Modeling of interaction between supernova ejecta and aspherical circumstellar material

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Abstract: We study the hydrodynamics of collisions between expanding supernova ejecta of supernovae and asymmetric circumstellar material (CSM). For time-dependent hydrodynamic modeling we use our own grid-based Eulerian multidimensional unsplit hydrodynamic code that is highly efficient for calculation of shocks and physical flows with large discontinuities. We examine the behavior of density, pressure, velocity, and temperature in the interaction zone under various geometrical configurations and various initial densities of CSM. We expect that subsequent study of the SN light curves powered by such interaction thermal energy excess will lead to a better understanding of the mass and density distribution of the CSM.

Expansion of envelope

We perform a model of the interaction of an expanding supernova (SN) envelope with asymmetric circumstellar medium (CSM) including a dense equatorial disk. Time-dependent numerical solution was calculated using our own 2D spherically gridded hydrodynamic code based on Roe's method (Kurfürst et al. 2017). We assume the following stellar parameters: $M_\star = 15\,M_\odot$, $R_\star = 10^{14}$ cm, and the injected explosion energy $E = 10^{51}$ erg. We initiate the simulation as the "thermal bomb" within the radius $0.2\,R_\star$ where the photon gas pressure $p_{\rm ini} = E/(3V)$. We adopt the initial stellar density and temperature profile of red supergiant from MESA model (used in SNEC code, Morozova et al. 2015). The early phase of SN envelope expansion can be basically described as a self-similar adiabatic process (Chevalier & Soker 1989).

Circumstellar medium

We assumed a spherically symmetric CSM with axially symmetric circumstellar disk. The initial density profile of a spherically symmetric CSM (created, for example, by stellar wind of the progenitor) is $\rho \propto r^{-2}$ while its initial base density is $\rho_0 \approx 10^{-10}\,\mathrm{g\,cm^{-3}}$. 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 $\rho_{\rm eq}$ corresponding to isotropic CSM. The pressure profile of CSM is given by the equation of state of isothermal ideal gas.

Conclusions

The models show the aspherical evolution of density, velocity, and temperature structure of the SN ejecta where the mass may expand to the area outside the dense equatorial disk. In case of the disk initial base density values $\rho_{0,\rm disk} \gtrsim 10^{-11}\,\mathrm{g\,cm^{-3}}$ may such equatorial disk effectively block the SN expansion with significant over-dense and over-heated regions near the SN-disk interaction zones.

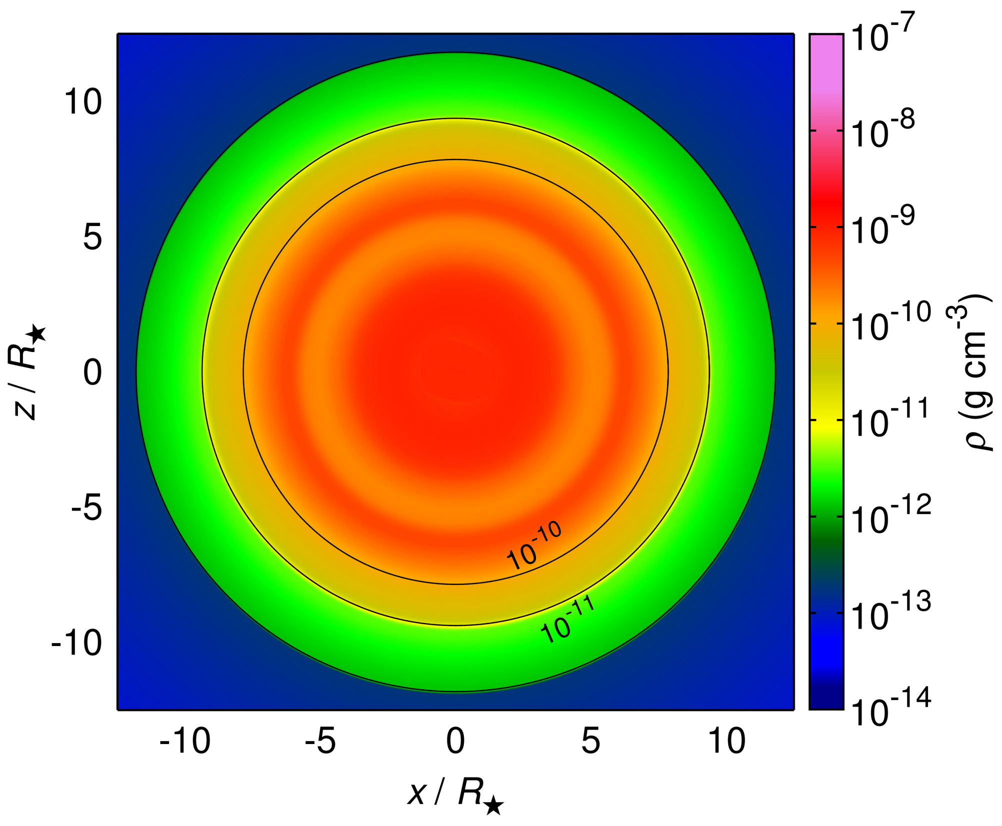

Fig. 1: 2D density structure of the interaction of SN with perfectly spherically symmetric CSM at $t = 30$ d after shock emergence. Stellar and CSM parameters are described above.

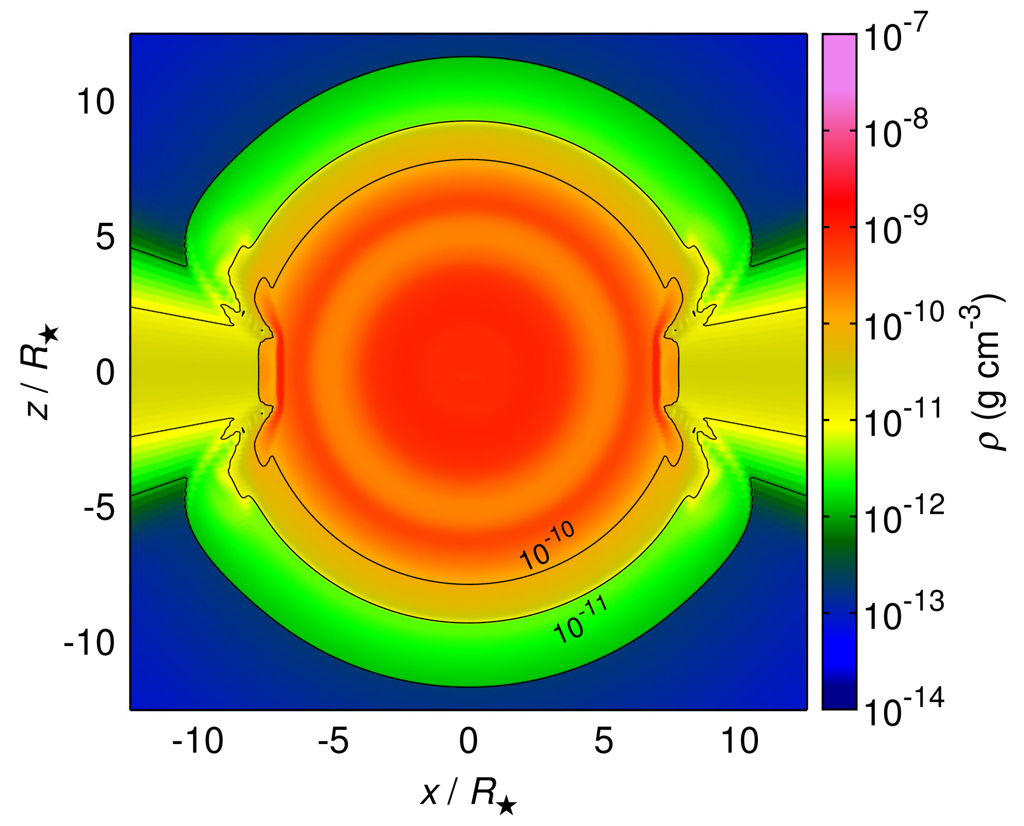

Fig. 2: Density structure of the interaction of SN with asymmetric CSM that forms a dense equatorial disk, at time $t = 30$ d. Characteristic 1D sections of the model are shown in Figs. 5 and 6.

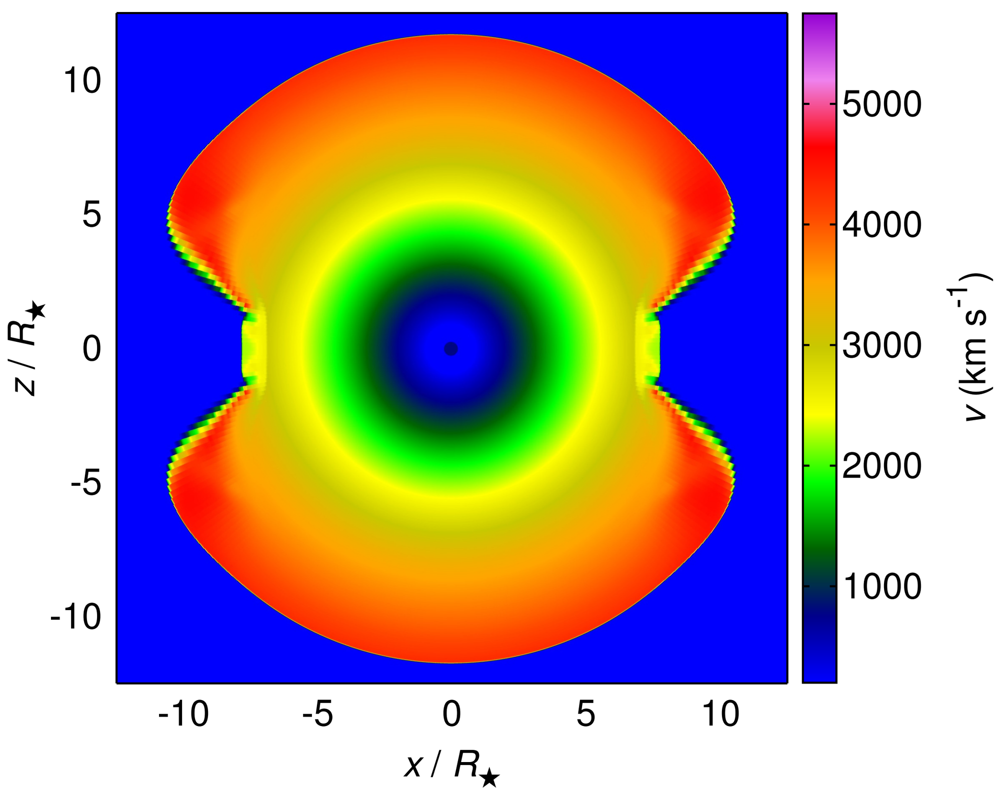

Fig. 3: 2D structure of expansion velocity of the model described in Fig. 2, at the same time.

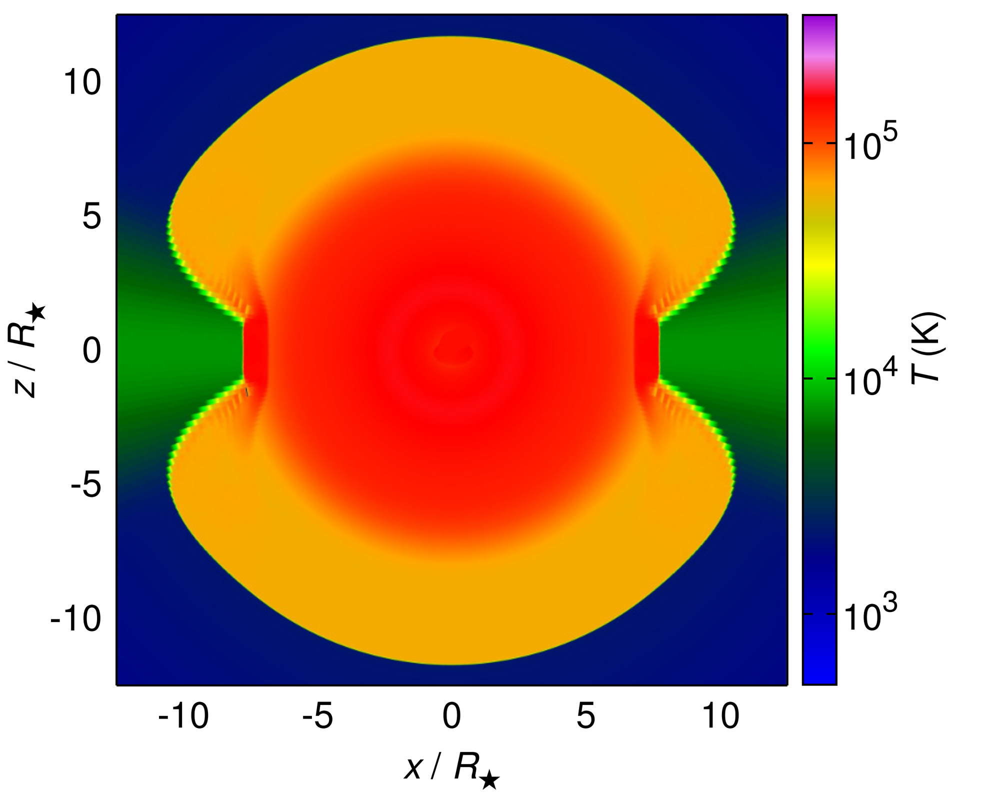

Fig. 4: 2D temperature structure of the model described in Fig. 2, at the same time.

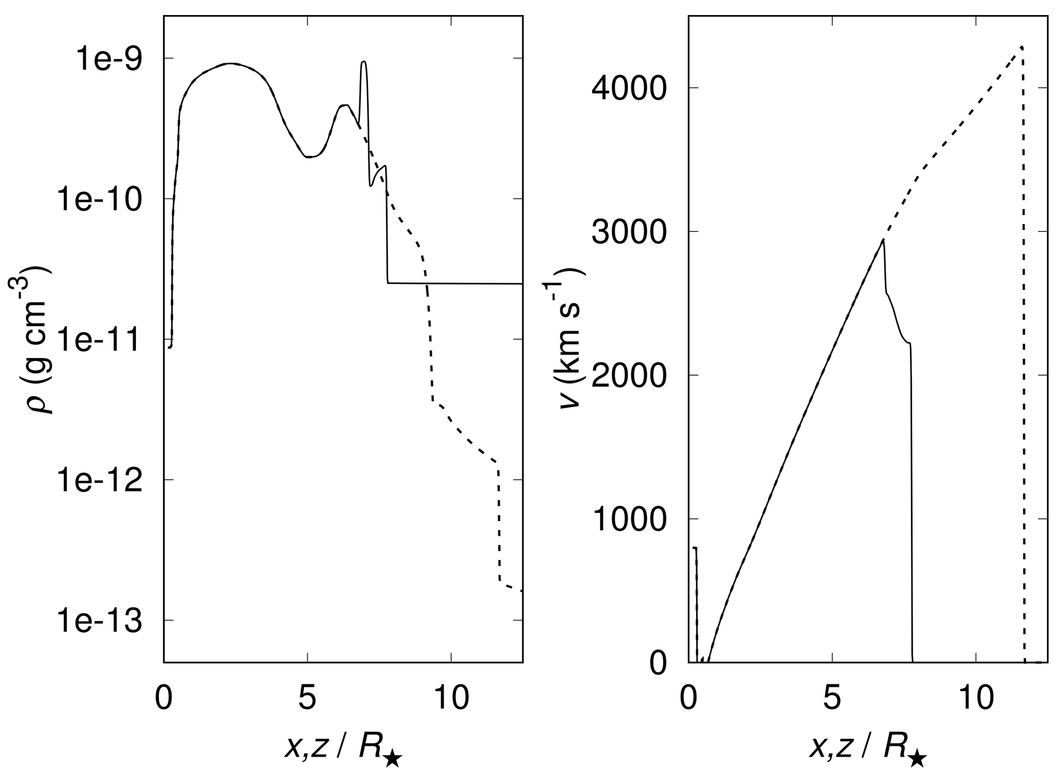

Fig. 5: 1D slices of density (*left*) and velocity (*right*) in equatorial (*solid line*) and polar (*dashed line*) plane.

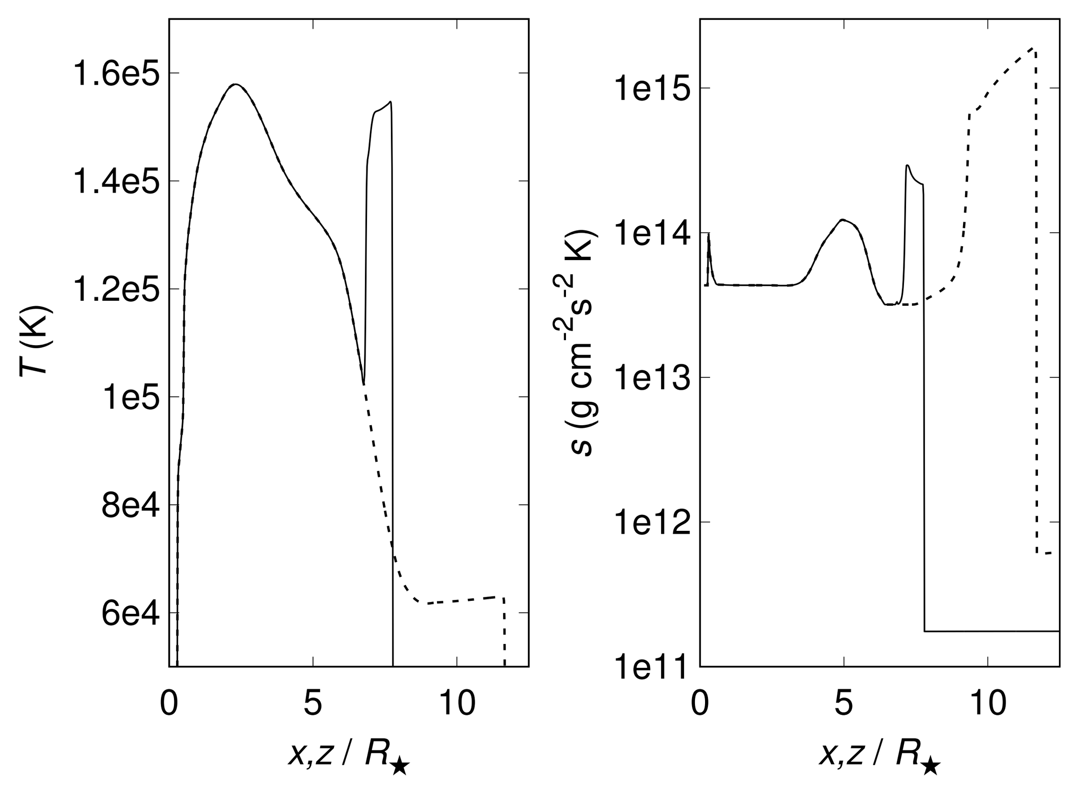

Fig. 6: 1D slices of temperature (*left*) and entropy (*right*) in equatorial (*solid line*) and polar (*dashed line*) plane.

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