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Magnetised gas nebulae of evolved massive stars

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Abstract. Massive stars are amongst the rarest but also most intriguing stars. Their extreme, magnetised stellar winds induce, by wind-ISM interaction, famous multi-wavelengths circumstellar gas nebulae of various morphologies, spanning from large-scale wind bubbles to stellar wind bow shocks, rings and bipolar shapes. We present two- and three-dimensional magneto-hydrodynamical (MHD) simulations of the circumstellar medium of such massive stars at different phase of their evolution. Particularly, we investigate the stability properties of 3D MHD bow shock nebulae around the runaway red supergiant stars IRC-10414 and Betelgeuse. Our results show that their astrospheres are stabilised by an organised, non-parallel ambient magnetic field. These findings suggest that Betelgeuse's bar is of interstellar origin. Last, we explore the circular aspect of the young nebula around the Wolf-Rayet stars. It is found that Wolf-Rayet nebulae are not affected by the ISM gas distribution in which the stellar objects lie, even in the case of fast stellar motion: as testifies the ring-like surroundings of the Milky Way's fastest Wolf-Rayet star, WR124. The morphology of these nebulae is tightly related to their pre-Wolf-Rayet wind geometry and to their phase evolution transition properties, which can generate bipolar shapes. We will further discuss their diffuse projected emission by means of radiative transfer calculations and show that the projected diffuse emission can appear as bipolar structures as in NGC6888.

Keywords. MHD - radiative transfer - circumstellar matter - stars: massive.

1. Introduction

Massive stars are infrequent, seminal and generate ionized superbubbles around stellar clusters (Langer 2012). Throughout their life, their strong winds and explosive death enrich the interstellar medium (ISM), drive away turbulence regulating future star formation and produce cosmic rays. The large variety of scales and physical mechanisms involved therein reflects in their so-called circumstellar medium, shaping as pc-scale bubbles (Weaver *et al.* 1977) or bow shocks (van Buren *et al.* 1988) and finally to remnant nebulae (Meyer *et al.* 2020a; Meyer 2021b).

For decades, magnetic fields have been neglected in the modelling of circumstellar nebulae around evolved massive stars, and only recent works of the past years started investigating the magneto-hydrodynamics (MHD) of the circumstellar medium (van Marle *et al.* 2015). We continue in this direction.

This proceeding is divided as follows. First we will present the 3D MHD models for the circumstellar medium of Betelegeuse and its bar (Section 2), then we will discuss the origin of infrared rings co-moving with some Galactic runaway Wolf-Rayet stars (Section 3). Finally, we will investigate the effects of magnetic fields and wind asymmetries in the

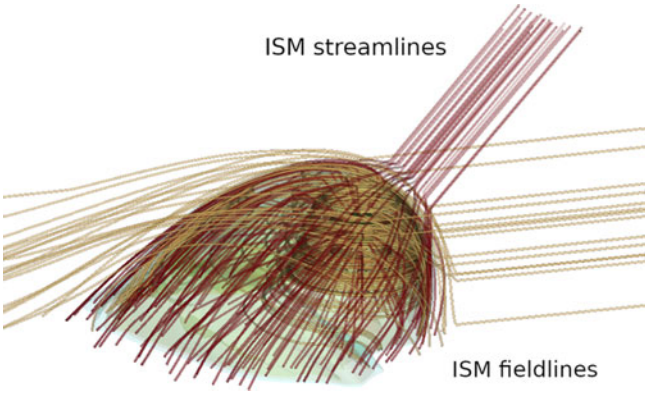

Figure 1. Bow shock nebula of the runaway supergiant star IRC-10414. The transparent surfaces are isodensity contours of the bow shock. The red and yellow lines mark the gas velocity streamline and the magnetic fieldlines, respectively.

shaping of bipolar nebulae around Wolf-Rayet stars (Section 4). Our conclusions are presented in Section 5.

2. 3D MHD stellar wind bow shock around red supergiant stars

In Meyer *et al.* 2021c we used the PLUTO code (Mignone *et al.* 2012) in order to perform full 3D MHD models tailored of the astropsheres of the runaway red supergiant stars IRC-10414 (Gvaramadze *et al.* 2014) and Betelgeuse (Mohamed *et al.* 2012), respectively. The simulations have been carried out on a uniform Cartesian grid, using radiative cooling and heating and we account for special boundary conditions by imposing the runaway star a direction of motion that is not parallel to any of the Cartesian axis, in order to reduce grid effects (Blondin *et al.* 1998).

In Fig. 1 we show a rendering for the surroundings of the runaway supergiant star IRC-10414, with coloured isosurfaces for the astrosphere density structure, as well as gas velocity (in red) streamlines and magnetic fieldlines (in yellow). One sees that the 3D nature of the calculations permits to investigate situations where the star does not move along the same direction as to the local magnetic field direction, while precedent 2D models could not (van Marle *et al.* 2012; Meyer *et al.* 2014b; van Marle *et al.* 2014).

This angle θ between directions of magnetic fields and stellar motion revealed that in the non-parallel case ($\theta \geqslant 5$ degrees), extra magnetic stress and pressure provided by the ISM magnetic field, stabilises the outer region of the astrosphere. It is therefore no more ragged and clumpy as modelled in Blondin *et al.* (1998); Meyer *et al.* (2014b), but adopts a smooth appearance. This profoundly affects the projected emission of the stellar surroundings (see Meyer *et al.* 2021c).

Last, we run a model tailored to the young bow shock of Betelgeuse (Mohamed *et al.* 2012). Radiative transfer calculation for optical Hα emission are shown in Fig. 2 together with HERSCHEL 170 μm infrared emission (ESA Herschel Science Archive Observation ID: 1342242656). It shows that the mysterious bar of Betelgeuse can be explained as an additional interstellar structure to the astrosphere, unlike the pure circumstellar model of Mackey *et al.* 2012.

3. Rings around runaway Wolf-Rayet stars

Wolf-Rayet stars are stellar objects of particularly high initial mass, evolving to a particular phase characterised by mass-loss rates $\geq 10^{-5}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ and wind velocities

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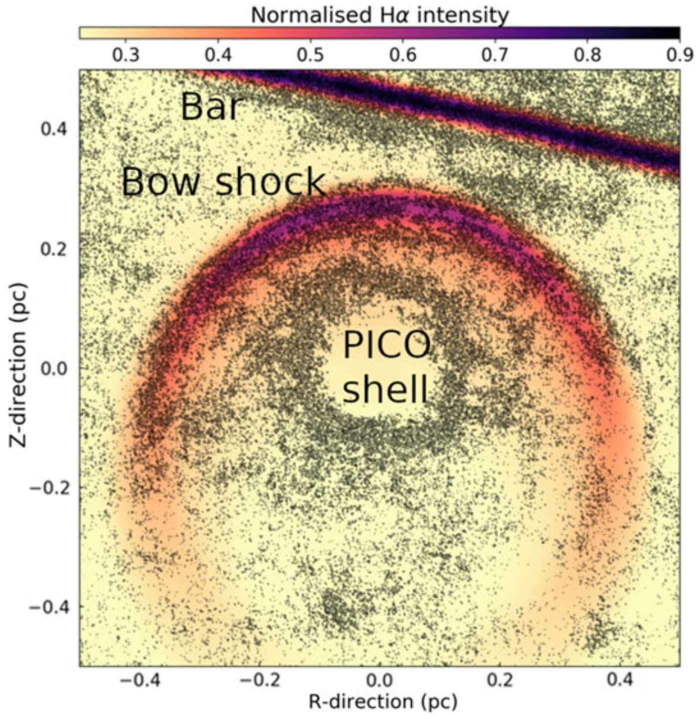

Figure 2. Synthetic Hα image of the circumstellar medium of Betelgeuse (colour), with overplotted Herschel data (black contours). The different elements of this peculiar stellar surroundings are indicated, with the astrosphere (bow shock), the outer bar and the inner photo-ionized-confined shell (PICO, see Meyer *et al.* 2021c), respectively.

$3000-5000\,\mathrm{km\,s^{-1}}$ (Hamann *et al.* 2006). These stars display a variety of circumstellar nebulae, both in optical and infrared, generated by the interaction of their wind with their ambient medium. Some of them even run away from their parent cluster and reach the high latitudes of the Milky Way. However, despite of the fact that one could expect such runaway Wolf-Rayet stars to generate bow shocks, no one display one. More intriguingly, some fast-moving Wolf-Rayet stars carry a ring visible in the infrared waveband (Gvaramadze *et al.* 2010).

In Meyer 2021b we performed 2D MHD simulations of the evolution of the circumstellar medium of the $60\,\mathrm{M_{\odot}}$ massive star of Groh *et al.* (2014). This star undergoes a complex pre-supernova evolution, including a main-sequence phase, a B-type phase, several luminous blue variable eruptions and three successive, so-called WN, WC, WO, Wolf-Rayet phases. We showed that an infrared-faint bow shock is produced by the pre-Wolf-Rayet stellar winds, making room for the Wolf-Rayet material to expand into its last precedent wind. Such wind-wind interaction engenders a dense infrared-bright ring which growths as it expands away from the star while conserving its spherical morphology (Fig. 3).

4. Asymmetric nebulae of Wolf-Rayet stars

Amongst the many shapes the surroundings of Wolf-Rayet stars can adopt, several examples reported a bipolar morphology (see Chu *et al.* 1982a), see also the nebula NGC6888 around the star WR 136 (Treffers *et al.* 1982). Although the dust properties of this circumstellar structure suggests that its central star has previously undergone a red supergiant phase (Mesa-Delgado *et al.* 2014), the spherical character of both the red supergiant and Wolf-Rayet winds can not explain the form of NGC6888.

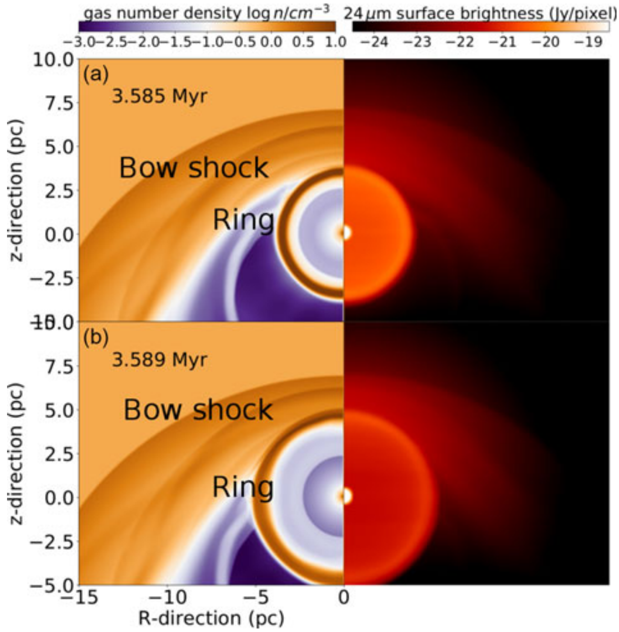

Figure 3. Surroundings of a runaway Wolf-Rayet star, displaying near-infrared bow shock and bright inner ring formed by wind-wind collision (Meyer 2021d).

We explore, by means of 2D simulations, the scenario of a star undergoing a blue supergiant phase before its Wolf-Rayet wind start blowing. As luminous blue variable stars have been observed to expel asymmetric winds into their circumstellar medium, we assume that the blue supergiant wind is blown according to a high polar-to-equatorial density distribution, which we model with the asymmetry function of Raga *et al.* 2008.

Fig. 4 displays two Wolf-Rayet nebulae produced by wind-wind interaction, either assuming an asymmetric blue supergiant wind (left) or a symmetric wind (right). The first generates a peanut-like, bipolar Wolf-Rayet nebula while the latter induces a ring-like spherical bubble. The overplotted contours mark the toroidal component of the wind velocity (solid black line) and velocity (dashed red line), respectively. From this we concluded that the star driving NGC6888 must have undergone a blue supergiant phase in which the wind was launched along the equator.

5. Conclusion

We find that the surface stellar magnetic field of supergiant stars are dynamically unimportant to the shaping of their stellar wind bow shocks, although it makes the simulations more stable computationally. Particularly, when direction of stellar motion and direction of ISM magnetic fields are different, the bow shocks are stabilised and adopt a smoother shape (Meyer *et al.* 2021c). Projection effects, e.g. at Hα, of the 3D MHD bow shocks are important and reveal a diversity of morphologies similar to that in many observed optical and infrared nebulae (van Buren *et al.* 1988). Additionally, we use the 3D MHD models to propose the nature of Betelgeuse's bar as a being interstellar, and not circumstellar as it had been previously suggested (Mackey *et al.* 2012).

Moreover, we explained the formation of rings around the fastest runaway Wolf-Rayet stars such as WR124 by wind-wind collision (Meyer *et al.* 2020b), and showed that an asymmetric pre-Wolf-Rayet wind can drastically change the shape of its subsequent circumstellar medium by forming a bipolar nebula like NGC6888 (Meyer 2021d). These

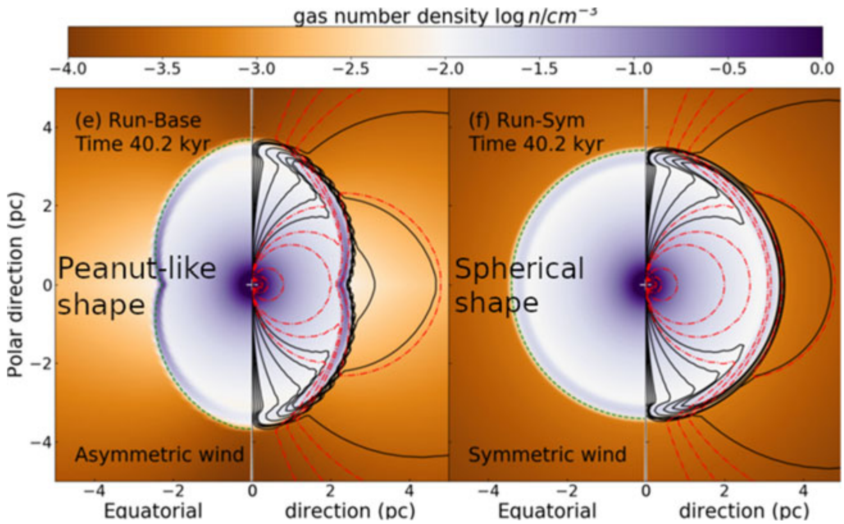

Figure 4. Stellar wind nebulae generated around Wolf-Rayet stars. The circumstellar nebulae are formed by wind-wind interaction, with a blue supergiant wind blown prior to the Wolf-Rayet phase, that is either asymmetric (left) or spherical (right). The subsequent nebulae adopt morphologies which are function of the blue supergiant wind geometry.

surroundings of Wolf-Rayet stars constitute a fantastic laboratory for numerical hydrodynamists and stellar evolution physicists, which should be further investigated by means of high-performance computing simulations.

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