Part 4

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The Progenitors of Type Ia Supernovae

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Abstract. Using binary population synthesis (BPS), we studied the birthrates of SNe Ia for two progenitor models – the single degenerate model and the double degenerate model. We find that the birthrates from both models are within a factor of a few comparable to those inferred observationally. For each model, we investigate different star-formation histories (single star burst or constant star formation), different metallicities (Z =0.02, 0.004, 0.001), different parameters for the BPS model (mass transfer efficiency during stable mass transfer, common-envelope ejection parameters) and obtain the evolution of birthrates with time.

1. Introduction

Type Ia supernovae (SNe Ia) are an important cosmological distance indicator, although the nature of their progenitors has still remained an unsolved question. Theoretically, SNe Ia events are probably thermonuclear disruptions of accreting carbon-oxygen (CO) white dwarfs (WD). Based on the characteristics of observed SNe Ia (e.g. lightcurves, chemical stratification), it seems most likely that they occur when the accreting CO WD reaches the Chandrasekhar limit (sub-Chandrasekhar models appear not to be consistent with the observations of SNE Ia). Chandrasekhar-mass WDs can be created through two channels:

(1) *The single degenerate channel,* where the CO WD accretes mass from a non-degenerate companion, either a main-sequence (MS) star or a red giant (RG) (Hachisu, Kato & Nomoto 1999);

(2) *The double degenerate channel,* where two CO WDs with a total mass larger than the Chandrasekhar mass coalesce (Iben & Tutukov 1984; Webbink & Iben 1987).[1]

In this contribution, we employ a binary population synthesis (BPS) approach to study the birthrates of SNe Ia from these two channels, the evolution of the birthrates and their dependence on metallicity and the BPS model parameters.

[1] Note, however, that in this case it is possible, perhaps even likely, that the merger product experiences core collapse rather than a thermonuclear explosion, in which case it would *not be a SN Ia* (Nomoto & Iben 1985).

2. Simulations

The primary of a relatively wide binary system will fill its Roche lobe as a red giant, where mass transfer may be dynamically unstable. This leads to the formation of a common enevlope (CE: Paczýnski 1976) and the spiral-in of the core of the giant and the secondary inside this envelope (due to friction with the CE). If the orbital energy released in the orbital decay is able to eject the envelope, this produces a rather close binary consisting of the WD core of the primary (here, a CO WD) and the secondary. As is usually done in BPS studies, we assume that the CE is ejected if

$$\alpha_{\rm CE}\Delta E_{\rm orb} \geq |E_{\rm bind}| \tag{1}$$

where $\Delta E_{\rm orb}$ is the orbital energy released, $E_{\rm bind}$ the binding energy of the envelope, and $\alpha_{\rm CE}$ the common-envelope ejection efficiency, i.e. the fraction of the released orbital energy used to overcome the binding energy. We adopt $E_{\rm bind} = E_{\rm gr} - \alpha_{\rm th} E_{\rm th}$, where $E_{\rm gr}$ is the gravitational binding energy, $E_{\rm th}$ is the thermal energy, and $\alpha_{\rm th}$ defines the fraction of the thermal energy contributing to the CE ejection. The CO WD binary system continues to evolve, and the secondary will at some point also fill its Roche lobe; the WD will then start to accrete mass from the secondary and convert the accreted matter into CO. We assume that this ultimately produces a SN Ia (in this single degenerate channel) if, at the beginning of this RLOF phase, the orbital period, $P_{\rm orb}$, and secondary mass, M_2, are in the appropriate regions in the (M_2,$P_{\rm orb}$) plane to produce, according to Hachisu et al. (1999), a SN Ia.

In the case, where the first RLOF phase is dynamically stable, the evolution of the binary depends on the fraction $\alpha_{\rm RLOF}$ of the envelope mass that is transferred onto the secondary rather than is ejected from the system (where we assume that matter lost from the system carries away the specific angular momentum of the system). Stable RLOF leaves a wide WD binary system. Thus both stable RLOF and the CE ejection channel produce WD binaries. This system may experience another CE phase, ultimately producing a system consisting of two white dwarfs (i.e. a double degenerate [DD] system; in the case of interest, two CO WDs). The two CO WDs may coalesce due to angular momentum loss by gravitational wave radiation and this may lead to a SN Ia if the total mass is above the Chandrasekhar mass (the double degenerate channel).

In order to investigate the birthrates of SNe Ia, we have performed a series of detailed Monte Carlo simulations with the latest version of the BPS code developed by Han et al. (1995). The results are shown in Figure 1. In each simulation, we follow the evolution of 10^6 sample binaries according to grids of stellar models and the evolution channels described above. We adopt the following inputs for the simulations (see Han et al. 1995 for details). (1) The star-formation rate (SFR) is taken to be constant over the last 15 Gyr or, alternatively, a delta function, i.e. a single star burst. In the case of the constant SFR, we assume that a binary with its primary more massive than $0.8\,M_\odot$ is formed annually. For the case of a single star burst, we assume a burst of $10^{11}\,M_\odot$. (2) The initial mass function (IMF) of Miller and Scalo (1979) is used. (3) The mass-ratio distribution is assumed to be constant. (4) We assume that the distribution of separations is constant in $\log a$ for wide binaries, where a is the orbital separa-

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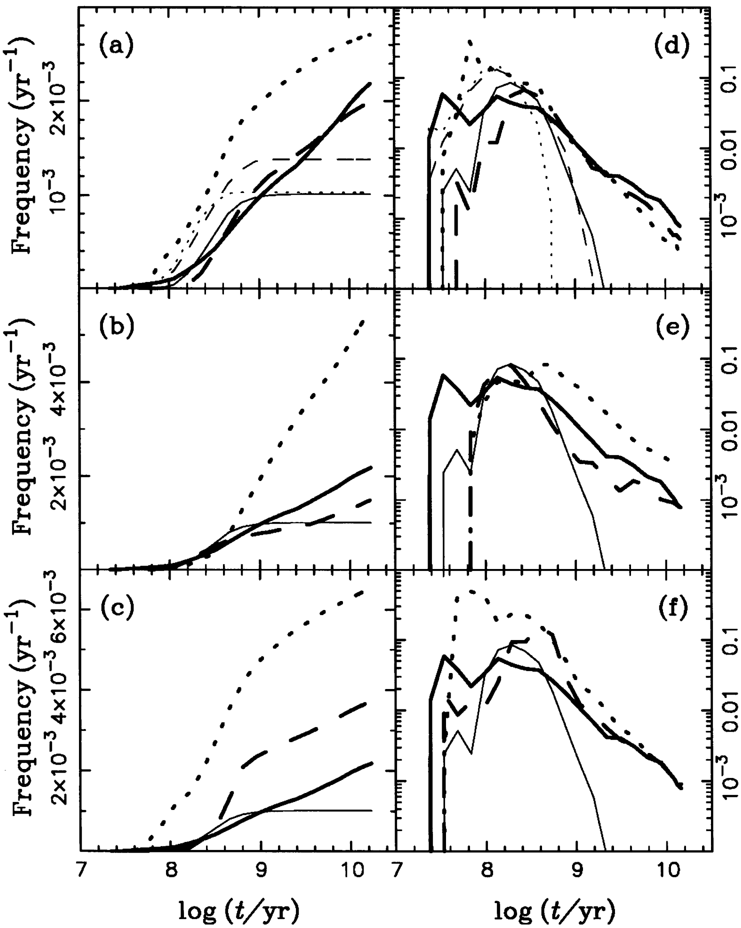

Figure 1. The evolution of birthrates of type Ia supernovae (SNe Ia). Thin curves: the single degenerate model; thick curves: the double degenerate model. The left panels assume a constant star-formation rate ($3.5\,M_\odot\,\mathrm{yr}^{-1}$), while the right ones assume a single star burst of $10^{11}\,M_\odot$ (note the different scalings, linear and logarithmic, in the respective panels). Panels (a) and (d) are for $Z = 0.02$ and $\alpha_{\rm RLOF} = 0.5$, with $\alpha_{\rm CE} = \alpha_{\rm th} = 1.0$ (solid), 0.75 (dashed) and 0.5 (dotted). Panels (b) and (e) are for $Z = 0.02$ and $\alpha_{\rm CE} = \alpha_{\rm th} = 1.0$, with $\alpha_{\rm RLOF} = 0.5$ (solid), 0.75 (dashed) and 1.0 (dotted). Panels (c) and (f) are for $\alpha_{\rm RLOF} = 0.5$ and $\alpha_{\rm CE} = \alpha_{\rm th} = 1.0$, with $Z = 0.02$ (solid), 0.004 (dashed) and 0.001 (dotted).

tion. Our adopted distribution implies that $\sim 50\,\%$ of stellar systems are binary systems with orbital periods less than 100 yr.

3. Discussion

As Figure 1 shows, the Galactic birthrates from both the single and the double degenerate model are comparable to those inferred observationally (i.e. within a factor of a few: $3 - 4 \times 10^{-3}$ yr^{-1}: van den Bergh & Tammann, 1991). We find a very similar frequency as Hachisu et al. (1999) for SNe Ia from the WD+MS channel (where a CO WD accretes from a main-sequence companion) in the single degenerate channel, but a much lower frequency from the WD+RG channel (where a CO WD accretes mass from a red-giant companion), since we have not included their proposed, but somewhat speculative mechanism to very efficiently reduce the separation of very wide WD systems.

In the double degenerate model, the birthrate of SNe Ia is strongly affected by the adopted model parameters. Low values of $\alpha_{\rm CE}$ and $\alpha_{\rm th}$, a high value of $\alpha_{\rm RLOF}$, and a low Z all tend to increase the birthrate. The dependence on the CE ejection parameters can be easily understood from the orbital-period distribution of the DD systems at birth: less efficient CE ejection leads to a systematically shorter orbital-period distribution which has the consequence that more systems can merge within a Hubble time. A large value of $\alpha_{\rm RLOF}$ (i.e. the first stable RLOF is more likely to be conservative) produces more DDs, while binaries with low Z have a shorter evolutionary timescale and their envelopes are more tightly bound, again leading to initially much closer DDs.

For the single degenerate model, the birthrates are not influenced much by the model parameters, except that the birthrate from WD+MS channel decresaes and the birthrate from WD+RG channel increaes when $\alpha_{\rm CE}$ and $\alpha_{\rm th}$ increase since this results in wider WD binaries. $\alpha_{\rm RLOF}$ does not affect the birthrates at all, as their is no stable RLOF phase for the progenitors. Since Hachisu et al. (1999) only considered a metallicity of $Z = 0.02$, we were not able to examine the metallicity dependence for the single degenerate channel.

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