

Supernova remnants of red supergiants: From barrels to loops

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ABSTRACT

Core-collapse (CC) supernova remnants (SNRs) are the nebular leftovers of defunct massive stars that died during a supernova explosion, mostly while undergoing the red supergiant phase of their evolution. The morphology and emission properties of those remnants are a function of the distribution of circumstellar material at the moment of the supernova, as well as the intrinsic properties of the explosion and those of the ambient medium. By means of 2.5-dimensional (2.5D) numerical magneto-hydrodynamic (MHD) simulations, we modelled the long-term evolution of SNRs generated by runaway rotating massive stars moving into a magnetised interstellar medium (ISM). Radiative transfer calculations reveal that the projected non-thermal emission of SNRs decreases over time, namely: older remnants are fainter than younger ones. Older (80 kyr) SNRs whose progenitors were moving with a space velocity corresponding to a Mach number of $M = 1$ ($v_* = 20 \text{ km s}^{-1}$) in the Galactic plane of the interstellar medium ($n_{\text{ISM}} = 1 \text{ cm}^{-3}$) are brighter in synchrotron than when moving with a Mach number of $M = 2$ ($v_* = 40 \text{ km s}^{-1}$). We show that runaway red supergiant progenitors first induce an asymmetric non-thermal 1.4 GHz barrel-like synchrotron SNRs (at the age of about 8 kyr), before further evolving to adopt a Cygnus-loop-like shape (at about 80 kyr). It is conjectured that a significative fraction of SNRs are currently in this bilateral-to-Cygnus loop evolutionary sequence. Therefore, this population should be taken into account with respect to interpreting the data as part of the forthcoming Cherenkov Telescope Array (CTA) observatory.

Key words. circumstellar matter – stars: winds, outflows – ISM: supernova remnants

1. Introduction

Supernova remnants (SNRs) are chemically enriched nebulae made of gas and dust left behind following the explosive death of certain stellar objects that do not eventually become white dwarfs or collapse as a black hole. In the case of high-mass ($\geq 8 M_{\odot}$) progenitors, the mechanism producing the explosion is the so-called core collapse process (Woosley & Weaver 1986; Woosley et al. 2002; Smartt 2009; Langer 2012). As a result, mass and energies (Sukhbold et al. 2016) are released into the circumstellar nebula (CSN), which was originally shaped by the spectacular stellar wind-and-interstellar medium (wind-ISM) interaction at work prior to the explosion (Weaver et al. 1977; Gull & Sofia 1979; Chevalier & Liang 1989; Wilkin 1996; Bear & Soker 2021). Hence, the morphological and emission characteristics of SNRs are a function of the past evolution of their progenitor, which had left a strong imprint on their circumstellar medium (CSM). They later channel the propagation of the supernova shock wave as the remnant becomes larger and older, for both high-mass (Kesteven & Caswell 1987; Wang & Mazzali 1992; Vink et al. 1996; Uchida et al. 2009) and low-mass (Vink et al. 1997; Vink 2012; Williams et al. 2013; Broersen et al. 2014) SNRs. To understand their observed non-thermal emission and to constrain the feedback of SNRs from massive stars into the

ISM of the Milky Way, it is necessary to first understand in detail their shape. This medium can only be probed by numerical simulations.

Thus, carrying out a realistic modelling procedure for global SNRs via (magneto)hydrodynamical simulations is a two-step procedure. First, the wind-ISM interaction must be calculated and, secondly, the supernova explosion must be realised in it, with their interaction subsequently simulated. Examples of solutions for SNRs of low-mass progenitors can be found in the studies of Orlando et al. (2007); Petruk et al. (2009); Vigh et al. (2011); Chiotellis et al. (2012, 2013, 2020, 2021). Simulations of remnants of high-mass progenitors are presented in the studies of Orlando et al. (2007, 2012, 2019, 2020, 2021); van Marle et al. (2010). Among the many degrees of freedom in the parameter space that is controlling the morphologies of core-collapse SNRs (CCSNRs), the supersonic motion that affects a significant fraction of massive stars, namely, of core-collapse progenitors, is a preponderant element. Thus, it ought to be accounted for with respect to our understanding of asymmetric SNRs (Bear & Soker 2017; Meyer et al. 2020, 2023) and even up to its influence on the pulsar wind nebulae (PWN; also known as plerion), which are the remnants of high-mass progenitors in which a neutron star forms (Meyer et al. 2023). Interestingly, the peculiar radio emission of barrel-like and horseshoe SNRs can be explained by

invoking the coupling of the stellar wind history with the bulk motion of a progenitor undergoing a Wolf–Rayet phase before exploding (Meyer et al. 2021b).

Core-collapse SNRs have been observed by means of both their thermal and non-thermal emission and the mass of their progenitor constrained in Katsuda et al. (2018), although their classification remains open (Soker & Kaplan 2021; Soker 2023a,b; Shishkin & Soker 2023). This study shows that an exploding red supergiant star might generate most of such remnants. These stars shape the stellar surroundings at the pre-supernova time in a particular manner, which is a key question to explore (Soker 2021). A noticeable example is the Cygnus-Loop nebulae, whose peculiar morphology may arise from the interaction of a supernova shock wave with the walls of a cavity carved by the stellar wind of a defunct runaway red supergiant star (Fang et al. 2017). A deeper understanding of the internal functioning of such remnants requires an additional numerical effort, bringing together a higher spatial resolution, along with the stellar rotation and magnetisation of the cold pre-supernova wind, as well as a better post-processing of the results to extract synchrotron emission maps to be directly compared with real observations. This is of great interest, especially for the Cherenkov Telescope Array, as explained in Acharyya et al. (2023); Acero et al. (2023); Cherenkov Telescope Array Consortium (2023).

In this paper, we continue our numerical exploration of the morphologies and non-thermal synchrotron emission properties of CCSNRs of runaway massive stars, initiated in Meyer et al. (2023) by means of 2.5-dimensional (2.5D) magneto-hydrodynamical simulations. This paper focuses on the comparison between SNRs of the zero age main sequence (ZAMS) at $20 M_{\odot}$ that are exploding while undergoing a red supergiant and those at $35 M_{\odot}$ that are finishing their lifetimes as Wolf–Rayet stars. We generated 1.4 GHz synchrotron emission maps using the method developed in Villagran et al. (2024), which allows for the recovery of the physical units of the projected emissions, which are often presented in a normalised fashion. It is therefore possible to compare the brightnesses of the modelled SNRs as a function of time and of the initial conditions of the simulations. The synthetic emission maps are compared and discussed with real observations of SNRs.

The paper is organised as follows. In Sect. 2, we introduce the numerical methods used to generate the results detailed in Sect. 3. We further discuss the results in this study in Sect. 4 and present our conclusions in Sect. 5.

2. Method

In this section, we present the boundary and initial conditions of the magneto-hydrodynamical simulations performed in this study. It details the stellar evolution models utilised, along with the applied calculation strategy, numerical methods, and assumptions adopted for the radiative transfer calculations with the aim of comparing our results with real observations.

2.1. Interstellar medium

The assumed ISM number density is taken as $n_{\text{ISM}} = 0.79 \text{ cm}^{-3}$, which corresponds to that of the warm phase of the Galactic plane (Wolfire et al. 2003). The gas is assumed to be ionised and has a temperature of $T_{\text{ISM}} = 8000 \text{ K}$ (Meyer et al. 2023). Its magnetic field of strength $B_{\text{ISM}} = 7 \mu\text{G}$ (Meyer et al. 2024) is considered to be uniform and organised linearly, parallel to the direction of motion of the star. This configuration is imposed by

the 2D nature of the calculations, see van Marle et al. (2015); Meyer et al. (2017). The gas is initially in equilibrium between the cooling of the material at high temperature and the heating provided by the starlight, which ionises the circumstellar gas.

The heating rate, Γ , stands for the recombining hydrogenic ions that are ionised by photospheric photons. The liberated electrons get the quantum of energy transported by the ionising photon. This process happens at a rate that is taken from the recombination coefficient $\alpha_{\text{H}}^{\text{B}}$, interpolated from Table 4.4 of Osterbrock (1989). The cooling term, Λ , includes contributions from H, He, and metals at solar helium abundance, Z (Wiersma et al. 2009; Asplund et al. 2009), modified to include the H recombination line cooling by use of the energy-loss coefficient case B of Hummer (1994) and the O and C forbidden lines by collisionally excited emission presented in Henney et al. (2009). Our study uses species abundance at $\text{O}/\text{H} = 4.89 \times 10^{-4}$ in number density (Asplund et al. 2009).

2.2. Magnetised, rotating stellar wind

The stellar wind terminal radial velocity is calculated as:

$$v_w(t) = \sqrt{\beta(T) \frac{2GM_{\star}(t)}{R_{\star}(t)}}, \quad (1)$$

where G is the gravitational constant, $M_{\star}$ the stellar mass, and $R_{\star}$ the stellar radius, respectively. The factor $\beta(T)$ is a piecewise function of the temperature that is taken from the study of Eldridge et al. (2006). In this study, as in the former work of this series (Meyer et al. 2023), the escape wind velocity is calculated using the photospheric luminosity and the effective temperature to compute the stellar radius and, thus, the wind terminal speed. This reduces values for the Wolf–Rayet phase (at 5.33 Myr after the ZAMS). The physics for the terminal wind velocity of WR stars is not well understood and our values are still largely in accordance with observations of weak-winded ($< 1000 \text{ km s}^{-1}$) Galactic Wolf–Rayet stars, for instance: WR16, WR40, and WR105 (Hamann et al. 2019). The radial dependence of the stellar wind density is expressed as:

$$\rho_w(r, t) = \frac{\dot{M}(t)}{4\pi r^2 v_w(t)}, \quad (2)$$

with $\dot{M}$ the mass-loss rate of the massive star at a given time t .

We consider massive stars, which, at the onset of their main sequence, initially rotate as per:

$$\frac{\Omega_{\star}(t=0)}{\Omega_K} = 0.1, \quad (3)$$

and with,

$$\Omega_{\star}(t) = \frac{v_{\text{rot}}(t)}{R_{\star}(t)}, \quad (4)$$

where $\Omega_{\star}$ and Ω_K are the equatorial and Keplerian rotational velocities, respectively, and v_{rot} the toroidal velocity. The latitude-dependent toroidal component of the rotation surface is thus:

$$v_{\phi}(\theta, t) = v_{\text{rot}}(t) \sin(\theta), \quad (5)$$

while its polar component is set to $v_{\theta} = 0$; we also refer to the 2.5D approach developed for the modelled magnetised wind of rotating stars in Parker (1958); Weber & Davis (1967);

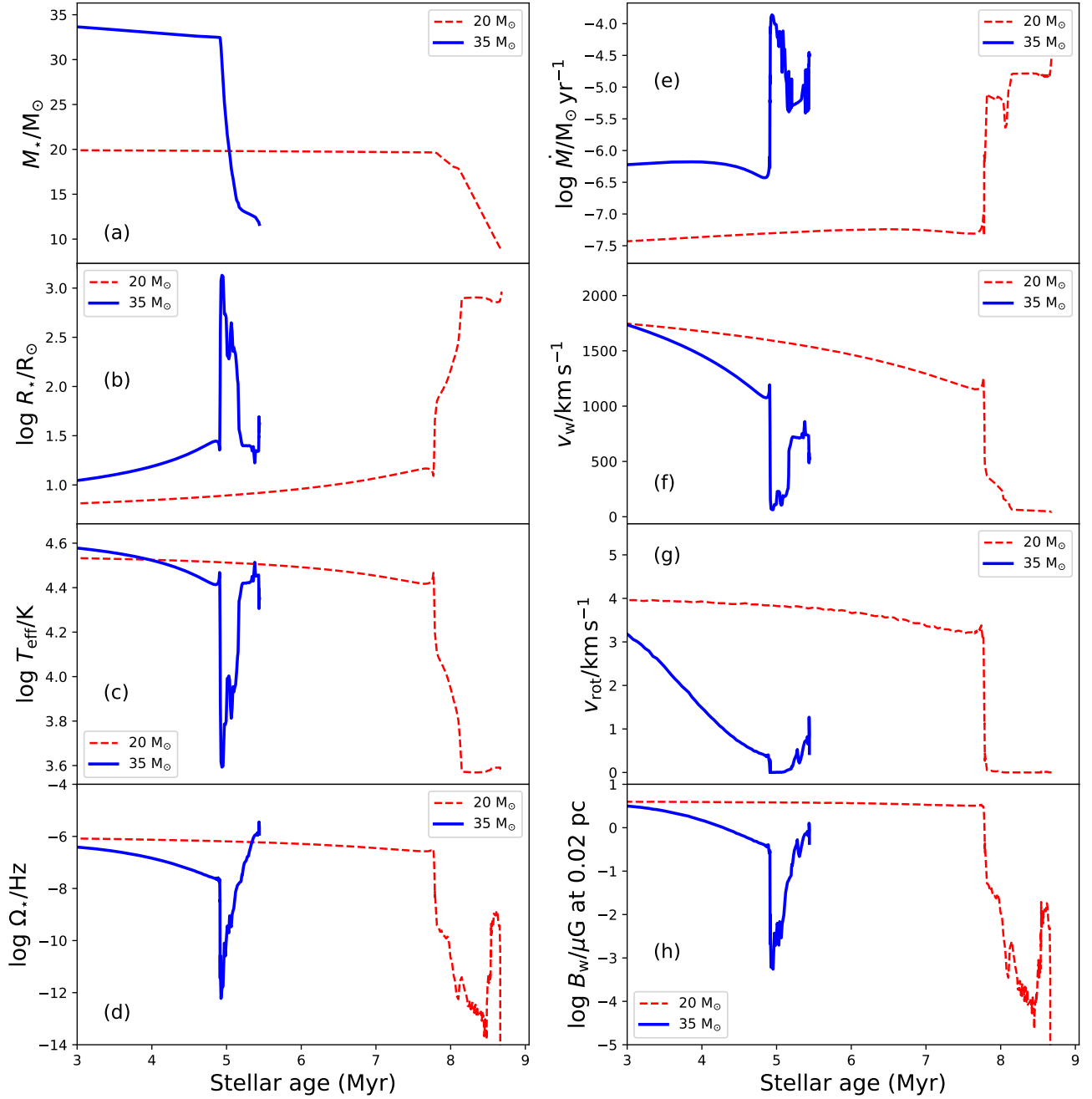


Fig. 1. Temporal evolution (in Myr) of the supernova progenitors of ZAMS $20 M_{\odot}$ (dotted red line) and $35 M_{\odot}$ (solid blue line) considered in our study. The panels display the stellar mass $M_{\star}$ (panel a, in $M_{\odot}$), radius $R_{\star}$ (panel b, in $R_{\odot}$), effective temperature T_{eff} (panel c, in K), angular frequency at the surface $\Omega_{\star}$ (panel d, in Hz), mass-loss rate $\dot{M}$ (panel e, in $M_{\odot} \text{ yr}^{-1}$), wind velocity v_w (panel f, in km s^{-1}), equatorial rotation velocity v_{rot} (panel g, in km s^{-1}), and the magnetic field in the wind at 0.02 pc $B_{\star}$ (panel h, in μG).

Pogorelov & Semenov (1997); Pogorelov & Matsuda (2000); Chevalier & Luo (1994); Rozyczka & Franco (1996).

The other characteristic stellar parameters were interpolated from the tabulated evolution models from the GENEVA library¹ (Eggenberger et al. 2008; Ekström et al. 2012), which provides the evolutionary structure and effective surface properties of high-mass stars from their ZAMS mass to their pre-supernova time when the Si burning phases take place. Our model, therefore, assumes that the mass-loss rate and the radial component of the wind velocity of the progenitor star are spherically symmetric throughout its entire pre-supernova

evolution. Such an approach is typical, with origins in the early developments of stellar evolution codes (Heger et al. 2000; Eggenberger et al. 2008; Brott et al. 2011a,b; Ekström et al. 2012), treating the hydrodynamic stellar structure equations for massive stars in a 1D fashion, as long they do not rotate close to their critical angular velocity (Georgy et al. 2011); this is also supported by observations of the massive star’s stellar wind close to the termination shock of their pc-scale nebulae (Weaver et al. 1977; van Buren & McCray 1988; Wilkin 1996; Peri et al. 2012, 2015), also leading to a spherically symmetric theory for hot-star wind acceleration driven by line-emission and radiation pressure (Abbott 1980, 1982; Friend & Abbott 1986). However, many factors (e.g. binarity, affecting up to 70% of massive stars)

¹ <https://www.unige.ch/sciences/astro/evolution/en/database/syclist/>

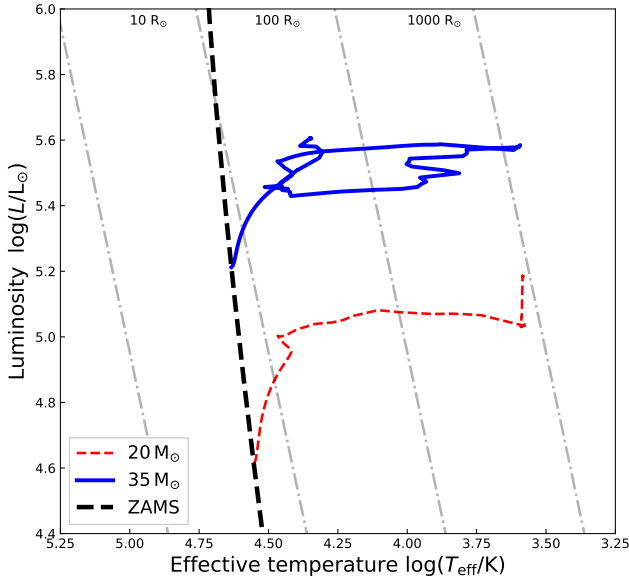


Fig. 2. Evolutionary tracks in the Hertzsprung–Russell-diagram of the two progenitor stars of initial masses $20 M_{\odot}$ (dotted red) and $35 M_{\odot}$ (solid blue) considered in this study (Ekström et al. 2012).

impose azimuthal deviations to these winds, especially in the region in the vicinity of the orbital plane of massive multiple system (Sana et al. 2012). Additionally, the alternation of high and slow winds at the phase transitions such as the onset of the red supergiant, blue supergiant, or Wolf–Rayet evolutionary sequences are also a source of asymmetry (Parkin et al. 2011; Madura et al. 2013; Gvaramadze et al. 2015; Martayan et al. 2016; El Mellah et al. 2020). Since we are focussed on the large-scale surroundings of single, slowly rotating objects, the spherically symmetric assumption for stellar winds is acceptable. For completeness, the Hertzsprung–Russell diagram of the two progenitor stars we consider in this study is plotted in Fig. 2.

The stellar magnetic field structure is assumed to be a Parker spiral,

$$B_r(r, t) = B_{\star}(t) \left(\frac{R_{\star}(t)}{r} \right)^2, \quad (6)$$

$$B_{\phi}(r, t) = B_r(r, t) \left(\frac{v_{\phi}(\theta, t)}{v_w(t)} \right) \left(\frac{r}{R_{\star}(t)} - 1 \right), \quad (7)$$

and

$$B_{\theta}(r, t) = 0, \quad (8)$$

respectively. The total stellar wind magnetic field is therefore expressed as:

$$B_w(r, t) = \sqrt{B_r(r, t)^2 + B_{\phi}(r, t)^2 + B_{\theta}(r, t)^2}. \quad (9)$$

The magnetic field strength at the surface of the star is scaled to that of the Sun, as described in Scherer et al. (2020); Herbst et al. (2020); Baalmann et al. (2020, 2021); Meyer et al. (2021a). We adopted the time-dependent evolution of the surface magnetic field, $B_{\star}$, of the supernova progenitor as derived in Meyer et al. (2023, 2024). The main sequence surface magnetic field strength is taken to $B_{\star} = 500$ G (Fossati et al.

2015; Castro et al. 2015, 2017; Przybilla et al. 2016), the red supergiant phase one to that of Betelgeuse, namely: $B_{\star} = 0.2$ G (Vlemmings et al. 2002, 2005; Kervella et al. 2018), whereas for the Wolf–Rayet phase, we assume $B_{\star} = 100$ G (Hubrig et al. 2016; de la Chevrotière et al. 2014; Meyer 2021).

2.3. Supernova ejecta

The supernova blastwave, whose properties are determined by the mass of the ejecta, M_{ej} , and energy of the explosion, E_{ej} (Shishkin & Soker 2023), was modelled using the method of Truelove & McKee (1999). First, the blastwave is injected at the time of the explosion considering the following radial density profile:

$$\rho(r) = \begin{cases} \rho_{\text{core}}(r) & \text{if } r \leq r_{\text{core}}, \\ \rho_{\text{max}}(r) & \text{if } r_{\text{core}} < r < r_{\text{max}}, \end{cases} \quad (10)$$

with an inner constant region, the so-called core, characterised by a density of:

$$\rho_{\text{core}}(r) = \frac{1}{4\pi n} \frac{(10E_{\text{ej}}^{n-5})^{-3/2}}{(3M_{\text{ej}}^{n-3})^{-5/2}} \frac{1}{t_{\text{max}}^3}, \quad (11)$$

and an outer steeply decreasing region with a density of

$$\rho_{\text{max}}(r) = \frac{1}{4\pi n} \frac{(10E_{\text{ej}}^{n-5})^{(n-3)/2}}{(3M_{\text{ej}}^{n-3})^{(n-5)/2}} \frac{1}{t_{\text{max}}^3} \left(\frac{r}{t_{\text{max}}} \right)^{-n}, \quad (12)$$

where the exponent $n = 11$ is typical for massive progenitor stars (Chevalier & Liang 1989) and where r_{max} is the outer limit of the blastwave at that time. The age of the blastwave is determined using the iterative procedure of Whalen et al. (2008), such that:

$$t_{\text{max}} = \frac{r_{\text{max}}}{v_{\text{max}}}, \quad (13)$$

with $v_{\text{max}} = 3 \times 10^4$ km s^{−1}.

The velocity profile of the blastwave is taken as:

$$v(r) = \frac{r}{t}, \quad (14)$$

which ensures that the early blastwave propagates homologously in the pre-supernova stellar wind of the progenitor. The ejecta velocity at a distance, r_{core} , from the center of the explosion is expressed as:

$$v_{\text{core}} = \left(\frac{10(n-5)E_{\text{ej}}}{3(n-3)M_{\text{ej}}} \right)^{1/2}, \quad (15)$$

as per Truelove & McKee (1999); Whalen et al. (2008); van Veelen et al. (2009); van Marle et al. (2010). The mass of defunct stellar material in the supernova ejecta is determined by subtracting the mass of a neutron star $M_{\text{NS}} = 1.4 M_{\odot}$ to that of the progenitor at the moment of the explosion,

$$M_{\text{ej}} = M_{\star} - \int_{t_{\text{ZAMS}}}^{t_{\text{SN}}} \dot{M}(t) dt - M_{\text{NS}}, \quad (16)$$

which is $7.28 M_{\odot}$ and $10.12 M_{\odot}$ for the $20 M_{\odot}$ and $35 M_{\odot}$ progenitors, respectively.

Our setting of the supernova blastwave assumes spherical symmetry of the radial component of the supernova ejecta. This is a classical approach to numerical simulations such as ours (van Veelen et al. 2009; van Marle et al. 2010). Specifically, this requires us to consider that the homologous expansion of the supernova material through the last stellar wind is not affected by any latitude- or azimuthal-dependent hydrodynamical flow. We should mention that the physics of core-collapse supernova (CCSN) explosion is complex and far beyond the simple prescription used in this study. In particular, the anisotropic in the emission of a released neutrino can substantially change the explosion energy and channel it in the direction of the neutrino anisotropies, producing an anisotropic blastwave (Shimizu et al. 2001; Müller et al. 2012; Gabler et al. 2021). Furthermore, the presence of a binary companion leads to additional blastwave-circumstellar interactions, potentially producing so-called common envelope jet supernova (CEJSN) in which a first component explodes, leading to a compact object (black hole or neutron star) that accretes material from its post-main-sequence companion, such as a supergiant star (Papish & Soker 2011, 2014; Gilkis et al. 2016; Bear & Soker 2018; Kaplan & Soker 2020; Soker 2022a,b,c, 2023a). Since our work considers single stars explosion of the canonical energy of 10^{51} erg, we neglected any anisotropy in the supernova blastwave and/or jet pushing out the gas of the former common envelope.

2.4. Governing equations

The equations solved on the grid meshing the computational domain are those of the non-ideal magneto-hydrodynamics (MHD). They are expressed as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0, \quad (17)$$

$$\frac{\partial m}{\partial t} + \nabla \cdot (m \otimes v - B \otimes B + \hat{I} p_t) = 0, \quad (18)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E + p_t)v - B(v \cdot B)) = \Phi(T, \rho), \quad (19)$$

$$\frac{\partial B}{\partial t} + \nabla \cdot (v \otimes B - B \otimes v) = 0, \quad (20)$$

where ρ is the mass density, v the vector velocity, m the vector momentum, and B the vector magnetic field, respectively. In the above relations, $\hat{I}$ is the identity vector, 0 is the null vector, and p_t is the total pressure (thermal p plus magnetic $B^2/8\pi$) of the gas. The total energy of the gas is:

$$E = \frac{p}{(\gamma - 1)} + \frac{m \cdot m}{2\rho} + \frac{B \cdot B}{8\pi}, \quad (21)$$

and the system is closed with the relation,

$$c_s = \sqrt{\frac{\gamma p}{\rho}}, \quad (22)$$

with c_s the sound speed of the gas, with γ the adiabatic index.

The right-hand side term,

$$\Phi(T, \rho) = n_H \Gamma(T) - n_H^2 \Lambda(T), \quad (23)$$

of Eq. (19) represents the losses and heating by optically-thin radiative processes. The H gas number density is:

$$n_H = \frac{\rho}{\mu(1 + \chi_{\text{He,Z}})m_H}, \quad (24)$$

with μ the mean molecular weight, $\chi_{\text{He,Z}}$ the He and metals (species of atomic number larger or equal to 2), and m_H the proton mass, respectively, and

$$T = \mu \frac{m_H}{k_B} \frac{p}{\rho}, \quad (25)$$

is the temperature of the gas.

2.5. Synchrotron emission calculation

Our study aims to investigate the radio appearance of the SNRs. To this end, we first call the relativistic electron energy distribution:

$$N(\gamma) = K \gamma^{-p} \propto \gamma^{-p}, \quad (26)$$

with K as a proportionality constant, p an index function of the spectral index via $p = 2\alpha + 1$, and γ the Lorentz factor:

$$\gamma = \frac{E}{E_0} = \frac{\gamma m_0 c^2}{m_0 c^2}, \quad (27)$$

with m_0 representing the rest mass of the electrons and c the speed of light.

The synchrotron emissivity at a frequency ν is defined for a given Lorentz factor range as:

$$\epsilon_{\text{sync}}(\nu, \theta) = \frac{1}{4\pi} \int_{\gamma_1}^{\gamma_2} N(\gamma) P_{\text{sync}}(\nu, \gamma, \theta) d\gamma, \quad (28)$$

with $\gamma_1 < \gamma_2$. Using Eq. (4.43) in Ghisellini (2013), this can be rewritten as:

$$\epsilon_{\text{sync}}(\nu) = \frac{3\sigma_T c K U_B}{8\pi^2 \nu_L} (\sin \theta)^{(p+1)/2} \left(\frac{\nu}{\nu_L} \right)^{-\frac{p-1}{2}} f_{\text{sync}}(p), \quad (29)$$

with σ_T the Thomson cross section, the special function:

$$f_{\text{sync}}(p) = 3^{p/2} \frac{\Gamma\left(\frac{3p-1}{12}\right) \Gamma\left(\frac{3p+19}{12}\right)}{p+1}, \quad (30)$$

the magnetic density energy,

$$U_B = \frac{B^2}{8\pi}, \quad (31)$$

and the Larmor frequency,

$$\nu_L = \frac{eB}{2\pi m_e c}, \quad (32)$$

where m_e is the electron mass.

The local magnetic field strength B in the above relations is substituted by its component normal to the line of sight of the unit vector, $\mathbf{l}$, defining the viewing angle of the observer

$\theta_{\text{obs}} = \angle(\mathbf{l}, \mathbf{B})$. The magnetic total intensity relates to the normal component:

$$B_{\perp} = |\mathbf{B} \cdot \mathbf{l}| = |\mathbf{B}||\mathbf{l}| \sin(\theta_{\text{obs}}) = |\mathbf{B}| \sin(\theta_{\text{obs}}), \quad (33)$$

which we express as:

$$B_{\perp} = |\mathbf{B}| \sqrt{1 - \cos(\theta_{\text{obs}})^2}, \quad (34)$$

where,

$$|\mathbf{B}| = \sqrt{B_R^2 + B_z^2 + B_{\phi}^2}, \quad (35)$$

with B_R , B_z , and B_{ϕ} as its cylindrical components. We need to find the value of $\cos(\theta_{\text{obs}})$, namely, via the following vectorial product:

$$|\mathbf{B} \times \mathbf{l}| = |\mathbf{B}||\mathbf{l}| \cos(\theta_{\text{obs}}) = |\mathbf{B}| \cos(\theta_{\text{obs}}), \quad (36)$$

or

$$\cos(\theta_{\text{obs}}) = \frac{|\mathbf{B} \times \mathbf{l}|}{|\mathbf{B}|}, \quad (37)$$

and, finally, by combining Eqs. (34) and (37), we obtain:

$$B_{\perp} = |\mathbf{B}| \sqrt{1 - \left(\frac{|\mathbf{B} \times \mathbf{l}|}{|\mathbf{B}|} \right)^2}, \quad (38)$$

respectively. The modulus of the cross product (left-hand side is of Eq. (36)) is calculated explicitly with the cylindrical components of $\mathbf{B}$ and $\mathbf{l}$ expressed in the cylindrical coordinate system of the numerical simulation.

Recalling that both non-thermal electron density and non-thermal electron energy are linked to the plasma number and energy densities via the following relations:

$$x_n n = \int_{\gamma_{\min}}^{+\infty} K \gamma^{-p} d\gamma \approx \frac{K}{p-1} \gamma_{\min}^{-p+1}, \quad (39)$$

and,

$$x_e \epsilon_g = \int_{\gamma_{\min}}^{\infty} K \gamma^{-p} (\gamma - 1) m_e c^2 d\gamma, \quad (40)$$

with n as the number density and ϵ_g as the energy density of the gas, respectively. The quantities x_n and x_e are fractions that are dependent on $\gamma_{\min}$, with $x_n > 0$ being related to the injection factor of the accelerated particles and x_e a variable related to the non-thermal electrons cooling. Then, we can rewrite Eqs. (39)–(40) as:

$$x_e \epsilon_g = \int_{\gamma_{\min}}^{+\infty} K \gamma_e^{-p} (\gamma_e - 1) m_e c^2 d\gamma = \quad (41)$$

$$\approx m_e c^2 \underbrace{\frac{K}{p-1} \gamma_{\min}^{-p+1}}_{=\chi_n n} \underbrace{\left(\frac{p-1}{p-2} \gamma_{\min} - 1 \right)}_{\gg 1}, \quad (42)$$

with

$$\gamma_{\min} = \frac{x_e \epsilon_g}{x_n n} \frac{p-2}{p-1} \frac{1}{m_e c^2}, \quad (43)$$

and with the above proportionality constant of Eq. (3),

$$K = (p-1) x_n n \gamma_{\min}^{p-1}, \quad (44)$$

respectively.

The frequency-dependent synchrotron emissivity finally takes the form of:

$$\epsilon_{\text{sync}}(\nu) = C_{00} C_{01} \left(\frac{(p-1) x_n n}{(m_e c^2)^{p-1}} \right) (\sin \theta)^{(p+1)/2} \nu^{-\frac{p-1}{2}} f_{\text{sync}}(p), \quad (45)$$

with the coefficients,

$$C_{00} = \frac{3}{8} \frac{\sigma_{\text{TC}}}{\pi^2} c \frac{B^2}{8\pi} \left(\frac{eB}{2\pi m_e c} \right)^{\frac{p-3}{2}}, \quad (46)$$

and

$$C_{01} = \left(\frac{x_e}{x_n} \frac{p-2}{p-2} \frac{\epsilon_g}{n m_e c^2} \right)^{p-1}, \quad (47)$$

respectively, which we calculate assuming that $x_e = x_n = 0.1$ and $p = 2.2$ as in Villagran et al. (2024).

The intensity emission map at a given frequency ν is finally generated by projecting the non-thermal emissivity,

$$I_{\text{sync}}(\nu) = \int \epsilon_{\text{sync}}(\theta_{\text{obs}}) d\mathbf{l}, \quad (48)$$

to obtain an emission map with an aspect angle, θ_{obs} , between the observer's line of sight and the plane on which the SNR lies.

2.6. Modelling strategy and numerical methods

This project extends the study of Meyer et al. (2023) to the regime of CCSNe progenitors, which do not undergo a Wolf–Rayet phase but end their lives as red supergiant stars. To this end, such an approach compares the morphologies and non-thermal appearances of their middle-aged to older (80 kyr) SNRs. The stellar wind-ISM interaction is first modelled during the entire star's life, providing the circumstellar medium's MHD structure, which is later used as the initial conditions for the blastwave-surroundings interaction. The progenitor star wind is injected into the computational domain in a circular zone of radius $r_{\text{in}} = 0.01$ pc from the origin. Throughout the simulations, stellar motion is taken into account by setting a velocity $v = -v_{\star}$, with $v_{\star}$ as the velocity of the moving star along the direction of the magnetic field lines (Meyer et al. 2017). A parameter space of two distinct velocities is explored, namely, $v_{\star} = 20 \text{ km s}^{-1}$ and $v_{\star} = 40 \text{ km s}^{-1}$. We summarise the models in this work in Table 1.

The ejecta-CSM is calculated in the frame of the moving star in a 2.5D cylindrical coordinate system ($O; R, z$) or origin, O , that includes a toroidal component for each vector, which is rotationally invariant with respect to the axis of symmetry, Oz . The equations are solved in a computational domain $[0; 100] \times [-50; 50] \text{ pc}^2$ mapped with an uniform mesh of 2000×4000 cells. The numerical simulations are performed using the PLUTO code (Mignone et al. 2007, 2012; Vaidya et al. 2018)², with a Godunov-type solver made of HLL Riemann solver (Harten et al. 1983) and a Runge-Kutta integrator and the divergence-free eight-wave finite-volume algorithm (Powell 1997), respectively. For further details on the numerical scheme

² <http://plutocode.ph.unito.it/>

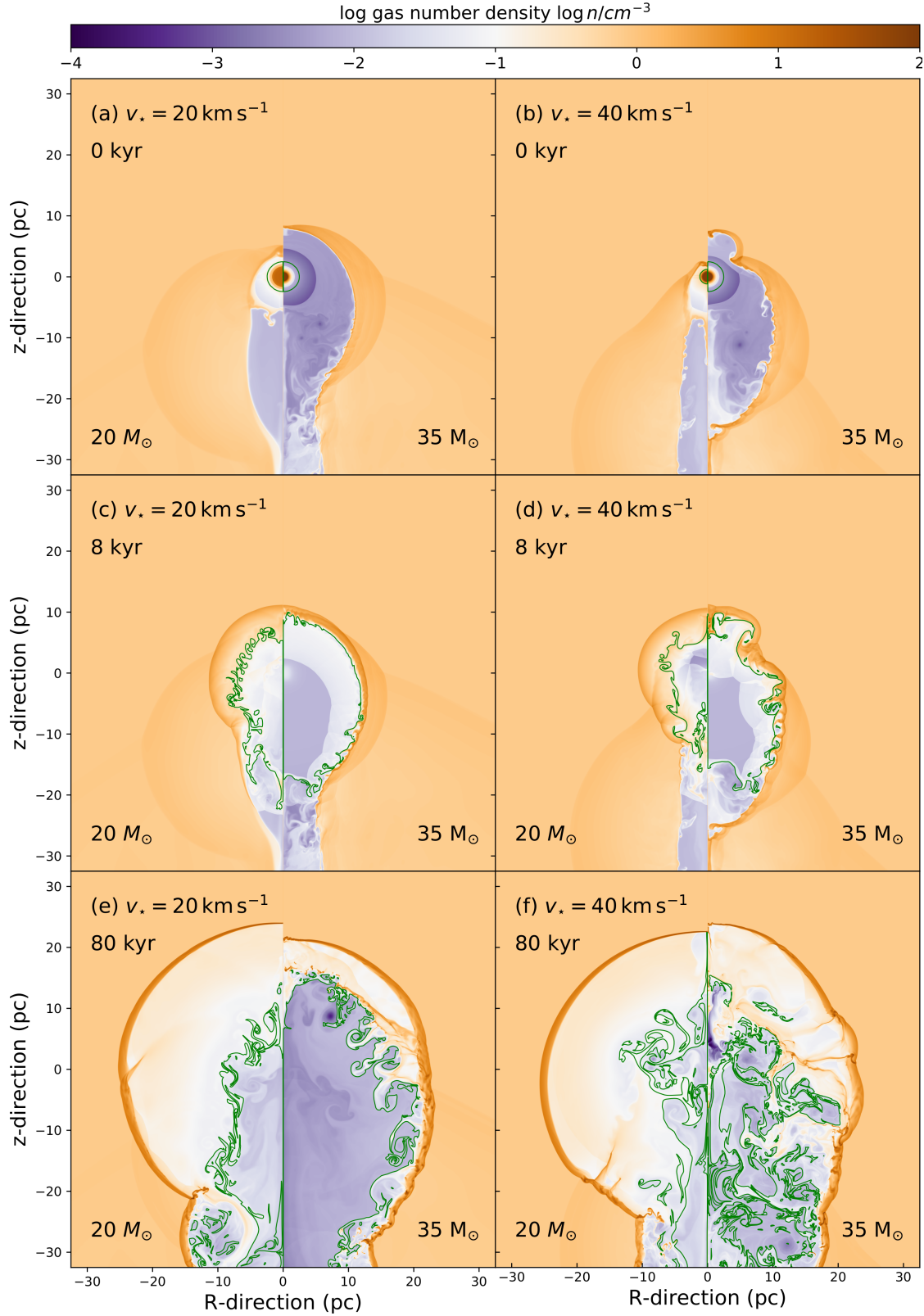


Fig. 3. Comparison between the number density fields in the supernova remnant models of a runaway $20 M_{\odot}$ (left-hand side) and a $35 M_{\odot}$ (right-hand side) star rotating with $\Omega_{\star}/\Omega_K = 0.1$, moving with a velocity of $v_{\star} = 20 \text{ km s}^{-1}$ (left column) and $v_{\star} = 40 \text{ km s}^{-1}$ (right column). The green contour mark the parts of the SNRs, with a 50% contribution from the ejecta.

Table 1. Numerical models.

Model	$M_\star$ ($M_\odot$)	$v_\star$ (km s $^{-1}$)	Evolution history
Run-20-MHD-20-SNR	20	20	MS $\rightarrow$ RSG $\rightarrow$ SN
Run-20-MHD-40-SNR	20	40	MS $\rightarrow$ RSG $\rightarrow$ SN
Run-35-MHD-20-SNR ^(a)	35	20	MS $\rightarrow$ RSG $\rightarrow$ WR $\rightarrow$ SN
Run-35-MHD-40-SNR ^(a)	35	40	MS $\rightarrow$ RSG $\rightarrow$ WR $\rightarrow$ SN

Notes. All simulations assume a rotating massive progenitor of a ZAMS mass, $M_\star$ (in $M_\odot$), at solar metallicity and moving with velocity, $v_\star$, through the warm phase of the Galactic plane. The table indicates the stellar evolution history in each model from the MS (main sequence) phase to the final SN (supernova) explosion and ultimately to the pulsar wind nebula (PWN) through the red supergiant (RSG) and WR (Wolf–Rayet) stages.

References. ^(a)Meyer et al. (2023)

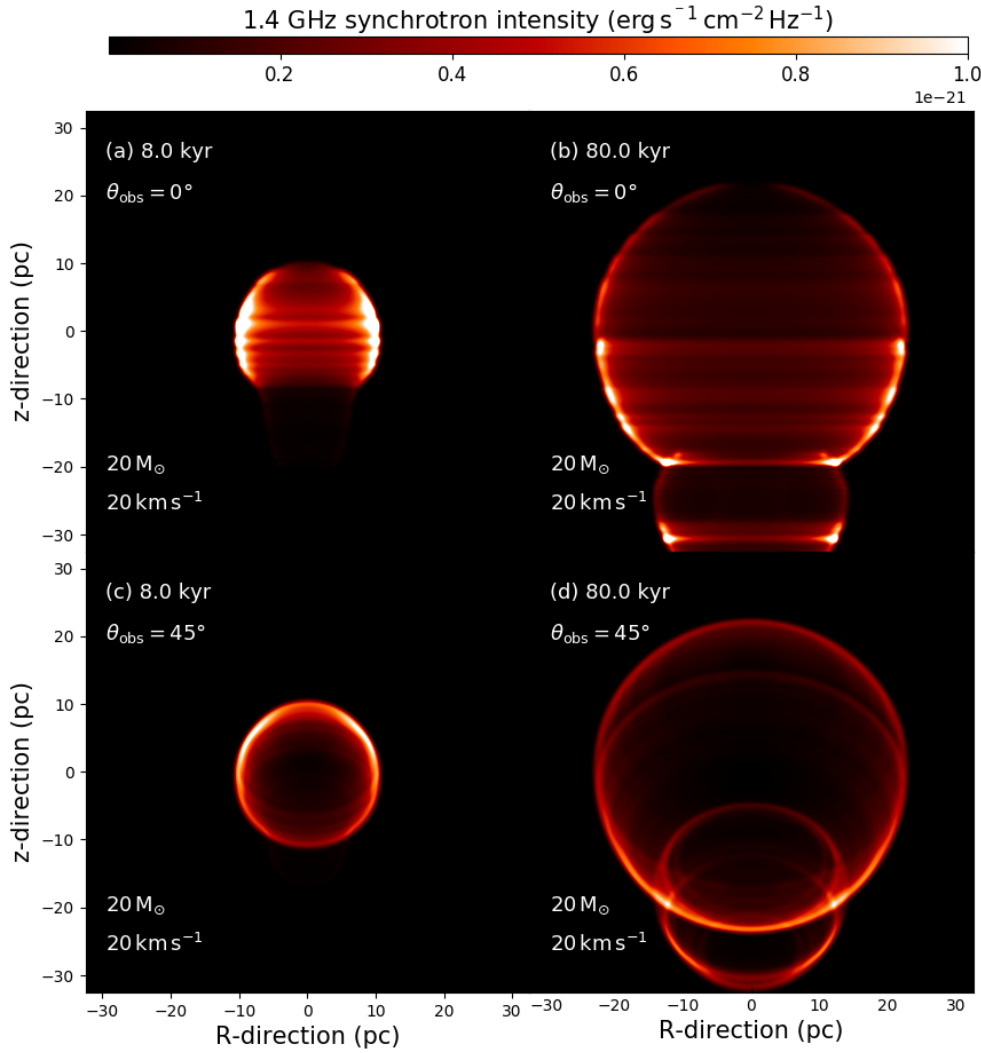


Fig. 4. Non-thermal 1.4 GHz synchrotron emission maps (in $\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{Hz}^{-1}$) for the SNR generated by a $M_\star = 20 M_\odot$ progenitor moving at $v_\star = 20 \text{ km s}^{-1}$, respectively. The remnants are shown at times 8 kyr (left panels) and 80 kyr (right panels) after the explosion, with a viewing angle of the observer that is inclined by $\theta = 0^\circ$ (top panels) and $\theta = 45^\circ$ (bottom panels) with respect to the plane of the object. The ring-like structures result in the mapping of 2.5D simulations being mapped into a 3D shape.

and on the limitations of the method, we refer to the study of Meyer (2021). The projection of the synchrotron emissivity is performed using a modified version of the radiative transfer code RADMC-3D³, which performs the ray-tracing along a particular line of sight. The physical and characteristic quantities of the supernova progenitors are plotted in Fig. 1.

3. Results

3.1. Supernova remnant morphology

In Fig. 3, we plot the surroundings of the supernova progenitors considered in this study, at the time of onset of the blastwave propagation and at later times, when it propagates through the wind bubble. In each panel, the left-hand side refers to the model for the ZAMS $M_\star = 20 M_\odot$ star, while the right-hand side concerns the $M_\star = 35 M_\odot$ progenitor star. The simulations are displayed for runaway stars moving with a velocity of $v_\star = 20 \text{ km s}^{-1}$ (left column of panels) and $v_\star = 40 \text{ km s}^{-1}$

³ <https://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/>

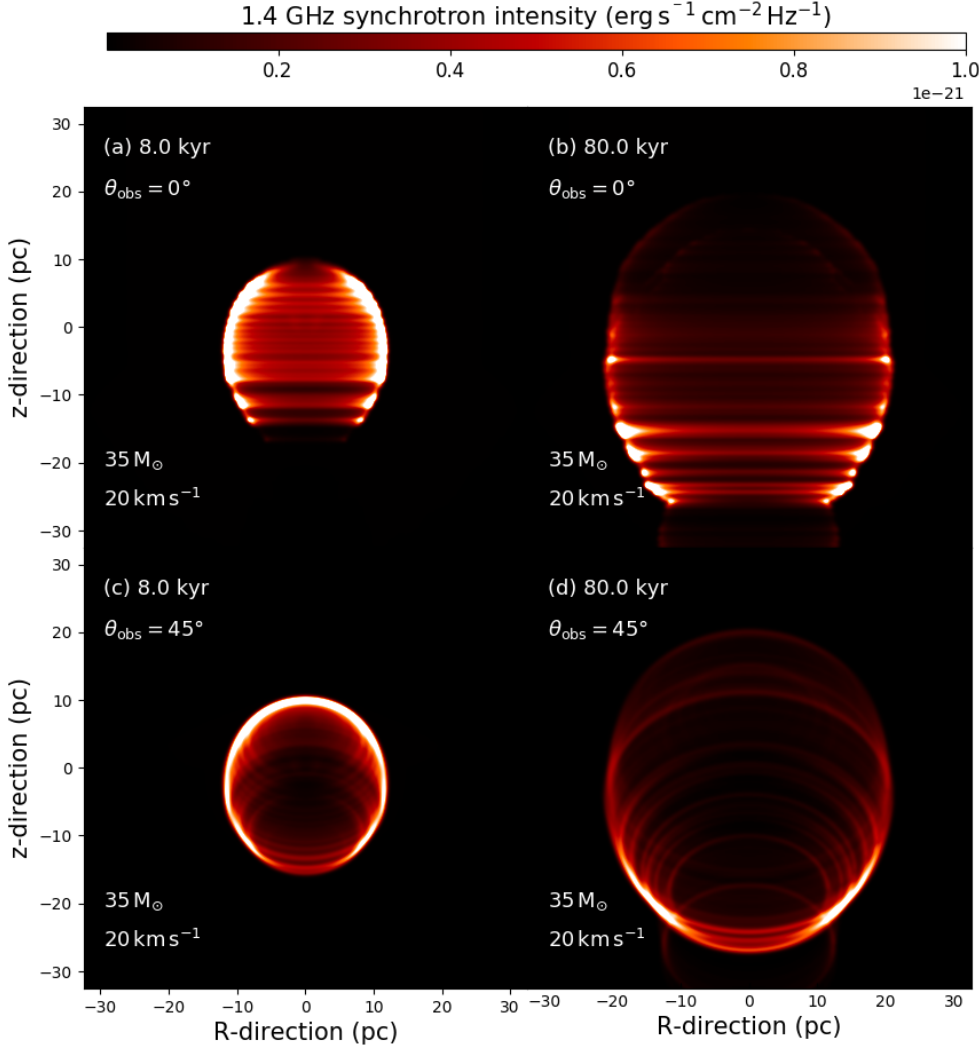


Fig. 5. As in Fig. 4, but for a $M_{\star} = 35 M_{\odot}$ progenitor moving with a velocity of $v_{\star} = 20 \text{ km s}^{-1}$. The ring-like structures result in the mapping of 2.5D simulations being mapped into a 3D shape.

(right column panels). They represent the number density field (in cm^{-3}) in the simulations, onto which a green isocontour marks the regions of the SNRs that are made of equal quantities of ejecta and stellar wind material.

In both models, the CSM has the typical morphology produced around an evolving stellar wind that runs through the ISM, with a bow shock ahead of the direction of stellar motion and a cavity behind it (see Figs. 3a,b). In the early phase of their evolution, the SNRs conserve the global appearance of their progenitor’s circumstellar medium since the blastwave has not yet interacted with the stellar surroundings. They are constituted of a large, complex stellar wind bow shock, the result of the interaction of the wind blown by the star throughout the various evolutionary phases of its life (Meyer et al. 2015). The power of stellar winds is stronger for Wolf–Rayet stars than for red supergiant progenitors. Their associated final bow shocks are wider and present large eddies due to Rayleigh–Taylor instabilities in the case of the $M_{\star} = 35 M_{\odot}$ model (Brighenti & D’Ercole 1995b,a), as shown in Figs. 3a,b. In contrast, the $M_{\star} = 20 M_{\odot}$ model is much smoother, as noted in previous studies on the close surroundings of runaway red supergiants (Noriega-Crespo et al. 1997; Decin et al. 2012; Mohamed et al. 2012; Meyer et al. 2021a). Our model raises the question of the nature of the large-scale instabilities developing into the bow shock of the last pre-supernova stellar wind, as it is the first circumstellar structure

that the blastwave will encounter when expanding past the snow-plough phase. This is particularly pronounced in the supernova remnant generated by a $M_{\star} = 35 M_{\odot}$ progenitor star moving at a velocity of $v_{\star} = 40 \text{ km s}^{-1}$ that is of potential numerical origin. This feature develops with our code for the combination of bulk motion and ISM number density that we consider and disappears in the model with lower $v_{\star}$ values (see Figs. 3a,b), which offers evidence for a physical origin in the growth of such Rayleigh–Taylor-based instabilities (Vishniac 1994; van Marle et al. 2014). However, the role of the symmetry axis of our coordinate system in triggering the instabilities is known and should be kept in mind (Mignone 2014). Full 3D models of such systems would enable us to answer this question (Blondin & Koerwer 1998; Meyer et al. 2021a), while also allowing us to explore the stabilising role of the ambient medium magnetic field on the overall morphology of the supernova remnant and the mixing of material therein.

At 8 kyr, the supernova shock wave has reached and interacted with the bow shocks in each model (Fig. 3c,d). Along the direction of stellar motion, we can see the effect of the mass that is trapped into the circumstellar medium – in the sense that the forward shock of the expanding blastwave has gone through the bow shock and propagates further into the unperturbed ISM as a mushroom-like outflow. This process is more important in the case of the supergiant progenitor than that of

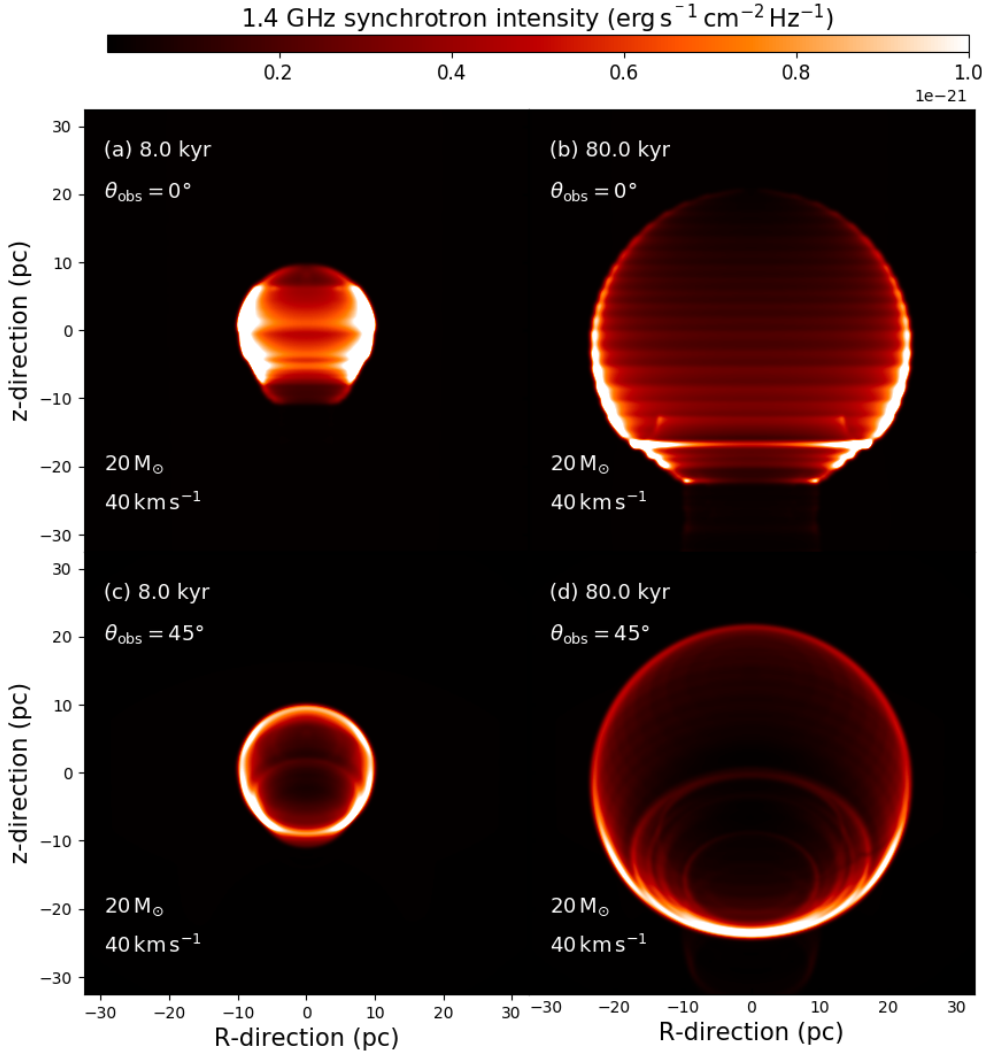


Fig. 6. As Fig. 4, but for a $M_{\star} = 20 M_{\odot}$ progenitor moving with a velocity of $v_{\star} = 40 \text{ km s}^{-1}$. The ring-like structures result in the mapping of 2.5D simulations being mapped into a 3D shape.

the $M_{\star} = 35 M_{\odot}$ progenitor (Meyer et al. 2015). At times of 80 kyr, the reverse shock of the supernova is more advanced in its reverberation towards the centre of the explosion in the simulation with a $M_{\star} = 20 M_{\odot}$ progenitor, since the small bow shock triggers it sooner. Nevertheless, the unstable character of this inward-moving shock front is more pronounced in the case of the model with a Wolf-Rayet supernova progenitor because the shock surface is wider. The instabilities had more time to grow due to the ejecta-wind strong contrast in density and velocity in the ejecta-CSM interface (green contours), as seen in Figs. 3e,f.

3.2. Synchrotron emission maps

In Fig. 4, we show the 1.4 GHz emission maps of the supernova remnant generated by the moving progenitors with velocity $v_{\star} = 20 \text{ km s}^{-1}$, considering viewing angles of $\theta_{\text{obs}} = 0^\circ$ (top panels) and $\theta_{\text{obs}} = 45^\circ$ (bottom panels), at 8 kyr (left panels) and 80 kyr (right panels) of evolution. These maps correspond to the case of a progenitor with $M_{\star} = 20 M_{\odot}$. The remnant in the model Run-20-MHD-20-SNR, for $\theta_{\text{obs}} = 0^\circ$, displays a barrel-like morphology at 8 kyr while a Cygnus-loop-like appearance is observed at 80 kyr (Figs. 4a,b). If the remnant is observed with $\theta_{\text{obs}} = 45^\circ$, it takes the shape of rings (Figs. 4c,d). The model Run-35-MHD-20-SNR, involving a $M_{\star} = 35 M_{\odot}$ progenitor moving

with velocity $v_{\star} = 20 \text{ km s}^{-1}$, displays a horseshoe-like morphology if considered at times of 8 kyr with an angle $\theta_{\text{obs}} = 0^\circ$ (Fig. 5a) that evolves to a bilateral morphology at 80 kyr (see Fig. 5b). This remnant, seen at a viewing angle of $\theta_{\text{obs}} = 45^\circ$, has the shape of a ring and a bright arc.

Figure 6 displays the emission maps for the red supergiant model moving with the velocity $v_{\star} = 40 \text{ km s}^{-1}$ before the explosion. Under a viewing angle of $\theta_{\text{obs}} = 0^\circ$, the remnant has a bilateral morphology that is closer to that of the Cygnus loop than in that with velocity $v_{\star} = 20 \text{ km s}^{-1}$, which evolves to a rounder morphology at a later time (Figs. 6a,b); whereas the viewing angle of $\theta_{\text{obs}} = 45^\circ$ produces a quasi-circular observed morphology in projection. The $M_{\star} = 35 M_{\odot}$ progenitor star moving with velocity $v_{\star} = 40 \text{ km s}^{-1}$ displays an irregular morphology that originates from the more complex distribution of the circumstellar medium at the moment of the explosion (Figs. 7c,d). The supernova remnant appears as a large ovoidal structure reflecting the instabilities of the circumstellar medium, generated with the Wolf-Rayet stellar wind interacts with the previous wind bow shocks. In other words, no Cygnus-loop SNRs are produced when the fast-moving ($v_{\star} = 40 \text{ km s}^{-1}$) supernova progenitor undergoes an evolutionary phase beyond the red supergiant.

Figure 8 offers a comparison of the horizontal cross-sections taken through the emission maps of the SNRs, seen with viewing angle of $\theta_{\text{obs}} = 0^\circ$ (Figs. 8a,b), $\theta_{\text{obs}} = 45^\circ$ (Figs. 8c,d), for the

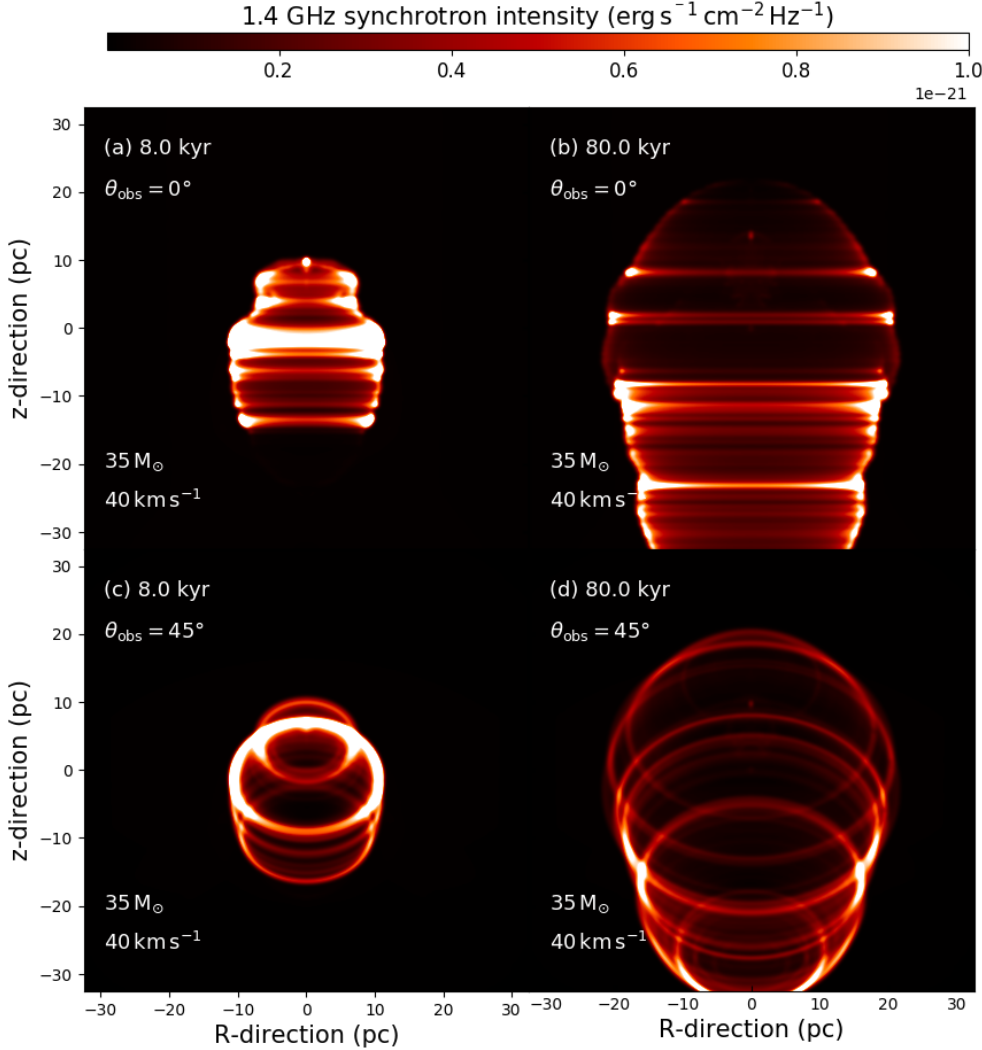


Fig. 7. As Fig. 4, but for a $M_{\star} = 35 M_{\odot}$ progenitor moving with a velocity of $v_{\star} = 40 \text{ km s}^{-1}$. The ring-like structures result in the mapping of 2.5D simulations being mapped into a 3D shape.

progenitors moving with velocities $v_{\star} = 20 \text{ km s}^{-1}$ (Figs. 8a,c) and $v_{\star} = 40 \text{ km s}^{-1}$ (Figs. 8b,d). Regardless of the viewing angle under which their remnants are considered for both progenitors, the synchrotron surface brightness diminishes with time, see solid and dashed lines at times 8 kyr and 80 kyr (Figs. 8a,c). The Wolf-Rayet remnant is slightly brighter than the red supergiant remnant, although it is still of the same order of magnitude in terms of surface brightnesses, which are $\approx 0.5\text{--}2.0 \times 10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$. This increase in non-thermal emission is due to stronger shocks that form in these remnants, compressing the magnetic field better. The bottom panel of Fig. 8 displays slices taken vertically through the SNRs. They are globally dimmer at $v_{\star} = 20 \text{ km s}^{-1}$ and brighter at $v_{\star} = 40 \text{ km s}^{-1}$ because of the denser filaments forming in them, for both viewing angles $\theta_{\text{obs}} = 0^{\circ}$ and $\theta_{\text{obs}} = 45^{\circ}$, respectively. Again, the differences arise later than the remnants' initial state (Figs. 8b,d).

4. Discussion

This section offers a comparison of the results with real, available observations. We specifically focus our analysis on bilateral and Cygnus-loop-like SNRs.

4.1. Limitations of the model

As in the previous papers of this series (Meyer et al. 2023), the present 2.5D MHD simulations would benefit from a full 3D

treatment of the wind-ISM interactions and that of the ejecta-bubble calculation. Such simulations will add realism to the solution to our problem, especially concerning the stability of the pre-supernova magnetised circumstellar medium and fix the artificial ring-like artefacts arising from mapping 2.5D models into 3D shapes. It is not the maximum synchrotron surface brightness that would change, but rather the west-east symmetry concerning the $R = 0$ direction that would disappear, as well as the series of horizontal bright lines ($\theta_{\text{obs}} = 0^{\circ}$) and ring-like ($\theta_{\text{obs}} > 0^{\circ}$) filaments located inside of the supernova remnant image, respectively. Those arcs will appear more ragged and clumpy while displaying more random distribution throughout the remnant's interior. An illustration of the effects of full 3D emission maps can be found within the example of the optical $H\alpha$ bow shock of runaway red supergiant stars, described in Meyer et al. (2014, 2021a).

The microphysical processes included in the numerical models also leave room for improvement, for instance, by including heat transfers or the ionisation of the supernova progenitor of the material of its circumstellar medium. The multi-phased character of the Galactic plane of the Milky Way is also an ingredient in our numerical model, which would benefit from future improvements. Particularly, initiating the wind-ISM models in a medium including turbulence, granularity provided by colder clumps and hotter cavities could potentially affect the supernova blastwave's propagation and modify the current results. These issues will

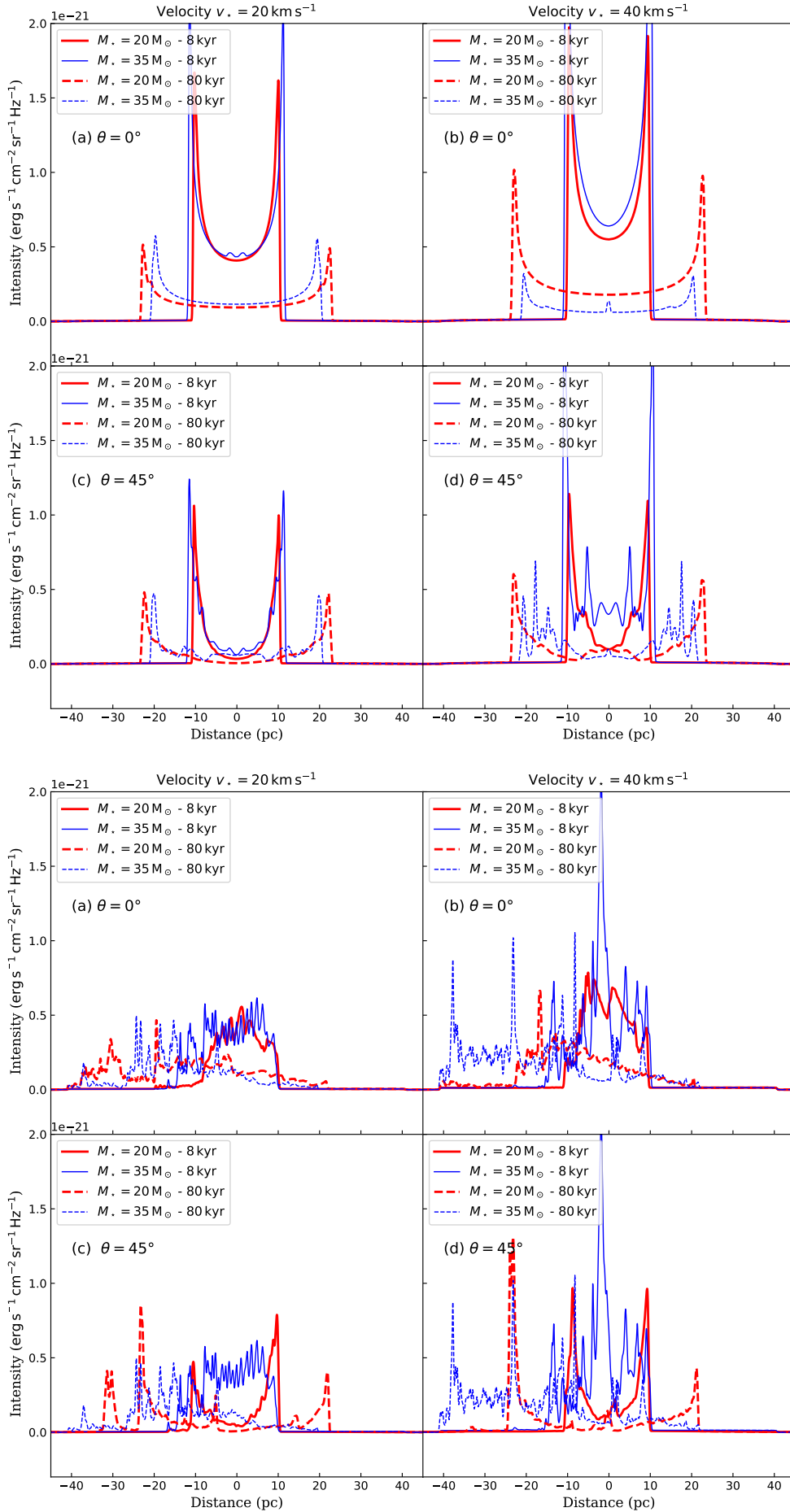


Fig. 8. Horizontal (top) and vertical (bottom) cross-sections taken through non-thermal 1.4 GHz synchrotron emission maps of the SNRs.

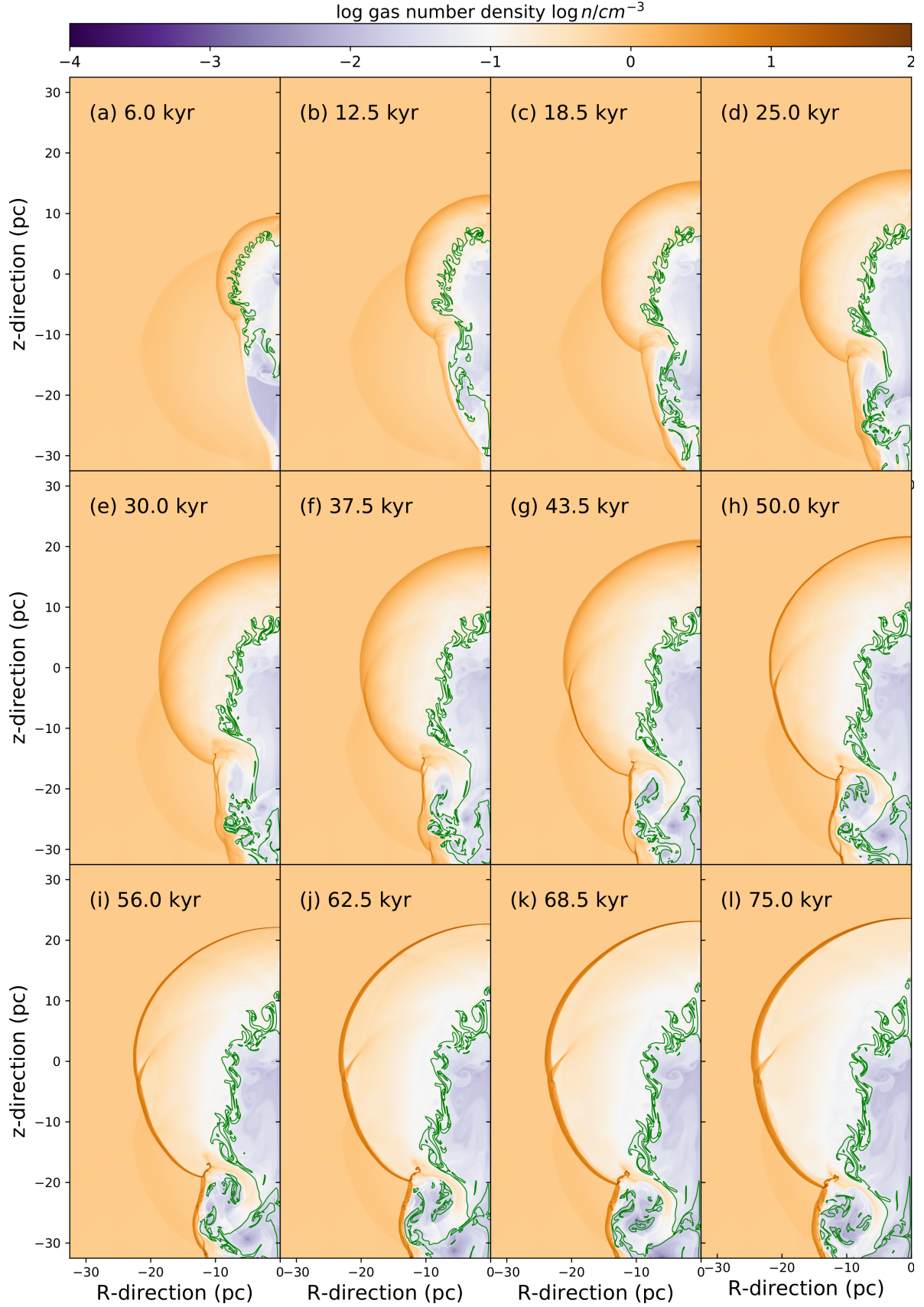


Fig. 9. Time-sequence evolution of the number density fields in the model corresponding to the most common supernova remnant, that is, generated by a $20 M_{\odot}$ moving with velocity $v_{*} = 20 \text{ km s}^{-1}$. The remnant morphology evolves from bilateral to Cygnus Loop. The green contour mark the parts of the SNRs with a 50% contribution of ejecta.

be considered in follow-up works. Lastly, the presence of a pulsar wind nebula could further modify the results (Blondin et al. 2001; Temim et al. 2015, 2017, 2022).

4.2. A possible time-sequence evolution

This work covers the parameter space of the most common runaway massive supernova progenitors to investigate their morphologies and non-thermal radio appearance. The models in our study reveal that most of them undergo the formation of a bilateral supernova remnant when their supernova blast-wave propagates through the preshaped circumstellar medium. Indeed, all models but one, namely, all remnants generated by a red supergiant progenitor ($M_{\star} \geq 20 M_{\odot}$) or by a Wolf–Rayet progenitor ($M_{\star} \geq 35 M_{\odot}$) that is a slow runaway ($v_{\star} \approx 20 \text{ km s}^{-1}$), induce a bilateral supernova remnant. It made up of two arcs, produced when the shock wave interacts with the walls of the low-density cavity left behind the progenitor when moving before the explosion, at least for the ISM densities we consider here. Additionally, in the case of a red supergiant progenitor, the bilateral morphology always precedes that of a Cygnus-loop-like morphology. We propose that each Cygnus-loop supernova remnant first came through an earlier phase during which it harboured a bilateral morphology. However, a bilateral shape will likely (but not necessarily) evolve.

In particular, we conjecture that the Cygnus-loop nebula once had a bilateral shape. We also propose that the same must apply to Simeis 147, a supernova remnant of similar observed features: a bulb shape appears near the interaction between the blastwave and the circumstellar medium of its progenitor.

4.3. Occurrence of Cygnus-loop-like SNRs

The initial mass of massive stars as they form in the cold phase of the ISM of the Milky Way is determined by the so-called initial mass function, which, for high-mass stellar objects, expressed as:

$$dN(M_{\star}) \propto M_{\star}^{-\zeta}, \quad (49)$$

where dN is the differential element of massive stars and $\zeta = 2.3$ (see Kroupa 2001). Similarly, the space velocities of runaway massive stars as produced when a component of a massive binary system explodes is:

$$dN(v_{\star}) \propto e^{-v_{\star}/v_{\max}}, \quad (50)$$

with $v_{\max} = 150 \text{ km s}^{-1}$ (see Bromley et al. 2009). The above-mentioned distributions indicate that (i) most CCSN progenitors are massive stars in the lower region of the high mass spectrum (typically ending their lives as red supergiants and (ii) runaway massive stars mostly move with small Mach numbers through the ISM (with typical supersonic velocities of $v_{\star} \approx 20 \text{ km s}^{-1}$ in the plane of the Galaxy).

Our sample of supernova progenitors and space velocities (see Table 1) therefore covers the parameter space of the most common runaway progenitors; half of them (i.e. those involving a red supergiant progenitor) generate a Cygnus-loop morphology during the older times of their evolution. Since such progenitors are the most common runaway high-mass objects, we conjecture that a majority of SNRs of moving objects (i.e. those are either in the field or in the high latitudes of the Milky Way) display or are in the process of forming a Cygnus-loop-like remnant. These objects are fainter than those of higher-mass progenitors and, therefore, more difficult to observe. Consequently, we find the

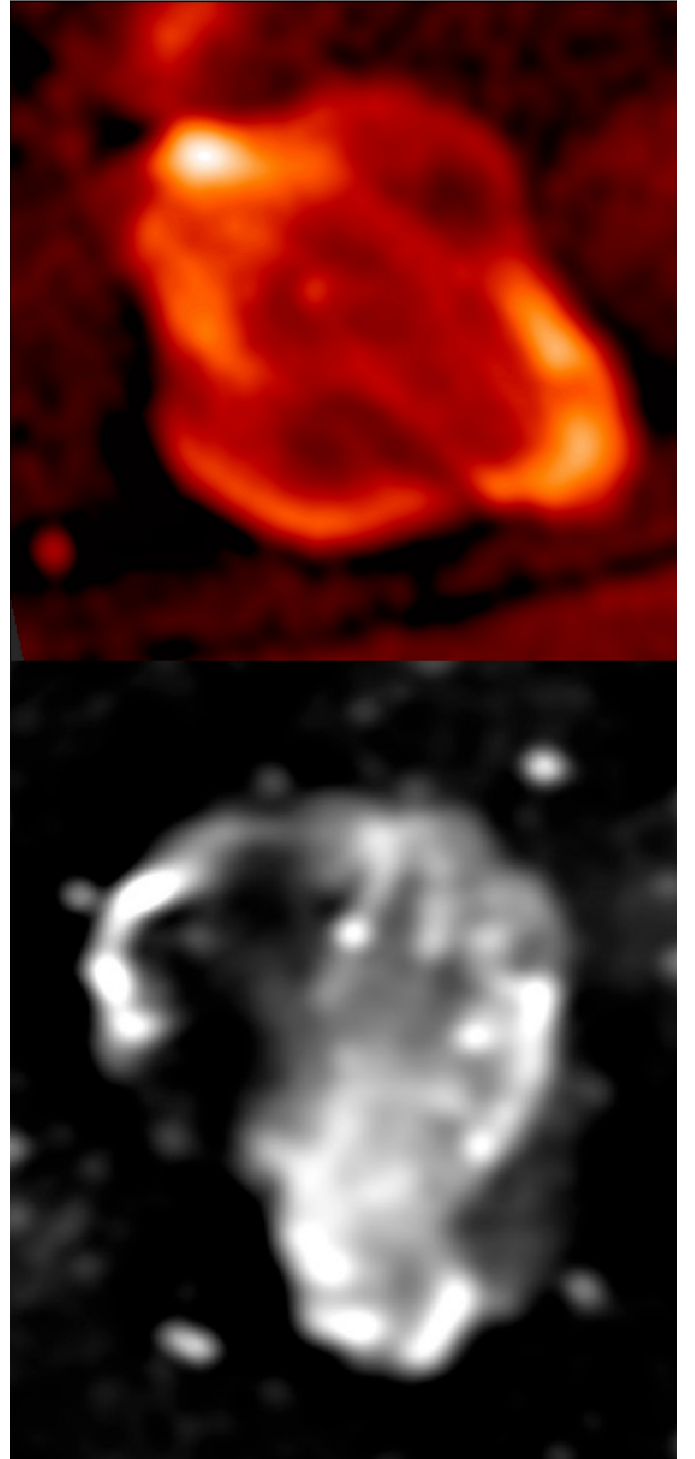


Fig. 10. Radio images show a bilateral G309.2-00.6 (top panel, Ferrand & Safi-Harb 2012) and the Cygnus Loop (bottom panel, Uyaniker et al. 2004) CCSNRs. This study conjectures that bilateral remnants from massive stars are less common than those of Cygnus Loops but also that these shapes constitute a time-sequence of morphological evolution affecting the remnants of the most common runaway red supergiant progenitors.

SNRs that are to be discovered in the next decade by means of, for instance, the current *James Webb* Space Telescope (JWST) or the forthcoming Cherenkov Telescope Array (CTA) observatories (Acharyya et al. 2023; Acero et al. 2023; Cherenkov Telescope Array Consortium 2023), will reveal a majority of

SNRs that are either in the bilateral or in the Cygnus-loop case, with a subset of the early ones going on to further evolve to the latter stage.

4.4. Predictions for the most common SNRs

Figure 9 displays the number density field in the simulation of the supernova remnant of initial mass $20 M_{\odot}$ moving with a velocity of $v_{\star} = 20 \text{ km s}^{-1}$ through the ISM, for times spanning from 6 kyr to 75 kyr. The green line marks the location of the discontinuity between supernova ejecta and the other kind of material (stellar wind and ISM). At early times the blastwave interacts strongly with the lateral region of the circumstellar medium; namely, the wings of the stellar wind bow shock, which generates a bilateral shape (see Figs. 9a–d). The Cygnus Loop morphology begins to form at time 25 kyr after the onset of the explosion, with its characteristic shape made up of two components: the overall mushroom of expanding supernova ejecta plus the tube of channelled material into the low-density cavity produced behind the progenitor as a result of its bulk motion through the ambient medium. The density of the shocked layer of ejecta, the ISM, and the stellar wind that is swept up by the forward shock of the supernova blastwave increases over time, compressing the local magnetic field better and enhancing the synchrotron emissivity (Figs. 9j–l). We conclude that this remnant spends about $18.5/80.0 \approx 23\%$ of its early evolution time in the bilateral shape, while it harbors a Cygnus Loop-like morphology the rest of the time. Our results indicate therefore that the population of Cygnus Loop is three times greater than that of bilateral remnants, at least for the conditions of ambient medium that we consider here. However, the early ones are brighter than the later ones (Fig. 4), which is consistent with the more numerous detection of bilateral objects than Cygnus Loop amongst the known population of middle-aged to older CCSNRs. Future high-resolution telescopes will help in building larger population statistics, which will better tests our prediction in the future.

We consider how close our predictions to real data, plotting in Fig. 10 the radio appearance of two CCSNRs of bilateral and Cygnus Loop morphology, respectively. G309.2-00.6 is a bilateral remnant with an age of $\leq 4 \text{ kyr}$ and size of $2\text{--}7 \text{ kpc}$, which has a complex shape, superimposing large symmetric equatorial ears with two polar arcs, as seen in the top panel of Fig. 10. The literature on G309.2-00.6 is mostly observational. It soon revealed strong deviations of its morphology from the Sedov–Taylor solution, requiring the inclusion of circumstellar material pre-shaped by the progenitor’s stellar winds (Gvaramadze 1999) and an explosive jet responsible for the second series of protuberances (Gaensler et al. 1998; Gaensler 1999). Its size and age are consistent with our model with $20 M_{\odot}$ and $v_{\star} = 20 \text{ km s}^{-1}$ (see Figs. 9a,b). Differences in the shape might be caused by the explosive jet that we do not model (Soker 2023a) and/or by a different viewing angle of the supernova remnant. The Cygnus Loop is a peculiar supernova remnant that has been more studied, both by means of observations and with numerical models, than G309.2-00.6. Initially interpreted as a champagne outflow produced by a supernova explosion located at the edge of a molecular cloud (Aschenbach & Leahy 1999), the Cygnus Loop nebula might be the outflow of a blast wave from a stellar wind bow shock (Meyer et al. 2015; Fang et al. 2017). Its size is estimated to be about 37 pc and its age $\approx 20 \text{ kyr}$, which is in accordance with our same numerical model (see Figs. 9c,d). Hence, both remnants of different typical morphologies can

qualitatively be explained by our model with $20 M_{\odot}$ and $v_{\star} = 20 \text{ km s}^{-1}$.

5. Conclusion

In this study, we investigate the differences between the non-thermal synchrotron emission of SNRs generated by moving massive stars. Our parameter space covers the most common of such CCSN progenitors of a ZAMS mass of $M_{\star} = 20$ and $M_{\star} = 35 M_{\odot}$, ending their lives as a red supergiant or as a Wolf–Rayet star and moving into the warm phase of the Galactic plane, with bulk velocities of $v_{\star} = 20 \text{ km s}^{-1}$ and $v_{\star} = 40 \text{ km s}^{-1}$, respectively. The evolution of the SNRs is followed from the onset of the explosion to older ages (80 kyr). The methodology consists of performing 2.5D MHD numerical simulations of supernova blastwaves released into the CSM shaped by the interaction of the stellar wind of these moving progenitors with the ambient medium, see Meyer et al. (2023). Synchrotron emission calculations complete the MHD structure to generate radio maps with physical units, instead of the usual normalised maps presented in most papers, that we compare to observations.

We find that most SNRs generated by a runaway massive star should undergo a phase exhibiting a bilateral morphology, but that only those either generated by a red supergiant or (to a lesser extent) produced by a slightly supersonically moving Wolf–Rayet evolving progenitor, further develop as a Cygnus-loop-like SNR (Aschenbach & Leahy 1999; Meyer et al. 2015; Fang et al. 2017). Our 1.4 GHz non-thermal emission maps (Velázquez et al. 2023; Villagran et al. 2024) indicate that SNRs reveal duller projected intensities as the blastwave propagates through the defunct stellar surroundings and the unperturbed ISM and the remnant gets older. In all explored scenarios, SNRs generated by faster-moving stars are brighter than those induced by stars, which were moving slower before dying. Their Cygnus-loop appearances do not survive when the viewing angle between the observer and the place of the sky is important ($\theta_{\text{obs}} = 45^{\circ}$).

Our methodology permits to investigate the time-dependant evolution of the brightness of SNRs and, in future studies, we will apply it in the context of (plerionic) SNRs of static massive stars (Meyer et al. 2022, 2024). In particular, our work proposes a non-thermal synchrotron bilateral to Cygnus-loop-like morphological time-sequence evolution for the appearance of Galactic SNRs. We also suggest that it is expected to affect most of the dead stellar surroundings in the field, since red supergiant progenitors are more common than heavier exploding stars. This implies that among the many SNRs to be discovered in the future, for instance, by means of the forthcoming CTA observatory (Acharyya et al. 2023; Acero et al. 2023; Cherenkov Telescope Array Consortium 2023), a significant fraction of them would be expected to be undergoing this bilateral-to-Cygnus-loop evolutionary sequence.

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