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A numerical simulation of the W 50-SS 433 system

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Abstract. We present results of numerical simulations performed to study the evolution and interaction of jets propagating inside of Supernova Remnants (SNRs). There are new observations which show this kind of jet/SNR interaction (Dubner et al. 1998, Gaensler et al. 1998). From our numerical simulations, we compute synchrotron emission maps, in order to directly compare the numerical results with the radio maps.

Our aim is to explain the strange morphologies some SNRs exhibit in the radio-continuum, such as the case of SNR W 50 in which a shell is interacting with the jets from the SS 433 source. In recent radio images (at 328 and 1465 MHz, Dubner et al. 1998), the SNR W 50 shows a helical structure in its Eastern lobe.

Our numerical results are consistent with the radio-continuum observations, and reveal that a probable origin for the helical structure in the Eastern lobe of W 50, is the generation of incident and reflected secondary shock waves in the jet beam. Furthermore the simulations show that the cocoon gas is pushing out the SNR shell, filling up its interior, and increasing the expansion velocity of the shell.

Key words: ISM: supernova remnants – stars: supernovae: individual: W 50 – ISM: jets and outflows – hydrodynamics – methods: numerical

1. Introduction

At the end of their life, some stars can lose their thermal-gravitational equilibrium and die in a supernova explosion. A supernova is an event that occurs in extremely short timescales (the explosion itself takes just a few seconds, but the supernova can be visible for years after the explosion). A supernova remnant is composed of a shock wave, generated at the explosion time, the material ejected by the star, and the interstellar medium swept up by the supernova shock wave. In spite of the short lifetime of supernovae, their remnants can hold on for hundreds of thousand years, drastically modifying their environments and emitting energy in the whole electromagnetic spectrum, although the characteristic feature of SNRs is that they are strong sources of radio emission of non-thermal origin (synchrotron radiation).

Astrophysical jets are highly collimated flows which have been observed in many types of astrophysical objects (i.e. the nuclei of active galaxies, regions of stellar formation and compact objects).

Both jets and SNRs have been studied by means of observations (in different wavelengths) and theoretical work. Previously, there has been little interest in studying the interaction between jets and SNRs. However, there is new observational evidence showing that this kind of interactions are possibly occurring in some objects (Dubner et al. 1998 for the SNR W 50 case; and Gaensler et al. 1998 for SNR G309.2-00.6).

In this work we model the strange morphology observed in the radio emission of the system composed by the source of relativistic jets SS433 and the SNR W 50. To this effect, we use a 2D (axisymmetric) adaptive grid code to simulate the encounter of a jet with a SNR shell.

SS 433 is a compact object (maybe a binary system) which emits two precessing jets in opposite directions, and is located at the center of the supernova remnant W 50. The precession cone has an initial half angle of 20° and the precession time is of 164 days (Hjellming & Johnston 1988).

The SNR W 50 shows a morphology at radio-frequencies which is far from being a spherical shell (which is the typical morphology of supernova remnants expanding into a homogeneous and isotropic medium) because it has two lateral extensions or lobes, in the East-West direction. Its angular sizes are $2^\circ \times 1^\circ$, which correspond to 104×52 pc assuming a distance of 3 kpc to the object (according to the HI study of Dubner et al. 1998). These radio lobes are aligned with the cone axis of the SS 433 jets, as shown by X-ray observations (Safi-Harb & Ögelman 1997). Furthermore, there is optical emission with filamentary structure, located at the beginning of the radio lobes (van den Bergh 1980, Kirshner & Chevalier 1980 and Mazeh et al. 1983).

Several authors have given possible scenarios to describe the SS 433/W 50 system, using analytical and numerical models. These scenarios can be divided into two groups. The models in the first group are based on the hypothesis that this system is a bubble which was formed by the interaction between the

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SS 433 jets and the surrounding interstellar medium or that the jets are expanding into an ISM swept up by the wind of a stellar partner of SS 433 (e.g. König 1993; Begelman et al. 1980). Kochanek & Hawley (1990) carried out a numerical study inspired by the SS 433 system. Their work was not an attempt to give a complete model of this system but they just wanted to gain some understanding about the physics of hollow conical jets and possible mechanisms to produce a refocusing of the jets. On the other hand, the models in the second group consider that the elongated morphology of W 50 is due to the encounter between the jets from SS 433 and an SNR shell (Zealey et al. 1980; Downes et al. 1986; Murata & Shibazaki 1996).

In view of the alignment of the jets and lobes and observational (radio, optical, and X-ray) evidence which support the framework of a jet propagating inside of a SNR, we consider the models of the second group as the best possibility for describing this problem.

Our aim is to try to understand the process of interaction between jets and SNRs and to simulate the radio emission (synchrotron mechanism) in order to compare the models with observations.

2. The model

2.1. General considerations and initial conditions

As we mentioned in Sect. 1, the direction of the jets of SS 433 precesses, close to the source, within a 20° half opening angle cone with a period of 164 days (Hjellming & Johnston 1988). However, far from SS 433, the opening angle of the cone decreases to 10°. This collimation of the beams could be a consequence of the interaction between the jet and SNR shocks, which generates secondary reflected shock waves along the symmetry axis.

The precession period is much shorter than the typical dynamical evolution time of the jet, which is defined as $t_{dyn} = R_l/v_j \simeq 140\,\mathrm{yr}$, where R_l and v_j are the mean radius of the eastern lobe and the jet velocity, respectively. Therefore, in our analysis we can model the SS 433 jet as two oppositely directed cones of 10° of half opening angle moving into the surrounding ISM. The flow into the conical surfaces can be taken as continuous since at large distances from the center, the gaps between successive coils are expected to fill in by the velocity dispersion of the outflowing gas (Murata & Shibazaki 1996). The central region of the cone might also be filled in as a result of the jet beam expansion.

The calculation was carried out with the Coral code (Raga et al. 1997) on a 5-level binary adaptive grid with a maximum resolution of 2.44×10^{17} cm. The jet was modeled as a filled cone moving with a velocity of $7\times10^{9}\mathrm{cm\ s}^{-1}$ (which is close to the real speed of the SS 433 jets). We impose an initial radius and length of 1.25×10^{18} cm for the jet and as initial jet density and temperature we take $0.5\mathrm{cm}^{-3}$ and 5×10^{7} K, respectively, following the X-ray work of Brinkmann et al. 1988.

We take the analytical Sedov solution for a strong explosion to initialize the density, velocity and pressure distributions of the SNR (assuming that the SNR is in its adiabatic evolutionary stage). After several tests, we have chosen an initial radius and explosion energy of 10 pc (3×10^{19} cm) and 4.5×10^{50} ergs (a typical energy for Type II supernova explosions), respectively.

For the surrounding interstellar medium we have chosen a density of $1\mathrm{cm}^{-3}$ and a temperature of 10^4 K.

The numerical simulations are adiabatic, which seems to be appropriated for our problem. Considering the ISM density and the initial energy of the SN explosion, we can estimate that this SNR would enter to radiative SNR phase at $t = 40000\,\mathrm{yr}$ and $R = 19.5\,\mathrm{pc}$. These values are not reached in our simulation, so that the adiabatic approach is indeed applicable.

2.2. Simulation of the synchrotron emission

We are interested in obtaining predictions of the radio emission from the lobe formed after the encounter between the jet and the SNR shell.

Following the work of Clarke et al. (1989) and Jun & Norman (1996), the synchrotron emission intensity can be written as:

$$i(\nu) = C_1\,\rho^{1-2\alpha}\,p^{2\alpha}(B\,\sin\psi)^{\alpha+1}\,\nu^{-\alpha}, \tag{1}$$

with C_1 being a constant, ρ the density, p the pressure, B the intensity of the magnetic field, α the spectral index parameter, ψ the angle between the direction of the magnetic field and the plane of the sky, and ν the frequency.

We assume that the magnetic field is toroidal ($\mathbf{B} = B\,\hat{\theta}$). For this magnetic field configuration, the intensity of the magnetic field can be modeled with the relation (Chan & Henriksen 1980):

$$B\;=\;C_2\,\frac{\rho\;r}{r_i}, \tag{2}$$

where C_2 is a constant and r is the radial cylindrical coordinate, and r_i is the initial cylindrical radius of the fluid parcel which has been transported by the flow to the $(z,\,r)$ position. In our numerical simulation, we track the initial radius r_i of the fluid parcels (at all positions of the flow) with an advection equation, which is integrated together with the gasdynamic equations. Then, considering Eq. (2) and fixing the frequency, Eq. (1) can be rewritten as:

$$i\;=\;A_\nu\,\rho^{2-\alpha}\,p^{2\alpha}\,\left(\frac{r}{r_i}\right)^{\alpha+1}\,(\cos\theta)^{\alpha+1}. \tag{3}$$

In this equation, θ is the polar angle around the symmetry axis of the cylindrically symmetric jet flow, defined such that for $\theta=0$, the $\hat{\theta}$ direction is parallel to the line of sight (the coordinate system is sketched in Fig. 1). If the angle ϕ between the jet axis and the plane of sky is 0, we have $\psi\;=\;\pi/2-\theta$. The hypothesis of a toroidal magnetic field might be appropriate for describing the synchrotron emission from the jet lobe, but it might not be appropriate for simulating the radio continuum emission from the SNR shell.

When the angle ϕ between the jet axis and the plane of the sky is nonzero, it is straightforward to show that Eq. (3) takes the form:

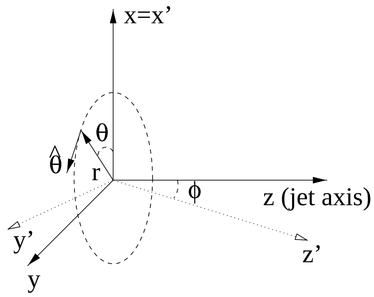

Fig. 1. Coordinate system employed to simulate the synchrotron emission. The $x'z'$-plane is the plane of the sky. The z-axis is the symmetry axis of the outflow, and the polar angle θ (which lies on the xy-plane) is measured from the $+x$-direction towards the observer. The lines of sight are parallel to the y'-axis.

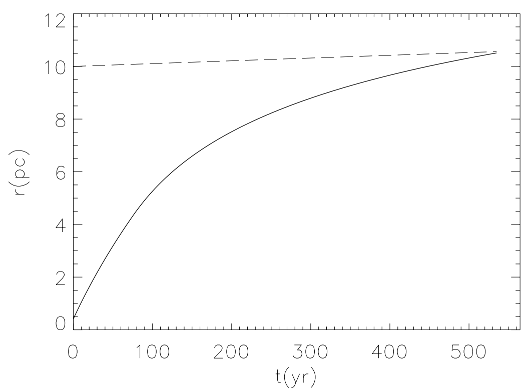

Fig. 2. Determination of the time of encounter t_e. The position of the working surface as a function of time t is represented with a solid line. The dashed line represents the SNR shock wave position.

$$i \ = \ A_\nu \, \rho^{2-\alpha} \, p^{2\alpha} \, \left(\frac{r}{r_i}\right)^{\alpha+1} (\cos^2\theta + \sin^2\phi)^{(\alpha+1)/2}. \qquad (4)$$

We check whether the gas has been shocked by computing the specific entropy for each computational cell and comparing it with the entropy of the unshocked material. We then set to zero the emission in the region filled with unshocked gas. For the W 50 case, the spectral index α was fixed at 0.5, following the work of Dubner et al. (1998) and we chose $\phi = 21^\circ$ (following the work of Hjellming & Johnston 1988).

3. Results

We carried out several runs with different geometries to describe the SS 433 jet. Hollow and filled conical jets with different aperture angles were tried. With hollow cone configurations and taking into account aperture angles greater than 15°, we obtain results which are similar to the ones of Kochanek & Hawley (1990), which do not describe well the morphology of W 50. The SNR shell is distorted and lose its spheroidal shape. We have therefore considered a filled cone with the initial conditions described in Sect. 2.1.

The interaction between a jet and a SNR is a process which can be divided into three phases or stages (Murata & Shibazaki 1996). In the first stage, the jet material propagates ballistically in the ISM which has already been swept up by the SNR shock wave. The jet generates a head with a double shock structure (the "working surface"), formed by a bow shock moving into the SNR gas, a reverse shock or Mach disk which decelerates the jet gas, and a contact discontinuity between them, separating the shocked SNR and jet gas. The working surface has a velocity v_{ws} (obtained assuming pressure equilibrium between the material entering through the bow shock and the Mach disk) given by:

$$v_{ws} = \frac{\beta(x)\ v_j \ + u_{SNR}(x)}{1 \ + \ \beta(x)}, \qquad (5)$$

where v_j is the jet velocity, u_{snr} is the velocity of the gas inside the SNR and $\beta = \sqrt{\rho_j(x)/\rho_{snr}}$ is the square root of the jet to SNR density ratio ($\rho_j(x) \propto x^{-2}$ where x is the working surface position).

The working surface continues moving into SNR material, but more slowly because it encounters denser zones. However, the working surface still moves faster than the SNR shock front and, after a time t_e, the head of the jet catches up and collides with the SNR shell and begins to push and distort the shell (as is shown in Fig. 3, in the t=450 and 550 yr frames). This is the second stage of the jet/SNR interaction.

The encounter time, t_e, can be determined considering that $v_{ws} = dx_{ws}/dt$, integrating Eq. (5) and comparing $x_{ws}(t)$ with the Sedov solution. We obtain that the jet catches up with the SNR shock wave at $t_e = 540$ yr (see Fig. 2), which is consistent with our simulation (see Fig. 3).

The encounter process is complex. To follow it we use the pressure maps (see Fig. 3). A detailed analysis reveals that the interaction occurs between 450 and 550 yrs and that a lobe starts to protrude at 550 yrs. According to the work of Kochanek & Hawley (1990), in conical jets the input jet momentum will spread over an increasing area, which produces an eventual stalling of the jet movement. The stalling point occurs at a distance from origin, which is approximately given by:

$$A_w \ = \ M_j^2 \, A_j, \qquad (6)$$

where A_w and A_j are the working surface cross section at the stalling point and the initial cross section of the jet, respectively. M_j is the initial Mach number of the jet. Taking into account the initial conditions of our model, the jet would have to stop at 8 pc from the origin. Clearly, in our results this does not occur. In the pressure maps it is possible to note that the jet suffers a change in its direction. The pressure of "the cocoon" around the jet (which is formed by jet, SNR and ISM shocked gas) compresses the jet gas, producing this recollimation.

In the third stage, the jet drags the SNR material and propagates more quickly into the unperturbed ISM, forming an elongated lobe. From 550 to 900 yrs, this lobe completely breaks the spherical shape of the SNR shell. In the t=850, 900 and 950 yr frames, an incident and a reflected secondary shock wave can be observed. These shocks produce an extra collimation of the jet beam, which generates another breakdown of the lobe surface (t=950 and 1050 yr frames, Fig. 3).

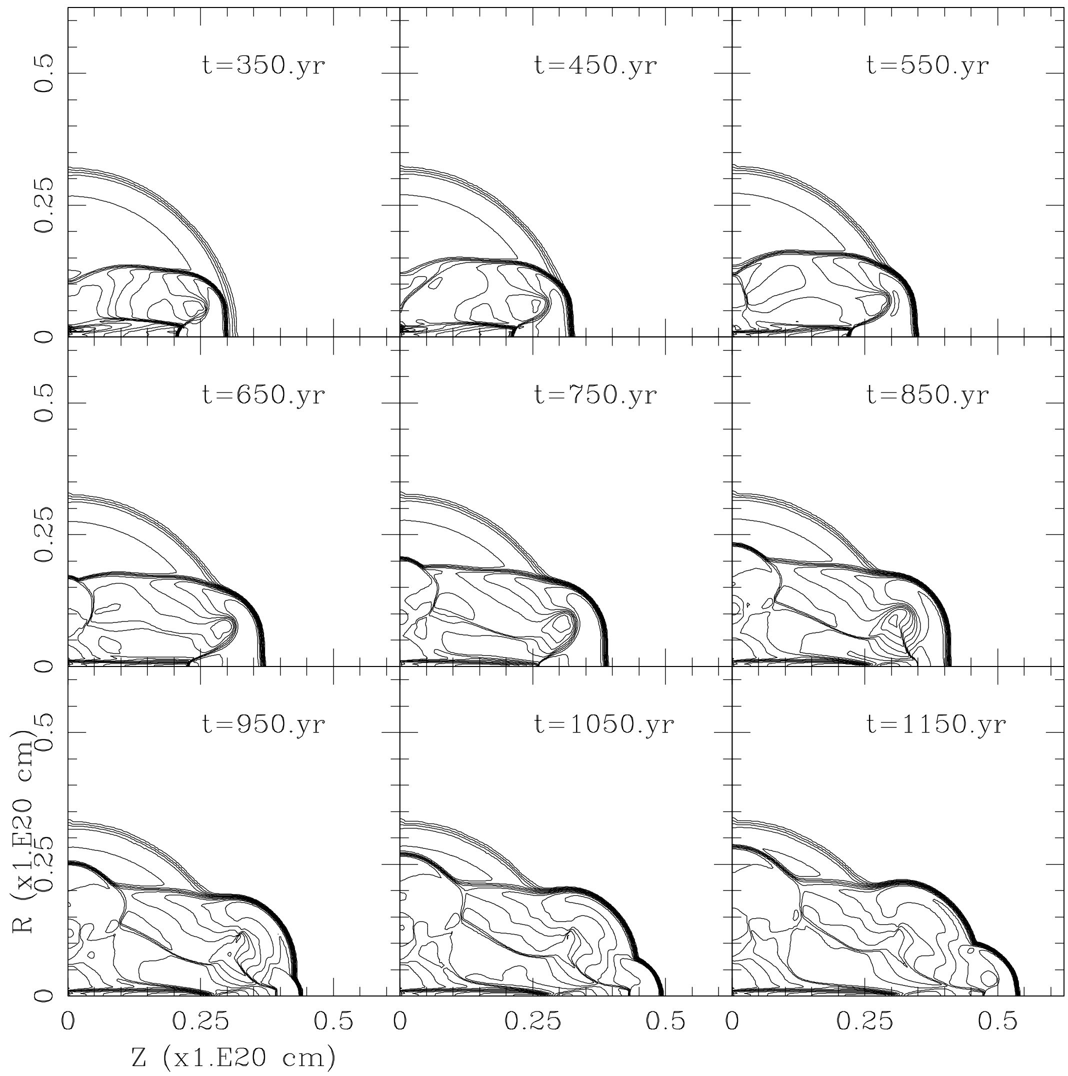

Fig. 3. Pressure contours of the interaction of a jet with a SNR from t=350 to 1050 yrs. The successive contours correspond to factors of two in the pressure. The plots are labeled with the time (in years) since the beginning of the jet ejection.

The dynamics of the gas lobe are dominated by the jet, and a new Mach disk appears close to the head of the lobe (see the t=1050 and 1150 yr frames, Fig. 3). The formation of secondary incident and reflected shock waves seems to be repeated several times producing a wavy structure in the surface of the lobe (see the 1200, 1500 and 1800 yr frames of Fig. 4). Another possible origin for this wavy structure is the Kelvin-Helmholtz instability between the jet, the cocoon and the external medium.

In the radial direction, the SNR maintains its spherical shape but in the last frames of Fig. 4 (t=1500, 1800, 2100, 2400 yr), the cocoon fills up the SNR interior and pushes out the SNR shell. From the t=2400 yr frame, we obtain a radius of 13.3 pc for the spherical shell. If we use Sedov's formulae to obtain the SNR age for this radius, we obtain a value of 15000 yr. However, the age from our simulations is of 9900 yrs, which implies an error in the age determination (via the Sedov solution) of the order of 51%. The difference between the numerical and the Sedov solutions is due to the pushing out of the SNR shell by the cocoon of the jet.

Finally, in order to compare these numerical results with radio observations, we simulated the synchrotron emission, following the steps described in Sect. 2.2. Fig. 5 shows the normalized radio emission at different times. The simulated non-thermal radio emission was computed considering that the angle between the jet axis and the plane of the sky has $\phi = 0°$ and $\phi = 21°$ values (the latter value being the real angle between the plane of the sky and the precession axis of the jets from SS 433). The bright region close to the head of the lobe corresponds to the Mach disk.

Annular structures can be observed on several of the predicted synchrotron maps, being this effect more notable in the $\phi = 21°$ case. Fig. 5 (with t=1200, 1500, 1800, 2100, 2400 yr frames), shows that the separations between successive rings have values of the order of the local lobe radius. A similar ef-

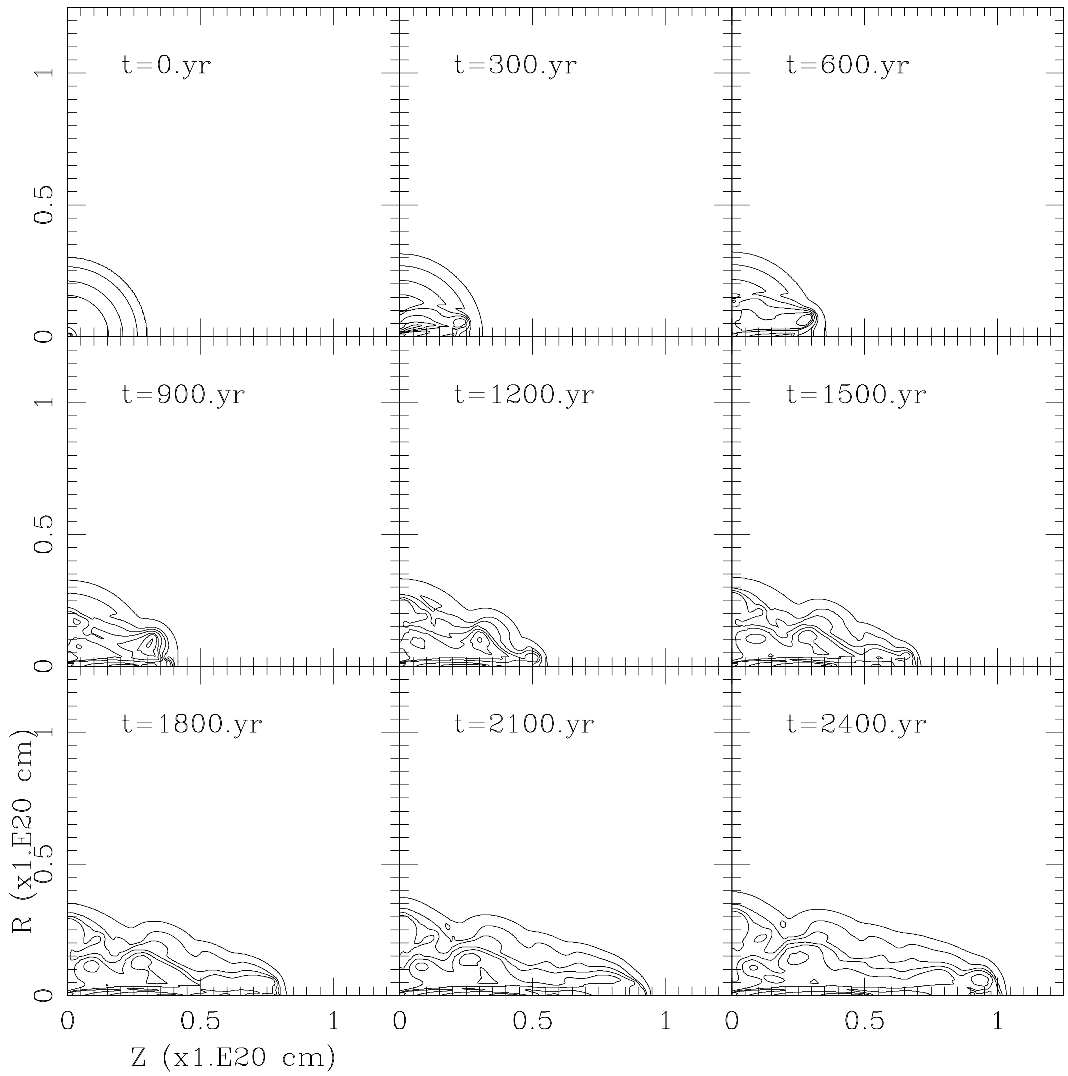

Fig. 4. Density stratifications of the interaction of a jet with a SNR shell. The successive contours correspond to factor of two in the density.

fect is observed in the real radio image (see the Eastern lobe in Fig. 1b of Dubner et al. 1998).

4. Discussion

We show that a model in which a jet interacts with a SNR shell successfully explains the elongated morphologies of some SNRs, and in particular the W 50 SNR. If we compute a model of a hollow conical jet propagating into a homogeneous ISM, the morphology of W 50 is not reproduced (as we obtain results similar to the ones of Kochanek & Hawley 1990).

The simulated radio maps reveal the existence of annular structures, which are in good qualitative agreement with radio maps of W 50. A probable origin for these helical structures is the propagation of incident and reflected shock waves, in the jet beam. Alternatively, these structures could be the result of Kelvin-Helmholtz instability between the jet, the cocoon and/or the surrounding environment (Velázquez et al. 2000).

An analysis of our simulations shows that the jet dominates the dynamics of the lobe after the encounter between the working surface of the jet and the SNR shock wave. The cocoon also pushes out and accelerates the SNR shell (in the radial direction). Several authors use the apparent unperturbed radius of the W 50 shell to determine the SNR age. If this part of the SNR shell is being pushed by the cocoon, the age of the SNR could be overestimated if we use the standard solution of SNRs, which would strictly no longer apply.

A future step is to model the optical filaments observed in the SNR W 50. These Hα filaments could be the result of collisional excitation in the collisional ionization relaxation region right behind an adiabatic shock, and very high spatial resolution will be necessary in order to model this emission.

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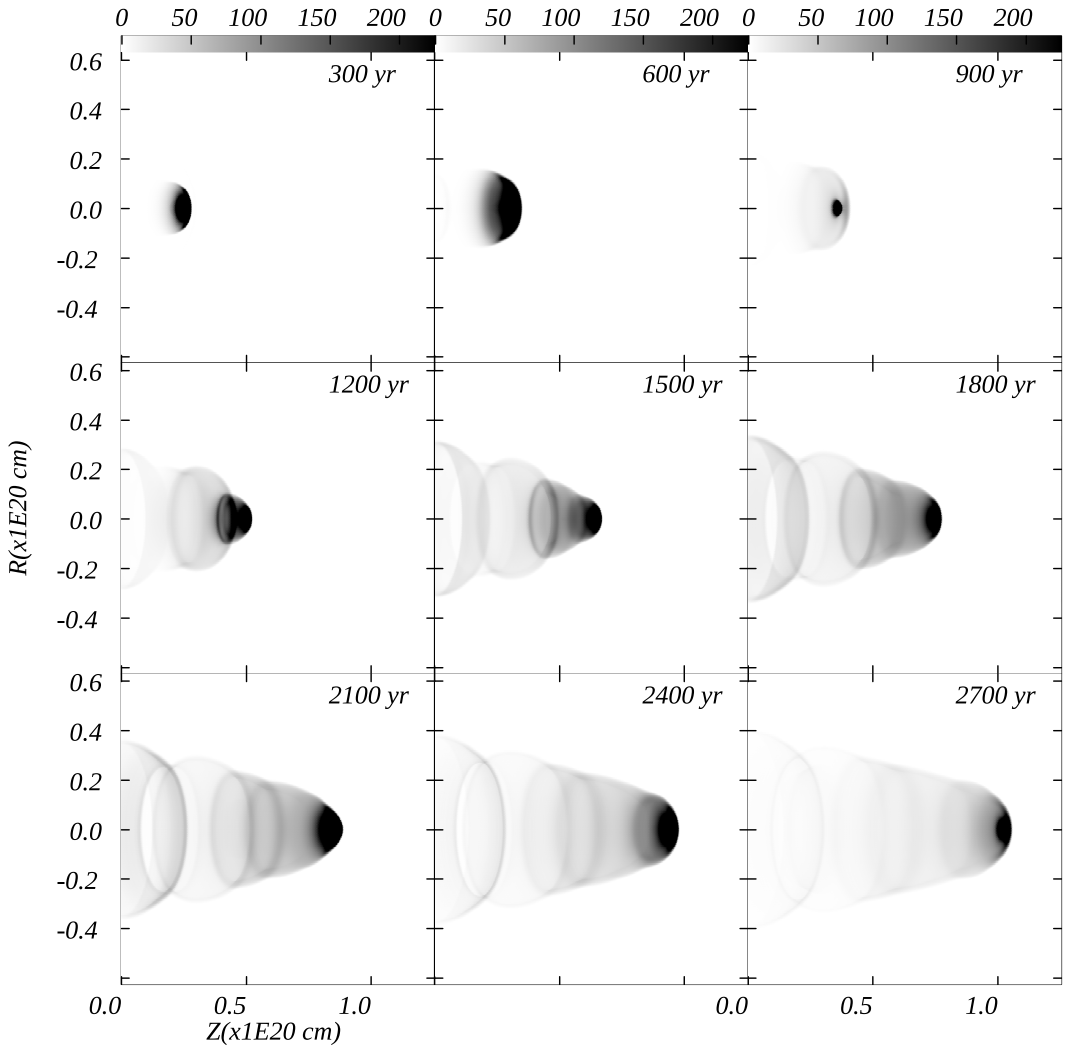

Fig. 5. Normalized synchrotron emission of the interaction of a jet with SNR shell. The grayscale range is [0.0,0.225]. The angle of the jet axis with the plane of the sky is $\phi = 21^\circ$.

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