Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Origin of Ultra-High Energy Cosmic Rays: Nuclear Composition of Gamma-Ray Burst Jets

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Abstract. Ultra-high energy cosmic rays (UHECRs) are the most energetic particles flying from space and their source is not clarified yet. Recently, the Pierre Auger Observatory (PAO) suggests that UHECRs involve heavy nuclei. The PAO results require that a considerable fraction of metal nuclei must exist in the accelerating site, which can be realized only in the stellar interior. This puts strong constraints on the origin of UHECRs. In order to definitize the constraints from PAO results, we investigate the fraction of metal nuclei in a relativistic jet in gamma-ray burst associated with core-collapse supernova. If the jet is initially dominated by radiation field, quasi-statistical equilibrium (QSE) is established and heavy nuclei are dissociated to light particles such as ^{4}He during the acceleration and expansion. On the other hand, if the jet is mainly accelerated by magnetic field heavy or intermediate mass nuclei can survive. The criterion to contain the metal nuclei is that the temperature at the launch site is below 4.5×10^9 K. Therefore, if the composition of UHECRs is dominated by metal nuclei, a GRB with the magnetized jet is the most plausible candidate of the accelerating site.

Keywords. gamma rays: bursts, nuclear reactions, nucleosynthesis, abundances, MHD,

1. Introduction

The most energetic cosmic rays with $E \geqslant 10^{18}$ eV are called ultra-high energy cosmic rays (UHECRs). Their accelerating site is not clarified yet, although a few astronomical objects have been proposed as the candidate of the accelerating source.

Recent experiments clarify nuclear composition of UHECRs by measuring depth of air shower maximum. In particular, results of the Pierre Auger Observatory indicate that UHECRs are dominated by heavy nuclei at high energy (Abraham *et al.* 2010). This indicate the metallicity at the accelerating site is extremely high.

Therefore, we focus on gamma-ray bursts (GRB) as the candidate of the accelerating site, since GRB is associated with a death of massive star and there are alot of metals in the stellar interior. We investigate whether the jets can possess metal nuclei with high metallicities.

2. Method & Model

We treat a GRB jet as a steady, spherically symmetric, magnetized outflow with efficient magnetic dissipation. We assume that magnetic fields in the outflow are dominated by a toroidal component and that the field efficiently dissipates via magnetic reconnection as the outflow expands. Such efficient dissipation of magnetic fields creates strong magnetic pressure gradient that makes possible a direct conversion of magnetic field energy

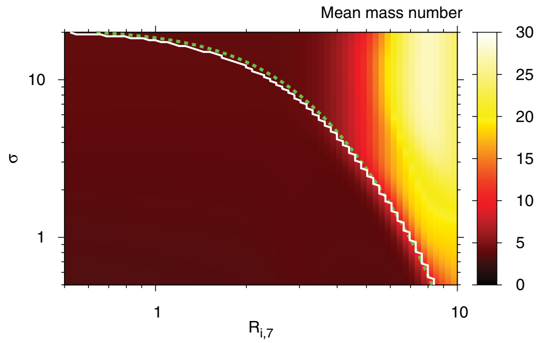

Figure 1. Mean mass number of final composition of the jet.

into kinetic energy (Drenkhahn 2002). Solving the equations for such outflow numerically, time evolution of density and temperature are obtained and then nuclear reactions in the outflow are calculated as a postprocessing. The nuclear reaction network includes 281 isotopes up to ^{79}Br.

We parameterize the GRB outflow with six parameters: isotropic energy deposition rate L_j^{iso}, initial radius of the outflow R_i, initial Lorentz factor Γ_i, maximum Lorentz factor Γ_{max}, angular frequency of central object (including dimensionless factor) $\epsilon\Omega$, and initial magnetization parameter σ_i defined by $\sigma_i \equiv b_i^2/w_i$, where b_i and w_i is the initial magnetic four-vector and the initial enthalpy, respectively.

The initial composion of the outflow is set to be an integration of accreted matter which is obtained by a calculation of relativistic jet-induced explosions of C+O stars with the use of a two-dimensional relativistic Eulerian hydrodynamic code with the Newtonian self-gravity (Tominaga 2009).

3. Results & Conclusion

Figure 1 shows mean mass number of final nuclear composition as functions of R_i and σ_i for the models with $L_j^{iso} = 4 \times 10^{52}$ ergs^{-1}, $\Gamma_i = 1.22$, $\Gamma_{max} = 100$, and $\epsilon\Omega = 10^3$ s^{-1}. The white solid line represents the criterion for establishment of quasi statistical equilibrium (QSE; e.g., Woosley *et al.* 1973). This criterion is well fitted by a contour of initial temperature $T_{i,9} = T_i/10^9$K $= 4.5$ (a dotted line in Figure 1). In the models with lower σ_i and smaller R_i than the white solid line, the composition is described by QSE and the metal nuclei are almost destroyed due to the high entropy. On the other hand, the condition for QSE is avoidable in the models with appropriate R_i and σ_i which realize $T_{i,9} < 4.5$.

Therefore, we conclude that the metal nuclei-dominated UHECRs can be originated by GRBs if the relativistic GRB jets are accelerated by the magnetic field and initial temperatures of the jets are smaller than 4.5×10^9 K.

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