

The interaction of core-collapse supernova ejecta with a stellar companion

Zheng-Wei Liu^{1,2} , T. M. Tauris³, F. K. Röpkke^{4,5}, T. J. Moriya⁶,
M. Kruckow^{1,2}, R. J. Stancliffe³ and R. G. Izzard⁷

¹Yunnan Observatories, Key Laboratory for the Structure and Evolution of Celestial Objects, CAS, Kunming 650216, China,

²Center for Astronomical Mega-Science, CAS, Beijing, China
email: zwliu@ynao.ac.cn

³Argelander-Institut für Astronomie, Auf dem Hügel 71, D-53121 Bonn,

⁴Heidelberger Institut für Theoretische Studien, Schloss-Wolfsbrunnenweg 35, D-69118 Heidelberg, Germany,

⁵Zentrum für Astronomie der Universität Heidelberg, Institut für Theoretische Astrophysik, Philosophenweg 12, D-69120 Heidelberg, Germany,

⁶National Astronomical Observatory of Japan,

⁷University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom.

Abstract. The progenitors of many core-collapse supernovae (CCSNe) are expected to be in binary systems. By performing a series of three-dimensional hydrodynamical simulations, we investigate how CCSN explosions affect their binary companion. We find that the amount of removed stellar mass, the resulting impact velocity, and the chemical contamination of the companion that results from the impact of the SN ejecta, strongly increases with decreasing binary separation and increasing explosion energy. Also, it is found that the impact effects of CCSN ejecta on the structure of main-sequence (MS) companions, and thus their long term post-explosion evolution, are in general not dramatic.

Keywords. stars: supernovae: general, stars: kinematics, binaries: close

1. Introduction

The discovery of many low-mass X-ray binaries and millisecond pulsars in tight orbits, i.e. binary neutron stars with orbital periods of less than a few hours, provides evidence for supernova (SN) explosions in close binaries with low-mass companions. The nature of the SN explosion determines whether any given binary system remains bound or is disrupted (Hills 1983). An additional consequence of the SN explosion is that the companion star is affected by the impact of the shell debris ejected from the exploding star (Wheeler *et al.* 1975). Besides chemical enrichment, such an impact has kinematic effects and may induce significant mass loss and heating of the companion star. Core-collapse supernovae (CCSNe) arise from massive stars. There is growing observational evidence that the fraction of massive stars in close binary systems is large. Sana *et al.* (2012) found that more than 70% of massive stars are in close binary systems, which supports the idea that binary progenitors contribute significantly to the observed CCSNe.

After a SN explosion occurs in a binary system, the ejected debris is expected to expand freely and eventually impact the companion star. The companion star may be significantly heated and shocked by the SN impact, causing the envelope of the companion star to be partially removed due to the stripping and ablation mechanism (e.g., Wheeler *et al.* 1975, Marietta *et al.* 2000, Liu *et al.* 2012, Liu *et al.* 2013, Pan *et al.* 2012,

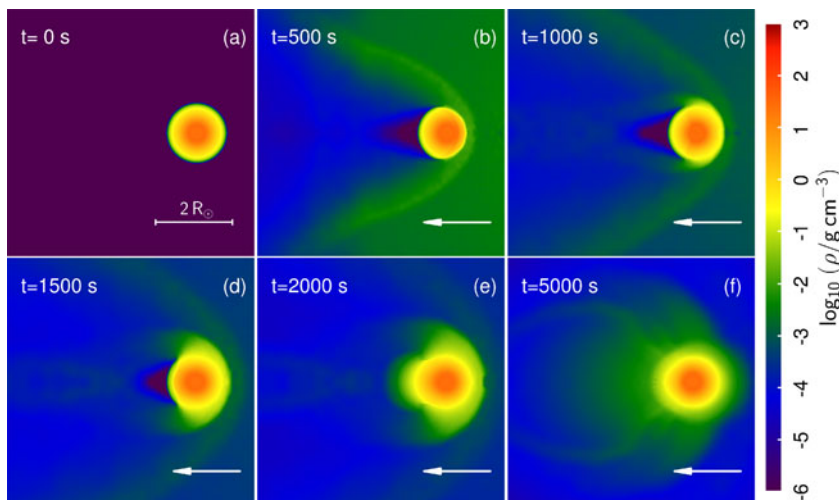


Figure 1. Density distributions of all gas material as a function of the time in our impact simulations for a G/K-dwarf companion model with a binary separation of $5.48 R_{\odot}$. The direction of motion of the incoming SN shell front is from right to left (see arrow symbols). The color scale shows the logarithm of the mass density in g cm^{-3} .

Hirai *et al.* 2018). In this work, we perform impact simulations using a three-dimensional (3D) smoothed particle hydrodynamics (SPH) method to systematically study, for the first time, the impact of CCSN ejecta on MS companion stars.

2. Results and conclusions

We use the BEC stellar evolution code to construct the detailed companion structure at the moment of SN explosion. The impact of the SN blast wave on the companion star is followed by means of 3D SPH simulations using the STELLAR GADGET code (Pakmor *et al.* 2012). Figure 1 illustrates the temporal density evolution of the SN ejecta and companion material of our hydrodynamics simulations for a G/K-dwarf companion model. Figure 2 shows the effects of varying the orbital separation parameter a/R_2 , by a factor of about 6, on the total amount of removed companion mass (ΔM_2), the resulting impact velocity (v_{im}), and total accumulated ejecta mass (ΔM_{acc}), for the $0.9 M_{\odot}$ and $3.5 M_{\odot}$ companion star models.

To discuss the effects of an explosion on the companion star in CCSNe of Type Ib/c, we perform populations synthesis calculations for SNe with the `binary_c/nucsyn` code (Izzard *et al.* 2004, Izzard *et al.* 2009). Under an assumption of a Galactic star-formation rate of $0.68 - 1.45 M_{\odot} \text{ yr}^{-1}$ and the average stellar mass of the Kroupa initial mass function ($0.83 M_{\odot}$), the total CCSN rate of the Galaxy predicted from their population synthesis is $0.93 - 1.99 \times 10^{-2} \text{ yr}^{-1}$ (36% SNe Ib/c, 10% SNe IIb, 54% SNe II), consistent with the estimated Galactic CCSN rate of $2.30 \pm 0.48 \times 10^{-2} \text{ yr}^{-1}$ from recent surveys (Li *et al.* 2011).

In our populations synthesis calculations, most SNe Ib/c have an orbital separation of $\gtrsim 5.0 R_2$, which is about a fraction of $\gtrsim 95\%$ in our binary population synthesis calculations. Furthermore, with the distributions of a/R_2 in Fig. 3, we can simply estimate ΔM_2 , v_{im} and ΔM_{acc} by applying our power-law relationships stated in Fig. 2. We caution that there are large uncertainties in population synthesis studies, which may influence the results. In this case, these mainly relate to the input physics of common-envelope evolution and the subsequent Case BB roche-lobe overflow from the naked helium star prior to its explosion.

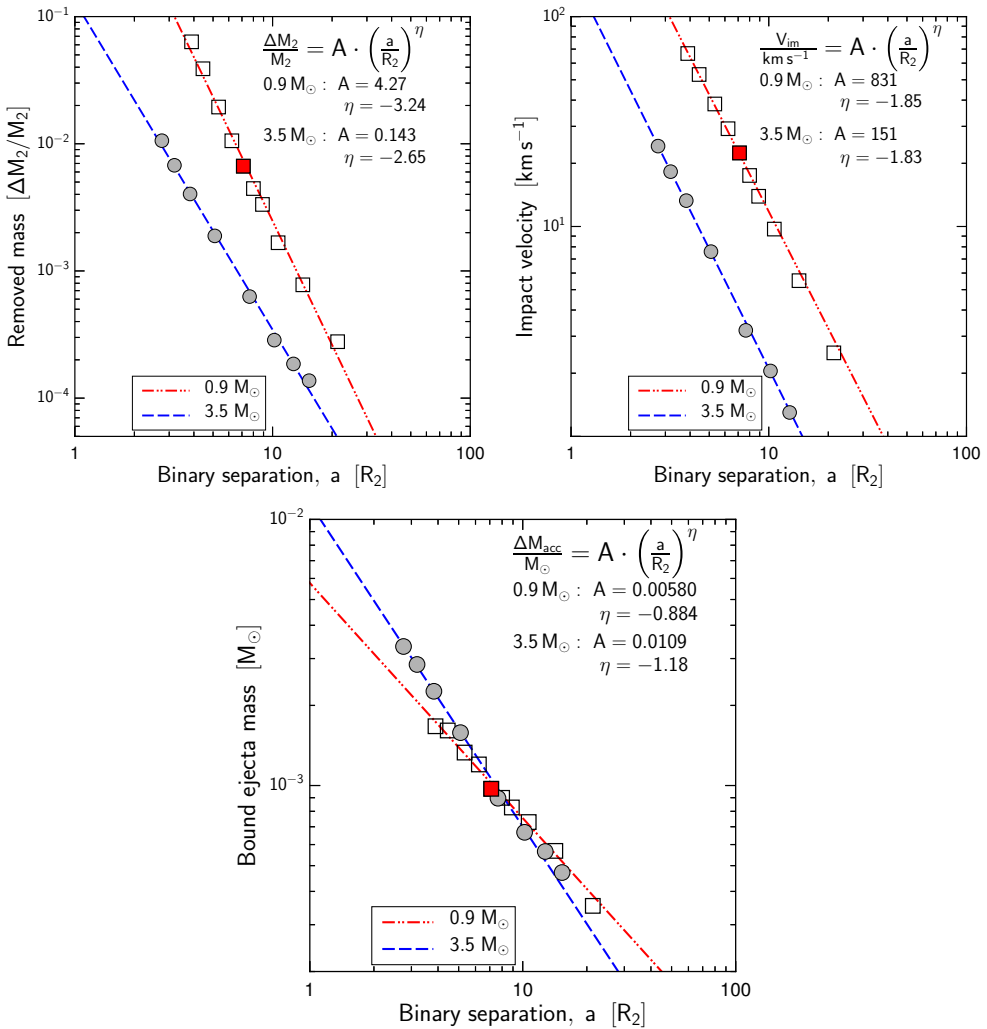


Figure 2. Total removed companion mass (top-left panel), resulting impact velocity of the companion star (top-right panel) and the amount of accreted contamination from the SN ejecta (bottom panel), as a function of initial binary separations for a G/K-dwarf (square symbols, $M_2 = 0.9 M_\odot$ and $R_2 \approx 0.77 R_\odot$) and a late-type B-star (filled circle symbols, $M_2 = 3.5 M_\odot$ and $R_2 \approx 2.18 R_\odot$) companion model. Power-law fits are also presented in each panel.

We have investigated the impact of SN ejecta on the companion stars in CCSNe of Type Ib/c using the SPH code STELLAR GADGET. Our main results can be summarized as follows (see also Liu *et al.* 2015):

i) The dependence of total removed mass (ΔM_2), impact velocity (v_{im}) and the amount of accreted SN ejecta mass (ΔM_{acc}) on the pre-SN binary separation (a) can be fitted with power-law functions. All three quantities are shown to decrease significantly with increasing a , as expected (see Fig. 2).

ii) If our population synthesis is correct, we predict that in most CCSNe less than 5% of the MS companion mass can be removed by the SN impact (i.e. $\Delta M_2 / M_2 < 0.05$). In addition, the companion star typically receives an impact velocity, v_{im} , of a few 10 km s^{-1} , and the amount of SN ejecta captured by the companion star after the explosion, ΔM_{acc} , is most often less than $10^{-3} M_\odot$.

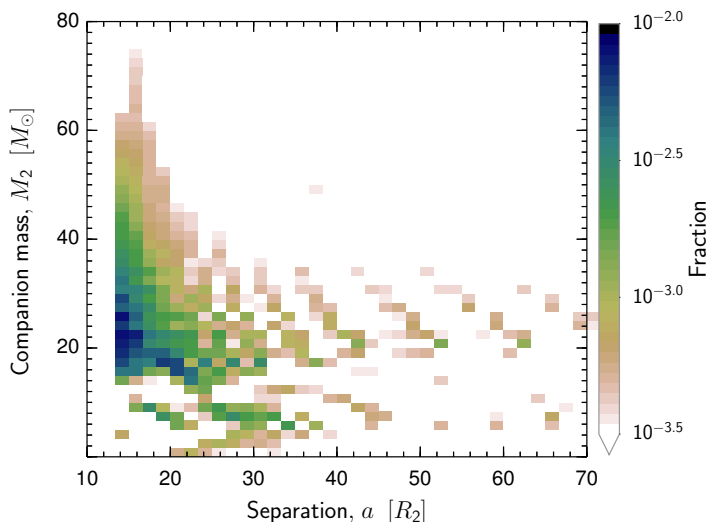


Figure 3. Population synthesis distribution of the companion star mass (M_2) as a function of the binary separation (a) in case the SN explodes as a Type Ib/c. Nothing is plotted in the regions with number fraction smaller than $10^{-3.5}$.

iii) Because a typical CCSN binary companion is relatively massive and can be located at a large pre-SN distance, we do not expect, in general, that the effects of the SN explosion on the post-impact stellar evolution will be very dramatic.

iv) In the closest pre-SN systems, the MS companion stars are affected more strongly by the SN ejecta impact, leading to $\Delta M_2/M_2 \simeq 0.10$, $v_{\text{im}} \simeq 100 \text{ km s}^{-1}$ and $\Delta M_{\text{acc}} \simeq 4 \times 10^{-3} M_{\odot}$, depending on the mass of the companion star. In addition, these stars are significantly bloated as a consequence of internal heating by the passing shock wave.

v) It is possible that the SN-induced high velocity stars (HVSs), or more ordinary, less fast, runaway stars, may be contaminated sufficiently to be identified by their chemical peculiarity as former companion stars to an exploding star if mixing processes are not efficient on a long timescale.

References

- Hills, J. G. 1983, *ApJ*, 267, 322
- Hirai, Ryosuke, Podsiadlowski, Ph., & Yamada, S. 2018, *ApJ*, 864, 119
- Izzard, R. G., Tout, C. A., Karakas, A. I., & Pols, O. R. 2004, *MNRAS*, 350, 407
- Izzard, R. G., Glebbeek, E., Stancliffe, R. J., & Pols, O. R. 2009, *A&A*, 508, 1359
- Li, Weidong, Chornock, R., Leaman, J., Filippenko, A. V., Poznanski, D., Wang, Xiaofeng, Ganeshalingam, M., & Mannucci, F. 2011, *MNRAS*, 412, 1473
- Liu, Zheng-Wei, Pakmor, R., Röpke, F. K., Edelmann, P., Wang, B., Kromer, M., Hillebrandt, W., & Han, Z. W. 2012, *A&A*, 548, A2
- Liu, Zheng-Wei, Pakmor, R., Seitzzahl, I. R., Hillebrandt, W., Kromer, M., Röpke, F. K., Edelmann, P., Taubenberger, S., Maeda, K., Wang, B. & Han, Z. W. 2013, *ApJ*, 774, 37
- Liu, Zheng-Wei, Tauris, T. M., Röpke, F. K., Moriya, T. J., Kruckow, M., Stancliffe, R. J., Izzard, R. G. 2015, *A&A*, 584, A11
- Marietta, E., Burrows, A., & Fryxell, B. 2000, *ApJS*, 128, 615
- Pakmor, R., Edelmann, P., Röpke, F. K., & Hillebrandt, W. 2012, *MNRAS*, 424, 2222
- Pan, Kuo-Chuan, Ricker, P. M., & Taam, R. E. 2012, *ApJ*, 750, 151
- Sana, H., de Mink, S. E., de Koter, A., Langer, N., Evans, C. J., Gieles, M., Gosset, E., Izzard, R. G., Le Bouquin, J.-B., & Schneider, F. R. N. 2012, *Science*, 337, 444
- Wheeler, J. C., Lecar, M., & McKee, C. F. 1975, *ApJ*, 200, 145