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r-process nucleosynthesis in the neutrino-heated relativistic collapsar jet model for gamma-ray bursts

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We have investigated r-process nucleosynthesis within the collapsar jet model for long-duration gamma ray bursts. We simulated the core collapse of a rotating 35 solar mass progenitor star and followed the magnetohydrodynamic evolution to form a stable black-hole accretion disk. The transport of neutrinos emitted from the accretion disk was then evolved using a ray-tracing method to estimate the heating via neutrino pair annihilation in the polar region above the black hole leading to the production of a relativistic jet. We then distributed test particles in the outflow and followed the time evolution of the temperature, entropy, electron fraction, and density along each trajectory. Nuclear species were evolved for these trajectories with a large nuclear reaction network including more than 5,000 nuclei. We found that an r-process-like abundance distribution forms in material ejected in the collapsar jet.

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1. Introduction

About a half of the abundance of nuclei heavier than iron is produced by the rapid neutron-capture nucleosynthesis process (*r*-process). Even after studies for many years, however, no one has succeeded in identifying the astrophysical site responsible for *r*-process nucleosynthesis. A number of astrophysical candidate sites have been proposed which may satisfy the physical requirements for the *r*-process. Among these, the most popular models at present are: neutrino driven winds from core-collapse supernovae [1]; binary neutron star mergers [2]; and magnetohydrodynamic jets from supernovae [3].

None of these possible sites, however, is without problems. For example, the neutrino driven wind model needs high entropy ($s > 300k_{\rm B}$/baryon) to reproduce the observed *r*-process abundance distribution up to the 3rd ($A \sim 195$) *r*-process peak. Such high entropy, however, has been difficult to achieve in recent core-collapse simulations. Moreover, recent state-of-the-art numerical supernova simulations including neutrino transport have shown that the weak interaction between neutrinos and nuclei may result in a higher electron fraction, Y_e, than previously thought. The electron fraction is a critical factor for the *r*-process and heavy element production via the *r*-process is nearly impossible in flows with $Y_e > 0.5$, even with a high entropy condition. Also, in the neutron star merger model, it is not clear whether the mergers can occur early enough to account for the observed early enrichment of *r*-process material in the Galaxy.

On the other hand, there has been recent interest in the possibility that the *r*-process could occur in the relativistic jets associated with the collapsar model for gamma-ray bursts (GRBs). This model is currently a favored candidate for the production of long-duration GRBs. In the collapsar model the central iron core of a massive star collapses to a black hole. Angular momentum in the progenitor star leads to the formation of a heated accretion disk around the nascent black hole. Magnetic field amplification and the pair annihilation of thermally generated neutrinos emanating from this accretion disk can then heat material in a polar funnel region. This leads to a relativistic outflow of matter along the rotational polar axis.

In this article we report on *r*-process nucleosynthesis calculations for extremely high-entropy flows emanating from a numerical magnetohydrodynamic (MHD) simulation of a GRB collapsar jet powered by neutrino-annihilation heating. This 3D MHD plus neutrino heating GRB simulation is limited by the high computational expense. Only the first ~ 200 ms after a stable accretion disk has developed could be simulated. This timescale is long enough to form the jet but too short for a study of *r*-process nucleosynthesis in the jet. Hence, we perform follow-up studies of the hydrodynamics of material in the heated jet and the associated nucleosynthesis out to the much later times and lower temperatures associated with the *r*-process. We present numerical results of *r*-process nucleosynthesis within this heated jet outflow and show that this environment indeed produces a an *r*-process-like abundance distribution.

2. Numerical simulations of a GRB jet

We take a 35 solar mass model [4] as a progenitor of the collapsar. The collapse of the rotating massive star was evolved for at least ~ 10 seconds using a relativistic axisymmetric MHD code. The collapse calculation did not include heating by neutrino pair annihilation, but included thermal

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neutrino production and cooling in the accretion disk. After about 9 seconds a stable accretion disk was formed and the total neutrino luminosity exceeded 10^{52} erg s^{-1}.

As the stable accretion disk develops, the heating time scale, $\tau_{\rm heat}$, by neutrino pair annihilation becomes shorter than the dynamical timescale, $\tau_{\rm dyn}$, for material to be ejected in the funnel region [5]. Material for which $\tau_{\rm dyn}/\tau_{\rm heat} > 1$ can gain enough thermal energy to drive the jet to highly relativistic escape velocities from the gravitational field. After about 9.1 seconds this condition was satisfied. Therefore, in the calculation reported here, the jet evolution calculation was restarted at this phase to compute the neutrino-induced heating in the funnel region above the nascent black hole [6].

We assume a Fermi-Dirac neutrino distribution and take account of radiation emanating from the neutrino sphere of the accretion disk. We then follow the jet production and the propagation for an additional ~ 200 ms. Figure 1 shows the density and velocity structures of the jet from the present calculation based upon the MHD+neutrino-heating simulation. One can see that by the end of this phase of the simulation the outflowing material is in a narrowly focused jet that has reached relativistic velocity with a Lorentz factor of a few. This jet is expected to become an ultra-relativistic outflow in the outer low-density envelope. Ultimately, it would be observed as a long-duration GRB.

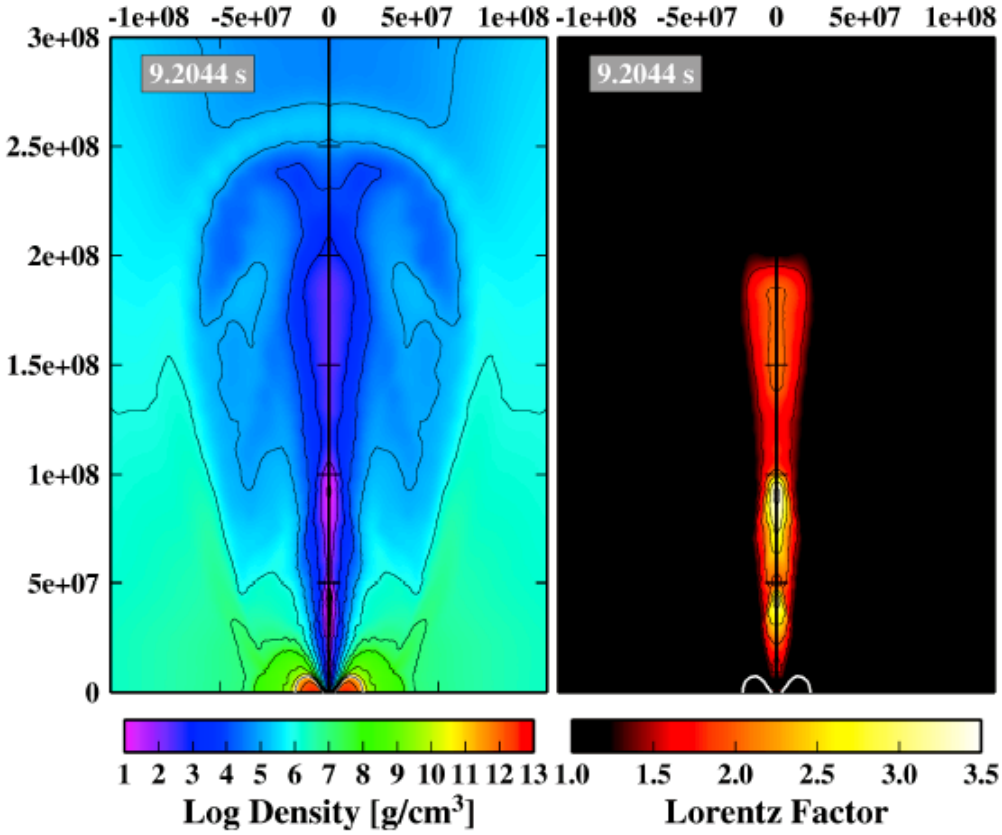

Figure 1: Profiles of density and Lorentz factor for the GRB jet at the end of the MHD+neutrino-heating simulation.

The temperature of material, T, at the outer edge of the grid at the end of the the MHD+neutrino-heating simulation is $T \sim 9 \times 10^9$ K. At this temperature all nuclei are photodissociated into free nucleons and alpha particles. A continuation of the outflow and cooling in the outer region of the jet is necessary to follow the cooling into the *r*-process temperature range $5 \times 10^9\,\mathrm{K} > T > 3 \times 10^8\,\mathrm{K}$. By the end of the MHD+neutrino-heating simulation, the heated material in the jet is far enough from the accretion disk to no longer be affected significantly by neutrino scattering or the magnetic field. In the present work, therefore, we supplement the model of MHD+neutrino heating with a relativistic axisymmetric hydrodynamic simulation to follow the jet as it propagates through the outer layers of the progenitor star. Within that flow we evolve the nucleosynthesis of 1289 ejected tracer particles, chosen from $20,000$ test particles, participating in the MHD+neutrino heated jet and finally being ejected. The final abundance distribution could then be obtained from a mass-weighted sum of those outflowing trajectories.

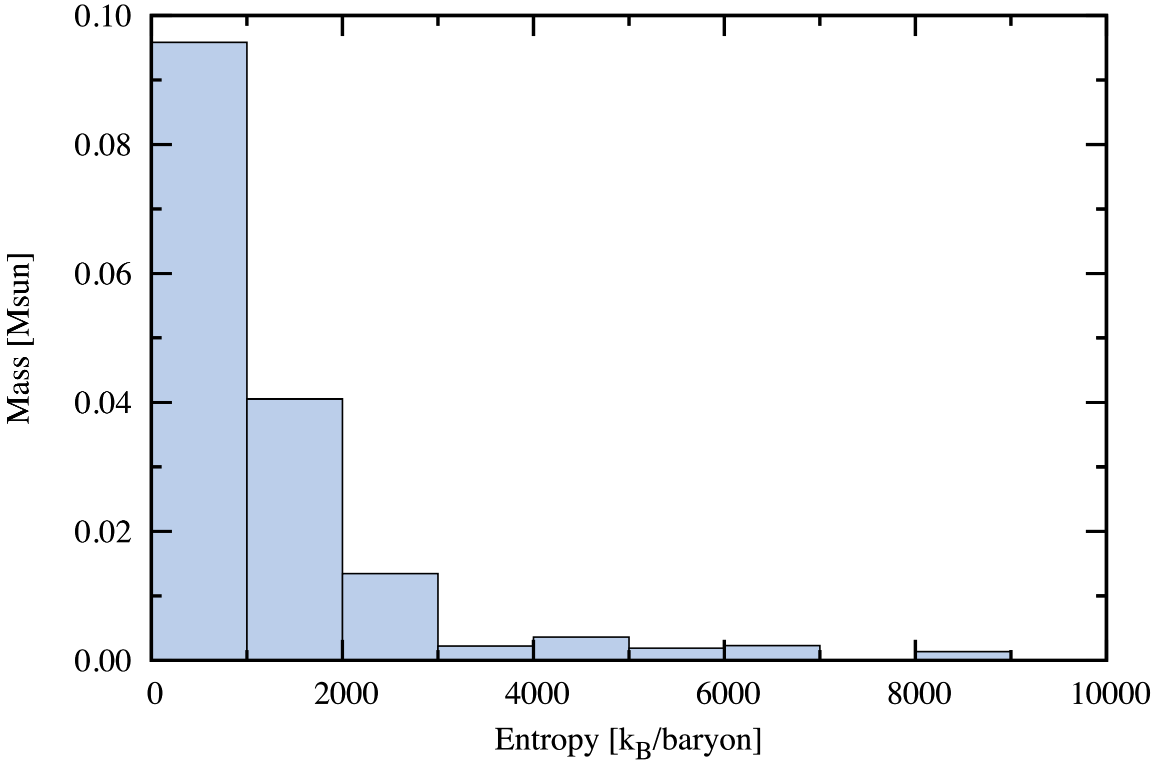

Figure 2: Mass distribution as a function of initial entropy per baryon for the 1289 ejected test particles.

3. Nucleosynthesis results and discussion

Figure 2 shows the ejected mass as a function entropy per baryon for the 1289 ejected trajectories. We found that trajectories emitted close to the polar axis have relatively high entropy ($s > 1000k_{\mathrm{B}}$/baryon) and can produce heavy elements up to and beyond the 3rd *r*-process abundance peak. On the other hand, a significant fraction of the ejected mass involves trajectories emitted at angles away from the polar axis with relatively lower entropy per baryon ($100k_{\mathrm{B}}$/baryon $< s < 1000k_{\mathrm{B}}$/baryon). These trajectories only produce light elements up to the 2nd *r*-process peak.

The final weighted abundance distribution for all 1289 trajectories is shown in Figure 3. This is compared with solar-system *r*-process abundances. Here, we can see that this collapsar model produces elements up to the 3rd *r*-process peak and that the $A \sim 160$ abundance distribution in the universality region ($140 < A < 180$) is approximately reproduced. If we compare our result with the abundance pattern of the solar system in detail, however, there are some differences. One is that isotopes with $A \sim 120$ are significantly underproduced. Another is that the 2nd ($A \sim 130$) and the 3rd ($A \sim 195$) peaks are slightly shifted to higher mass numbers ($A \sim 132$ and $A \sim 200$). There is also a larger odd-even effect exhibited in the model calculations than in the solar-system abundances. The underproduction near $A = 120$ is a common feature in dynamic *r*-process calculations. This feature could be an artifact of an overestimated strength of the shell closure at $N = 82$, effects of beta-delayed neutron emission, or underestimated β-decay rates.

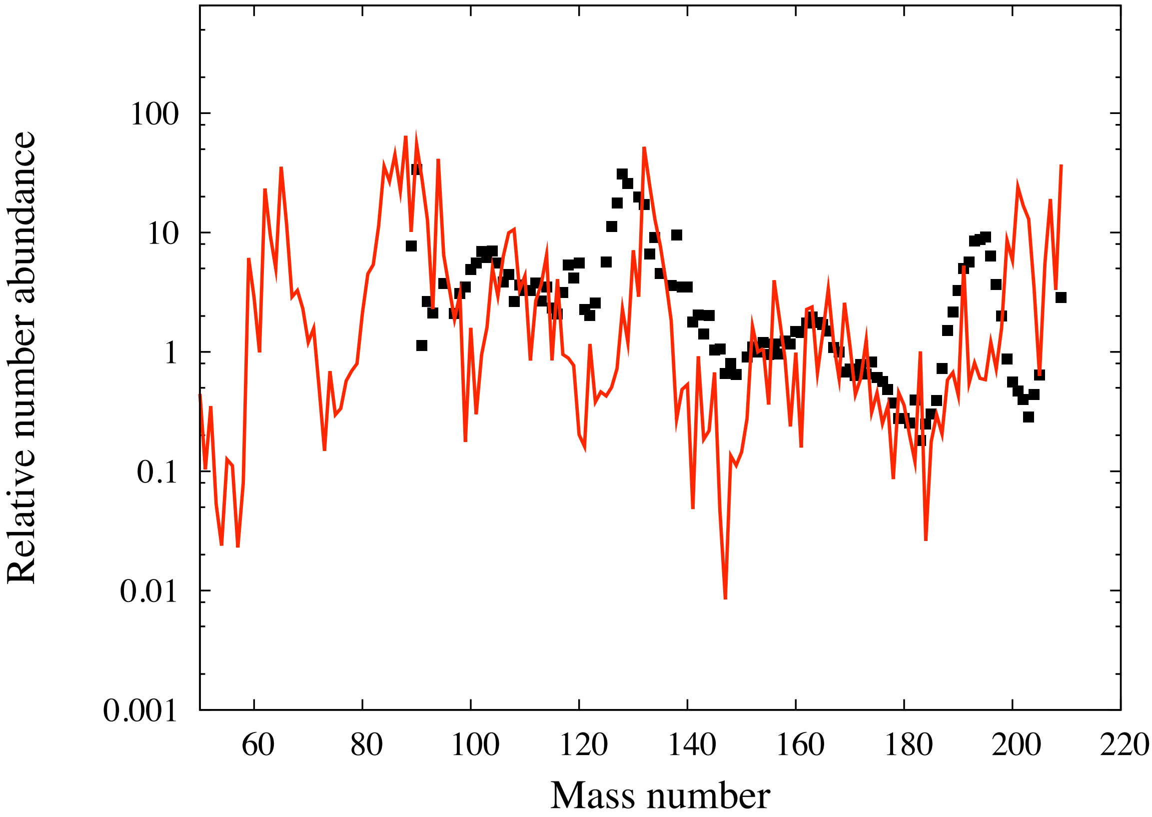

Figure 3: Summed mass-weighted abundance (solid line) for the 1289 ejected tracer particles. These are compared with the solar system *r*-process abundance (points) and normalized at ^{164}Er.

The shift of the peaks to higher mass number in the calculation can result if the neutron density at freezeout is too low or the temperature is too high. This causes the *r*-process path to run closer to stability thereby shifting the mass number at which the *r*-process path reaches the $N = 82$ and 126 neutron closed shells to higher mass numbers. This is also consistent with the large odd-even effect that can be smoothed if there are residual neutron captures after freezeout, but remains large if the neutron abundance diminishes too rapidly.

The shift of the *r*-process peaks may suggest that the jet does not cool fast enough in our model, or that the neutron density in the jet diminishes too rapidly. We note that if this shift is a general characteristic of the collapsar jet model, then one might hope to find such a unique abundance distribution in a small fraction of low metallicity halo stars whose abundance could reflect the yields of a single collapsar event.

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