NEUTRON STAR FORMATION BY COLLAPSE OF WHITE DWARFS

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ABSTRACT. Mass-accreting carbon-oxygen white dwarfs become thermally and dynamically unstable when they reach high enough central densities. Carbon ignition at the star's center likely propagates subsonically and, in the case of an initially solid core, leads to collapse if the rate of increase of the core's mass is sufficiently fast. Recent results indicate, however, that solidification of the core induces carbon-oxygen separation. The central regions are then made of pure oxygen while carbon is rejected to lower-density layers. Carbon ignition happens only after neutronization of the central (oxygen) regions. Collapse to a neutron star is then independent from the rate of mass increase and the only possible restrictions are set by the behaviour of the outer, accreted layers. X-ray sources, pulsars and Type I supernovae are likely outcomes of this process.

1. INTRODUCTION

Single star evolution is one possible origin for neutron stars. Massive stars ($M \gtrsim 10\ M_\odot$) may be able to eject enough matter by means of core bounce (Arnett 1980), neutrino energy deposition by core overturn (Buchler and Livio 1980, this volume), or by heating of the outer core by the reflected shock (Lichtenstadt, Sack, and Bludman 1980), to collapse to neutron stars (see, however, Bowers 1980, in this volume). The fate of intermediate-mass ($6 \pm 2\ M_\odot \lesssim M \lesssim 8 \pm 2$ to $3\ M_\odot$) is much more uncertain. If not enough mass is previously lost (Tinsley 1977), thermal runaway at carbon ignition ($\rho_c = 2$ to 3×10^9 g cm^{-3} and $T_c \gtrsim 3 \times 10^8$K) seems to lead to the complete dispersion of the star (Nomoto, Sugimoto, and Neo 1976; see, however, Buchler, Colgate, and Mazurek 1980). Finally, the mass range $8\ M_\odot \lesssim M \lesssim 12\ M_\odot$ might also produce neutron stars by collapse induced by the electron captures on Mg, Ne, and O (Miyaji *et al.* 1979).

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The currently estimated high pulsar birthrate (Taylor 1979), the low rate of death of massive stars needed to explain galactic nucleosynthesis (Arnett 1978), the existence of low-mass ($M_{tot} \lesssim 5\ M_\odot$) binary X-ray sources, are indications that another source of neutron stars is probably required (Canal 1980). White dwarfs in close binary systems are likely candidates. Accreting white dwarfs have been suggested as the origin of Type I supernovae (Whelan and Iben 1973). The problem of the collapse of carbon-oxygen white dwarfs when they are brought over their dynamical instability limit by mass accretion has been considered by Canal and Schatzman (1976), Ergma and Tutukov (1976), Canal and Isern (1978, 1979), and Canal, Isern, and Labay (1980a, b). Canal and Isern (1978, 1979) studied the case of thoroughly mixed $^{12}C-^{16}O$ white dwarfs and found collapse to nuclear matter densities for fast accretion, provided that the star's core were largely solidified. Here, we take into account the fact, reported by Stevenson (1980), that carbon and oxygen very likely separate when they freeze. The star's center being then made of almost pure oxygen, the chances of collapse are independent from the rate of increase of the core's mass. Remaining problems will be briefely pointed out.

2. RESULTS AND DISCUSSION

Our general scenario involves a carbon-oxygen white dwarf plus a main-sequence secondary, a very common kind of binary system (Webbink 1979). The degenerate core of the white dwarf is assumed to cool down and contract during the detached phase of the system. This phase may be very long ($t \gtrsim 10^9$ years), so there is enough time for the central layers to begin to crystallize (see Lamb and Van Horn 1975). The chemical composition is rather arbitrarily fixed: $X_C = X_O = 0.50$, by mass.

2.1. Completely mixed case

This case has been studied by Canal and Isern (1978, 1979). The dynamical instability is due to the electron captures on ^{16}O. It appears for $\rho_c = 1.92 \times 10^{10}$ g cm^{-3}, corresponding to $M = 1.365\ M_\odot$. Thermal stability is only possible, however, for $\rho_c \lesssim 6 \times 10^9$ g cm^{-3}, corresponding to $M = 1.357\ M_\odot$. In order to keep $\tau_\rho < \tau_{th}$ during the accretion phase previous to collapse (τ_ρ and τ_{th} being the time scales for the increase of central density and for nuclear heating, respectively), the accretion rate must be very high. This is illustrated in Figure 1 for the extreme composition $X_C = 1$, $X_O = 0$, and for an accretion rate equal to the Eddington limit. The carbon flash happens here for ρ_c slightly above 10^{10} g cm^{-3}. For $X_C = X_O = 0.50$, it occurs at practically the same density. If the nuclear burning

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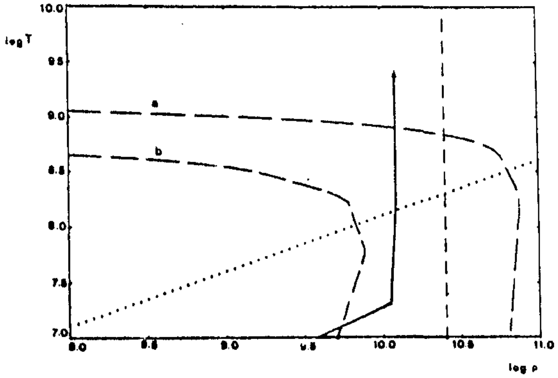

Figure 1. Carbon flash in a pure carbon white dwarf accreting mass at the Eddington limit. Dashed curve a is the limit for explosive burning; b, that for thermal stability. Vertical dashed line is the dynamical stability limit (due here to general-relativistic effects). Dotted line separates crystallization and Coulomb liquid states.

were to propagate supersonically (detonation wave), it would disrupt the entire star. But this pssibility seems unlikely (Mazurek et al. 1977). Carbon burning should then propagate as a deflagration. For low ($T_c \lesssim 10^7$K) initial temperatures most of the star's mass is in the crystallization zone of the temperature-density diagram. Burning propagates only by conduction and gravitational collapse ensues, following the electron captures on the incinerated material. Hydrodynamical calculations were carried only up to the time when the central density was $\rho_c \simeq 5\text{x}10^{11}$g cm^{-3}. Mass ejection was not possible to ascertain.

2.2. Carbon-oxygen separation

A very important result has recently been reported by Stevenson (1980). It concerns carbon-oxygen separation at the freezing point. A carbon-oxygen alloy can exist only for a particular composition (the "eutectic" composition) of 33.2% oxygen by number. The crystal initially formed will be almost pure carbon or almost pure oxygen, depending on whether the fluid phase is carbon-rich or carbon-poor relative to the eutectic composition. So, for $X_C=X_O=0.50$, the solid which first freezes from the mixture would be almost pure oxygen. Sinking oxygen "snow" will accumulate in the central regions of the star. When the eutectic is reached in the remaining fluid (which continuously rehomogenizes due to the "salt finger" instability), pure solid carbon can also form: this will rise and re-dissolve higher up, aiding the differentiation. The final state will be an almost completely differentiated body:

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a solid oxygen core and an overlying solid carbon mantle. It must be noted that the process do slow the rate of cooling of the star. So, it involves a longer time scale than the simpler process usually considered. The study of this phase is beyond the scope of the present paper.

Figure 2 illustrates the evolution of the star's center from the onset of accretion (assumed to produce only the corresponding increase of the core's mass). Two extreme rates are considered: $10^{-6} M_{\odot} yr^{-1}$ (roughly the Eddington limit) and $10^{-12} M_{\odot} yr^{-1}$ (time scale of accretion of the order of the Hubble time). The initial point in the temperature-density diagram ($T = 6 \times 10^{7}$ K; $\rho = 5 \times 10^{9}$ g cm^{-3}) is perfectly attainable by contraction and cooling of a stellar core unable to ignite carbon during the red-giant phase. It has been intentionally chosen very close to the melting line. The central density corresponds to a completely degenerate configuration of $\sim 1.4\ M_{\odot}$.

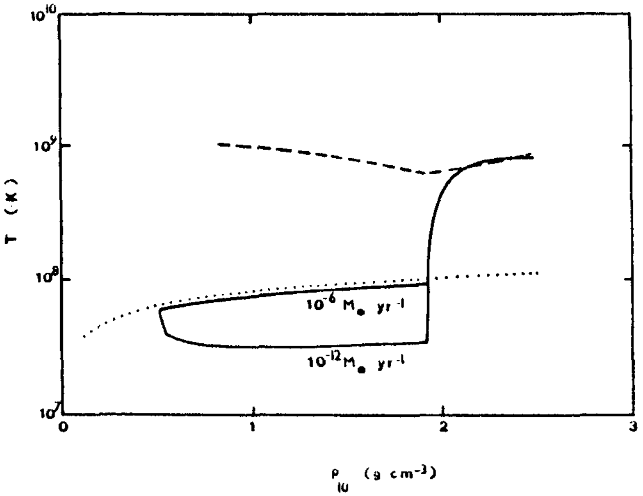

Figure 2. Evolution of the center of a pure oxygen white dwarf during mass accretion. Dotted curve is the melting line for ^{16}O. Dashed curve is the ignition line for ^{16}O; its shape takes into account ^{16}O exhaustion by the electron captures.

We see that, up to $\rho_c = 2 \times 10^{10}$ g cm^{-3}, compressional heating is counteracted by thermal neutrino cooling. Then, the electron captures: $^{16}O + 2e^- \rightarrow {}^{16}C + 2\nu_e$ produce a thermal runaway and the time scale of contraction changes to being governed by the electron captures. The situation, however, remains quasi-hydrostatical all the way. The progressive change in the shape of the curve is due to ^{16}O exhaustion (90% of the oxygen has been neutronized at the endpoint of the curve), to

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cooling by thermal neutrinos and to lower heating effect of the electron captures for higher temperatures. Although the final stabilization in temperature is obtained neglecting the thermal effect of $^{16}C+^{16}C$ reactions, this is not relevant for the outcome of the process, since the density at the beginning of the electron captures on ^{16}O is already high enough to ensure the collapse to nuclear densities, as we have seen in the preceding subsection.

Later, compression of the carbon layers also ignites them. Assuming a slightly lower initial temperature, most of the core's mass is solid and the carbon is confined to the outer half of the star's mass. When it flashes, the neutronized central oxygen layers are already collapsing.

The heating of the oxygen layers by the electron captures sets up a strongly superadiabatic gradient. So, when these layers progressively melt, convection develops, and fresh ^{16}O is brought to the central layers. Calculations taking into account this effect (Canal, Isern, and Labay 1980c) indicate that the overall picture does not change much, since the density at thermal runaway is high enough to ensure collapse to nuclear densities by electron captures on the incinerated (NSE) matter.

3. CONCLUSIONS

Separation of oxygen and carbon when they freeze should ensure the collapse of accreting $^{12}C-^{16}O$ white dwarfs. This is independentfrom the rate of mass accretion, as far as only the behaviour of the internal layers is concerned. Limitations might be set, however, by the processes taking place in the accreted layers (see Nomoto 1980, this volume). Ignition of the carbon layers might result in mass ejection, maybe observable as a SN I event. Calculations are under way (Canal, Isern, and Labay 1980c), to deal with this aspect of the problem. A possible effect of this mass ejection might be the disruption of the binary system and the formation of isolated pulsars. Mass accretion beginning at different stages of the cooling-separation phase should also produce different types of events. Also, the huge neutrino and antineutrino fluxes associated with stellar collapse are likely to induce, when interacting with the accreted layers, new types of nucleosynthesis of light isotopes, even perhaps appreciable deuterium synthesis.

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DISCUSSION

COLGATE: The crystallization of the core consists of enough strength to stop convection during deflagration. This solves the presupernova problem. I doubt, however, that the strength is enough for an off-center ignition.

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