R-process Nucleosynthesis in the Central Engine of Gamma-Ray Bursts, i.e. Neutrino-Heated Collapsar Jets

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Rapid neutron-capture (r-process) nucleosynthesis is responsible for about a half of the abundance of nuclei heavier than iron. Even after many years of study, the neutron-rich and probably high-entropy astrophysical site for the r-process nucleosynthesis has not yet been definitively identified. The collapsar model for long-duration gamma ray bursts (GRBs) has been proposed as a possible astrophysical site for the r-process nucleosynthesis. In this model, the central core of a rotating massive star collapses to a black hole. Angular momentum in the progenitor star leads to the formation of an accretion desk around the central black hole. Magnetic field amplification and/or heating from the pair annihilation of thermally generated neutrinos emanating from the accretion disk can heat material in a polar funnel region. This leads to a relativistic outflow of matter along the polar axis.

In this study [1], we follow the hydrodynamic evolution of material in the heated jet and the associated nucleosynthesis for a long duration time. For this purpose, our hydrodynamic study involves several steps: (1) Fist, there is the initial collapse of the progenitor massive star leading to the formation of the accretion disk and black hole; (2) As the accretion disk heats up and the magnetic fields are amplified, a funnel region above the pole of the black hole is heated by neutrinos and magnetic fields, and this heating leads to the launch of a relativistic jet which is eventually dominated by the propagation of a hydrodynamic shock through the outer layers of the progenitor; (3) The jet expands far enough from the accretion disk to no longer be affected significantly by neutrino heating, then the ejected material is cooled into the r-process temperature range $5 > T_9 > 0.3$. Here T_9 is the temperature in unit of 10^9 K.

We employ an initial progenitor model from the 35OC model of [2]. The step 1 is simulated based upon a relativistic axisymmetric magneto-hydrodynamic code [3], to describe the collapse of rotating magnetic massive star. After the stable accretion disk surrounding a central black hole develops, MHD driven outflow and neutrino-driven jet can launch from the funnel region above the pole of the black hole (step2; [4]). The late-time evolution of the associated jet (step 3) is then followed using axisymmetric special relativistic hydrodynamics. We utilized representative test particles to follow the temperature, entropy, electron fraction and density for material flowing within the jet from ejection from the accretion disk until several thousand kilometer above the black hole. The evolution of nuclear abundances from nucleons to heavy nuclei for ejected test particle trajectories is solved in a large nuclear reaction network. Finally we find that an r-process-like abundance distribution forms in material ejected in the collapsar jet. In our model the ejected mass of r-process material is high ($\sim 0.1\ M_\odot$). Nevertheless, this is a rare event compared to, for example, normal supernovae and the possible influence of such events on the abundance distribution in metal-poor halo stars needs to be explored.

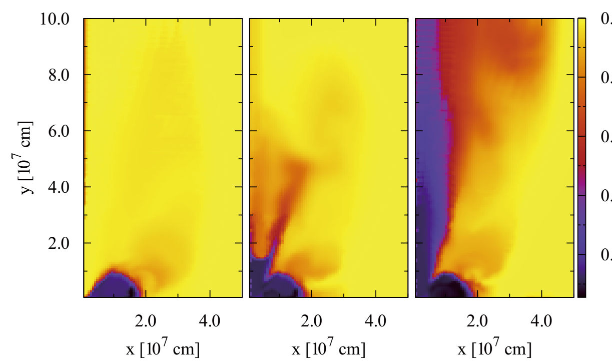

Figure 1: Profile of electron fraction Y_e for the jet at various stages up to the end of the MHD + neutrino-heating simulation. The low Y_e material in the torus and the developing central jet is clearly seen.

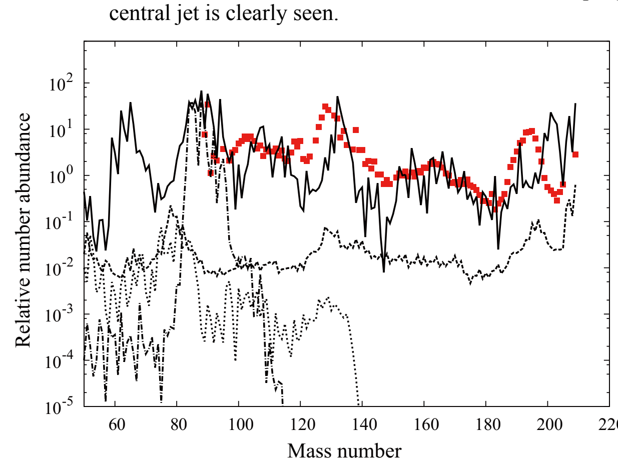

Figure 2: Final abundance pattern of the r-process compared with s.s. abundances (red dots). Solid, long-dashed, dotted and dot-dashed curves are the calculated abundances for high-to-low entropy flows in the neutrino-heated collapsar jets.

References

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