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The r-process nucleosynthesis in core-collapse supernovae with the magneto-rotational instability

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We investigate the r-process nucleosynthesis in the ejecta of core-collapse supernovae driven by rotation and magnetic fields. We adopt an explosion model based on axi-symmetric magneto-hydrodynamical simulation with the effects of magneto-rotational instability, which has been mostly ignored in previous studies. The hydrodynamics simulation also employs a very simplified treatment of neutrino transport on explosion dynamics, which includes the increase of explosion energy due to neutrino heating. We found that very neutron-rich matter in the jet-like explosion, producing heavy r-process nuclei, is ejected along the rotational axis driven by strong magnetic pressure. On the other hand, moderate neutron-rich matter is also ejected in the direction of the equatorial plane due to neutrino-heating associated with the magneto-rotational instability. This ejecta produces lighter and intermediate r-process nuclei rather than heavy isotopes $A > 130$. We compare these results with observed r-process abundances pattern.

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1. Cosmic origin of r-process elements

Astronomical origin of the r-process nuclei in nature, which has response for a half amount of heavy elements beyond iron, is still undetermined despite a lot of efforts by physicists and astronomers (for a review, [1]). For the successful progress of r-process producing heavy nuclei, which is a sequence of "r"apid neutron capture with β-decay, very neutron-rich conditions are required in explosive astronomical phenomena. Although recent studies have shown that the merger of binary neutron stars is the most promising astronomical source [2, 3, 4] rather than proto-neutron star (PNS) winds of CC-SNe [5], there are still serval problems to be solved, i.e, the severe under-production of lighter r-process nuclei ($A < 130$) and the difficulty of explaining the existence of r-process elements in metal-poor stars at the very early galaxy [6].

The explosion mechanism of core-collapse supernovae (CC-SNe) driven by rotation and magnetic fields has been investigated as an alternative source of r-process elements, because suitable neutron-rich ejecta is expected in energetic jet-like explosions [7, 8]. Although there are several studies on magneto-rotational driven supernovae (MHD-SNe), most studies have ignored the effect of the magneto-rotational instability (MRI), which is significant as an enhancement process of magnetic fields. On the other hand, recent studies by Sawai el al. [9, 10] included the effect of the MRI on global hydrodynamical evolution. They showed the MRI enhance the explosion energy even for moderate initial magnetic fields of pre-collapse core and can drastically change the composition (neutron-richness) of ejecta, which are different from canonical neutrino-heating driven CC-SNe.

In the present study, we focus on the effects of the MRI in MHD-SNe on the r-process nucleosynthesis. The explosion model of MHD-SNe in the axi-symmetric magneto-hydrodynamics simulations is described in Section 2. Properties of neutron-rich ejecta and produced r-process nuclei are discussed in Section 3.

2. MHD-SN explosion model

For the purpose of following r-process nucleosynthesis calculations, we adopt hydrodynamical evolution of an explosion model of MHD-SNe based on magneto-hydrodynamical simulations by the *YAMAZAKURA* code [11]. This MHD code resolves the growth of magnetic fields due to the MRI during core-collapse, which is based on high resolution numerical mesh in the two-dimensional spacial computational domain under the axisymmetry (for details including numerical tests, see, refs. by Sawai el al. [9, 10]).

The explosion model is based on a progenitor of $15M_{\odot}$ by S. E. Woosley (1995, private communication) with initial rotation and magnetic fields given by analytic formulae (described in Section 2 of ref. [10]). In the present study, we adopt the initial rotation strength with $T/|W| = 2.5\times10^{-4}$ (the ratio of the rotation energy (T) to the absolute value of total gravitational potential (|W|), of which maximum angular velocity is 2.7 rad s^{-1}. Additionally, the strength of poloidal dominant magnetic fields in the iron core is 2×10^{11} G.

In order to resolve the MRI inside the proto-neutron star (PNS), we choose numerical mesh with high resolution outside the surface of the PNS, where the grid interval is 0.1 km at 50 km distant from the center. Beside the effects of magnetic fields on explosion dynamics, we include neu-

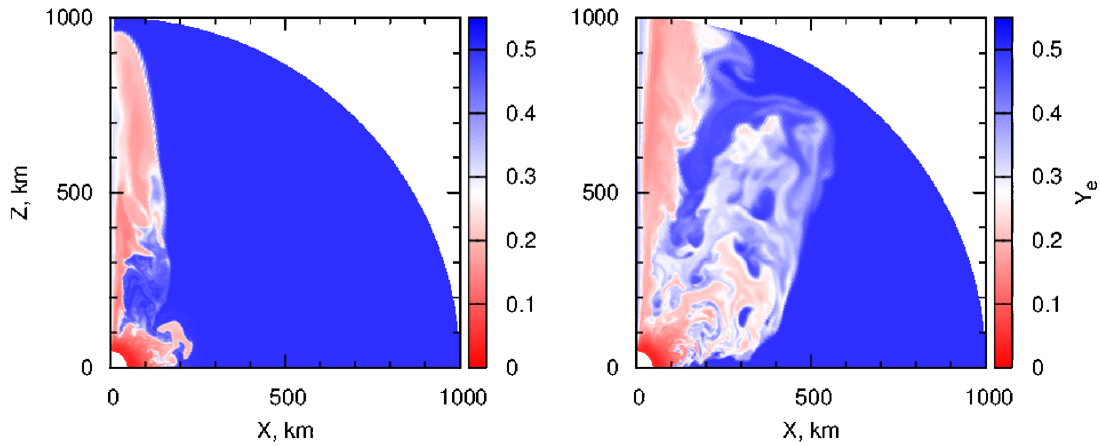

Figure 1: Evolution of Y_e of the explosion model. The jet-like explosion along the Z–axis (left) and outflow in the direction (right), which are 185 and 285 ms after the bounce, respectively.

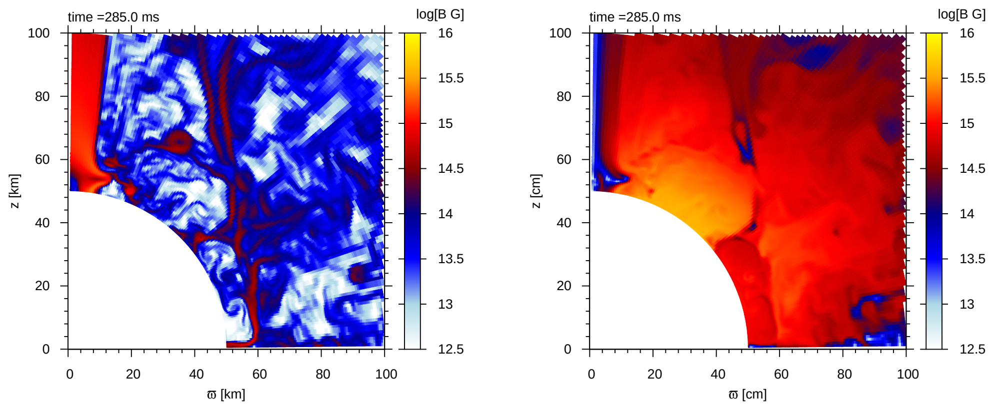

Figure 2: Magnetic fields of the explosion model 285 ms after the core-bounce. The strength of magnetic fields in G for the poloidal (left) and toroidal (right) components are shown, respectively.

trino heating employing the light-bulb scheme with a constant neutrino luminosity 1×10^{52} erg s^{-1} as a “point source”.

The dynamics of the explosion model is shown in Fig. 1, which is the distribution of the electron fraction (Y_e) in different times (185 and 285 ms after the core-bounce). After the core bounce the jet-like explosion launches around the PNS surface 135 ms after the bounce and reaches ~ 1000 km at 185 ms. Beside jet-like ejecta along the rotation-axis, strong convection occurs driven by the MRI taking place in the inner core region (< 500 km), which finally ejected in the direction between the axis and the equatorial plane (mentioned as the “no-jet” component, hereafter). This means that matter in this component is ejected by the effect of enhancement process by the MRI.

Fig. 2 shows the strength of magnetic fields in the explosion model for the poloidal and toroidal component at 285 ms after the bounce, respectively. The value of magnetic fields can exceed 10^{15} G

PoS(NIC XIII)128

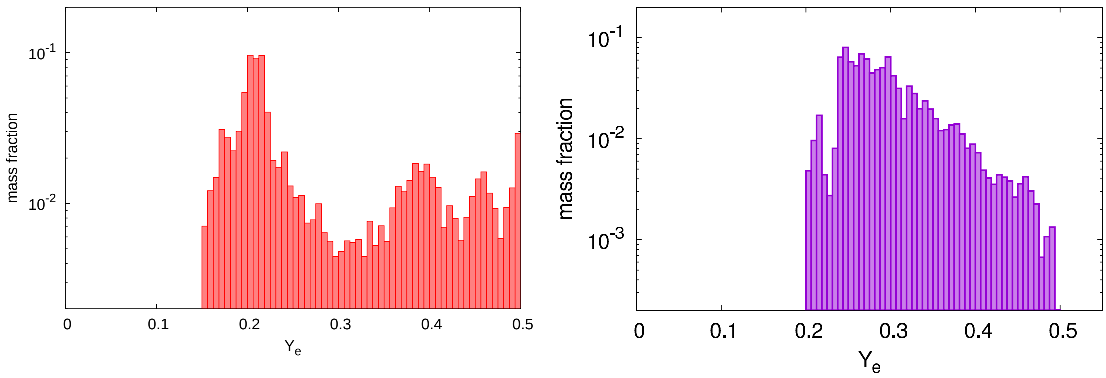

Figure 3: The histogram of Y_e for ejected matter. The mass fraction of each Y_e-bin is shown for ejecta in jet (left) and for non-jet component (right), respectively.

by wrapping due to rotation and the MRI. Due to activity of momentum transport, the radius of gain radius (affected by neutrino heating) expands, which causes higher bulk heating efficiency leading larger explosion energy.

The Y_e of ejecta is shown in Fig. 3 as the histogram of the mass fraction as a function of Y_e at the end of the nuclear statistical equilibrium (NSE), where 9 GK is adopted for the lower bound of validity. The ejecta in the jet-like explosion consists of very neutron-rich matter, of which $Y_e = 0.1$ – 0.2, due to the strong influence of electron capture at high densities as shown in the previous study [8]. The moderate neutron-rich matter, which exceeds $Y_e = 0.4$, in jet-component is mostly ejected from outer region of core swept by the jet-like explosion. On the other hand, the Y_e of ejecta in the no-jet component is larger, of which the peak of $Y_e = 0.3$. This no-jet component is ejected driven by neutrino-heating with MRI, whose Y_e increases due to neutrino-absorption and can exceeds 0.4.

We should note that we terminated the hydrodynamical simulation at 285 ms, so that we ignored matter that potentially ejected in the later phase. Thus, the explosion model seems to underestimate ejecta for less neutron-rich matter, $Y_e > 0.3$. To determine more comprehensive property of explosion models, distribution of Y_e for ejecta, further long-term simulations are necessary.

3. The r-process nucleosynthesis

We calculate r-process nucleosynthesis for the ejecta described in the previous section, using a nuclear reaction network code [7, 13, 14]. Results are shown in Fig. 4, which abundance patterns are separately plotted for the jet component and no-jet component, corresponding to Fig.3. As we expected the value of Y_e, nucleosynthetic yields in the jet shows the significant progress of the r-process, producing up to $A \sim 200$, with good agreement with the solar abundances. While, the no-jet component mostly produces nuclei up to the r-process second peak ($A \sim 130$) and heavier nuclei are under-abundant for reproducing the solar pattern.

The result of nucleosynthesis for each component reflects the value of Y_e, which final abundances are mostly determined by neutron-richness under the low entropy environment of such as supernova dynamical-ejecta. The final abundances of ejected from our explosion model will be

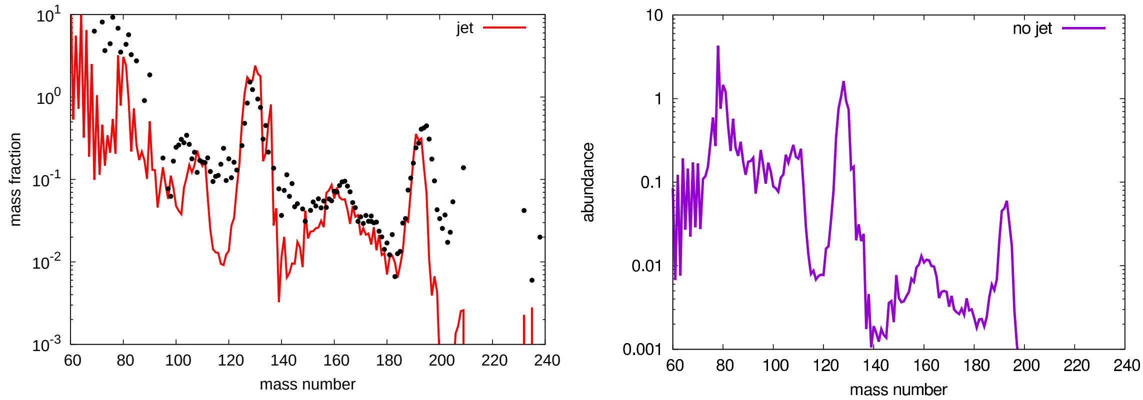

Figure 4: The final abundance distribution of nucleosynthesis calculations. Abundances of ejecta in the jet-outflow with the solar r-process abundances shown by dots [12] (left) and abundances in tiger component (right) are plotted, respectively.

the sum of both components. Although more long-term simulations are required to estimate all of ejecta from our explosion model, the no-jet component has a significant amount of ejecta compared with the jet component.

The previous studies of r-process nucleosynthesis in MHD-SNe have mostly focused on cases of strong jet-like explosion, which can eject very neutron-rich matter, as the source of r-process with the solar abundance pattern. However, the present results suggest another observational interpretation of MHD-SNe, which has "weak" r-process pattern appeared to metal poor stars [15]. Additionally, intermediate abundance patterns are expected in different parameters of initial rotation and magnetic fields. As shown in the previous section, the effect of the MRI is important to determine the composition of moderate Y_e ejecta especially for moderate steallar magnetic fields at the pre-collapse stage. Further comprehensive investigation is desirable in order to clarify the quantitative relation between MHD-SN explosions and their ejecta with r-process abundances.

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References

[1] M. Arnould, S. Goriely, and K. Takahashi, Phys. Rep. 450 (2007) 97.

[2] S. Goriely, A. Bauswein, and H.-T. Janka, ApJL 738 (2011) L32.

[3] O. Korobkin, S. Rosswog, A. Arcones, and C. Winteler, MNRAS 426 (2012) 1940.

[4] S. Wanajo, Y. Sekiguchi, N. Nishimura, K. Kiuchi, K. Kyutoku, and M. Shibata, ApJL 789 (2014) L39.

[5] S. Wanajo, ApJL 770 (2013) L22.

[6] C. Sneden, A. McWilliam, G. W. Preston, J. J. Cowan, D. L. Burris, and B. J. Armosky, ApJ 467 (1996) 819.

[7] N. Nishimura, T. Takiwaki, and F.-K. Thielemann, ArXiv e-prints astro-ph.SR 1501.06567.

[8] C. Winteler, R. Käppeli, A. Perego, A. Arcones, N. Vasset, N. Nishimura, M. Liebendörfer, and F.-K. Thielemann, ApJL 750 (2012) L22.

[9] H. Sawai, S. Yamada, and H. Suzuki, ApJL 770 (2013) L19.

[10] H. Sawai and S. Yamada, ApJL 784 (2014) L10.

[11] H. Sawai, S. Yamada, K. Kotake, and H. Suzuki, ApJ 764 (2013) 10.

[12] C. Arlandini, F. Käppeler, K. Wisshak, R. Gallino, M. Lugaro, M. Busso, and O. Straniero, ApJ 525 (1999) 886.

[13] N. Nishimura, T. Kajino, G. J. Mathews, S. Nishimura, and T. Suzuki, Phys. Rev. C 85 (2012) 048801.

[14] N. Nishimura, T. Fischer, F.-K. Thielemann, C. Fröhlich, M. Hempel, R. Käppeli, G. Martínez-Pinedo, T. Rauscher, I. Sagert, and C. Winteler, ApJ 758 (2012) 9.

[15] S. Honda, W. Aoki, T. Kajino, H. Ando, T. C. Beers, H. Izumiura, K. Sadakane, and M. Takada-Hidai, ApJ 607 (2004) 474.