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# COLLAPSE OF WHITE DWARFS IN LOW MASS BINARY SYSTEMS

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RESUMEN. Las fuentes de rayos X de masa pequeña y las variables cataclísmicas están formadas por una estrella compacta y una estrella no degenerada cuya masa es del orden de la del Sol. En el primer caso, la estrella degenerada es una estrella de neutrones y en el segundo una enana blanca. Las similitudes entre ambos sistemas son tales que parece útil analizar la posibilidad de obtener una estrella de neutrones a partir del colapso de una enana blanca que capture materia. El presente estudio sugiere que las enanas blancas masivas, inicialmente frías, que capturan materia a un ritmo superior a 1.0E-7 $M_\odot$ por año, pueden colapsar de forma no explosiva.

ABSTRACT. Low-mass binary X-ray sources and cataclysmic variables are composed of a compact star plus a non degenerate star with a mass of the order of 1 $M_\odot$. In the first case, the degenerate star is a neutron star. In the second case, the star is a white dwarf. The similarities of both systems are so high that it is worthwhile to look for the possibility of obtaining a neutron star from the collapse of a white dwarf that accretes matter. The present work shows that massive, initially cold white dwarfs can collapse non explosively if they accrete mass at a rate greater than 1.0E-7 $M_\odot$ per year.

*Key words:* STARS-COLLAPSED -- STARS-STRUCTURE -- STARS-WHITE DWARFS

## I. INTRODUCTION

Galactic X-ray sources are divided into Type I and Type II. Type I are composed of a neutron star plus a massive companion (10 $M_\odot$) that, according to the optical spectrum, is thought to be an early star. Their X-ray emission shows pulses and the X-ray spectrum is hard. They are distributed along the galactic plane and belong to the young stellar population. Type II X-ray sources are composed of a low-mass companion (1.0-1.5 $M_\odot$) and the spectrum is softer than that of Type I sources, indicating that the region where X-rays form is bigger and, except for two or three exceptions, they are non-pulsating. This is interpreted as that the magnetic field of the neutron star is weaker in Type II than in Type I sources (Van den Heuvel and Habets 1985). The origin of the neutron stars present in low mass binary sources is still an open question as the assumption that the neutron star comes from a supernova explosion seems excluded by the low value of the mass of the system.

Two mechanisms have been advanced in order to explain the presence of a neutron star in such systems: The capture of a previously formed neutron star and the non explosive collapse of a white dwarf that accretes matter from the companion.

The problem of theories that assume the capture of a neutron star is that Type II

X-Ray sources are composed by objects like globular cluster sources, Sco X-1 systems and so on. The capture mechanism is acceptable in the case of globular cluster sources as the star density is high and their relative velocities are low there. However, this mechanism does not work in the case of the galactic bulge sources because the dispersion velocity of the bulge stars is very high (100 Km/s) and the capture energy that must be dissipated by tidal forces is similar to the binding energy of the non degenerate star.

Theories that assume a non explosive collapse of white dwarfs face the problem that these stars are extremly fragile objects because they still have enormous amounts of nuclear energy (1.0E51 ergs in the case of a C-O white dwarf with 1 $M_\odot$) that can be released in an explosive way. In fact, these objects have been proposed successfully as progenitors of Type I supernovae (Schatzman 1963; Truran and Cameron 1971; Whelan and Iben 1973) and current models predict that no bound remnant is left after the explosion (Nomoto 1982).

The distribution of X-Ray sources and novae in M31 (Vader et al 1982) increases the interest of the idea of a non explosive collapse of a white dwarf. Novae and field bulge X-Ray sources follow closely the light distribution of the bulge of M31 except for a central region of $\sim 2'$ where novae are absent. As it is rather unlikely that these sources belong to optically unidentified globular clusters or that they come from globular clusters that evaporated or were destroyed by tidal forces during the past 1.0E9 years, Vader et al (loc. cit.) suggested that the X-Ray sources are the products of the long term evolution of novae and that the "novae hole" in M31 is due to the fact that novae had evolved beyond the nova stage. The similarities between cataclysmic variables and Type II X-Ray sources are so high (it is sufficient to change the white dwarf for a neutron star) that it is tantalizing to look for the posssibility of a direct collapse of a white dwarf into a neutron star (Schatzman 1956). So, the problem is how to prevent the explosion, or in other words, how can a white dwarf sometimes collapse and sometimes explode?.

One possibility is to assume a white dwarf composed of a chemical element less energetic than carbon. This is the case of the O-Ne-Mg white dwarfs proposed by Nomoto (1982). The evolution of 8-10 $M_\odot$ stars leads to the formation of O-Ne-Mg cores. If the mass loss is efficient enough (this implies a strong wind for a single star or a Roche lobe overflow for a close binary system) neon does not ignite and the star ends its life as an O-Ne-Mg white dwarf.

Another possibility is to take advantage of the fact that oxygen cristallizes first and falls to the center of the white dwarf (Stevenson 1979). This can lead to the complete chemical separation of the star. The inner part being composed by oxygen and the outer part by carbon. Calculations have shown that it is possible to obtain a collapse for a reasonable range of parameters of the system (Canal, Isern and Labay 1980; Isern et al 1983; Labay et al 1985). Here we want to show that even an ordinary, completely mixed C-O white dwarf can have the chance to collapse.

## II MODELS AND RESULTS

The outcome of thermonuclear runaway at the center of a white dwarf depends on the competition between the energy injected by thermonuclear reactions and the energy removed by the electron captures. If we want to obtain a collapse we have to favour the electron captures. This implies that we have to delay the ignition of fuel until densities become as high as possible.

The energy sources of an accreting white dwarf are nuclear reactions and compressional heating. If we want to minimize the effect of nuclear reactions, we have to assume that the star is very cold. In this case the nuclear reactions happen in the pycnonuclear regime (Salpeter and Van Horn 1969).

The major contribution to the compressional heating work comes from the external layers. Their contribution to the luminosity can be estimated as (Nomoto 1982):

$$L/L_\odot = 1.4\times10^{-3}\ T_7\ (\dot{M}\ /\ 10^{-10}\ M_\odot/yr)$$

that can be very high for high accretion rates. As a consequence of this compressional work a thermal wave propagates inward and can ignite the carbon. The time taken by the wave to go from the surface to the center is given by (Henyey and L'Ecuyer 1969):

$$\tau_{st} = \left[ \frac{3}{64\sigma} \int_0^R \left( \frac{\kappa\, C_p^{1/2}}{T^3} \right) \rho\, dr \right]^2$$

and the accretion lasts for a time given by

$$\tau_M = \frac{M_{ch} - M}{\dot{M}}$$

where $M_{ch}$ is the Chandrasekhar mass, M is the initial mass and M is the accretion rate. It can be shown that if $M > 1.2\ M_\odot$ and M is high, the thermal wave has no time to arrive to the center and the central layers evolve adiabatically. The adiabatic index is

$$\Gamma_3 - 1 = (0.815+0.215\,\Gamma^{1/4})/(0.945+0.646\,\Gamma^{1/4})$$

where $\Gamma$ is the plasma coupling constant. For the temperatures considered here $\Gamma \sim 200$ and $\Gamma_3 - 1 \simeq 0.5$, a rather low value. From these considerations we see that massive, cold white dwarfs that accrete matter at high rates are the best scenario for delaying the thermonuclear runaway to high densities.

In order to obtain more accurate figures about the ignition density threshold we have constructed models whose masses and central temperatures are given by Table 1 and the same input physics as in Isern et al (1983).

Table 1. Parameters of the initial models.

| $M_o$ | $T_7$ |
|---|---|
| 1.2 | 0.50 |
| 1.3 | 0.66 |
| 1.4 | 1.71 |

The central densities reached at the onset of the thermonuclear runaway are given in Table 2. The velocity of the burning front is very uncertain. A preliminary study (Woosley 1986) suggests that in the central region we have

$$v = 0.08 * r\ \mathrm{cm/s}$$

where r is the radius. The velocity of a conductive front is of the order of 1.0E7 cm/s. This implies that conduction will be dominant in the region r < 5.0E7 cm and the flame will take 5 s to go across it. At the same densities , the time scale for electron captures is

$$\tau_e = |Y_e / \dot{Y}_e| \mathrel{\hat{=}} 1 \text{ s}$$

so we expect that electron captures will be able to overcome the explosion and induce the collapse.

Table 2. Central ignition densities.

| $M(M_\odot)$ | 1.2 | 1.3 | 1.4 |
|---|---|---|---|
| $M_o(M_\odot/yr)$ | $\rho_9$ | $\rho_9$ | $\rho_9$ |
| 1E-6 | 12.5 | 13.2 | 13.9 |
| 1E-7 | 7.6 | 11.7 | 12.4 |
| 5E-8 | 6.9 | 11.0 | 12.0 |
| 1E-9 | 9.5 | 9.8 | 10.6 |

We can wonder if the initial conditions are reasonable. High accretion rates may be obtained if we assume that the secondary is a 1 $M_\odot$ giant or subgiant that is burning hydrogen in a shell around a helium core that has a mass of 0.2 - 0.4 $M_\odot$ (Webbink, Rappaport and Savonije 1983; Taam 1983) and that the system is wide (P days). In this case, the accretion rate would be

$$\dot{M} = 6.0E\text{-}10 \ (p/\text{days}) \ M_\odot/\text{yr} .$$

This scenario also provides a natural way to have a cold white dwarf because the time elapsed from the formation of the massive white dwarf to the Roche lobe overflow of the secondary is longer than 5.0E9 years.

## III. CONCLUSIONS

We have shown that old, solid and rather massive white dwarfs can reach high densities before the onset of the thermonuclear runaway provided that the mass accretion rate will be high enough. The collapse to nuclear densities is predicted on the basis of the high densities reached and on the low velocity of the convective burning front in the central regions. This picture is consistent with the scenarios proposed in order to explain the properties of low mass binary X-ray sources.

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## DISCUSSION

IBAÑEZ: ¿La onda térmica que se propaga hacia el centro es del tipo "Marshak wave"?

ISERN: El exceso de calor producido en la superficie se propaga por conducción térmica.

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