THE ASTROPHYSICAL JOURNAL, 372:L83–L86, 1991 May 10

THE OUTCOME OF EXPLOSIVE IGNITION OF ONeMg CORES: SUPERNOVAE, NEUTRON STARS, OR "IRON" WHITE DWARFS?

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Received 1990 October 11; accepted 1991 February 21

ABSTRACT

Electron-degenerate ONeMg cores result from the evolution of 8 $M_\odot \leq M \leq 12\ M_\odot$ stars. In the mass range 8 $M_\odot \leq M \leq 10\ M_\odot$, electron captures on ^{24}Mg and ^{24}Na first, and later on ^{20}Ne, precede Ne-O ignition. The same occurs in mass-accreting ONeMg white dwarfs, formed in close binary systems by mass loss from stars in the above mass range. Electron captures on ^{20}Ne (or maybe on ^{24}Mg and ^{24}Na) are the triggering mechanism of explosive ignition. Depending on the treatment of semiconvection, ignition density is most likely lower than 9.5×10^9 g cm^{-3}. In this case, hydrodynamic burning propagation may lead to complete disruption of the core and not to core collapse, in contrast with the usual assumption. Thus, while neutron star formation by accretion-induced collapse (AIC) of ONeMg white dwarfs critically depends both on ignition density and on the velocity of the burning front, thermonuclear supernova production (either Ia or Ib/c), or even "Fe" white dwarf formation by milder outbursts are open possibilities for the outcome of the explosive ignition of ONeMg cores.

Subject headings: stars: neutron — stars: supernovae — stars: white dwarfs

1. INTRODUCTION

Stars with masses $M \geq 8\ M_\odot$ ignite carbon nonexplosively (Woosley & Weaver 1986). Quasi-hydrostatic carbon burning then leads to growth of a core made of an admixture of ^{16}O, ^{20}Ne, and ^{24}Mg. The mass range 8 $M_\odot \leq M \leq 12\ M_\odot$ poses a distinct problem, however, since the electrons become degenerate prior to Ne-O ignition (Nomoto 1984). In the upper half of this mass range (10 $M_\odot \leq M \leq 12\ M_\odot$) this leads to Ne flashes but not to explosive disruption nor dynamical collapse, and evolution proceeds up to Si burning and growth of an electron-degenerate "Fe-Ni" (nuclear statistical equilibrium, NSE) core (Woosley & Weaver 1986). In the lower half of the mass range (8 $M_\odot \leq M \leq 10\ M_\odot$), before the point of Ne ignition is reached electron Fermi energies at the center of the star become larger than the thresholds for electron captures on ^{24}Mg (and shortly afterwards on ^{24}Na) first, and later on ^{20}Ne. These electron captures have a double effect: they lower the electron mole number Y_e (and with it Chandrasekhar's mass, which is proportional to Y_e^2) and, on the other hand, they heat up the plasma, eventually inducing Ne-O ignition (Miyaji et al. 1980; Miyaji & Nomoto 1987). Ignition densities are $\approx 10^{10}$ g cm^{-3}. Thus, electron degeneracy is not removed until the material has been processed to NSE and a hydrodynamic burning front propagates outwards from the center of the star. The exact density at which explosive ignition is triggered is crucial in determining the fate of those cores: depending on it, either electron captures on NSE material remove energy and pressure fast enough for gravitational collapse to ensue or, on the contrary, the energy released by the spreading burning completely disrupts the star (the case is analogous to that of electron-degenerate CO cores at C ignition: see Canal et al. 1990; Canal, Isern, & Labay 1990). Core masses corresponding to densities $\approx 10^{10}$ g cm^{-3} are close to Chandrasekhar's mass and thus small differences can lead to opposite outcomes.

Exact values of Ne-O ignition densities depend on the criterion adopted for the onset of convective instability, as well as on the relevant electron-capture rates. The ONeMg cores grow as material is being processed through the C-burning shell. Due to thermal neutrino losses, they become electron-degenerate. Thermal conduction by the degenerate electrons keeps a stable temperature gradient as core contracts while growing in mass. But the onset of electron captures on ^{24}Mg soon produces enough entropy as to make its gradient negative. The temperature gradient thus becomes larger than the adiabtic one: $\nabla_T > \nabla_{ad}$. This is, according to Schwarzschild's criterion, a sufficient condition for the start of convective motions. Convective heat transport would keep the temperature gradient at its adiabatic value and mix new material into the region where electron Fermi energies are higher than the electron capture threshold. But electron captures not only heat up the material and thus steepen the temperature gradient, they also produce a positive Y_e-gradient. Therefore, stability analysis has to include the effects of chemical inhomogeneity. The Ledoux criterion takes them into account. According to this criterion, the condition for onset of convection becomes $\nabla_T > \nabla_L$, where

$$\nabla_L \equiv \nabla_{ad} + \left[\left(\frac{\partial \ln P}{\partial \ln Y_e}\right)_T \Big/ \left(\frac{\partial \ln P}{\partial \ln T}\right)_{Y_e}\right] \nabla_{Y_e}, \qquad (1)$$

with

$$\nabla_{Y_e} \equiv -\frac{d \ln Y_e}{d \ln P}$$

(see, for instance, Cox & Giuli 1968). A much steeper temperature gradient has to be reached, in the present case, before convective mixing (and thus heat transport) sets in. Less material is involved in the electron captures and higher temperatures are attained. The mean Y_e for the whole core decreases more slowly (Miyaji & Nomoto 1987; Nomoto

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1987). Together with the electron-capture rates, this is very relevant to the ignition density of Ne-O burning. For the electron-capture rates derived from the gross theory of β-decay (Miyaji et al. 1980), when Schwarzschild's criterion is adopted, ignition (induced by electron captures on ^{20}Ne) does not happen until the central density is as high as $\rho_c \simeq 2 \times 10^{10}$ g cm^{-3} and the core is already contracting quasi-dynamically. Electron captures on the incinerated (NSE) material then induce core collapse (Miyaji et al. 1980; Nomoto 1987). With Ledoux criterion (and the same rates), after a sharp temperature rise at $\rho_c \simeq 4 \times 10^9$ g cm^{-3}, due to electron captures on ^{24}Mg and ^{24}Na, that nonetheless fails to ignite Ne, explosive ignition happens at $\rho_c \simeq 9.5 \times 10^9$ g cm^{-3} as an outcome of electron captures on ^{20}Ne and ^{20}F. In those calculations (Miyaji & Nomoto 1987) any propagation of the explosive burning was artificially suppressed. Collapse was thus obtained, as for ignition at higher densities. In this *Letter* we show that the outcome depends on the velocity of the burning front. If a turbulent burning front develops almost from the start and its velocity is parameterized in the way suggested by Woosley (1986), explosive disruption of the core is obtained for the most reasonable values of the parameters. Besides, more recent and better electron-capture rates on the relevant nuclides (Takahara et al. 1989) have changed significantly the above picture as to ignition densities: the capture rates on ^{24}Mg and ^{24}Na (and the corresponding heating) being larger by about one order of magnitude than previous ones (Miyaji et al. 1980; Fuller, Fowler, & Newman 1982) in the density range 4×10^9 g cm$^{-3} \leq \rho \leq 9.5 \times 10^9$ g cm^{-3}, mixing of fresh ^{24}Mg (hence, ^{24}Na) into the central, high-density regions of the core makes it possible to ignite Ne and O at densities even lower than the electron-capture threshold on ^{20}Ne. This would reinforce our conclusion. Actually, the situation where $\nabla_L > \nabla_T > \nabla_{ad}$ is *overstable* and can lead to formation of a double diffusive interface (Mochkovitch 1984).

2. MODELS, RESULTS, AND DISCUSSION

Our calculations start from a ONeMg core with mass $M = 1.38\ M_\odot$, central density, $\rho_c = 9.5 \times 10^9$ g cm^{-3}, central temperature (before explosive ignition) $T_c = 2.3 \times 10^8$ K, and a uniform chemical composition (but in the innermost layers): $X_O = 0.12$, $X_{Ne} = 0.72$, and $X_{Mg} = 0.12$, taken from current models (Miyaji & Nomoto 1987). In order to be consistent with previous evolution (with no mixing), ^{24}Ne is substituted to ^{24}Mg in the region from center to the point where electron Fermi energy equals the threshold energy for the corresponding capture. The equation of state for the ion component of the plasma is taken from Ichimaru, Iyetomi, & Ogata (1988). For the electron component we adopt an ideal Fermi gas plus electron-positron pairs. Matter is incinerated at the center, as in Miyaji & Nomoto (1987). The electron-capture rates on NSE material are calculated from the expressions of Epstein & Arnett (1975), recalibrated by comparison with the more recent rates of Fuller et al. (1982). The core model has 250 mass shells. Hydrodynamic burning propagation (in one dimension) is then simulated through a parameterized burning front velocity:

$$v_{\rm burn} = F c_s (1 - e^{-r/R_0}) , \qquad (2)$$

where c_s is the local sound speed, r is the distance to the center, and F and R_0 are the adjustable parameters (Woosley 1986). This is a fairly representative (and rough) simulation of the propagation of a turbulent burning front. It has more recently been revised to a power law based on the fractal dimension of the flame (Woosley 1990). Suggested values for the parameters are $F = 0.5$ and $R_0 = 2 \times 10^7$ cm, in the case of a carbon deflagration at lower densities (Woosley 1986). We explore here a range of these parameters in models A, B, C, and D of Table 1. In all of them the front velocity rises more slowly than in the aforementioned carbon case. This has been adopted because we already know, from the CO case, that the choice $F = 0.5$ and $R_0 = 2 \times 10^7$ cm leads to explosion even at the high densities considered here (Canal et al. 1990). Thus, only smaller values of F and/or larger values of R_0 could, in this parameterization, produce bound remnants. Physically, this would reflect the fact that the effective velocity of the flame is slower due to suppression of the Rayleigh-Taylor instability by electron capture behind the front (Woosley 1990, private communication). Nonetheless, the velocity should be larger than given by equation (2) from the center up to the point where equation (2) equals the conductive velocity.

Figure 1 shows the time evolution of central density, from ignition up to 0.5–1.5 s. Burning has been artificially suppressed when the density in the last layer reached by the front falls below 2×10^8 g cm^{-3}. This is purely a time-saving procedure that does not affect the issue of whether the star collapses or explodes, with the possible exception of model C. Models A and B are clearly disrupted in a supernova-like explosion. Only model D (an extremely slow deflagration) recontracts after the initial bounce to eventually collapse to a neutron star. Model C, instead, shows a frontier behavior: it expands and ejects $\simeq 0.14\ M_\odot$ to recontract afterwards to a white dwarf of smaller mass and with a 0.6 $M_\odot$ inner core made of Fe-peak nuclei. The total mass of this white dwarf (1.24 $M_\odot$) is below the Chandrasekhar mass for a white dwarf made of a 0.6 $M_\odot$ inner core of ^{56}Fe plus outer layers of ONeMg (i.e., with Coulomb corrections: 1.29 $M_\odot$). In the four last columns of Table 1 we give the incinerated masses, the ^{56}Ni masses, the kinetic energies, and the remnant masses, respectively, for models A–D. The difference in ^{56}Ni mass between models A and B not only arises from the difference in the respective masses of incinerated material but also from larger neutronization of the central layers in model B, the last producing more nonradioactive ^{56}Fe.

Cases A and B might correspond to some type of SN I

TABLE 1

MODEL CHARACTERISTICS

Model	F	R_0 (10^7 cm)	$M_{\rm inc}$ ($M_\odot$)	$M_{\rm Ni}$ ($M_\odot$)	$E_{\rm kin}$ (foe[a])	$M_{\rm remn}$ ($M_\odot$)
A	0.30	2.0	1.03	0.42	0.59	...
B	0.30	5.0	0.85	0.32	0.41	...
C	0.30	10.0	...	...	0.14	1.24 (WD)
D	0.15	10.0	...	...	...	1.38 (NS)

[a] 1 foe ≡ 10^{51} ergs.

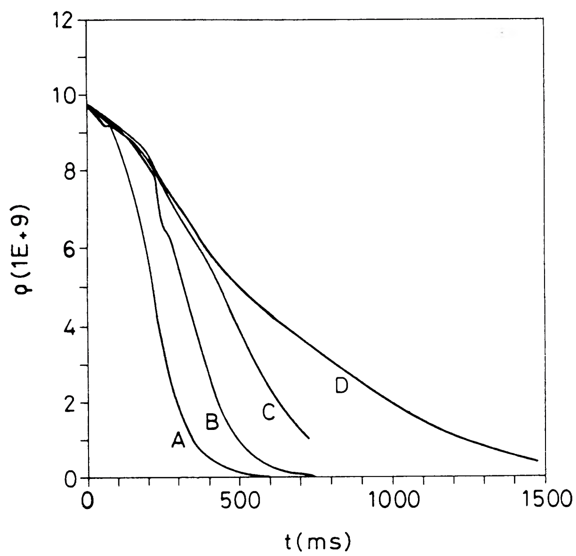

FIG. 1.—Central density versus time (up to 1.5 s after ignition) for models A, B, C, and D of Table 1. Models A and B are completely disrupted. Only model D (extremely slow deflagration) eventually collapses to nuclear matter densities. Model C is a limiting case: after ejecting $\simeq 0.1\ M_\odot$ it contracts again to form a "Fe" white dwarf.

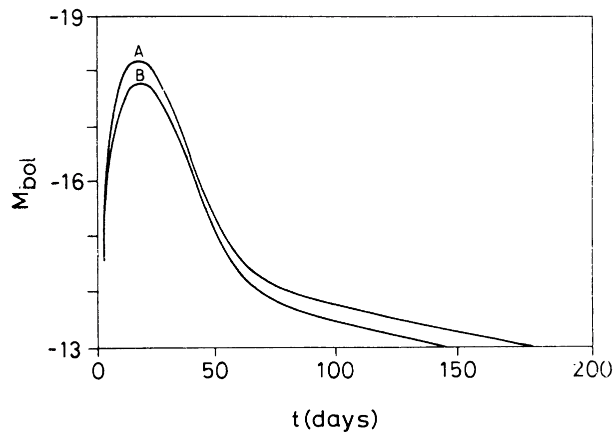

FIG. 2.—Semianalytical light curves for models A and B. The difference in their peak luminosities arises from the also different masses of radioactive ^{56}Ni that are synthesized in the two models: 0.42 $M_\odot$ in model A and 0.32 $M_\odot$ in model B. The smaller ^{56}Ni mass in model B results both from smaller incinerated mass and from larger neutronization of the central layers (the last giving a larger mass of stable ^{56}Fe).

outburst when taking place in a ONeMg white dwarf or in a single star having previously lost its H-rich envelope (otherwise, in the last case, a SN II would result). Semianalytical light curves (based on the approach developed by Arnett & Fu 1989) are presented in Figure 2, for models A and B (bare ONeMg cores). They might either correspond to a Type Ib/c supernova or still be within the suspected range of variation of SN Ia outbursts (Wheeler & Harkness 1990): more refined modeling is required.

Finally, case C would give a dim outburst but it might produce a "Fe" white dwarf. To properly elucidate this issue, burning at densities lower than 2×10^8 g cm^{-3} should be included (the extra energy released may induce larger mass ejection). Besides, burning will recommence when the white dwarf recontracts. This could increase the mass of the inner ^{56}Fe core but it might also lead to new episodes of mass ejection. Such a complete calculation is beyond the scope of this *Letter*. Here we only point out the possibility of producing white dwarfs with "Fe-peak" composition. The existence of these objects might be indicated by "Fe novae" such as Nova Mus 1983 (Freitas Pacheco & Codina 1983), or V1370 Aql (Snejders et al. 1984), as it has recently been speculated by Prialnik et al. (1989). It should be noted, in this respect, that explosive ejection of $\simeq 0.1\ M_\odot$ of material would not disrupt the close binary system (Taam & Fryxell 1984). It must be stressed, however, that because of the lack of lines in the visible part of the spectrum for many important ionization states, the evidence for Fe enhancement in both novae is weak.

From the present calculations it might be concluded that collapse to a neutron star is most unlikely for ONeMg cores (both in single stars and in mass-accreting white dwarfs) igniting Ne at densities $\rho_c \simeq 10^{10}$ g cm^{-3}. That depends, however, on the assumption (implicit in eq. [2]) that a turbulent flame front quickly develops as a consequence of the growth of a Rayleigh-Taylor instability. But at densities as large as 10^{10} g cm^{-3}, the density soon rises again behind the burning front due to the fast electron captures on the incinerated material. This can inhibit the growth of the instability, the width of the low-density region behind the initially conductive burning front remaining for a long way smaller than the minimum wavelength instability that can grow before being consumed by the flame (Woosley 1990, private communication). The conductive velocity being $\simeq 40$ km s^{-1}, the situation would thus be similar to our case D.

Returning now to the problem of at which exact density does Ne-O ignition actually take place, we must stress that modeling of the semiconvective region should be pursued along the lines traced by Mochkovitch (1984). Besides, the new electron-capture rates of Takahara et al. (1989) give lower ignition densities than those of Miyaji et al. (1980). In the case with no mixing, $\rho_{\rm ign} \simeq 8.5 \times 10^9$ g cm^{-3} is obtained. In the cases of mixing, there is competition between the more efficient heat transport associated with it and the larger local heating due to electron captures far above threshold made possible by the same mixing (Canal et al. 1991, in preparation).

ONeMg cores thus appear as extremely interesting objects: the physics of their explosive ignition may well be a key to such phenomena as SN Ia and SN Ib/c outbursts, or perhaps to a new type of object. Of course, only one of these possible outcomes will actually happen. Ignition density plus the velocity of the burning front are the keys to the issue.

We would like to thank S. E. Woosley for his valuable suggestions and also for communicating his unpublished results to us. This work has been supported in part by CICYT grants PB87-0304, PB87-0147, and PB87-0150.

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