Supernova ejecta with a powerful central engine

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Abstract

The origin of luminous supernovae (SNe), such as SNe associated with gamma-ray bursts and superluminous SNe, are still debated despite a lot of theoretical and observational studies. It is claimed that such luminous SNe harbor powerful "engines" at their centers. In the central engine scenario, a rotating magnetized proto-neutron star, a black accretion disk, or whatever is left in the supernova ejecta and serves as a power source for luminous thermal emission.

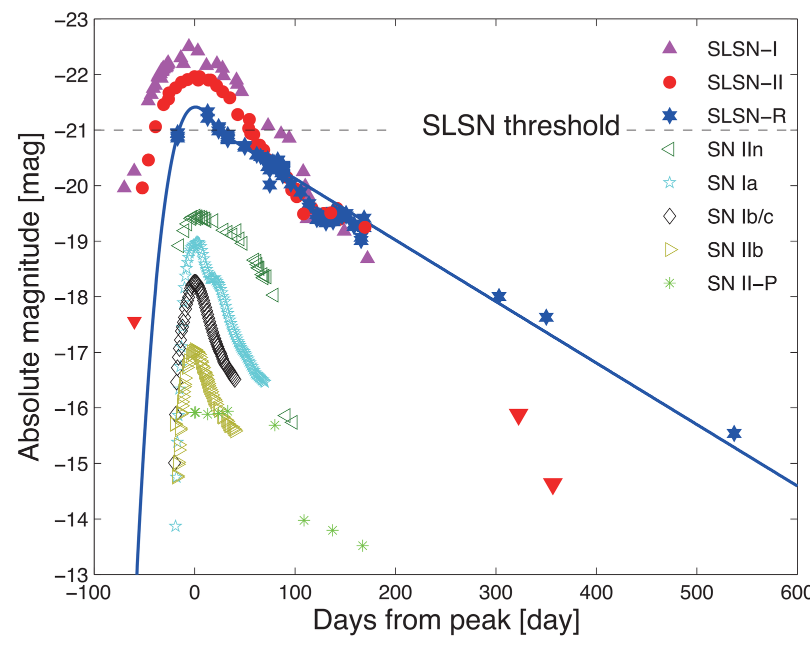
The energy injection at the center of SN ejecta create a hot bubble or a nebula, similar to pulsar wind nebulae, and its impact on the SN ejecta is non-negligible when considering sufficiently powerful engine realizing superluminous SNe.

We are investigating the effect of such powerful central energy source on the dynamical evolution of SN ejecta by using (radiation-)hydrodynamics simulations in 2D and 3D. In this presentation, we report the results of our past and ongoing studies on numerical modeling of SN ejecta with a powerful central energy source.

1. Motivation

There is growing evidence that several classes of unusual **core-collapse supernovae (CCSNe)** harbor a powerful "**engine**" at the center. Broad-lined Ic SNe (**SNe Ic-BL**) are characterized by broad absorption features in their spectra, indicating large explosion energies. It is widely known that some SNe Ic-BL are associated with long-duration **gamma-ray bursts** (**GRBs**) and thus require an ultra-relativistic jet penetrating the star (Woosley & Bloom 2006; Hjorth & Bloom 2012; Cano et al. 2017). In addition, one of the most plausible scenarios for the emerging new class of **hydrogen-poor superluminous SNe** (also known as type I superluminous SNe, **SLSNe-I**; Quimby et al. 2007; Barbary et al. 2009; Pastorello et al. 2010; Quimby et al. 2011; Chomiuk et al. 2011) is the so-called central engine scenario, in which the central compact object, a highly rotating magnetized neutron star (Kasen & Bildsten 2010; Woosley 2010) or a black hole accretion disk (Dexter & Kasen 2013) deposits additinal energy into SN ejecta to give rise to bright thermal emsision. Despite a lot of investigations on the effects of the putative central engine left in SN ejecta, there are still many problems remained unanswered, such as, how it is produced, how exactly it deposits an additional energy into the surrounding SN ejecta, and what kind of conditions should be met for their progenitor systems.

In this study, we investigate the impact of the central energy injection into freely expanding SN ejecta by performing 3D special relativistic hydrodynamic simulations.



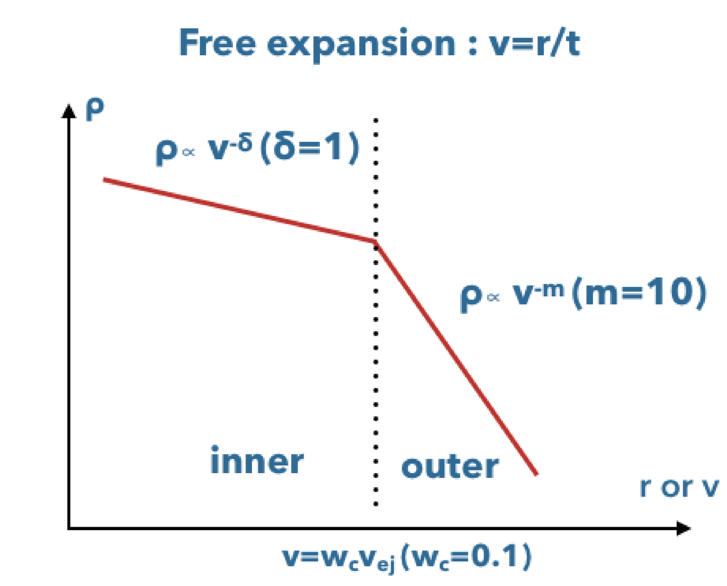
SLSN light curves, Gal-yam (2012)

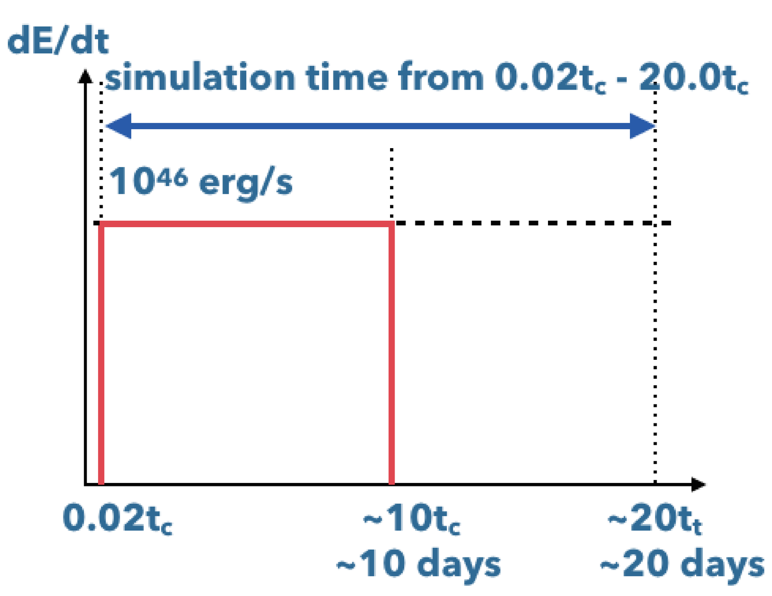
2. Numerical setups

Numerical simulations are carried out by using our **3D special relativistic hydrodynamics code** equipped with **AMR** (adaptive mesh refinement), Some details on the numerical treatment of hydrodynamics and AMR are found in Suzuki & Maeda (2017). We calculate the injection of energy into freely expanding SN ejecta, 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}.

We consider two models with different total injected energies, **10^{52} [erg]** and **10^{51} [erg]** (model E52 and E51). We inject an additional energy into the central region of the supernova ejecta. The energy injection rate is fixed to be $dE/dt=10^{46}$ [erg/s]. Therefore, it takes 10^6 sec and 10^5 sec for models E52 and E51. The injected gas has the energy-to-rest mass ratio of 20, i.e., the gas is highly relativistic. The energy injection is suddenly terminated when the total amount of the energy has been injected. The energy is injected into a spherical region and a spherical blast wave immediately forms. But, the shock front suffers from the Rayleigh-Taylor instability soon after the propagation, which rapidly destruct the spherical symmetry.





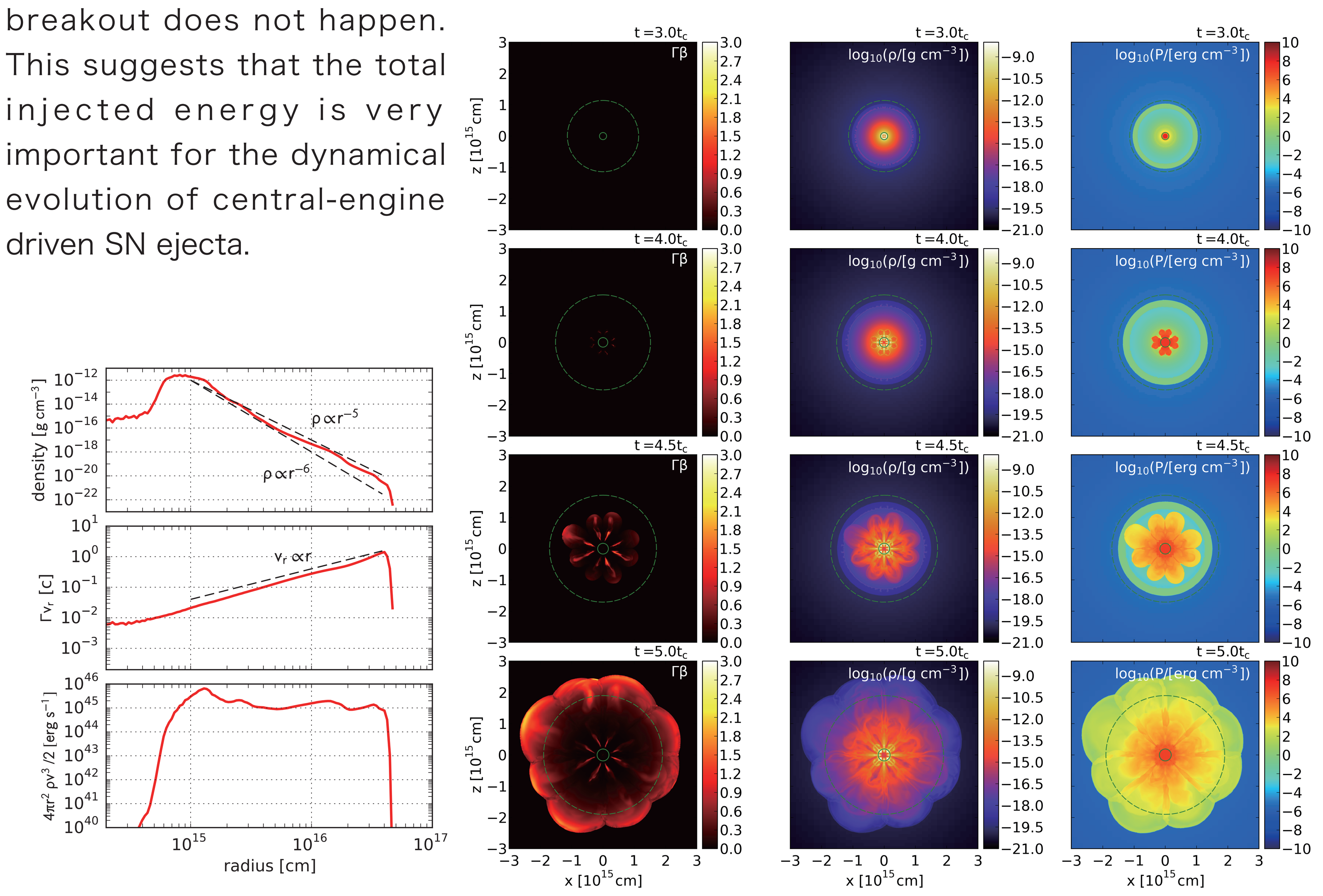
Reference

- Suzuki, A. & Maeda, K. (2017) MNRAS, 466, 2633
- Suzuki, A. & Maeda, K. (2018) MNRAS, 478, 110
- Suzuki, A. & Maeda, K. (2019) submitted to ApJ

3. Results

Below, we show the results of E52 model. At the beginning of the evolution, a quasi-spherical region with high pressure (**hot bubble**) appears around the center of the ejecta due to the energy injection. The forward shock driven by the pressure of the hot bubble propagates in the supernova ejecta. When the forward shock front is still in the inner part of the supernova ejecta, the ram pressure exerting on the post-shock gas is sufficiently large to contain the thermal pressure of the hot bubble, keeping the hot bubble nearly spherical. However, once the forward shock front passes through the interface separating the inner and outer parts of the ejecta, the ram pressure of the outer ejecta can no longer contain the hot bubble, leading to an efficient acceleration of the forward shock. On the course of the hot bubble expansion, the **Rayleigh-Taylor instability** develops around the contact surface, mixing the injected gas with the supernova ejecta. The forward shock modified by the development of the Rayleigh-Taylor instability efficiently expands in the outermost layer of the supernova ejecta, resulting in the **violent breakout** of the shock into the surrounding space.

On the other hand, for model E51, the hot bubble is stuck in the inner ejecta and the breakout does not happen. This suggests that the total injected energy is very important for the dynamical evolution of central-engine driven SN ejecta.



4. Discussion

When the central energy injection is significantly energetic, like model E52 in this study, the injected energy inflates the SN ejecta. In other words, the energy transport from the cental region to the outer layer of the SN ejecta is very efficient, accelerating the outer envelope of the SN ejecta to relativistic speeds. The radial density profile is characterized by a power-law distribution with a shallow slope, $-d\ln\rho/d\ln r=$ 5-6. This flat density profile likely makes the SN ejecta a bright radio source through the interaction with the ambient medium (Suzuki&Maeda 2018). In fact, for some radio-bright SNe, like SN 2009bb and 2012ap, radial density profiles similar to what we found in this study have been suggested.

Also, the radial density structure is of fundamental importance in spectral formation. For a shallow radial density profile, a specific range of density corresponds to wider radius and velocity ranges than for a steep radial density profile, making absorption troughs broad. Therefore, SN ejecta with the hot bubble breakout may show broad absorption feature, which is in line with broad-line Ic SNe and some SLSNe-I.