VRO 42.05.01: A supernova remnant resulting by a supersonically moving Wolf-Rayet progenitor star

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1. Introduction

VRO 42.05.01 (hereafter VRO) is a Galactic supernova remnant (SNR), which reveals an intriguing morphology consisted of two major components: a ~30´ diameter semicircular shell (a.k.a. 'the shell') and a much larger bow shaped (almost triangular) shell (a.k.a. 'the wing', see Fig. 1).

Up to date VRO's morphology has been attributed to the interaction of the SNR with a discontinuous ambient medium (Pineault et al. 1987, Landecker et al. 1989, Arias et al. 2019). However, observational surveys reveal no evidence of such an interaction between the remnant and the surrounding medium.

In this work, we present a novel model of VRO, which suggests that the SNR resulted by a supersonically moving Wolf-Rayet progenitor star. The strong stellar wind of the Wolf-Rayet progenitor was asymmetric and enhanced at the equatorial plane of the star. We perform 2-D hydrodynamic simulations of the wind bubble formation and the subsequent SNR evolution and we conclude that such a model is able to reproduce in detail the morphological characteristics of VRO.

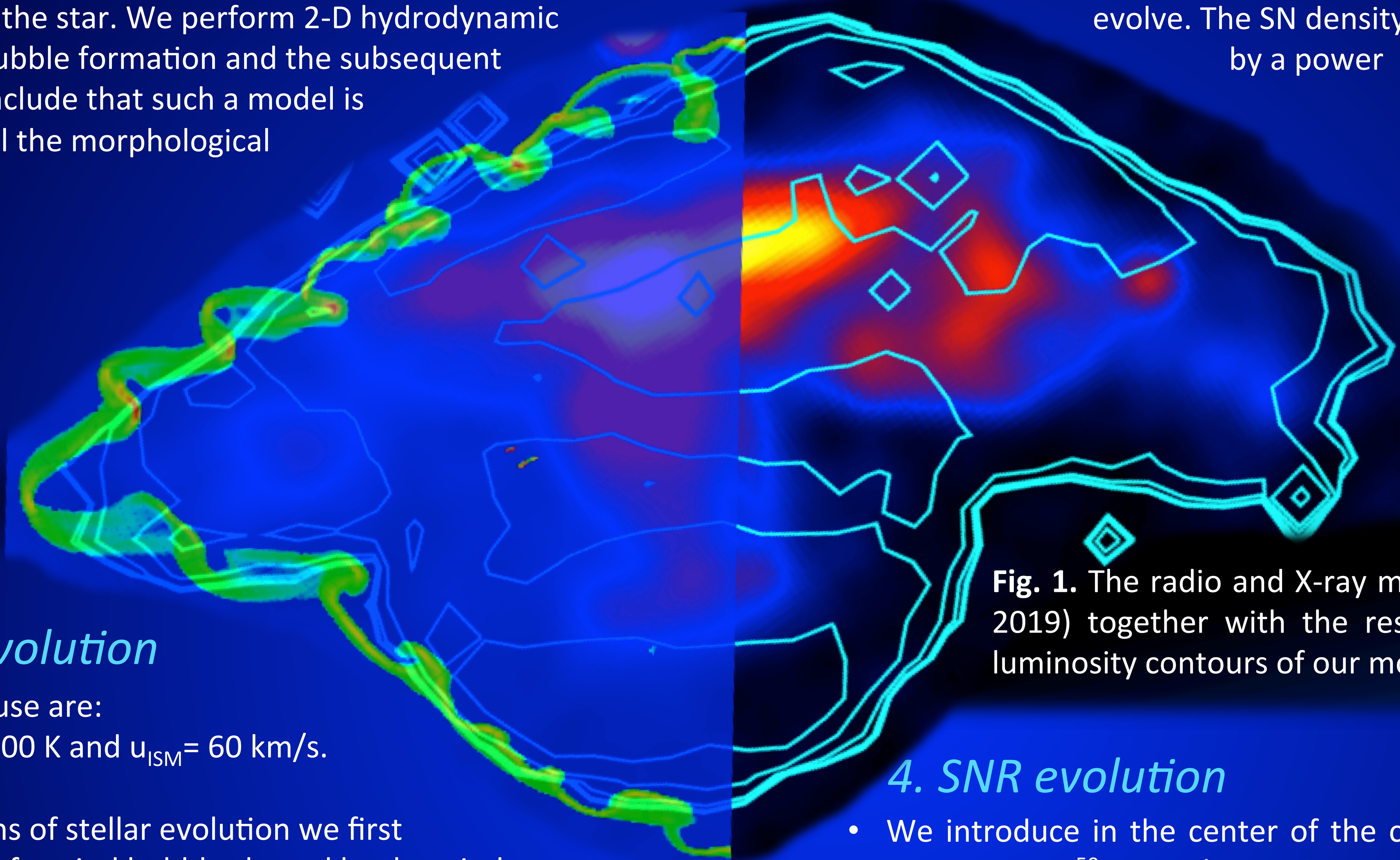

Fig. 1. The radio and X-ray mosaic of VRO 42.05.01 (Arias et al. 2019) together with the results of our hydrosimulations (2D luminosity contours of our model at t_{SNR}= 31,700 yr).

2. Methodology

- We employ the hydrodynamic code AMRVAC (Keppens et al. 2003) to simulate the wind bubble around the progenitor system and the subsequent evolution of the supernova ejecta.

- Wind bubble simulations: Isotropic, homogeneous gas is entering the grid antiparaller with the y-axis, which represents the motion of the ISM in the star's rest frame. The mass-losing star is located in the axis origin, where we let anisotropic wind flow enter the grid (Fig. 2). The equations of the anisotropic wind flow, which are utilised in the inner boundary conditions, are:

$$u_w(\theta)= u_{w,0}\,[1-\alpha(\sin\theta)^k]$$
$$4\pi r^2 \rho(\theta)= \dot{M}_0\,[1-\beta(\sin\theta)^k]^{-1}/u_w(\theta)$$

- SNR simulations: After the formation of the wind bubble we introduce the SN with energy E_{ej} and mass M_{ej} in the inner boundary of the grid and we let the SNR to evolve. The SN density profile is described by a power law with index n=9.

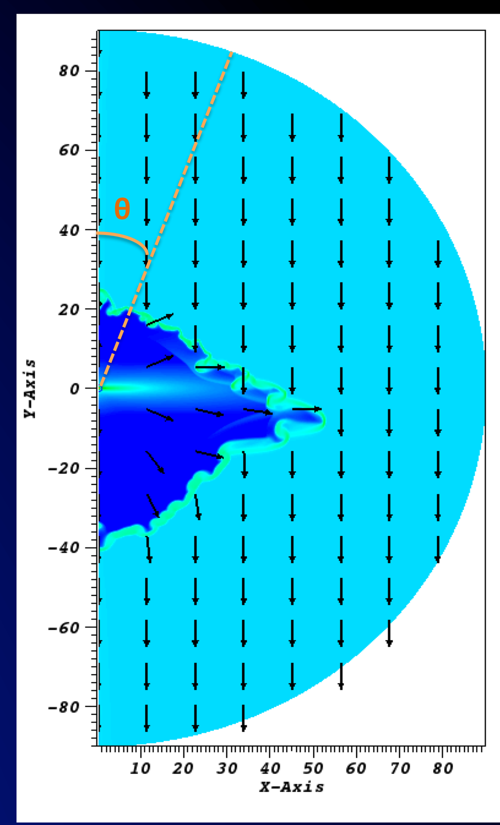

Fig. 2. The 2D density profile of the wind bubble simulation. The arrows represent the ISM and wind flows.

3. Wind bubble evolution

- The ISM properties we use are: n_{ISM}= 0.5 cm^{-3}, T_{ISM} = 1000 K and u_{ISM}= 60 km/s.
- Following the predictions of stellar evolution we first simulate the formation of a wind bubble shaped by the wind of a Red Supergiant (i.e. the previous stellar evolutionary state before the Wolf-Rayet phase). For the purposes of this simulation we set: $dM/dt= 10^{-4}\,M_{\odot}yr^{-1}$, u_w= 75 km/s and $\tau_{RSG}= 4 \times 10^4$ yr (Fig. 3a).
- Subsequently, in the axis origin we impose the anisotropic Wolf-Rayet wind with properties: $dM/dt= 3 \times 10^{-5}\,M_{\odot}yr^{-1}$, u_w= 1000 km/s, α=0.6, β=0.95, and k=2.
- The systemic motion of the Wolf-Rayet star in combination with its asymmetric outflows excavate an extended wind bubble that reveals a similar structure to this of VRO 42.05.01 (Fig. 3b, c, and d).

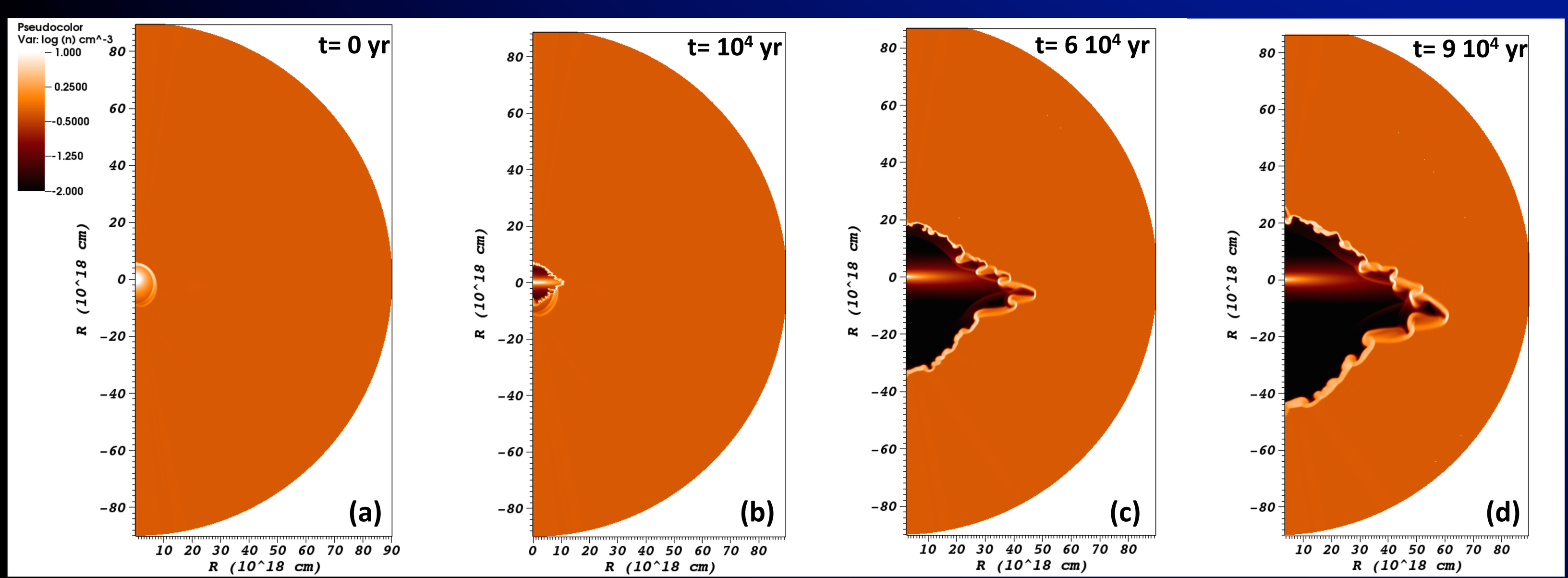

Fig. 3. The wind bubble of the RSG (a) and the time evolution of the wind bubble from the Wolf-Rayet progenitor star (b, c, and d).

4. SNR evolution

- We introduce in the center of the circumstellar structure of Fig. 3d the SN with energy 2×10^{50} erg and mass 6 $M_{\odot}$ and we let it evolve and interact with the CSM. The resulting SNR evolution is depicted in Fig. 4.
- Initially, the SNR is within the wind bubble and it reveals a bi-lobal shape due to the CSM density enhancement at the equatorial plane of the system. This bi-lobal shape is found frequently in mature SNRs (e.g. G 65.3+5.7, Boumis et al. 2004).
- Six thousand years after the explosion the SNR starts to collide with the shell of the wind bubble and it is substantially decelerated. The resulting SNR is dominantly shaped by the surrounding wind bubble revealing the current morphology of VRO 42.05.01.

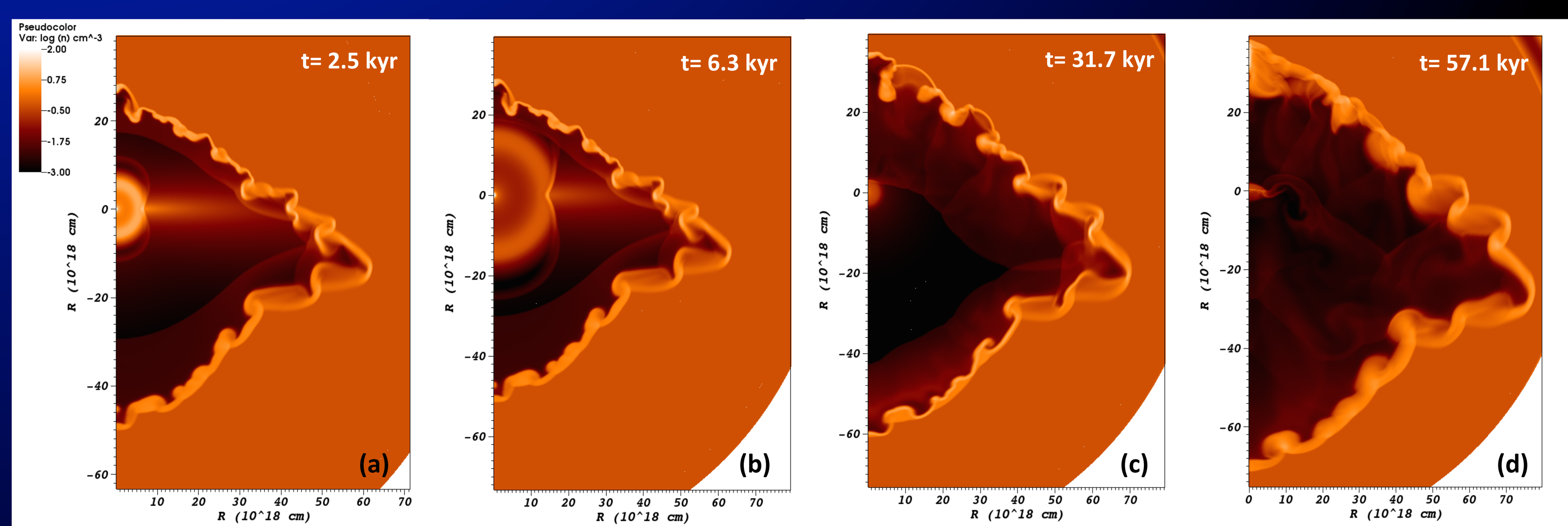

Fig. 4. The evolution of the SNR within the wind bubble of Fig. 3d.

5. Conclusions

- The intriguing morphology of VRO 42.05.01 can naturally be explained by the stellar wind properties of its progenitor star without the necessity of adopting peculiar ambient medium properties and discontinuities.
- We argue that the observed characteristics of VRO can be reproduced by a supersonically moving progenitor system from which strong anisotropic stellar winds, enhanced at the equatorial plane, were emanating. Such anisotropic outflows can be found either on fast rotating stars and/or in binary stellar systems.
- Our 2D hydrodynamic simulations of the suggested model are able to reproduce the structure of VRO in great detail. The wind properties of our best model are $dM/dt= 3 \times 10^{-5}\,M_{\odot}yr^{-1}$, u_w= 1000 km/s, properties that are best fitted for a Wolf – Rayet progenitor star.

References

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