Interaction of expanding supernova envelope with asymmetric circumstellar environment

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Abstract: Massive stars lose their mass either via isotropic stellar winds or by aspherical lobes or equatorial disks. We study dynamic and thermal effects of collision between expanding ejecta of supernovae (SNe) and asymmetric circumstellar medium (CSM) that may be formed during sgB[e] or LBV star phase, around Pop III stars, due to a binary companion, or by accretion. We examine the behavior of the interaction zone under various geometrical configurations and various initial densities of CSM. We calculate the evolution of SN - CSM systems and the rate of aspherical deceleration of the SN ejecta as well as the rate of conversion of the SN kinetic energy into thermal energy. We expect that subsequent study of SN light curves powered by the thermal energy excess of such interaction will lead to more accurate estimates of stellar mass-loss rate and to a better understanding of CSM density distribution.

Expansion of envelope

We perform a model of the interaction of an expanding supernova (SN) with asymmetric ambient circumstellar medium (CSM) including a dense equatorial disk. Time-dependent numerical solution was calculated using our own 2D hydrodynamic code based on Roe's method (Kurfürst et al. 2018). We assume the following initial stellar parameters: $M_\star = 15\,M_\odot$, $R_\star = 10^{14}\,$cm, $\langle\rho\rangle_\star = 3M_\star/(4\pi R_\star^3)$, SN explosion energy input $E = 10^{51}\,$erg. The initial stellar photon gas (with $\gamma = 4/3$) pressure $p_{\rm ini} = E/(3V) = E/(4\pi R_\star^3)$, that is, of the order of $10^8\,{\rm g\,cm^{-1}s^{-2}}$ while the initial pressure of the ambient medium may be of the order of $10^{-5}\,{\rm g\,cm^{-1}s^{-2}}$ or lower. The early phase of SN envelope evolution can be basically described as a self-similar adiabatic expansion forming a forward and reverse shock wave with a contact discontinuity between the two waves (Nadezhin 1985, Chevalier & Soker 1989).

Circumstellar medium

We assumed either spherically symmetric CSM or the equatorial disk. The initial density profile of a spherically symmetric CSM (created, for example, by thermal pulses of the progenitor before the explosion) is $\rho \propto r^{-2}$ while its initial base density is $\rho_{\rm int} \approx 10^{-9}\,{\rm g\ cm^{-3}}$. The vertical density profile of asymmetric component of CSM (dense equatorial disk) is Gaussian while its radial profile is approximately constant with the disk equatorial base density $\rho_{0,\rm disk}$ corresponding to isotropic CSM.

Conclusions

The current models show the aspherical evolution of the density, velocity, and temperature structure of the SN ejecta where the mass expands to the area outside the dense equatorial disk. In case of the disk initial base density values $\rho_{0,\rm disk} \gtrsim 10^{-11}\,{\rm g\ cm^{-3}}$ may such equatorial disk effectively block the SN expansion with significantly increased temperature in the region of SN-disk interaction.

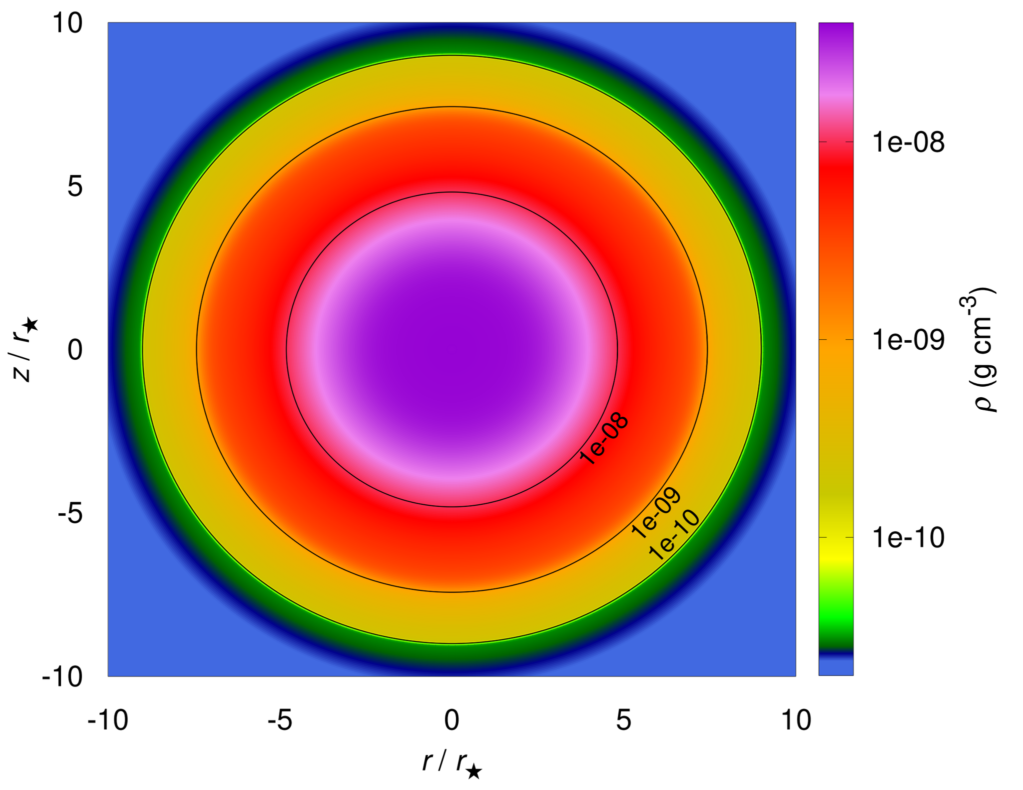

Fig. 1: 2D density structure of the interaction of SN with perfectly spherically symmetric CSM at $t = 20\,$d after shock emergence. Stellar and CSM parameters are described above.

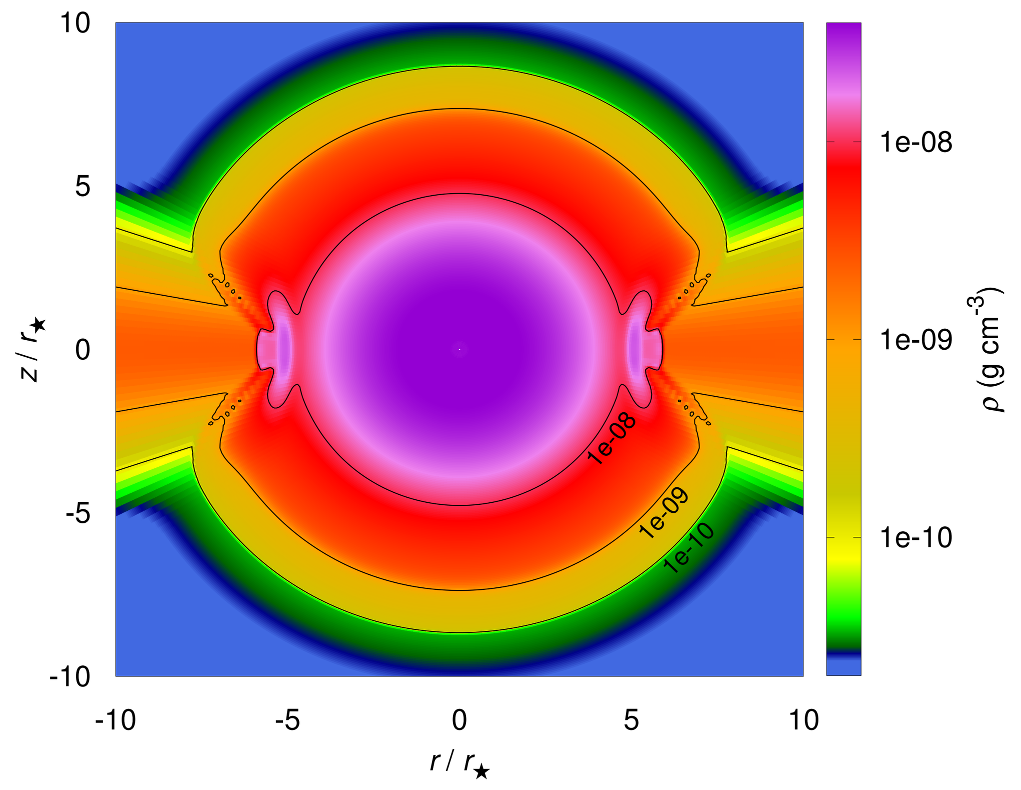

Fig. 2: Density structure of the interaction of SN with asymmetric CSM that forms a dense equatorial disk, at time $t = 20\,$d. Characteristic 1D sections of the model are shown in Figs. 5 and 6.

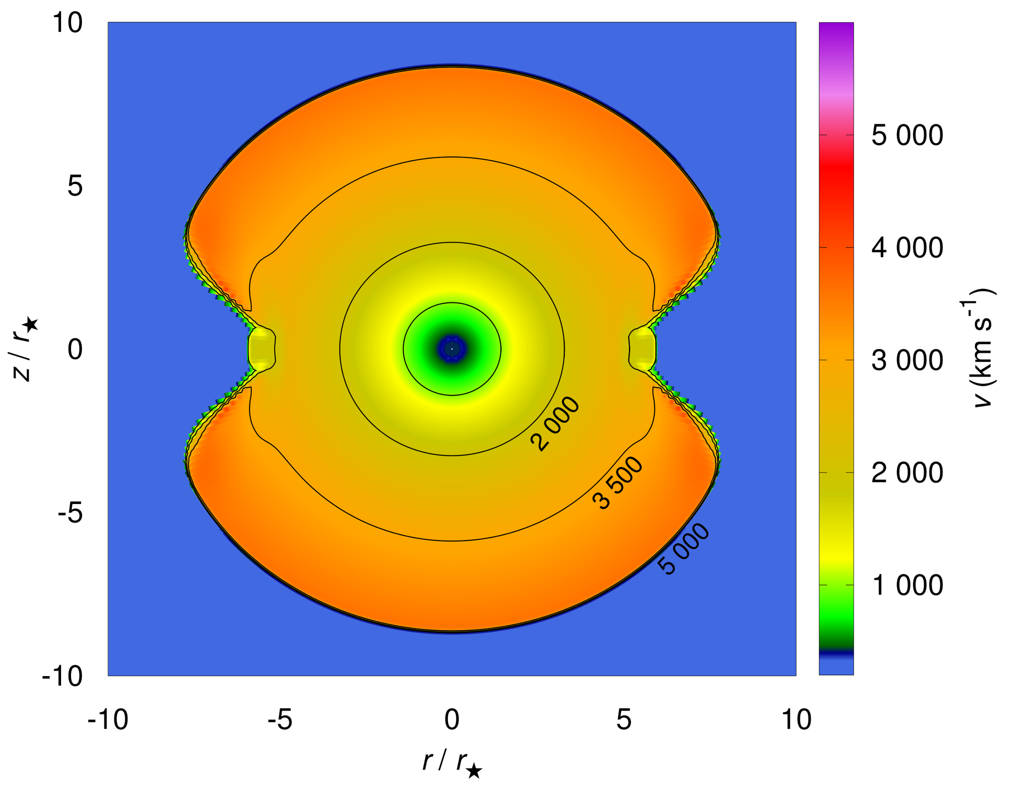

Fig. 3: 2D structure of expansion velocity of the model described in Fig. 2, at the same time.

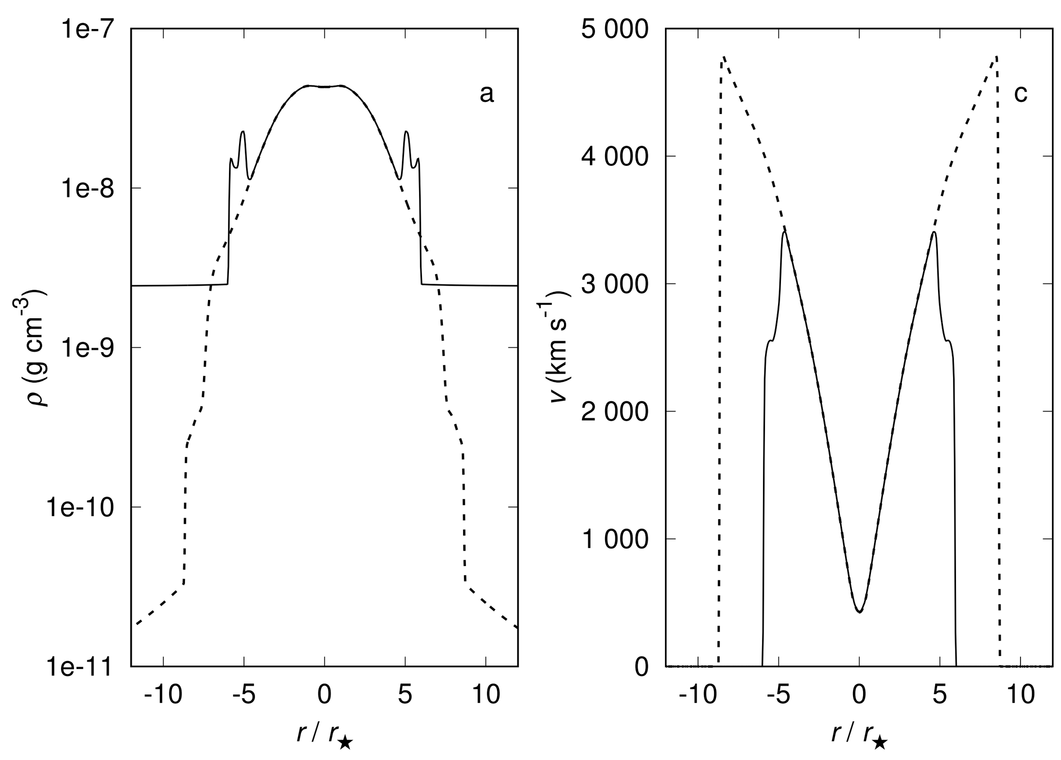

Fig. 5: 1D slices of density (*left*) and velocity (*right*) in equatorial (*solid line*) and polar (*dashed line*) planes.

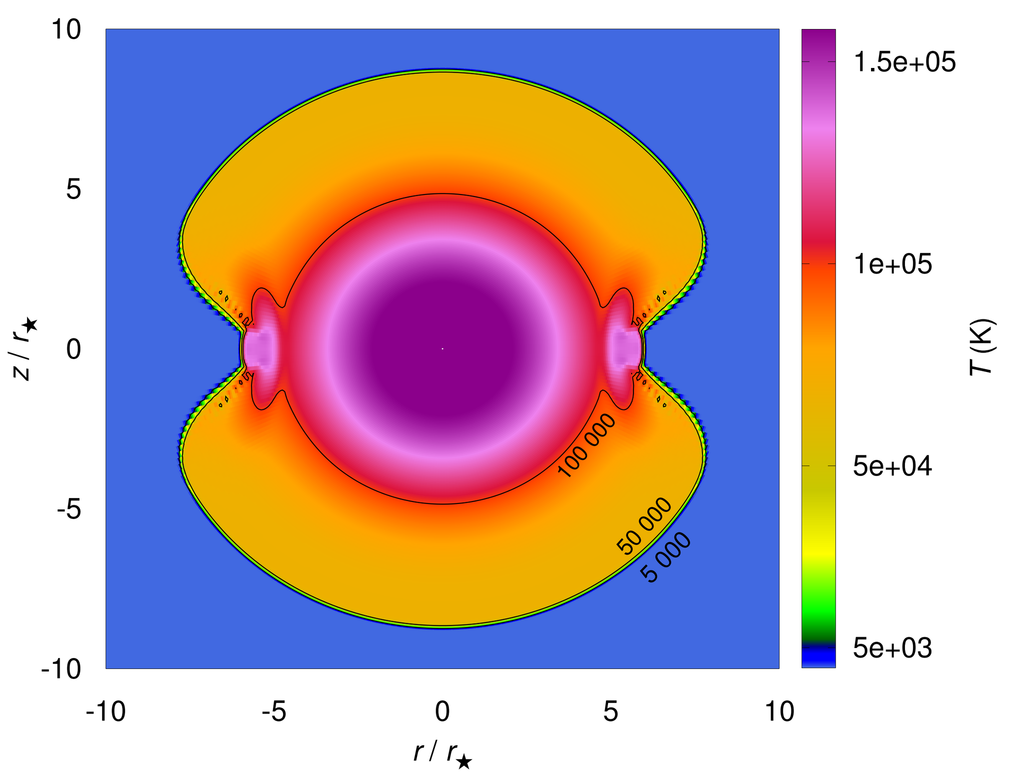

Fig. 4: 2D radiative temperature structure of the model described in Fig. 2, at the same time.

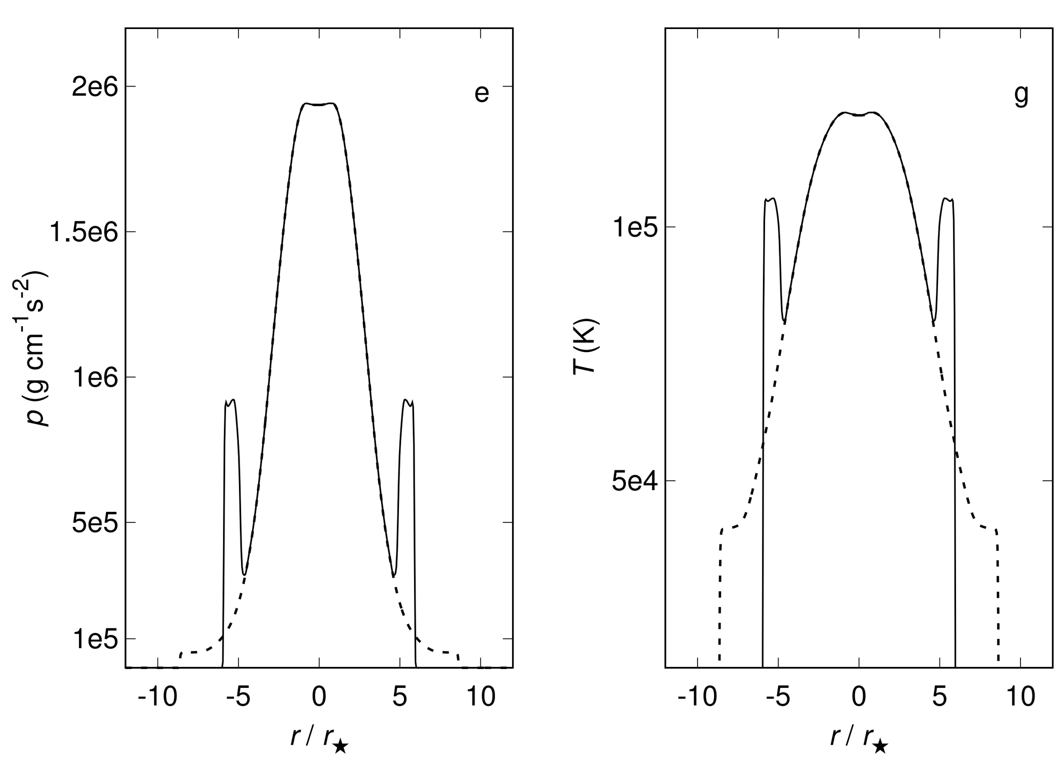

Fig. 6: 1D slices of pressure (*left*) and temperature (*right*) in equatorial (*solid line*) and polar (*dashed line*) planes.

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References

Nadezhin, D. K. 1985, *Ap&SS* **112**, 225

Chevalier, R. A. & Soker, N. 1989, *ApJ* **341**, 867

Kurfürst, P., Feldmeier, A., & Krtička, J. 2018, *A&A*, in press