Mem. S.A.It. Vol. 75, 178

Memorie della

Self-Regulating Accretion Toward Chandrasekhar Mass and SNe Ia Events in Binary Systems of Merging White Dwarfs

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

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

Abstract. We present a promising scenario which removes several main concerns related to supernova-like outcomes in double degenerate binary systems which merge. Rotation, which occurs naturally in stellar components of these systems, has been taken into account during the entire evolutionary process (i.e., pre-merging evolution, accretion phase, and final establishment of the accreting structure as a dynamically explosive configuration at the rotational Chandrasekhar mass value). The physical properties of the system are now such that a self-regulating accretion process (which operates until the mass of the accreting white dwarf component reaches the rotational Chandrasekhar mass limit) becomes unavoidable, as does the occurrence of central carbon ignition and an explosive outcome of supernova Ia proportions. We are optimistic that further investigations of this scenario will lead naturally to the (so far missing) correct explanation of observational properties of SN Ia events.

Key words. Supernovae – White Dwarfs – Accretion – Rotation

1. Introduction

Most of you, sirs, are well aware that supernova Ia events derive from a carbon-oxygen (CO) white dwarf (WD) accreting mass until it reaches the Chandrasekhar limiting mass. The various observational reasons which make this statement so strong will not be discussed here and can be found in several review papers of the last decade and also in older ones (for a recent review see Hillebrandt & Niemeyer 2000). The necessity that a binary stellar system must be the progenitor of such events is also out of debate. The debate becomes hot when the details of the binary system in which a WD can increase in mass to about $1.4 M_{\odot}$ are considered. Among the various proposed scenarios, only two have survived the challenge of time. These are called the single degenerate (SD) and the double degenerate (DD) scenarios. The first envisions a WD with a normal star companion from which the WD receives matter composed primarily of hydrogen and helium (Whelan and Iben 1973). Systems like this do exist in nature in several forms, are well studied and produce a variety of observational events (symbiotic stars, classical novae, cataclysmic variables, dwarf novae and many others). Whether in some of these systems the accreted matter is burned into a carbon and oxygen mixture and whether the mass of the CO WD will indeed increase up to the Chandrasekhar mass is not known. Theoretical constraints say that this cannot occur due to mass loss during helium flashes (Cassisi et al. 1998; Piersanti et al. 1999, 2000, 2001). The second scenario envisions a system composed of two tidally bound WDs which at a certain moment merge due to gravitational wave emission, with a total mass which exceeds the Chandrasekhar mass (Iben & Tutukov, 1984; Webbink 1984). Two major concerns afflict the DD scenario. The first is that real counterparts of these systems have not yet been observed (Robinson & Shafter 1987; Bragaglia et al. 1990; Saffer, Livio & Yungelson 1998; but see also Koen, Orosz & Wade 1998). The second is that, after the merger occurs, the accretion rate could be so high that, instead of an explosive central carbon ignition, a mild off-center carbon ignition occurs. In this case, an O-Ne-Mg white dwarf which collapses into a neutron star is the outcome (Nomoto & Iben 1985; Saio & Nomoto 1985; Saio & Nomoto 1998).

Here, in the light of the DD scenario, we attack the second question (leaving the first question unresolved, but assuming that DD systems indeed form in nature). We will show that, when the rotational effects on the individual stellar components are accounted for, the path to an explosive outcome is not only possible, but mandatory.

2. Modelling the Evolution of DD Systems

Details about how the numerical models are worked out are given elsewhere (Piersanti et al., in preparation). Here we summarize the path followed up to an explosion by a DD system which is initially composed of two WDs, each of mass about $0.8M_{\odot}$, at a separation of $\sim 1R_{\odot}$ (note that theory strongly supports the existence of such a system; Tornambé 1989; Iben & Tutukov 1984).

The evolution can be divided into three major phases. Initially, through the combined action of shear friction and tidal forces, the two components are spun up until their rotation rates become synchronized with the orbital revolution rate (Webbink & Iben 1988; Iben, Tutukov, & Federova 1998). The heating produced by the frictional stresses causes substantial changes in the thermal structure of the stars (Iben, Tutukov, & Federova 1998); even the external properties are modified, making the structure hotter and more luminous. Once synchronization is attained, it will persist up to the merger.

The second phase starts at merging, when matter from the less massive component, dissolved into a disk, starts to be accreted onto the companion. What the real initial accretion rate is, is not known, but it must be high, near the Eddington limit. The initial value of the accretion rate is the only parameter one has to assume. Fortunately, as we explain shortly, the choice of this parameter does not affect the further evolution at all (for details see Piersanti et al., 2003). This is a short and dramatic phase. Thermal energy is stored in the external layers which expand. Angular momentum is stored in the entire structure which increases its angular velocity. In a short time, the accreting structure attains the critical configuration in which, at the equator, gravitational and centrifugal forces become equal. Only the matter inside the critical radius can be considered to constitute a true stellar structure to which the standard equations of stellar structure can be applied and solved to give a configuration whose physical characteristics can be believed. No additional matter can be added to this structure if it remains as it is now. (It may be that, in the real world, matter escapes from the WD in equatorial zones and returns to the WD along zones near the poles, but the total mass of the WD remains fixed). In other words, accretion comes to a halt and can resume again only if and when, for some physical reason, the structure retreats from the critical condition. We can describe this situation as if there exists a gate which can be closed or open, depending on the actual physical conditions of the accreting WD. At first, a decreasing accretion rate allows the heat excess which has been deposited in the surface layers to diffuse toward the internal zones. This process implies a contraction and

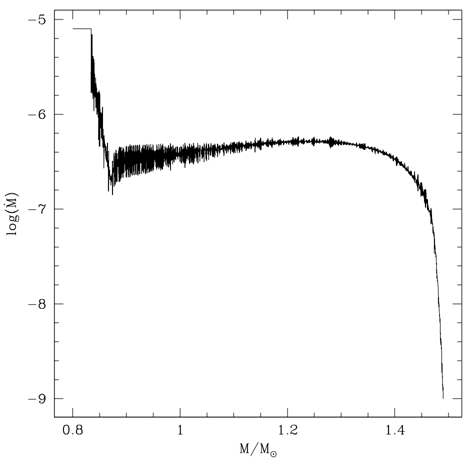

Fig. 1. Time evolution of the accretion rate during all the evolutionary phases experienced by the accreting WD (see text).

a spinning up which, due to angular momentum redistribution inside the structure, occurs at a rate smaller than the rate at which the critical angular velocity increases. The net consequence is that the WD recedes from the critical conditions.

Then, however, matter and angular momentum can once again be accreted until the critical conditions are attained. It is clear that, from this point onward, the accretion process will be finely self-tuned by the physical properties of the stellar structure (on a time scale which is basically the heat transfer time scale) and not by the conditions of the external matter. We have now a stellar structure continuously receding from, and attaining again, the critical conditions. Since accretion occurs in finite episodes, only a mean accretion rate is well defined. If this process continued indefinitely, with no additional physics coming into play, the mean accretion rate would decrease with time. This is because, as time goes by, the process of receding from the critical conditions becomes more and more difficult to be managed by the accreting star (less heat to be transferred). Thus, absent additional physical processes which intervene to keep it alive, the self-tuned accretion mechanism would come to a definitive halt well before the Chandrasekhar mass is attained.

Two physical processes occur which save the day: (1) a secular instability which occurs when the rotational energy of the accreting white dwarf exceeds about 10 % of the gravitational binding energy, and (2) gravitational wave radiation (GWR) which sets in when, in response to the instability, the WD structure adopts a triaxial form with a quadrupole moment. Triaxial configurations, known as Jacobi ellipsoids (Chandrasekhar 1970) and the process of angular momentum loss by gravitaional wave radiation are both well understood, thus eliminating the need for additional assumptions or use of free parameters. A third, long lived, phase ensues. As in the previous phase, the rate at which the accreting WD recedes from the critical conditions is determined by its structural properties and not by the external matter. The accretion process thus continues to occur in a self-regulated fashion. At a certain point of the evolution, the conditions to lose energy via GWR emission are no longer fulfilled. This occurs, however, when the Chandrasekhar mass limit for non-rotating structures has been already effectively achieved. Once the rotational velocity is further reduced, carbon burning is ignited at the center of the WD, giving rise to a SN event. Figure 1 reports the history of the accretion rate all along the discussed evolutionary phases.

3. The Observational Challenge

The evolutionary path in the HR diagram described by one of the two WDs before merging (dashed line) and by the accreting WD up to the explosive outcome (solid line) is reported in Fig. 2.

In the hope of identifying observational properties which may be detectable with present or future classes of telescopes, we will provide in a forthcoming paper color-luminosity diagrams in various bands as well as the expected luminosity function. Observations at optical wavelengths will have to be supported with observations at shorter wavelengths mainly during the disk phase. We will also discuss, for an assumed stellar popu-

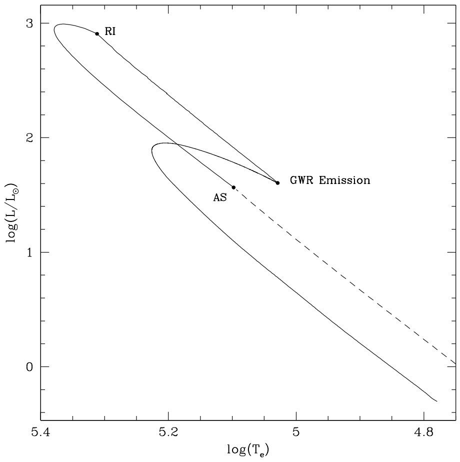

Fig. 2. Theoretical HR diagram for the accreting WD: the labels mark the point where accretion starts (AS), the Roche instability sets in (RI) and the GWR emission reaction is powered (GWR Emission). The dashed line refers to the evolution during the Pre-heating phase.

lation, the statistical properties of the systems during the three phases.

We close this short contribution noting that, in the case of rotating DD systems with the orbital plane coincident with the Earth, eclipses of duration between 0.5' and 2' are expected to occur.

References

Bragaglia, A., et al. 1990, ApJ, 365, L13
Chandrasekhar, S. 1970 Phys. Rev. Lett., 24, 611
Hillebrandt, W. & Niemeyer, J.C. 2000, ARA&A, 38, 191
Iben, I. Jr. & Tutukov, A.V. 1984, ApJSS, 54, 335
Iben, I. Jr., Tutukov, A. V., & Fedorova, A. V. 1998, ApJ, 503, 344
Koen, C., Orosz, J.A. & Wade, R.A., 1998, MNRAS, 300, 695
Nomoto, K.I. & Iben, I.Jr., 1985, ApJ, 297, 531
Piersanti, L., et al. 1999, ApJL, 521, 59
Piersanti, L., et al. 2000, ApJ, 535, 932
Piersanti, L., Cassisi, S. & Tornambè, A. 2001, ApJ 558, 916
Piersanti, L., et al. 2003, ApJ 583, 885
Robinson, E.L. & Shafter, A.W. 1987, ApJ, 332, 296
Saffer, R.A., Livio, M. & Yungelson, L.R. 1998, ApJ, 502, 394
Saio, H, & Nomoto, K.I. 1985, A& A, 150, L21
Saio, H, & Nomoto, K.I. 1998, ApJ, 500, 388
Tornambè, A. 1989, MNRAS, 239, 771
Webbink, R.F. 1984, ApJ, 277, 355
Webbink, R. F., & Iben, I. Jr. 1988, in proc. of Faint Blue Stars, ed. A. G. Davis Philip, D. S. Hayes, and J. W. Liebert (Schenectady: L. Davis), p. 445
Whelan, J., Iben, I. Jr. 1973, ApJ 186, 1007