RING NEBULAE AROUND MOVING WOLF-RAYET STARS

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Abstract. We present 2D numerical simulations of evolving ring nebulae around moving Wolf-Rayet stars. We have considered the interaction of the fast WR wind with the circumstellar matter modified by the previous action of the slow RSG wind. The resulting shell morphology is far from spherical and shows scallops due to several kinds of instabilities. The exact appearance of the ring nebula depends on the value of several parameters such as the unperturbed medium density and the velocity of the star.

Key words: stars: Wolf-Rayet – ring nebulae – hydrodynamics

Several 2D numerical models of the interaction of a fast Wolf-Rayet (WR) wind with the remnant of the dense, slow wind blown during the previous red supergiant (RSG) phase have been calculated. The aim of these models is to investigate the influence of the motion of the central star on the shape and dynamics of the resulting ring nebula. Here we show the results obtained in the case of a WR star moving with velocity $v_\star = 17\ \mathrm{km\,s^{-1}}$ through an interstellar medium (ISM) with number density $n_0 = 1\ \mathrm{cm^{-3}}$. The wind velocities and the rate of the mass loss suffered during the RSG and WR phases are $v_{\mathrm{RSG}} = 20\ \mathrm{km\,s^{-1}}$, $\dot{M}_{\mathrm{RSG}} = 3 \times 10^{-5}\ \mathrm{M_\odot\,yr^{-1}}$ and $v_{\mathrm{WR}} = 2\,000\ \mathrm{km\,s^{-1}}$, $\dot{M}_{\mathrm{WR}} = 3 \times 10^{-5}\ \mathrm{M_\odot\,yr^{-1}}$, respectively. In this model the duration of the RSG stage is assumed to be 8×10^5 yr, which is reasonable for a star with an initial mass of 40 $\mathrm{M_\odot}$.

In general, the earlier main sequence (MS) wind plays no role in this context, since during the RSG phase the star moves far away from the cavity carved in the previous MS stage (*cf.* Brighenti & D'Ercole 1994).

Figure 1a displays the density contours of the circumstellar matter (CSM) at the end of the RSG phase. The bow shock is isothermal and distorted by Kelvin-Helmholtz instabilities. The unperturbed wind extends downstream up to the end of the computational grid. Fig. 1b shows the CSM density structure after 1.8×10^4 yr since the onset of the WR wind. The portion of the ring expanding across the unperturbed RSG wind develops "knots" resulting from Vishniac (1983) instabilities and Rayleigh-Taylor instabilities occurring during the initial acceleration of the gas before the WR wind velocity reaches the final constant value. An adiabatic shock develops ahead

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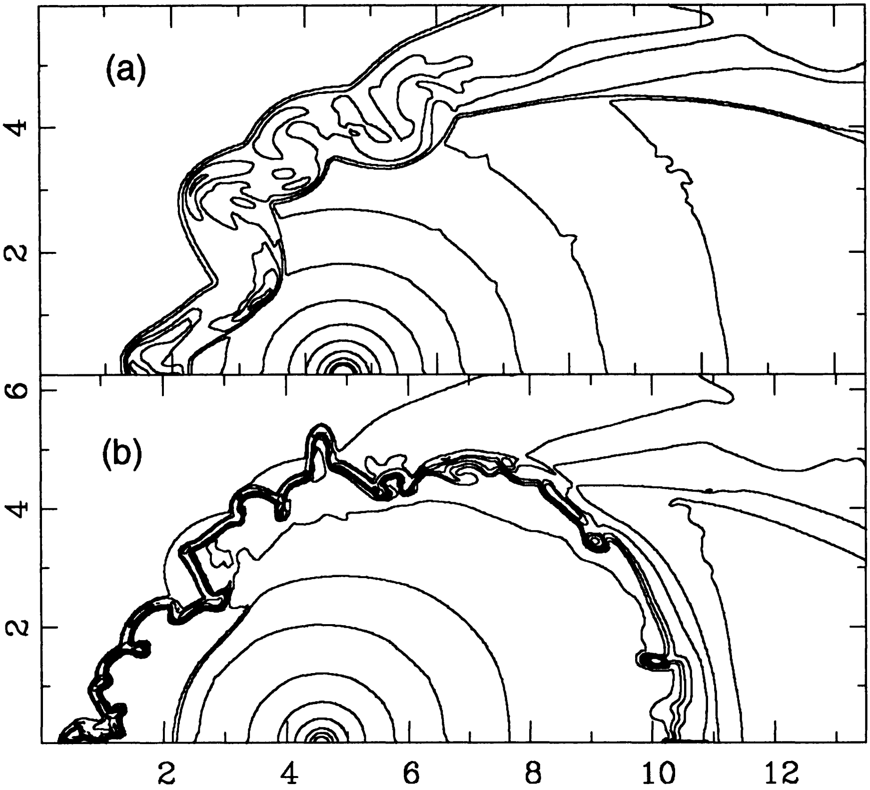

Fig. 1. a) 12 density contours at the end of the RSG phase (8×10^5 yr). b) 12 density contours after 18 000 yr since the onset of the WR phase. The numerical grid resolution is 0.035×0.035 pc^2. The labels are in parsec.

of the dense ring. Such a transition from radiative to nonradiative shock occurs when the pre-shock density of the unperturbed RSG wind becomes low enough to reduce the shock column density below the critical value (McKee & Hollembach 1980). The part of the ring hitting the RSG bow shock tends to thermalize the clumps inside while its front becomes more and more warped as it avances through the distorted bow shock.

Our models indicate that the nebular morphology is far from spherical and shows clumps, as actually has been observed in several cases (*cf.* Miller & Chu 1993).

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