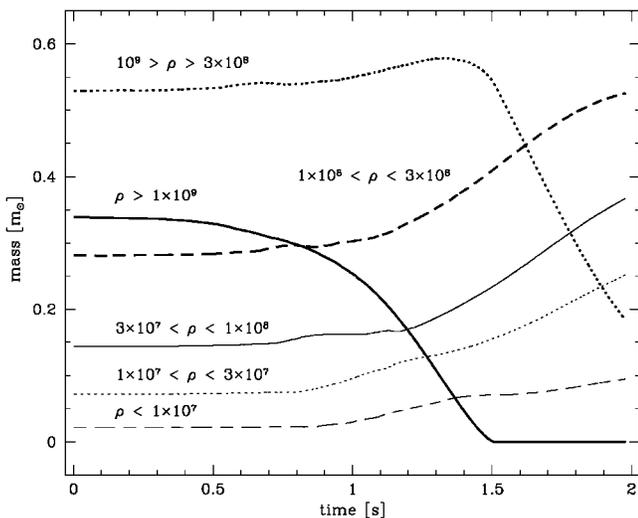


FIG. 3.—Evolution of the mass distribution in the model white dwarf. The amount of material in solar masses inside select density intervals is shown as a function of time. Significant stellar expansion takes place only after bubble breakout (about 0.9 s after the deflagration began near the center of the star). At the moment of the ignition of the detonation, almost half of the stellar mass has densities below $1 \times 10^8 \text{ g cm}^{-3}$.

particularly the amount of compression, will influence the results. The yield can also be modified by delaying or by accelerating the ignition of the detonation, and thus the amount of expansion, to create a diverse family of Type Ia supernovae. The timing depends on several factors. The structure of the progenitor influences energy release by the deflagration and affects the strength and mass of the stellar layers being pushed around the star. Also, the radius of the progenitor regulates the time required by the streaming matter to reach the confluence point. These factors determine the time available for stellar pre-expansion and are sources of diversity.

Some properties of the proposed model are, however, largely independent of the precise details of the ignition of the detonation or stellar progenitor. The explosion will be powerful. All stellar fuel will be consumed by the detonation similarly to the helium detonation model of Livne & Arnett (1995). Despite the perturbation introduced by the deflagration, the star will retain most of its radially symmetric stratification. The explosion will display characteristics typical of one-dimensional investigations (Höflich et al. 1998). In particular, we expect the distribution of nucleosynthetic products in velocity space to agree with the observed layered structure of Type Ia supernova ejecta.

The model also naturally admits certain asymmetries. The deflagration consumes only about 5% of the stellar mass. We expect a similar level of variation in the resulting spectra and luminosities, in agreement with the degree of diversity present in the observations (Li et al. 2001). In addition, because the stellar shape is distorted by the rising bubble and the formation of the detonation on one side of the star, we expect a noticeable asymmetry in the stellar ejecta. These orientation effects might be responsible for peculiar events such as SN 1991T (Filip-

penko 1997). Because the gross properties of observed Type Ia supernovae can be accounted for by the GCD model, detailed spectral and polarimetric observations will be required to verify the proposed mechanism.

In this communication, we presented a logical sequence of events that naturally leads to a Type Ia supernova explosion. Several of these steps need to be carefully studied. The initial conditions are far from being well understood. There exists a strong diversity of opinions about conditions in which the deflagration is born (Höflich & Stein 2002; Woosley et al. 2004), and careful numerical studies are still ahead. We recognize that the birth of the detonation depends on the composition of the matter involved. In particular, the presence of helium will make ignition easier to achieve and sustain. Also, the proposed detonation mechanism bears many similarities to the process of confined fusion studied in terrestrial laboratory experiments, which is notoriously difficult and prone to instabilities. For these reasons, the early stages of the detonation should be studied very carefully. The expected computational demands and challenges are severe and clearly approach the limits of feasibility. Despite the fact that such a study lies in the future, we are confident in the basic components of the proposed GCD mechanism.

The authors thank the anonymous referee for insightful comments and criticism that greatly improved this work. We also thank Alexei Khokhlov, Peter Höflich, Natasha Vladimirova, Ed Brown, Jim Truran, and the FLASH Code Group for their help. This work is supported in part by the US Department of Energy under grant B523820 to the Center for Astrophysical Thermonuclear Flashes at the University of Chicago.

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