Non-spherical core-collapse supernovae: the first three months revisited

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We study the hydrodynamic evolution of a non-spherical core-collapse supernova in multidimensions. We begin our study from the moment of shock revival -- taking into account neutrino heating and cooling, nucleosynthesis, convection, and SASI type instabilities of the supernova shock -- and continue for the first 3 months after the explosion when the expanding flow becomes homologous and the ejecta enter the early supernova remnant phase. We observe the growth and interaction of fluid flow instabilities resulting in an extensive mixing of the heavy elements throughout the ejecta.

We demonstrate that even in two spatial dimensions numerical convergence is difficult to achieve, due to the strongly non-linear nature of the problem. Furthermore, we show that the amount of mixing and the kinematic properties of radioactive species (i.e. ^{56}Ni) are extremely anisotropic. In particular, we find that our models display a strong tendency to expand laterally away from the equatorial plane and toward the poles. Although this tendency is usually attributed to numerical artifacts characteristic of computations assuming axisymmetry (axis-effect), this behavior can be largely explained by the structure of the neutrino-driven explosion model that originated from a low-mode, standing accretion shock instability (SASI).

The simulations demonstrate that significant lateral motions in the post-shock region, produced by the SASI and early convective overturn, act as triggers of later clump formation, and increase the anisotropy of the ejecta. Systematic future studies are needed to establish to what degree supernova remnants preserve memory about the explosion phase, especially in situations when the SASI is at work within the first second after core bounce. Preferably, such simulations should be performed with high resolution in three spatial dimensions using singularity-free grids that cover the entire sphere. Given the results of our 2D resolution study, present three-dimensional simulations must be regarded as underresolved.

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