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SNe Ia progenitors: a population synthesis approach

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Abstract. We show that, by assuming the rotating Double Degenerate scenario for the SNe Ia progenitors, the total mass of the progenitor systems is the leading parameter determining the observational properties of these events. Moreover, basing on population synthesis models, we show that the distribution of DD systems good candidate as SNe Ia progenitors in late and early type galaxies well explains the evidence that high luminosity events occurs only in star forming galaxies.

Key words. Supernovae: Type Ia – Stars: White Dwarfs – Stars: Binaries – Stars: Evolution – Stars: Rotation

1. Introduction

In spite of their pivotal role in observational Cosmology as well as in the chemical evolution of matter in the Universe, Type Ia Supernovae (SNe Ia) still remain mysterious objects in some respects. Basing on the observational evidence it can be argued that they are produced by the thermonuclear disruption of CO White Dwarfs (WDs) which accrete matter from their companions in binary systems (Hoyle & Fowler 1960). Notwithstanding, several aspects remain not fully understood up to now. For example, the details of the explosion are still missing and the typology of the companion in the binary system is under hot debate so far. This lack in the understanding of SNe Ia prevents the interpretation of some important observational aspects, such as the Phillips relation (Phillips 1993) which is the key ingredient to use SNe Ia as standard candles on cosmological distances.

Some hints to disentangle this puzzling situation can be obtained by the evidence that the most luminous SNe Ia occur only in late type galaxies, while intermediate and low luminosity events are observed in every galactic typology (Della Valle & Panagia 1992; Hamuy et al. 1995, 1996)[1]. Such a correlation (hereinafter *"brighter – sooner relation"*) suggests that an intrinsic difference there exists in the SNe Ia progenitor systems in late and early type galaxies, but no physi-

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[1] For a more recent analysis see also Fig. 1 in Gallagher et al. (2005) and the related discussion.

cal explanation has been provided so far. This scenario could be explained observing that for some very luminous events, such as the peculiar SN2003fg (Howell et al. 2006), it has been estimated a total mass of the exploding object as high as 2 $M_{\odot}$. This estimation contradicts the common opinion that a SN Ia event occurs when the WD total mass reaches the Chandrasekhar limit $M_{\rm Ch} \sim 1.4\ M_{\odot}$, but it can be naturally explained in the framework of the rotating Double Degenerate scenario (Piersanti et al. 2003). In fact, for DD systems the orbits synchronize on a very short time scale during the pre-merging phase due to the tidal interaction between the two components, so that at the merging time both the WDs rapidly rotate. Moreover, during the following accretion phase, angular momentum is deposited by the accreted matter, so that the remaining WD becomes a very fast rotator. In this condition rotation acts as a fine-tuning mechanism of the accretion rate, preventing the off-center ignition of C-burning and allowing the accreting WD to increase in mass up and beyond the standard non-rotating $M_{\rm Ch}$ (for more details see Piersanti et al. 2003). By adopting a rigid body approximation, Piersanti et al. (2003) have obtained exploding objects in the mass range 1.4-1.5 $M_{\odot}$, corresponding to the non-rotating and rigidly rotating Chandrasekhar limits, respectively. For these models, by adopting the Delayed Detonation model (Khokhlov 1991), the exploding phase and the related light curves and nucleosynthesis have been also computed (Domínguez et al. 2006). These simulations show that a variation of 0.1 $M_{\odot}$ in the total mass corresponds to a variation of about 0.15 mag in the magnitude at maximum. Obviously, the produced difference is too small to account for the observed spread of maximum magnitude, but it has to be noticed that it corresponds to a small variation in the total mass of the exploding objects. If the solid body approximation is relaxed, exploding objects as massive as 2.2 $M_{\odot}$ can be produced, the final mass being limited only by the total initial mass of the binary system. Moreover, by an inspection of Fig. 5 in Domínguez et al. (2006), it comes out that the magnitude at maximum does not increase linearly with the total mass of the SN Ia progenitor. According to these considerations, the observed differences in SNe Ia could be explained as a consequence of the different masses of the progenitors. When applying such an assumption to the *"brighter-sooner relation"*, it results that in late type galaxies the SNe Ia mean mass is higher than the one in early type.

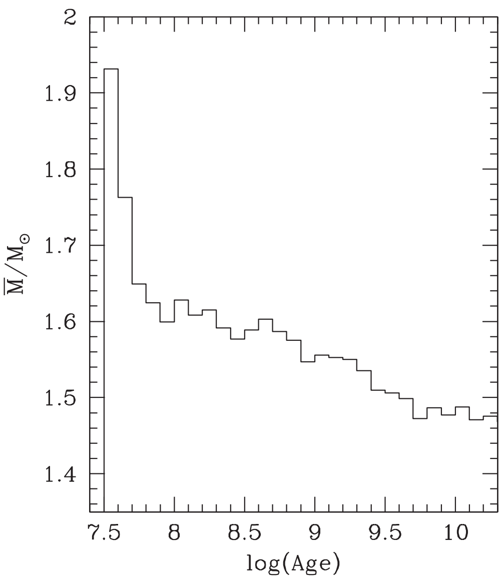

Fig. 1. Mass distribution of the exploding objects as a function of time (see text)

In the next section we analyze such a possibility by determining the mass distribution of DD systems more massive than $M_{\rm Ch}$ as a function of time and relating the obtained results to the evolution of spiral and elliptical galaxies. Hence, in the last Section we briefly summarize our results.

2. DD systems population models

We have developed a population synthesis code, based on a large data set of evolutionary tracks with $Z = Z_{\odot}$ in the mass range 1-11 $M_{\odot}$, computed with a very fine mass step ($\Delta M = 0.1\ M_{\odot}$) and covering all the evolutionary phases up to ignition of C-burning. We include in our data set also evolutionary tracks for pure Helium stars in the mass

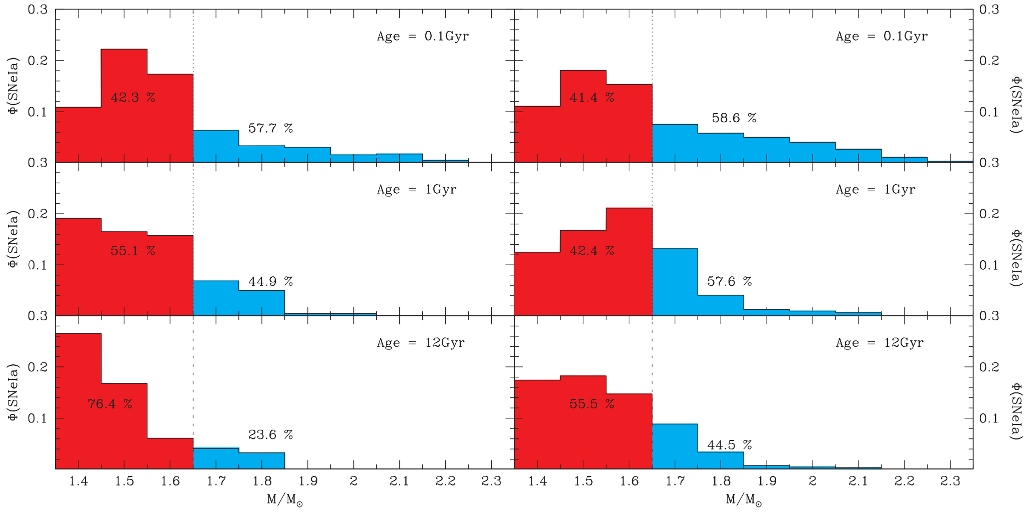

Fig. 2. Mass distribution of exploding DD systems at various ages, as labeled inside each panel. The plot on the left refers to a single SF burst while the right one refers to a continuous SF (for more details see text).

range 0.35-3 $M_{\odot}$. The mass distribution of initial binary systems is fixed according to the Salpeter mass function, while the distribution of mass ratio q is fixed according to that observed for a local sample of spectroscopic binaries (Halbwachs et al. 2003). The distribution of initial separation A is assumed flat in $\log(A)$, while the common envelope phase is treated according to Nelemans et al. (2001), by assuming that this process has efficiency $\alpha_{CE} = 1$. For a single burst of star formation (SF), the time distributions of the delay times and of the cumulative SNe Ia number we obtain are in fairly good agreement with those already existing in the literature (e.g. Greggio 2005).

In Fig. 1 we report the time distribution of the total mean mass of the exploding objects for a single SF burst. As it can be easily noticed, at short time after the SF episode the exploding objects are very massive ($\bar{M}_{tot} \sim 2$ $M_{\odot}$), whilst the long time component is dominated by low mass progenitors ($\bar{M}_{tot} \sim 1.5$ $M_{\odot}$). By a further analysis, it comes out that the high-mass, short-term systems arise from initial binaries with total mass in the range 13-18 $M_{\odot}$, mass ratios close to 1 and separation in the range 300-$10^3 R_{\odot}$; on the other hand the low-mass, long term component is related to initial binaries with total mass in the range 7-14 $M_{\odot}$, separation in the range 600-$10^4 R_{\odot}$ and mass ratio varying on the whole range.

In Fig. 2 we report the mass distribution at various ages of exploding DD systems as obtained for different assumptions on the SF history: in the left panel we adopt a single burst of SF, which can be considered as representative of elliptical galaxies, while in the right one we adopt a continuous SF, which can be considered as representative of spirals. As it can be noticed, elapsing the time, the frequency of the high mass component in ellipticals largely reduces, while the fraction of low total mass objects largely increases. On the other hand, for spirals the frequency of high mass component remains almost constant while the one of systems with mass smaller than 1.5 $M_{\odot}$ is largely reduced.

3. Final remarks

Our results show that the rotating DD scenario can account for the *"brighter-sooner relation"*; in fact, according to our simulation, when comparing the mass distribution of exploding objects in late– and early–type galaxies at the current estimated age of the Universe, the relative frequency of low mass

Table 1. Final outcome of binary systems with $M_{tot} = 8M_{\odot}$, $A_{ini} = 670R_{\odot}$ and $q = 1$ and different chemical composition (see text).

Z	M_r ($M_{\odot}$)	T_m ($10^8 yr$)	M_{exp} ($M_{\odot}$)	Out
10^{-4}	0.8711	1.39	1.7421	CH-Exp
10^{-3}	0.8108	1.51	1.6216	CH-Exp
2×10^{-2}	0.7139	11.92	1.4278	CH-Exp

systems is strongly reduced in star forming galaxies, while the one of the intermediate and high mass components becomes dominant. However, this result is very rude since in our modeling of spiral galaxies we have assumed that chemical evolution of matter does not occur at all. In order to evaluate the contribution of various stellar populations with different initial chemical composition, an age-metallicity and a helium-metallicity relations have to be assumed. Currently we are extending our database of evolutionary tracks in order to account for the effect of chemical evolution of matter and this topic will be addressed elsewhere. However, basing on simple considerations of stellar evolution, we can guess the final scenario. As it is well known, lowering the initial metallicity, stars are more compact and hotter and they evolve more rapidly. Hence, for a given intermediate mass star, the lower the metallicity, the larger the convective core during the MS phase, the larger the He core at the ignition of central He-burning, the larger the final CO degenerate core mass. This occurrence determines the well known decrease of M_{up} increasing the metallicity. This would imply that, by including the effects of chemical evolution in modeling star forming galaxies, the low-mass long term component strongly reduces. To make more clear this point, we report in Tab. 1 the final outcome of binary systems with the same initial total mass, separation and mass ratio, but with different chemical composition: as it can be noticed, increasing the total metallicity Z, the mass of the exploding object M_{exp} reduces and the SN Ia event occurs on a longer time scale. This scenario provides a very easy explanation also for the Phillips relation: in fact, by assuming that the total mass of the exploding star is the leading parameter in determining the observational properties of SNe Ia, it comes out that brighter objects are related to more massive progenitors, while dimmer ones correspond to initially low mass DD systems.

We want to remark that the spread in the total mass at the explosion is determined by the difference in the total initial mass of the Double Degenerate systems. This because rotation, which is not an artifact but a direct consequence of the Physics driving the evolution of these systems, regulates the accretion process and the evolution up to the explosive C-ignition. It is important to keep in mind that rotation plays an important role only in DD systems since in this case the components are fast rotators and, in addition, during the accretion process a huge amount of angular momentum is deposited. At contrast, Single Degenerate systems are wide, so that the initial angular velocity of the WD is very low, if not negligible, and the amount of angular momentum transferred during the accretion is not enough to produce the rapidly spinning up of the degenerate star.

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