Massive Stars Near and Far
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Magnetic massive stars from stellar mergers

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Abstract. The first magnetic field in a star other than the Sun was detected in 1947 in the star 78 Vir. Today, we know that about 10% of these intermediate-mass and high-mass stars have strong, large-scale surface magnetic fields whose origin has remained a mystery till today. It has been suggested that merging of main-sequence and pre-main-sequence stars could produce such strong fields. The massive star τ Sco is a well-known member of the group of magnetic stars and is a blue straggler given its apparently young age compared to that of other members of the Upper Scorpius association. Here, we present 3D magnetohydrodynamic simulations of the coalescence of two massive main-sequence stars and 1D stellar evolution computations of the subsequent evolution of the merger product that can explain τ Sco's magnetic field, apparent youth and other observed characteristics. We argue that field amplification in stellar mergers is a general mechanism to form strongly-magnetised massive stars. Such stars are promising progenitors of magnetars, which may give rise to some of the enigmatic fast radio bursts, and their supernova explosions may be affected by the strong magnetic fields.

Keywords. MHD, binaries: general, blue stragglers, stars: evolution, stars: magnetic fields

1. Introduction

Magnetic fields are ubiquitous in the Universe. They were discovered in our Sun in 1908 by Hale, and some 40 years later also in the intermediate-mass, A-type star 78 Vir (Babcock 1947). Surveys have shown that about 7% of all intermediate- and high-mass stars have strong, large-scale surface magnetic fields (Donati & Landstreet 2009; Grunhut et al. 2017; Schöller et al. 2017). Contrarily to solar-like and other low-mass stars, the magnetic field strengths are not found to correlate with mass of the star or rotational velocity (Kochukhov & Bagnulo 2006). This led to the interpretation that the fields are "fossil", i.e. that they are frozen into the stellar structure after they were created by some, as yet unknown process. This unknown process must be able to explain the existence of magnetic fields in a small subset of main-sequence and pre-main-sequence stars, and it must also explain the observed lack of magnetic stars in close binaries (Carrier et al. 2002; Neiner et al. 2015). Also, there are hardly any binaries known with two magnetic components (see Shultz et al. 2015, for one such example). Magnetic dynamo models or processes acting during the star-formation process have difficulties explaining why only a fraction of stars obtain strong surface magnetic fields and why this is even lower in close binaries. It has thus been suggested that the merging of stars may explain the strong magnetic fields in some stars (Ferrario & Wickramasinghe 2005; Ferrario et al. 2009; Langer 2012; Wickramasinghe et al. 2014) and this idea is further supported by identifying some magnetic stars as blue stragglers (Schneider et al. 2016). In this proceeding, we present our findings that merging of massive main-sequence stars indeed lead to strong magnetic-field amplification and that observed key properties of the blue straggler star τ Sco appear consistent with our merger models (Schneider et al. 2019, 2020).

2. Magnetic-field amplification in a stellar merger

From the apparent age of τ Sco in comparison to the age of its host environment, the Upper Scorpius Association, Schneider et al. (2016) were able to identify possible binary-progenitor configurations that may lead to a star resembling τ Sco via a stellar merger. In Schneider et al. (2019), we picked one of these configurations, namely a $9 + 8\,\mathrm{M}_\odot$ binary merging at an age of 9 Myr (fractional main-sequence age of ≈35%). The merger is carried out with the 3D moving-mesh, magnetohydrodynamic code AREPO (Springel 2010; Pakmor et al. 2011; Pakmor & Springel 2013). The divergence of the magnetic field is controlled following Powell et al. (1999). Snapshots of the density evolution and the magnetic-field amplification process are shown in Fig. 1.

The magnetic-field amplification process is complex, highly non-linear and proceeds exponentially, eventually reaching magnetic field strengths of up to 10^7 G. It is difficult to attribute the amplification to individual mechanisms. The magnetic field is first strongly amplified in a shear layer that forms around both stars by mass flows in the initial overcontact binary configuration. We have identified the magneto-rotational instability and Kelvin-Helmholtz-like instabilities to contribute to the exponential build-up of the magnetic field. Saturation is reached at a level larger than expected from equipartition with turbulent energy alone likely because of strong, ordered differential rotation that also feeds into the magnetic energy. While the amplification process first produces fields on local, small scales ($\approx 0.1\,\mathrm{R}_\odot$), they are later redistributed such that most of the magnetic energy is at larger scales of 1–5 $\mathrm{R}_\odot$ (Ohlmann et al. 2022). Magnetic flux freezing from the end of the 3D simulation to a star of τ Sco's radius results in surface magnetic field strengths of a few kG, i.e. in the ball park of values observed in magnetic massive stars.

In the merging process, a massive, rotationally-supported torus forms ($\approx 3\,\mathrm{M}_\odot$) that carries a large fraction of the initial angular momentum (≈60%). It is expected that this torus is quickly accreted onto the central merger remnant and it is during this accretion and co-evolution process that the final, total angular momentum of the merged star is determined (Schneider et al. 2019, 2020). This process is on timescales beyond what can be followed by our simulations such that the final angular momentum of the merged star remains uncertain. At the end of the merger simulation, the interior rotation profile approaches that of a solid body, which smoothly transitions into a Keplerian-rotation profile of the torus (the torus rotates at about 80% of the Keplerian value and is pressure supported).

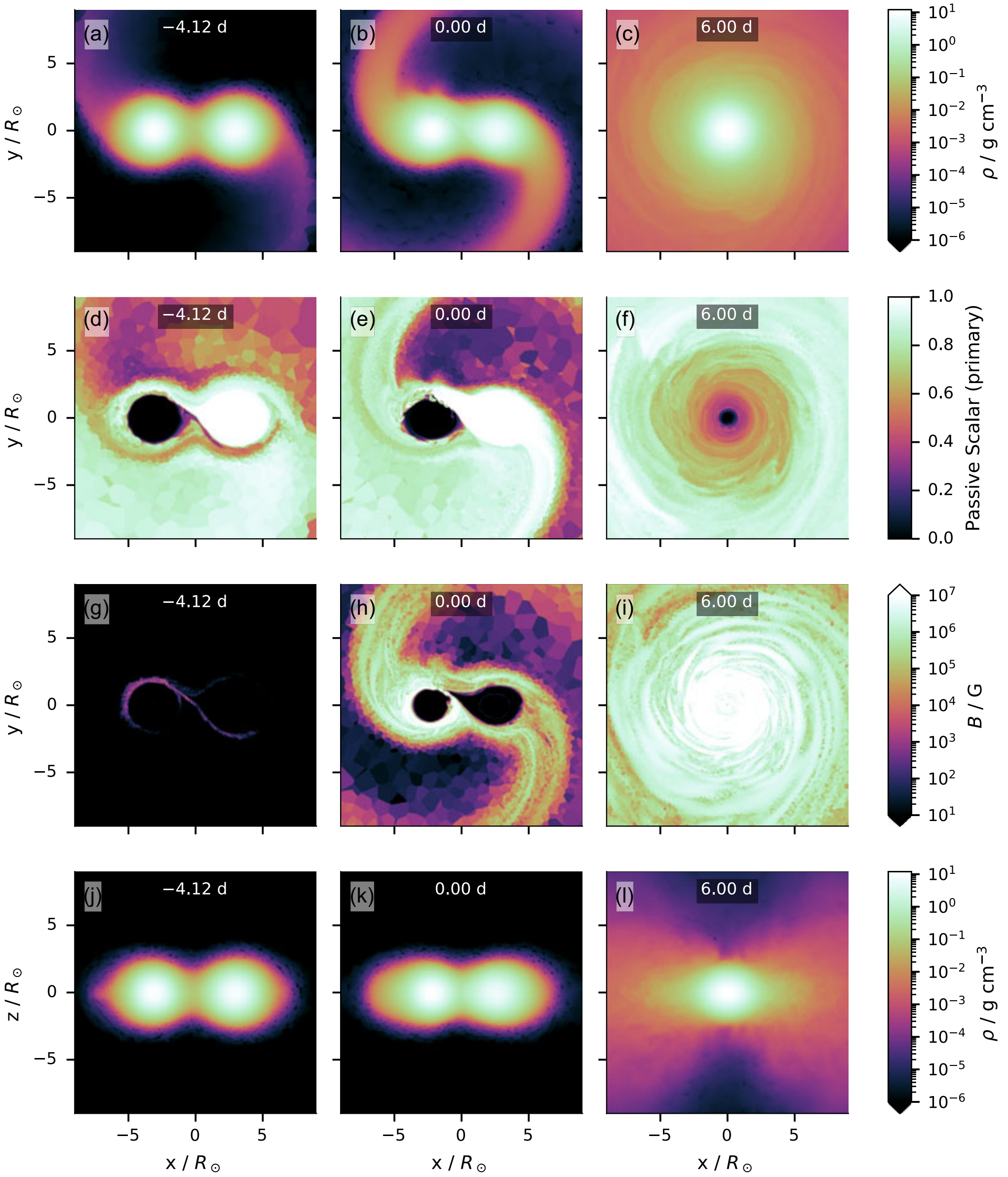

Figure 1. Evolution of density and absolute magnetic field strength in the orbital xy-plane and in its perpendicular, edge-on xz-plane. Figure adopted from Schneider et al. (2019).

3. Evolution of the post-merger star and comparison to τ Sco

Assuming that most of the torus is accreted onto the merger remnant and that the merged star is able to maintain its solid-body rotation profile matched to 80% of Keplerian rotation of the remaining torus material at the new stellar surface, we map the entropy profile of 3D merger simulation into the 1D stellar evolution code Mesa (Paxton et al. 2011, 2013, 2015; Paxton et al. 2018) as described in Schneider et al. (2019) and Schneider et al. (2020). The magnetic field is incorporated into the 1D model with a dipole radial scaling, and it contributes to angular-momentum transport and leads to magnetic braking. The merged star starts its evolution at an effective temperature of

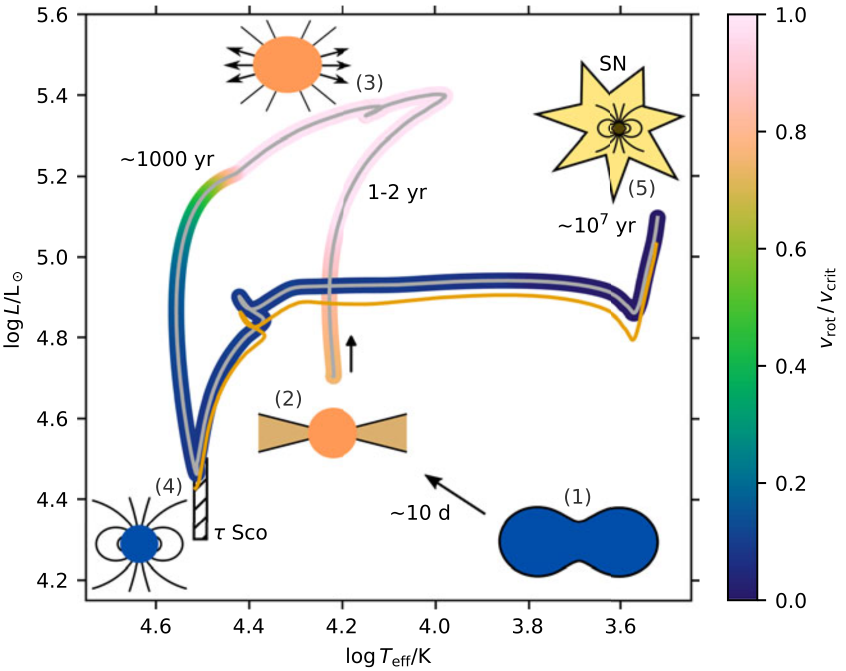

Figure 2. Hertzsprung–Russell diagram of the evolution of the merged star in comparison to a genuine single star of the same initial mass as the merger remnant (16.9 $M_\odot$). Colour indicates the surface rotational velocity with respect to the critical Keplerian value. The cartoons illustrate key evolutionary steps. Figure adopted from Schneider et al. (2019).

$\approx$14500 K and first undergoes a thermal relaxation phase (Fig. 2): its luminosity reaches a maximum value of $\log L/\mathrm{L}_\odot \approx 5.4$ within a few years before it contracts back to the main-sequence within 1000–10,000 yrs. During this relaxation phase, the star actually spins up while expanding and then spins down when contracting. This somewhat anti-intuitive behaviour is explained by a restructuring of the star's interior that modifies the moment of inertia (see Schneider et al. 2020, for more details). Only a negligible amount of angular momentum is lost in this short evolutionary phase despite mass shedding when rotating critically and magnetic braking. At the end of the relaxation phase when the star is back on the main sequence, the merger product resembles the magnetic star τ Sco in terms of its luminosity, effective temperature, surface gravity, apparent youth and also slow spin. Furthermore, the surface magnetic field, assuming magnetic flux freezing, is well in the range of what is observed in τ Sco and other magnetic stars.

4. Final fate of merged stars

The future evolution of the merged star closely follows that of a genuine single star of the same mass with one difference: the merged star has a higher average helium content in its envelope such that it evolves at a higher luminosity than the comparison single star (Fig. 2). The merger product is predicted to explode in a SN IIP upon reaching core collapse as a red supergiant. Ferrario & Wickramasinghe (2008) suggested that magnetic massive stars may be the direct progenitors of magnetars, i.e. neutron stars with the strongest known magnetic fields in the entire Cosmos. Magnetic flux freezing in the inner 1.5 $\mathrm{M}_\odot$ of the merger simulation to neutron-star dimensions results in surface magnetic fields of the neutron star of up to 10^{16} G. So even a much reduced magnetic flux could in principle result in magnetar-like field strengths. It should, however, be noted that it is as yet unknown how much (if any) of the magnetic flux might indeed survive until core collapse.

In Varma et al. (2022), the pre-supernova structure of our merger product has been successfully exploded in 3D under the assumption of a highly-magnetised pre-supernova core. A more energetic supernova explosion is found for a highly-magnetised core compared to a weaker magnetisation. Also, the forming neutron star may have magnetar-like surface magnetic fields, but it is too early to draw firm conclusions.

Magnetars are predicted to be born at a rate of ≈0.3 per century in the Milky Way (Keane & Kramer 2008) which converts into a magnetar birth fraction of ≈15% of all supernovae assuming the inferred core-collapse supernova rate of ≈2.0 per century by Diehl et al. (2006). This birth fraction of magnetars appears consistent with the observed incidence of magnetic massive stars of about 10%. While the exploding, merged star may be highly magnetised, we did not expect to find engine-driven explosions such as superluminous supernovae. Our merged star is probably slowly rotating and, even if it was rotating faster, it will likely lose much of its spin angular momentum in stellar winds before reaching the supernova stage.

5. Concluding remarks

Strong dynamical interactions in various binary systems have been found to lead to the formation of strong magnetic fields and thus seem to be an ubiquitous outcome of such phases. This includes stellar mergers of main-sequence stars as discussed here, but also mergers of white dwarfs (e.g. Zhu et al. 2015) and neutron stars (e.g. Price & Rosswog 2006); it may also extend to mergers of pre-main-sequence stars. Also strong magnetic fields emerge in the common-envelope phase where a companion is dragged into the envelope of a (super)giant star (e.g. Ohlmann et al. 2016) and even lead to the formation of fast bipolar outflows that help explain the shapes of (proto-)planetary nebulae (Ondratschek et al. 2022).

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References

Babcock H. W., 1947, Publications of the Astronomical Society of the Pacific, 59, 112
Carrier F., North P., Udry S., Babel J., 2002, A&A, 394, 151
Diehl R., et al., 2006, Nature, 439, 45
Donati J.-F., Landstreet J. D., 2009, ARA&A, 47, 333
Ferrario L., Wickramasinghe D. T., 2005, MNRAS, 356, 615
Ferrario L., Wickramasinghe D., 2008, MNRAS, 389, L66
Ferrario L., Pringle J. E., Tout C. A., Wickramasinghe D. T., 2009, MNRAS, 400, L71
Grunhut J. H., et al., 2017, MNRAS, 465, 2432
Hale G. E., 1908, ApJ, 28, 315
Keane E. F., Kramer M., 2008, MNRAS, 391, 2009
Kochukhov O., Bagnulo S., 2006, A&A, 450, 763
Langer N., 2012, ARA&A, 50, 107
Neiner C., Mathis S., Alecian E., Emeriau C., Grunhut J., BinaMIcS t., MiMeS collaborations 2015, preprint, (`arXiv:1502.00226`)
Ohlmann S. T., Röpke F. K., Pakmor R., Springel V., Müller E., 2016, MNRAS, 462, L121

Ohlmann S. T., Schneider F. R. N., Röpke F. K., Podsiadlowski P., Pakmor R., Springel V., Balbus S., 2022, in prep.

Ondratschek P. A., Röpke F. K., Schneider F. R. N., Fendt C., Sand C., Ohlmann S. T., Pakmor R., Springel V., 2022, A&A, 660, L8

Pakmor R., Springel V., 2013, MNRAS, 432, 176

Pakmor R., Bauer A., Springel V., 2011, MNRAS, 418, 1392

Paxton B., Bildsten L., Dotter A., Herwig F., Lesaffre P., Timmes F., 2011, ApJS, 192, 3

Paxton B., et al., 2013, ApJS, 208, 4

Paxton B., et al., 2015, ApJS, 220, 15

Paxton B., et al., 2018, ApJS, 234, 34

Powell K. G., Roe P. L., Linde T. J., Gombosi T. I., De Zeeuw D. L., 1999, Journal of Computational Physics, 154, 284

Price D. J., Rosswog S., 2006, Science, 312, 719

Schneider F. R. N., Podsiadlowski P., Langer N., Castro N., Fossati L., 2016, MNRAS, 457, 2355

Schneider F. R. N., Ohlmann S. T., Podsiadlowski P., Röpke F. K., Balbus S. A., Pakmor R., Springel V., 2019, Nature, 574, 211

Schneider F. R. N., Ohlmann S. T., Podsiadlowski P., Röpke F. K., Balbus S. A., Pakmor R., 2020, MNRAS, 495, 2796

Schöller M., et al., 2017, A&A, 599, A66

Shultz M., Wade G. A., Alecian E., BinaMIcS Collaboration 2015, MNRAS, 454, L1

Springel V., 2010, MNRAS, 401, 791

Varma V., Mueller B., Schneider F. R. N., 2022, arXiv e-prints, p. arXiv:2204.11009

Wickramasinghe D. T., Tout C. A., Ferrario L., 2014, MNRAS, 437, 675

Zhu C., Pakmor R., van Kerkwijk M. H., Chang P., 2015, ApJL, 806, L1