The Impact of type Ia Supernovae on main sequence companions

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Abstract. We use hydrodynamical (SPH) simulations to investigate the effect of the impact of type Ia supernova ejecta on the main sequence companion star in the single degenerate scenario. We calculate the amount of hydrogen that is stripped from the companion star. We reproduce previous results that predicted a much larger amount of stripped material than found in observations. However, for more realistic progenitor systems, we find that the amount of stripped hydrogen is about a factor of 10 less. Our new results therefore make this scenario consistent with observations again.

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INTRODUCTION

In recent years significant of progress was made in modelling the explosion of a SN Ia [e.g., 1, 2, 3, 4, 5, 6]. However, despite their importance not only for cosmology, but also for galaxy evolution and the production of heavy elements, the nature of their progenitor systems remains unknown. There is general agreement only that SN Ia are thermonuclear explosions of white dwarfs in binary systems. Beyond that, two main progenitor channels are discussed.

In the *single degenerate scenario* the companion star is a main sequence star or a red giant. The white dwarfs accretes hydrogen from its companion star and burns it to carbon. This way it grows until it reaches the Chandrasekhar mass and explodes. In case the white dwarf accretes helium instead of hydrogen, it may be possible that it explodes earlier [for a recent work, see 7].

In the *double degenerate scenario* the progenitor system is a white dwarf binary. As the system looses angular momentum by gravitational wave emission, at some point the system will become unstable and merge. The resulting object may then be a progenitor of a SN Ia.

It is hard to distinguish between these scenarios observationally. One option is to look for hydrogen in the supernova ejecta, as the presence of hydrogen is a fundamental difference between single and double degenerate scenario. Double degenerate systems should not contain any hydrogen at all. Single degenerate systems with hydrogen donors on the other hand obviously contain hydrogen. In this case, hydrogen from the envelope of the companion star is expected to be stripped off by the impact of the supernova ejecta. The stripped hydrogen is then mixed into the ejecta and may be visible in spectra.

Previous simulations by Marietta et al. [8] found that the impact of the supernova ejecta strip about $0.15 M_\odot$ of material from the companion star. Currently the tightest upper limits on the amount of hydrogen that can be hidden in SN Ia spectra are from the work of Leonard [9], who studied nebular spectra of SN 2005am and SN 2005cf. He found an upper limit of $0.01\mathrm{M}_\odot$ for hydrogen. This is in clear contradiction to the theoretical predictions by Marietta et al. [8].

MODELLING

In order to simulate the impact of SN Ia on main sequence companions, we use the smoothed particle hydrodynamics code GADGET2 [10] with a few modifications described in [11] for our calculations. The setup is done in 2 steps:

First we take a spherical model of the companion star, calculated by the stellar evolution code GARSTEC [12], and map it to a particle distribution that resembles the model. This star is then relaxed for $1.0 \times 10^4\,\mathrm{s}$ by evolving the configuration. Then the supernova is added at a distance given by the final separation of the progenitor system just before the explosion. This starts the actual simulation. For the supernova we use the well established W7 model [13].

All simulations were run for 5000s. After this time, the amount of mass stripped from the companion star does not change anymore [for details, see 14].

We use two different kinds of initial conditions. In order to compare our results to the HCV scenario of Marietta et al. [8], we place a solar-like $1.0\,\mathrm{M}_\odot$ star at a distance to the explosion given by the conditions of Roche-lobe overflow. This scenario does not take into account any effects of the evolutionary path of the binary system as mass transfer or mass loss.

In addition we use the results of a detailed binary evolution study presented by Ivanova and Taam [15]. They followed different possible SN Ia progenitor systems from the onset of mass transfer until the white dwarf reaches the Chandrasekhar mass. They present in detail six representative progenitor systems that are likely to end up in a SN Ia. We take the initial properties of these systems at the onset of mass transfer to construct a model for the companion star. Then we use the given average mass loss rate to evolve the star through the mass transfer phase. The final star is then used as the target of the explosion.

For resultion tests and details of the setup, see [14].

RESULTS

Using the same initial conditions and analysis as [8] in their HCV scenario, we find that in total $0.143\mathrm{M}_\odot$ are stripped from the companion star. This result is in close agreement with the original result of $0.15\mathrm{M}_\odot$ of stripped material. Also the kick velocity we found of $81.4\,\mathrm{km\,s^{-1}}$ is in good agreement with the velocity of $85.7\,\mathrm{km\,s^{-1}}$ found in the work of Marietta et al. [8].

We then extended our work to the more realistic progenitor systems described before. Their properties and main results are shown in table 1. The properties of the progenitor systems are the mass of the companion star at the beginning of the mass transfer $M_{\mathrm{d,i}}$ and at the time of the explosion $M_{\mathrm{d,f}}$, the length of the mass transfer period Δt_{tr} and the orbital period P_{f} and distance between white dwarf and its companion star just before

TABLE 1. Parameters of the progenitor models

Model	$M_{\rm c,i}$ [$\mathrm{M}_\odot$]	$M_{\rm c,f}$ [$\mathrm{M}_\odot$]	$\Delta t_{\rm tr}$ [yr]	$P_{\rm f}$ [d]	$a_{\rm f}$ [10^{11} cm]	$M_{\rm stripped}$ ($M_\odot$)	$v_{\rm kick}$ [$\mathrm{km\,s^{-1}}$]
rp3_28a	2.8	0.6	7.7×10^5	1.7	5.21	0.032	52.8
rp3_20a	2.0	1.17	3.9×10^6	0.55	2.68	0.032	46.6
rp3_20b	2.0	1.25	2.0×10^6	1.08	4.26	0.0095	24.1
rp3_25a	2.5	1.37	1.7×10^6	0.51	2.62	0.058	60.5
rp3_24a	2.4	1.4	8.4×10^5	1.1	4.39	0.010	26.6
rp3_20c	2.0	1.46	2.6×10^6	1.44	5.29	0.012	17.0

the explosion $a_{\rm f}$. The main results are the mass stripped from the companion $M_{\rm stripped}$ and its kick velocity $v_{\rm kick}$, 5000 s after the explosion.

We found that for these models the particular amount of mass that is stripped from the companion star ranges from $0.01\,\mathrm{M}_\odot$ to $0.06\,\mathrm{M}_\odot$. This is significantly (a factor of 3–15) less than previous studies [8, 16] predicted. The main difference to the work of Marietta et al. [8] is the binary evolution history of the companion star that we take into account. During the mass transfer phase, mass is constantly removed from the outer layers of the companion star. This results in a more compact object at the time of the explosion with less weakly bound material in the outer layers compared to a star with the same mass and age, that did not have mass loss. Consequently less material is stripped from the surface of the companion star when it is hit by the supernova ejecta.

Unlike previous results, our simulations are in agreement with the best upper limits ($0.01\,\mathrm{M}_\odot$) by Leonard [9] on the amount of hydrogen that can be hidden in observed nebular spectra. Therefore they make the single degenerate scenario with a main sequence companion compatible with observations and a valid progenitor scenario again. However they also predict, that lowering the current upper limits by an order of magnitude should lead to a detection of hydrogen in nebular spectra of SN Ia. If not, this scenario has to be questioned again.

OUTLOOK

The best current upper limits on the amount hydrogen in supernova spectra are derived from nebular spectra. However, the derivation has to make a few assumptions. Therefore it is more stringent to calculate spectra from the outcome of our simulations and compare them directly to observations. This will be addressed in future work.

Another future goal is to expand this type of study to other possible progenitor systems, especially single degenerate scenarios with red giant companions.

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