Radiation-hydrodynamic simulations of SN ejecta interacting with circumstellar disks

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Abstract

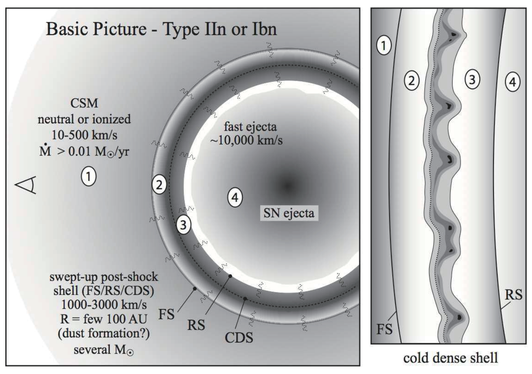
We perform a series of two-dimensional radiation-hydrodynamic simulations of the collision between supernova ejecta and circum-stellar media (CSM). The hydrodynamic interaction of a fast flow and the surrounding media efficiently dissipates the kinetic energy of the fast flow and considered as a dominant energy source for a specific class of core-collapse supernovae. However, multi-dimensional effects in the ejecta-CSM interaction, such as hydrodynamic instabilities and aspherical CSM structure, are relatively unexplored.

Our numerical simulations equipped with an adaptive mesh refinement technique successfully reproduce hydrodynamic instabilities developing around the ejecta-CSM interface. We also investigate effects of disk-like CSM on the dynamical evolution of supernova ejecta. We present bolometric light curves of supernova powered by the interaction with spherical and disk-like CSMs and discuss possible observational implications based on the simulation results.

1. Motivation

Circumstellar media (**CSM**) surrounding massive stars play important roles in **core-collapse supernova explosions** (CCSNe). Massive stars are thought to produce CSMs by shedding a part of their envelopes via several mechanisms, e.g., stellar winds and binary interactions. When a massive star undergoes the gravitational collapse of the iron cores, a core-collapse supernova (CCSN) happens and its bright emission illuminates the surrounding medium. CCSNe showing observational signatures of hydrogen-rich CSMs are commonly found in SN surveys and they make up a special spectral class, known as **type IIn SNe** (Schlegel 1990; Filippenko 1997; Smith 2017).

One of the highly uncertain but important issues among interacting SNe is multi-dimensional effects. Deviations from spherical symmetry are expected even in cases where ejecta and CSM are both spherical because of the development of hydrodynamic instabilities, the Rayleigh-Taylor instability and the Vishniac instability (Vishniac 1983; Ryu & Vishniac 1987), around the ejecta-CSM interface. In addition, the CSM itself can be asymmetric and/or clumpy (e.g., Chugai & Danziger 1994). In this work, we investigate the SN ejecta-CSM interaction by using 2D radiation-hydrodynamic simulations. We especially focus on SN ejecta interacting with a CSM disk.



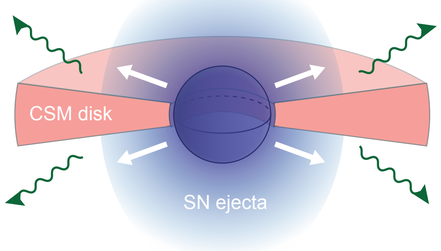
Smith (2016)

2. Numerical setups and tests

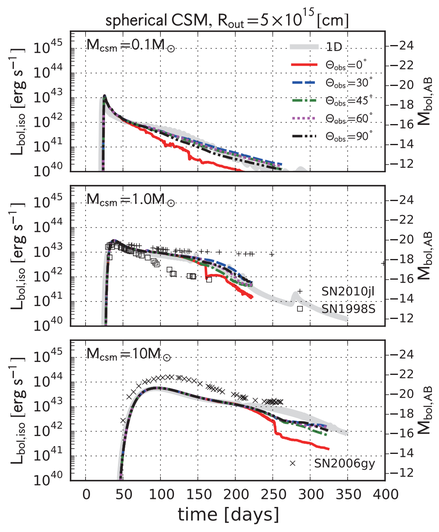
Numerical simulations are carried out by using our **2D radiation-hydrodynamics code** equipped with **AMR** (adaptive mesh refinement), Some detailes on the numerical treatment of radiative transfer are found in Suzuki, Maeda, and Shigeyama (2016). We calculate the collision of SN ejecta with a spherical or disk-like CSM, which is schematically shown below.

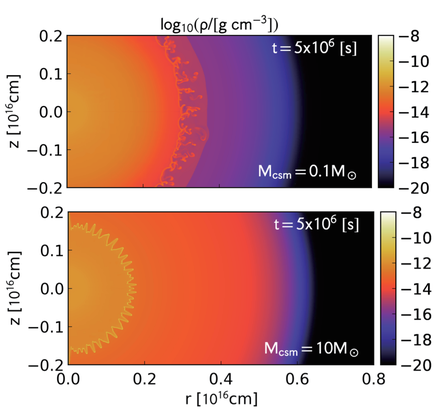
The ejecta have the total mass of 10M$_\odot$ and the kinetic energy of 10^{51} erg. The density distribution of the SN ejecta is described by the widely used broken power-law function with the inner and outer slopes of $\rho \propto v^{-1}$ and v^{-10}.

For the CSM, we assume three different CSM masses, **0.1, 1.0, and 10M$_\odot$** for spherical and aspherical cases. The opening angles of **10 and 20 degrees** are considered for disk-like CSM. The radiation transport is treated in the so-called **gray approximation**, in which we only deal with the frequency integrated quantities for radiation.



We first performed test calculations in 1D spherical coordinate employing a spherical CSM and then extend the calculations to 2D cylindrical coordinate. The right figure shows the resultant bolometric light curves for 1D and 2D spherical models. For 2D models, light curves with different viewing angles are plotted. The top, middle, and bottom panels correspond models with the CSM masses of 0.1, 1.0, and 10.0M$_\odot$. For more massive CSMs, the interaction-powered emission evolves more slowly. In these spherical CSM models, the viewing angle dependence is weak. However, light curves are certainly affected by some hydrodynamic instabilities, such as the Rayleigh-Taylor instability and the Vishniac instability as seen in the density distribution in the right panels.



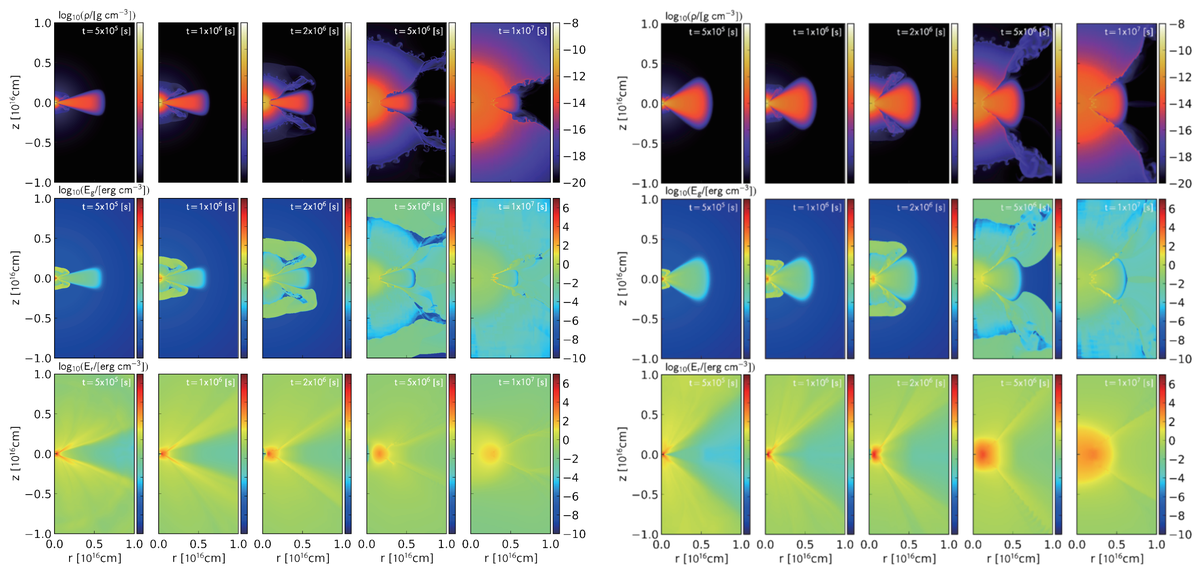


3. SN ejecta - disk interaction

More drastic aspherical effects are seen in disk models. In the figures below, the density, gas energy density, and radiation energy density distributions are shown for the disk CSM model with the CSM mass of 1M$_\odot$ and the opening angle of 10 [deg] (left) and 20 [deg] (right). The epochs of the snapshots are roughly 5, 10, 20, 50, and 100 days.

In the presence of a CSM disk, a part of the ejecta traveling around the equator decelerates efficiently, resulting in highly aspherical ejecta structure. The polar part of the ejecta is not covered by the CSM and thus the ejecta can expand almost freely. On the other hand, the equatorial part of the ejecta is covered by the CSM disk, which prevents the ejecta from expanding freely. As a result, the ejecta is squeezed in the presence of the CSM disk and a ring-like region with no radially expanding ejecta appears behind the CSM disk. One of the important consequences of this ejecta–disk interaction is that the kinetic energy dissipation is most efficiently happening in the equator, where the ejecta is adjacent to the CSM disk. This is clearly seen in the spatial distributions of the radiation energy density (bottom panels),

Because of this aspherical nature, light curves of this phenomena from different views are expected to be significantly different from each other.



4. Light curves

Clear differences are indeed found in light curves from different viewing angles. In the figure below, some bolometric light curves from a series of the simulations are shown (6 models with the three CSM mass and the two disk opening angle, and 5 different viewing angles for each model).

We can divide the presented light curves into two classes, those with a steep rise and slow rise. The light curves with smaller viewing angles are characterized by a steep rise. On the other hand, an observer around the equator (Θ_{obs} = 90 deg) would see less luminous and slowly evolving emission lasting for ~ 1 yr. The presence of the CSM disk makes the light curve dim and long-lasting due to the photon diffusion through the dense CSM disk.