ACCRETION-INDUCED COLLAPSE OF OLD WHITE DWARFS

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ABSTRACT. There is observational evidence of the presence of young neutron stars in old binary systems. A likely explanation is that those neutron stars were produced in the collapse of old CO white dwarfs. We show how mass accretion on initially solid white dwarfs can leave central solid cores when dynamical instability sets in and we study the different effects of the existence of such cores on the outcome of the competition between thermonuclear explosion and gravitational collapse.

1. INTRODUCTION

Type II galactic X-ray sources are thought to be formed by a neutron star plus a non degenerate low-mass star ($M \sim 1\ M_\odot$). This class of X-ray source includes globular cluster sources, galactic bulge sources, Sco X-1 sources and X-ray bursters. Several mechanisms have been suggested in order to explain the existence of such objects:

a) Capture of a previously formed neutron star. This kind of process might be a valid explanation for the globular cluster sources, but it cannot explain the other ones, specially the X-ray bulge sources due to their high relative dispersion velocity (Van den Heuvel 1981, Van Paradijs 1984).

b) The X-ray source could have been formed inside a globular cluster that evaporated or was destroyed. However, it seems that the number of such clusters is much lower than the observed number of X-ray sources (Vader et al 1981).

c) Non explosive or midly explosive collapse of a massive whidwarf that accretes matter in a close binary system during the accretion process. This idea is, by far, the most simple if we are able to reconcile it with the fact that a white dwarf is an extremly fragile object that still contains 10^{51} ergs of thermonuclear energy that can be liberated explosively. Evidently, one way to solve this paradox is to take

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into account white dwarfs that have a low nuclear energy content. This is the case of the O-Ne-Mg white dwarfs proposed by Miyaji et al (1980) and Nomoto (1982, 1984). However, as ordinary C-O white dwarfs are more common it is worthwhile to consider the plausibility of the collapse of such stars.

There is observational evidence that young neutron stars are present in old binary systems. The wide binary pulsars PSR 0820-20 and PSR 1953+29 (the 6 ms pulsar) have companions with a mass in the range of 0.2-0.4 M⊙ and have magnetic fields with strengths of $3.3x10^{11}$ and $2.5x10^{9}$ gauss respectively. So the age of the system must be greater than 5 billion years and the age of the neutron star lower than 100 million years (Van den Heuvel 1984).

The orbital characteristics of such systems are so similar to that of X-ray bulge sources that it is generally accepted that they are descendents of low-mass X-ray binaries whose neutron star was spun up by the accretion of matter from the companion ($M \lesssim 1.2$ M⊙) which eventually becomes a white dwarf with a mass in the range of 0.2-0.4 M⊙ (Savonije 1983; Paczynski 1983; Joss and Rappaport 1983; van den Heuvel and Taam 1984; Van den Heuvel 1984; Rawlwy et al 1986).

In order to link both systems, Webbink, Rappaport and Savonije (1983) and Taam (1983) have constructed models composed of a neutron star plus a giant or subgiant low-mass star ($M \sim 1$ M⊙) that is burning hydrogen in a shell around a helium core. As the mass of the core increases, the radius and the luminosity of the giant increase and the giant overflows the Roche lobe. The accretion rates are very high at the beginning but they rapidly settle to a constant value. For a neutron star of 1.3 M⊙ and a giant of 1M⊙, the accretion rate tends towards:

$$M \simeq 6x10^{-10}(P/days)\ M_{\odot}\ yr^{-1}$$

where P is the initial period in days and the mass transfer lasts for 60 million years, that is enough to account for the characteristics of low-mass X-ray sources. It is evident from this scenario that if the neutron star was form during the accretion process, the paradox posed by the presence of a young neutron star in an old binary system might be removed. (Van den Heuvel and Habets 1985)

2. MODELS AND RESULTS

We have evolved models of accreting white dwarfs that belong to wide and very old binary systems. This means that the time elapsed since the formation of the white dwarf and the onset of the mass transfer is several times 10^{9} years. As the time necessary to crystallize half the mass of a 1 $M_{\odot}$ star is $2x10^{9}$ years (Mochkovitch 1983), we expect that those white dwarfs will be almost completely solid. Table 1 displays the characteristic values of the models considered here; M^{o}_{T} represents the initial mass, M^{o}_{s} the size of the solid core and T_{7c} the temperature (of course, both parameters are not independent). All the quoted models are composed of a mixture of 50% of carbon and 50% of oxygen. As we are assuming that the companion is a giant or a subgiant low-mass star, the accreted matter will be composed of hydrogen. The nova phenomenon sets a lower limit of 10^{-9} $M_\odot$/yr to the accretion rate, and the Eddington limit an upper limit of 10^{-6} $M_\odot$/yr. The imput physics is similar to that described in Isern et al. (1983)

The final results, as to the greater or lesser extent of core melting, arise mainly from the compression of the external layers. Their luminosity is given by (Nomoto 1982):

$$L/L_\odot = 1.4x10^{-3}\ T_7\ \dot{M}_{10}$$

and the time taken by a thermal signal to go from the surface to the center is (Henyey and L'Ecuyer 1969):

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

where k, ρ, T, σ and c_p have their usual meaning. This time has to be compared with the time necessary for the white dwarf to reach the Chandrasekhar limit:

$$\tau_{CH} = (M_{CH} - M_T^0)/\dot{M}$$

It is evident, therefore, that the persistence of a solid core will be favoured in the case of massive white dwarfs that accrete mass at a high rate. Table 2 displays the central density of the white dwarf at the onset of the ignition (that is always central) and the size of the remaining solid core.

The two most relevant characteristics of the models are:

a) The nuclear reactions happen in the pycnonuclear regime and the density reached by the models is very high. They are near to those for which Bruenn (1972) found collapse even when a detonation was assumed to form. At such high densities, even for fluid layers, any delay in the start of the convection (remember that the gravity is zero at the center) would already produce the collapse (Buchler, Colgate and Mazurek 1979).

b) As the majority of the models presented here still have an important solid core, the thermonuclear burning must propagate conductively. Characteristic velocities are given by (Landau and Lifchitz 1970):

$$v = (\chi/\tau)^{1/2}$$

where χ is the conductivity coeficient (in cm^2/s) and τ is the characteristic time of thermonuclear reactions. Conductive velocities (100 km/s) are always smaller than the local sound speed (10.000 km/s). The importance of this phenomenon can be seen from the following figures. If we take a CO solid core with a central density $\rho_c = 10^{10}$ g/cm^3 and a radius of $5x10^7$ cm, a detonation initiated at the center would sweep the entire core in 0.1 s. A convective deflagration would take 1s and a conductive deflagration 3-17 s. The time scale for the incinerated material at the center is 1s.

3. CONCLUSIONS

We have shown that old,solid white dwarfs can remain so after mass accretion up to the point of thermonuclear instability. The high ignition density as well as the relative slowness of the conductive burning front predicted by our models indicate that a collapse to nuclear densities is the most likely outcome.

These properties of the white dwarfs are consistent with the properties of low-mass binary X-ray sources and the wide binary pulsars. Therefore, our model could provide a natural explanation for the presence of a young neutron star in an old binary system.

TABLE I

Solid mass fractions and central temperatures for the initial models

M_T^0	M_S^0	T_7^C
1.2	1.10	0.50
1.3	1.20	0.66
1.4	1.25	1.71

TABLE 2

Ignition densities (in $g.cm^{-3}$) and final solid core masses for models in Table 1 at the onset of the dynamical instability

$M_T^0 / M_\odot$	1.2		1.3		1.4	
$\dot{M}(M_\odot/yr)$	9	$M_c/M_\odot$	9	$M_c/M_\odot$	9	$M_c/M_\odot$
10^{-6}	12.5	0.32	13.2	0.63	13.9	1.15
10^{-7}	7.6	0.00	11.7	0.18	12.4	1.08
$5x10^{-8}$	6.9	0.00	11.0	0.14	12.0	1.09
10^{-9}	9.5	0.61	9.8	0.76	10.6	1.22

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