Mem. S.A.It. Vol. 74, 949

Memorie della

DD systems as SNe Ia Progenitors

Piersanti L.[1], Gagliardi S.[1,2], Iben I. Jr[3], and Tornambé A.[1]

[1] INAF-Osservatorio Astronomico di Teramo via M. Maggini, 64100 Teramo ,Italy, e-mail: piersanti,gagliardi,tornambe@te.astro.it
[2] Dipartimento di Fisica, Università degli Studi di Roma III, via della Vasca Navale 84, 00146 Roma, Italy,
[3] Astronomy Department, University of Illinois 1002 W. Green Street, Urbana, IL 61801 e-mail: icko@astro.uiuc.edu

Abstract. If the lifting effect of rotation is taken into account in modeling the evolution of CO WDs accreting CO-rich matter as a consequence of a merging process, it turns out that rotation triggers the accretion rate in such a way that the WD can increase in mass up and over the Chandrasekhar limit. In this case the braking due to the viscous friction between the accretion disk and the WD as well as to the possible GWR emission produces the contraction of the accreting structure so that the physical conditions suitable for explosive Carbon burning are attained at the center. These results are valid for WDs with total masses in the range $1.4 \div 1.5 M_{\odot}$, independently on the braking efficiency.

Key words. Binaries: general – Stars: rotation – Supernovae – White Dwarfs

1. Introduction

The observational evidence suggests that type Ia Supernovae (SNe Ia) are produced by the thermonuclear disruption of CO White Dwarfs (WDs) which accrete mass from their companions in binary systems. In this way the accreting WD can attain the Chandrasekhar mass limit ($M_{\rm Ch}$) so that Carbon burning is ignited at the center in highly degenerate physical conditions, thus producing the explosion. The matter accreted onto the WD can be composed mainly by hydrogen (Single Degenerate scenario) or by a mixture of Carbon and Oxygen (Double Degenerate scenario). In the first case it is assumed that the WD accretes matter from a normal star with an H-rich envelope, while in the latter it is assumed that the binary system is composed by two CO WDs with total mass of the system of the order of or greater than the Chandrasekhar mass limit and with initial separation such that the merging of the two component via gravitational wave radiation (GWR) emission can occur in a time smaller than the Hubble time.

Although the SD scenario is currently considered more promising as SNe Ia progenitor, it has been shown (Cassisi et al. (1998), Piersanti et al. (2003), Piersanti et al. (2000), Piersanti et al. (2001)) that if H-rich matter is accreted the WD can not grow in mass up to the Chandrasekhar mass limit. In this case an explosive event of the He-detonation type can be produced for a very narrow range of accretion rate and initial mass of the WD, but the produced nucleosynthesis does not reproduce some spectral features of SNe Ia. On the other hand the DD scenario is considered not promising as SNe Ia progenitor system since up to now only a DD system with the right orbital parameters has been observed (KPD 0422+5421 - see Koen et al. (1998)). In addition the extant numerical models describing merging systems suggest that at the merging time the less massive component disrupts forming an accretion disk around the more massive one so that CO-rich matter is accreted directly at a very high rate (Tutukov & Yungelson (1979), Iben & Tutukov (1984), Benz et al. (1990), Rasio & Shapiro (1995), Mochkovitch et al. (1997)). In this case off-center Carbon burning is ignited well before the WD could attain $M_{\rm Ch}$ so that the final outcome is an O-Ne-Mg WD, not a SN event (Mochkovitch et al. (1997), Nomoto & Iben (1985), Rasio & Shapiro (1995), Saio & Nomoto (1985), Saio & Nomoto (1998)).

However, according to the results of stellar population synthesis, the right number of DD systems to account for the observed frequency of SNe Ia has to form (Iben & Tutukov (1997), Livio (2000)), but these systems are intrinsically very faint so that a large part of them can not be observed with the current generation telescopes. Moreover, the extant numerical results on DD merging binaries have been obtained by assuming that rotation is negligible in the evolution of accreting models. This assumption, which is generally well-founded in stellar Astrophysics, is no longer valid for DD systems since, in this case, the synchronization of the orbits occurs on a very short time scale. As a consequence, during the GWR-driven shrinking, each component rotates around its own rotational axis at the same angular velocity at which it rotates around the center of mass of the system itself so that at the merging time the angular velocity of the accreting WD can be as high as 0.1 rad/s and rotation becomes a leading parameter in the evolution of the accreting WD.

2. Results

With the aim of analyzing the effect of rotation on the evolution of WDs accreting CO-rich matter directly, we have considered a DD system composed by a 0.8 $M_\odot$ and a 0.7 $M_\odot$ stars with initial separation $A = 1R_\odot$, so that the merging of the two components via GWR occurs in $\sim 10^8$ yr. At the merging stage the angular velocity of the WD is 0.17 rad/s and we assume that the matter flows from the disk to the WD at $\dot{M} = 8 \times 10^{-6} M_\odot yr^{-1}$.

As it is well known (see Nomoto & Iben (1985), Piersanti et al. (2003)), when the accreted matter falls onto the WD surface, it delivers gravitational energy which is locally stored as thermal energy; this is due to the fact that the local value of the thermal diffusion time scale ($\tau_{\rm diff}$) is greater than the compressional heating one ($\tau_{\rm ch}$). The thermal energy excess causes a local over-pressure which makes work against the local gravity and produces the expansion of the external layers. In standard (non-rotating) models this occurrence causes the decrease of the local value of $\tau_{\rm diff}$ and, when it becomes smaller than the local $\tau_{\rm ch}$, thermal energy begins to be transferred inward efficiently and the structure contracts. Rotation magnifies the expansion since, for a fixed $\dot{M}$, higher the angular velocity lower the temperature level of the WD and, hence, higher the thermal energy excess produced by the accreted matter. As a consequence, if rotation is accounted for, the structure continues to expand since $\tau_{\rm diff}$ can not become lower than $\tau_{\rm ch}$. On the other hand, increasing the surface radius, the local value of the gravitational force decreases and when it becomes smaller than the centrifugal one the structure becomes gravitationally unbound (Roche instability).

At a first sight this occurrence could suggest that the accretion process comes to a halt; however, in the real world the Roche

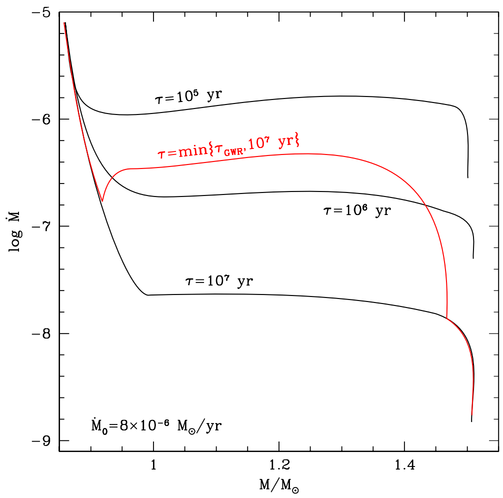

Fig. 1. Time evolution of the accretion rate for a rotating 0.8 $M_{\odot}$ WD which accretes CO-rich matter. The label on each curve indicates the time scale on which the braking mechanism occurs (see text).

instability implies that the WD has to accrete matter at a lower rate in such a way to remain gravitationally bound. In fact if $\dot{M}$ decreases, a smaller amount of angular momentum is deposited onto the WD so that the increase of the angular velocity occurs more slowly. In addition, the delivered gravitational energy which powers the expansion decreases and, hence, $\tau_{\rm ch}$ becomes higher than $\tau_{\rm diff}$ so that the accreting structure can contract.

It has also to be remarked that, since both the WD and the accretion disk are rotating, some braking produced by viscous forces between the WD and the disk has to be accounted for (Ma (2002)). In this case a part of the angular momentum of the system WD+disk is carried away so that the increase of the total angular momentum of the WD occurs more slowly. In some case it can also occur that the rotational energy of the WD becomes of the order of one tenth of the gravitational one: hence, the mass distribution can become asymmetric and the structure acquires a quadrupole momentum. As a consequence GWR can be emitted so that also in this case angular momentum is subtracted from the WD. Previous considerations suggest that rotation acts as the tuning mechanism of $\dot{M}$ in such a way that the WD continues to increase in mass up and over 1.4 $M_{\odot}$. This occurrence is clearly shown in Fig. 1 where the time evolution of $\dot{M}$ is plotted for different value of the braking efficiency, which means for different braking mechanisms. As it can be noticed, the accretion rate first decreases and then it attains a plateau value whose level depends on the braking efficiency. The plateau phase corresponds to an equilibrium configuration in such a way that the amount of angular momentum deposited by the accreted matter is counterbalanced exactly by the angular momentum loses due to the braking.

When the total mass of the accreting structure is of the order of $1.52 M_{\odot}$ the sudden decrease of the accretion rate is due to the fact that the WD is approaching the rotating Chandrasekhar mass limit so that it contracts rapidly.

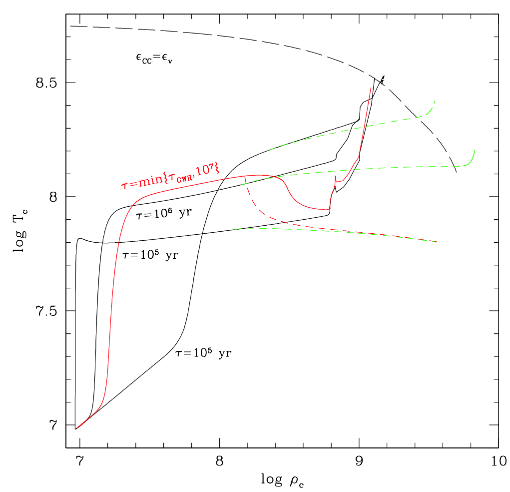

Fig. 2. Evolution in the $\rho - T$ plane of the center of a CO WD accreting matter at rates indicates in Fig. 2. The label attached to each curve represents the braking efficiency (see text).

It is important to remark that all these models attain the physical conditions suitable for explosive central Carbon ignition as it is clearly shown in Fig. 2 where the evolution in the $\rho - T$ plane of the center of the previously discussed model is reported (solid lines). This occurrence is valid also for WDs with total mass in the $1.39 \div 1.52 M_{\odot}$. In fact if the accretion process is switched off and the model is allowed to evolve under the effect of braking the WD undergoes a strong compression due to the reduction of the local centrifugal force and it heats up homologously so that Carbon burning is ignited at the center in highly degenerate physical conditions (see Fig. 2 - dashed lines).

3. Final remarks

We have shown that DD systems can represent the right solution for the problem of SNe Ia progenitors if the lifting effect of rotation is properly taken into account in modeling the thermal evolution of the accreting WD. In fact rotation acts as the tuning mechanism of the accretion process in such a way that also for initially high value of the accretion rate the accreting structure can continue to increase in mass up and over the non-rotating Chandrasekhar mass limit. In addition the braking process produces the physical conditions suitable for explosive Carbon burning at the center, independently on the braking efficiency. It is important to remark that the braking is not an artificial mechanism but it is a natural consequence of the fact that the accreting WD is rotating.

References

Benz, W., Cameron, A.G.W., Press, W.H. & Bowers, R.L., 1990,Ap.J, 348, 647

Cassisi, S., Iben, I.Jr & Tornambeé, A., 1998, ApJ, 496, 376

Iben, I.Jr. & Tutukov, A.V., 1984, ApJSS, 54, 335

Iben, I.Jr. & Tutukov, A.V., & Yungelson, L.R. 1997, ApJ, 475, 291

Koen, C., Orosz, J.A. & Wade, R.A., 1998, MNRAS, 300, 695

Livio, M., 2000, in *The greatest Explosions since the Big Bang: Supernovae and Gamma-Ray Bursts*, Eds. M. Livio, N. Panagia & K. Sahu, in press

Ma, F., 2002, astro-ph/0202040

Mochkovitch, R., Guerrero, J. & Segretain, L., 1997, in *Thermonuclear Supernovae*, Eds. P. Ruiz-Lapuente, R. Canal & J. Isern, Kluwer, Dordrecht, p. 187

Nomoto, K.I. & Iben, I.Jr., 1985, ApJ, 297, 531

Rasio, F.A. & Shapiro, S.L., 1995, ApJ, 438, 887

Piersanti, L., Cassisi, S., Iben, I.Jr & Tornambeé, A., 1999, ApJ Lett., 521, L59

Piersanti, L., Cassisi, S., Iben, I.Jr & Tornambeé, A., 2000, ApJ, 535, 932

Piersanti, L., Cassisi S. & Tornambé, A., 2001, ApJ, 558, 916

Piersanti, L., Gagliardi, S., Iben, I.Jr & Tornambeé, A., 2003, ApJ, in publication

Saio, H, & Nomoto, K.I., 1985, A& A, 150, L21

Saio, H, & Nomoto, K.I., 1998, ApJ, 500, 388

Tutukov, A.V., & Yungelson, L.R., 1979, Acta Astr, 29, 665