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The delay time distribution of type Ia supernovae: theory and observation

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Abstract. Using a population number synthesis code, the theoretical time distributions of type Ia supernovae in starburst galaxies are calculated, using competing models for the formation of such events: the single degenerate (a white dwarf accreting matter from a late main sequence or red giant companion) and double degenerate (the merger of two white dwarfs) scenario. The code includes the latest results in determining the progenitors for both models. Examples are the mass stripping effect in the case of the single degenerate scenario and the differentiation between the α- (based on the balance of energy) and γ- (based on the balance of angular momentum) description of energy conversion during common envelope evolution of binaries. The shape and extent of the obtained delay time distributions critically depends on which formation scenario is used. Comparing these results to the latest observed distributions allows to draw conclusions about the constraints put on the theoretical models by these observations. We also specifically investigate the influence of the degree of conservatism during Roche lobe overflow on the delay time distribution. We conclude that the single degenerate scenario alone cannot reproduce the observed delay time distributions, and that most double degenerate type Ia supernovae are formed through a quasi-conservative Roche lobe overflow phase followed by spiral-in, as opposed to a double common envelope evolution.

Keywords. Binaries: close, supernovae: general, galaxies: starburst

1. Introduction

Type Ia supernovae (SNe Ia) are widely believed to be caused by the thermonuclear deflagration of a C/O white dwarf (WD) exceeding the Chandrasekhar limit (see e.g. Livio (2001)). They thus require the addition of mass to the progenitor WD, implying that they can only occur in multiple star systems. SNe Ia are key to the chemical evolution of the universe, as they are essential sources of iron for later generations of stars. They also play a critical role as distance indicators in cosmology, commonly being used as standard candles. However, the exact formation process of these events is still unclear. There are two widely supported formation scenarios, the single degenerate (SD) and double degenerate (DD) scenario. In the first one (see e.g. Nomoto (1982)), the progenitor WD accretes matter from a companion star in a binary, thus eventually exceeding the Chandrasekhar limit. This companion can either be a late main sequence (MS) star or a red giant (RG). In the DD scenario (see e.g. Webbink (1984) and Piersanti *et al.* (2003) for a rebuttal of common arguments against the possibility of this scenario) the SN Ia is caused through the merger of two WDs in a binary, the combined mass of which exceeds 1.4 $M_{\odot}$. The stars come together through the emission of gravitational wave radiation (GWR), which causes them to spiral into each other. It is very important to know which scenario is the dominant formation channel for actual SNe Ia, not in the least as this may have implications for their use as standard candles.

Within the DD scenario, there are two types of systems that can lead to a double WD binary, eventually merging and resulting in a DD SN Ia. Both types of systems consist of progenitors with a few solar masses and a mass ratio rather close to one. In the first scenario, the so called Roche lobe overflow (RLOF) channel, these stars have an initial orbital period of a few days. When the most massive of the two leaves the MS, a first mass transfer phase occurs, which is normal RLOF. This process is taken to be conservative, i.e. all matter lost by the donor star is accepted by the accretor. The system emerges from this phase with a more extreme mass ratio and a much larger period, on the order of 100 days. When the originally least massive star, now the heaviest one, also leaves the MS, a second mass transfer phase is initiated, towards what in the meantime has become a WD. This will result in a phase of common envelope (CE) evolution, during which the stars spiral-in due to viscosity. They eventually emerge as a double WD binary with a period on the order of a few hours. In order to merge and produce a DD SN Ia, the system needs to emit GWR during a few Gyr, placing the SN Ia multiple Gyr after star formation. If on the other hand the first RLOF phase is assumed to be totally non-conservative (i.e. the accretor star accepts no matter whatsoever), the system will merge before a double WD is formed, and thus no SN Ia will occur. Another channel through which a DD SN Ia can occur is the so called CE channel. Here, the system starts with about the same masses, but with a much larger orbital period, on the order of a few hundred days. In that case, already the first mass transfer phase will result in a CE evolution, meaning that the system comes out of this phase with a period of only a few days. The result is that after the second phase of mass transfer, also a CE resulting in spiral-in, the system is left with a period of just a few hundred seconds. It thus only needs a few kyr of GWR before it merges, placing the DD SN Ia already a few hundred Myr after star formation.

2. Methods and assumptions

A comparison with observations is possible through the concept of delay time distributions (DTDs). These indicate the number of SNe Ia per unit time (often per Gyr) as a function of time elapsed since starburst. They are empirically constructed through the observation of elliptical galaxies (in this context serving as starburst galaxies) at different redshifts. DTDs for starburst galaxies can also be theoretically constructed, using either of the formation scenarios, and the two can then be compared to infer conclusions on their prevalence. A very recent and extended observational DTD is the one by Totani *et al.* (2008), which includes an observation at 11 Gyr by Mannucci *et al.* (2006). This DTD indicates a decay of the SN Ia rate following a 1/time distribution. The normalisation between data and models is arbitrary, i.e. carried out at this most important data point at high redshift, which means that only the functional shape of theoretical and observational DTDs can be compared, not the absolute number of events.

Other authors have previously constructed theoretical DTDs for the SD and DD scenarios. Authoritative studies are e.g. those by Yungelson & Livio (2000), Han & Podsiadlowski (2004) and Ruiter *et al.* (2009). For the first time however, we specifically investigate the influence of conservatism during RLOF in close binaries. To this effect, the updated population number synthesis code by De Donder & Vanbeveren (2003) is used. For the SD scenario, progenitors are identified as given by Hachisu *et al.* (2008), namely as contours for different WD mass, as a function of initial orbital period and companion mass. A SD SN Ia is assumed to result if the evolution track of the progenitor system traverses this contour. In determining the systems leading to a SD event, the mass stripping effect is included. This accounts for the stellar wind of the accretor star, which deflects some of the incoming material. The result is that some systems avoid a CE

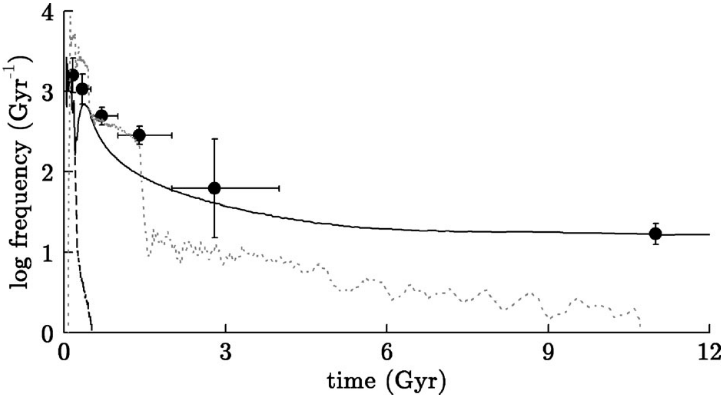

Figure 1. DTDs for $\beta = 1$ in case of the DD (solid black) and the SD (dotted grey) scenario as well as DTD for $\beta = 0$ in case of the DD (dashed black) scenario. Observational data points of Totani *et al.* (2008).

evolution and result in a SD SN Ia, while they would otherwise have merged. As far as the DD scenario is concerned, the assumption is made that each WD merger of which the combined mass exceeds the Chandrasekhar mass gives rise to a DD SN Ia. Using these evolution scenarios, a study is made to investigate the influence of certain parameters, the most important being the fraction β of RLOF-material accepted by the accretor star. If $\beta < 1$, i.e. in the case of non-conservative RLOF, it is assumed that matter leaves the system with the specific angular momentum of the accretor. For the description of energy conversion during CE, the α-scenario of Webbink (1984) is employed.

3. Results

Figure 1 shows the theoretically obtained DTDs for the SD and DD scenario, as well as the observational data points of Totani *et al.* (2008) and Mannucci *et al.* (2006). As mentioned before, the normalisation of these should be considered arbitrary. It is obvious that for $\beta = 1$ the DD scenario is dominant during most of the time, as well as in reasonably good agreement with the shape of the observational DTD. The SD DTD however drops much faster than 1/time after the first 1.4 Gyr, afterwards lying an order of magnitude too low in order to match the observations. It is thus not possible that the SD formation channel is the sole or most important contributor to SNe Ia. We also find that most of the SD SNe Ia form through the WD+MS scenario as opposed to the WD+RG scenario. While this result is contrary to those of Ruiter *et al.* (2009), it is in agreement with those of Hachisu *et al.* (2008) and Han & Podsiadlowski (2004).

A most important result, also inferred from Figure 1, is that a great majority of DD SNe Ia are formed through the RLOF channel, as opposed to the CE channel. This can be seen from the fact that after 0.20 Gyr, the DD DTD for totally non-conservative RLOF ($\beta = 0$) drops dramatically, leaving virtually no events after 0.50 Gyr. The events prior to 0.20 Gyr (which are also present in the case of $\beta = 1$) must thus be caused through the CE scenario. However, all events after 0.50 Gyr, which account for 80 percent of all SNe Ia in the case of $\beta = 1$ but are absent if $\beta = 0$, must be created through the RLOF scenario. These conclusions are in agreement with the typical formation timescales for CE (on the order of 0.1 Gyr) and RLOF (on the order of 1-10 Gyr) events derived earlier, as well as with the impossibility of creating a RLOF event in the case of non-conservative mass transfer. In order for the theoretical DTD to follow the 1/time decay exhibited by

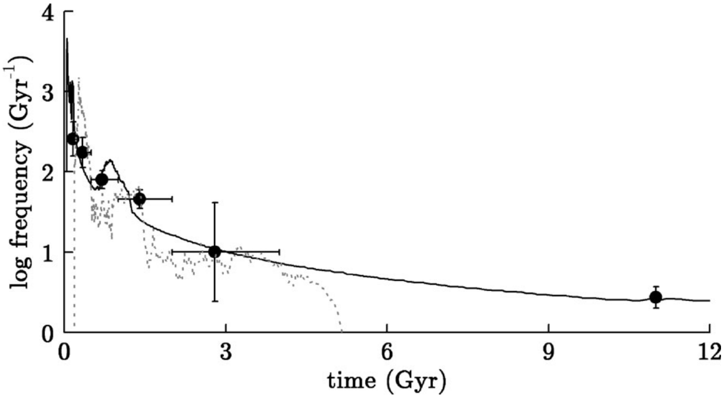

Figure 2. DTDs for $\beta = 1$ in case of the DD (solid black) and the SD (dotted grey) scenario using the γ-scenario for CE evolution. Observational data points of Totani *et al.* (2008).

the observational one, β thus has to be close to one. Further calculations have shown that $\beta \geqslant 0.9$ is required for the DD DTD to be compatible with the observations. RLOF thus being largely conservative, the commonly employed technique in analytical studies of taking the formation timescale for a DD SN Ia equal to the nuclear lifetime of the least massive star plus the time needed for GWR spiral-in, is not justified. A last observation here is that the SD DTD is not severely influenced by β: if $\beta = 0$, it drops only a little lower than the one for $\beta = 1$ shown in Figure 1. This can be easily understood, since the occurrence of SD SNe Ia is determined by the evolution tracks crossing the contours of Hachisu *et al.* (2008), which is not very much affected by β.

Also the influence of the way energy conversion is described during CE evolution has been investigated. Until now, the so called α-scenario by Webbink (1984) has been used. This is based on the conservation of angular momentum and the balance of energy. Alternatively, Nelemans & Tout (2005) proposed the γ-scenario, based on the conservation of energy and the balance of angular momentum, which is claimed to better describe systems containing a WD, i.e. cataclysmic variables or double WDs. Figure 2 shows the DD and SD DTD obtained when employing this γ-scenario with $\beta = 1$, as well as the observational data points of Totani *et al.* (2008) and Mannucci *et al.* (2006). It is obvious that here also, the SD DTD soon lies more than an order of magnitude too low in order to be compatible with the observations. The DD DTD cannot be excluded based on the comparison with the (arbitrarily normalised) observational DTD, but it would mean a SN Ia rate almost an order of magnitude lower than obtained with the α-scenario. When the calculation is made for $\beta < 1$, both DTDs drop lower, although the decrease of the DD DTD is not as dramatic as in the case of the α-scenario.

4. Conclusions

The SD formation scenario for SNe Ia can by itself not reproduce the observed DTD. The DD scenario does produce a DTD compatible with the observations, but only if β is close to one. Since the combined mass of a DD SN Ia progenitor is not necessarily exactly equal to 1.4 $M_\odot$, the concept of SNe Ia as perfectly identical standard candles might have to be reconsidered. Most of these DD SNe Ia are formed through the RLOF channel, as opposed to a double CE evolution. The fact that the DTD strongly depends on the mass transfer efficiency during RLOF and on the physics of CE evolution might be a way to find out more about these processes.

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