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Nucleosynthesis from neutrino-dominated accretion disks in gamma-ray bursts and its application

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Abstract. We investigate the element distribution in neutrino-dominated accretion flows around black holes with the proton-rich nuclear statistical equilibrium. According to our calculations, the radial nuclei distribution (around equatorial plane) is dominated by free nucleons, ^{4}He, and ^{56}Fe in the inner, middle, and outer region, respectively. For the vertical distribution, the heavy nuclei tend to be produced in a thin region near the disk surface, in which we find that ^{56}Ni is dominant for the flow with low accretion rate but it would switch to ^{56}Fe for high accretion rate. Our results imply that ^{56}Ni produced by central engine would tend to outflow and subsequently decay to drive the bumps observed in the light curves of the core collapse supernovae.

1 Introduction

A popular model for the central engine in gamma-ray bursts (GRBs) is based on the so-called neutrino-dominated accretion flow (NDAFs, see, e.g., [1–12]). NDAF involves a hyperaccreting stellar black hole with mass accretion rates in the range of $\dot{m} = 0.01 \sim 10$ ($\dot{m} = \dot{M}/M_{\odot}$ s^{-1}). The extreme state is a hotbed to produce heavy nuclei and the central region of GRBs, actually, is an ideal location to supply an extremely hot and dense state for nucleosynthesis, which should also be involved in NDAF model. The purpose of this paper is to investigate the nuclei distribution in the radial and vertical directions of NDAFs with detailed neutrino physics and precise nuclear statistical equilibrium (NSE) [13]. The detailed equations already have been presented in [9] and [12].

2 Structure

2.1 Radial structure

We investigate one-dimensional global solutions of NDAFs [12], taking account of general relativity in Kerr metric, neutrino physics and nucleosynthesis [13] more reasonable than previous works [2].

Since the detailed nucleosynthesis is considered in our model, we can obtain and trace the radial variations for more than 40 nucleons in our calculations. Figure 1 shows the radial distributions of the

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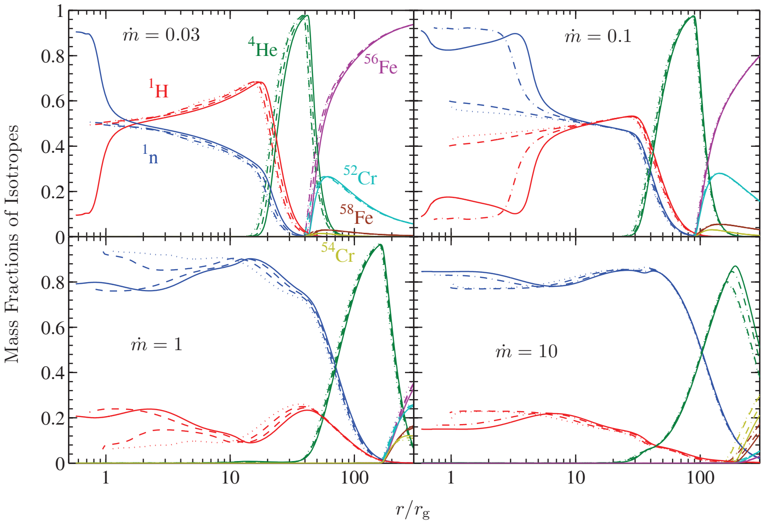

Figure 1. The radial distributions of the mass fraction for seven major nucleons ^{1}n, ^{1}H, ^{4}He, ^{52}Cr, ^{54}Cr, ^{56}Fe. The line styles, dotted, dashed, dot-dashed, and solid denote the different black hole spin $a_* = 0$, 0.5, 0.9, and 0.99, respectively.

mass fractions of seven major nucleons ^{1}n, ^{1}H, ^{4}He, ^{52}Cr, ^{54}Cr, ^{56}Fe and ^{58}Fe, which cover almost 99% mass in the flow. The mass fraction of ^{56}Fe always dominates in the outer region. In the middle region, ^{4}He becomes dominant. Free neutrons and protons are dominant via photodisintegration in the inner hot and dense region. The size of the region dominated by free nucleons positively depends on the accretion rate $\dot{m}$. The spin of black hole is also a factor affecting the ratio of numbers of free protons and neutrons in the inner region. Most of the free protons turn into the free neutrons due to the Urca process [2], which causes the dominance of free neutrons and the decrease of electron fraction.

2.2 Vertical structure

We also investigate the vertical structure and nuclei distribution of NDAFs around black holes in spherical coordinates (r, θ, ϕ) [9]. Figure 2 shows the variations of the mass fraction (also approximately equal to the number density) of the free neutron and proton, and the major nuclei (include ^{4}He, ^{52}Cr, ^{54}Cr, ^{54}Fe, ^{56}Fe, ^{56}Ni, and ^{58}Ni, corresponding to the lines with different colors) with θ at $r = 10r_g$ and $100r_g$ for $\dot{m} = 0.05$ and 1. ^{56}Ni dominates at the disk surface for $\dot{m} = 0.05$, and ^{56}Fe dominates for $\dot{m} = 1$, corresponding to the electron fraction Y_e around 0.49 and 0.47, respectively. Other heavy nuclei also appear in these cases. The solutions show the proportion of the nuclear matter increases with radius for the same accretion rate. The mass fraction of ^{56}Ni or ^{56}Fe increases with radius near the surface. In the middle region, ^{4}He is dominant for all the accretion rates. The free neutrons and protons become dominant around the equatorial plane of the disk in the hot and dense state. Most of the free protons turn into the free neutrons due to the Urca process [2], which causes free neutrons to be dominant and the decrease of electron fraction. In the model, the density and temperature are determined by the accretion rate. Furthermore, the radial and vertical distribution of the density and temperature determines the electron fraction and nuclei distribution. In simple terms,

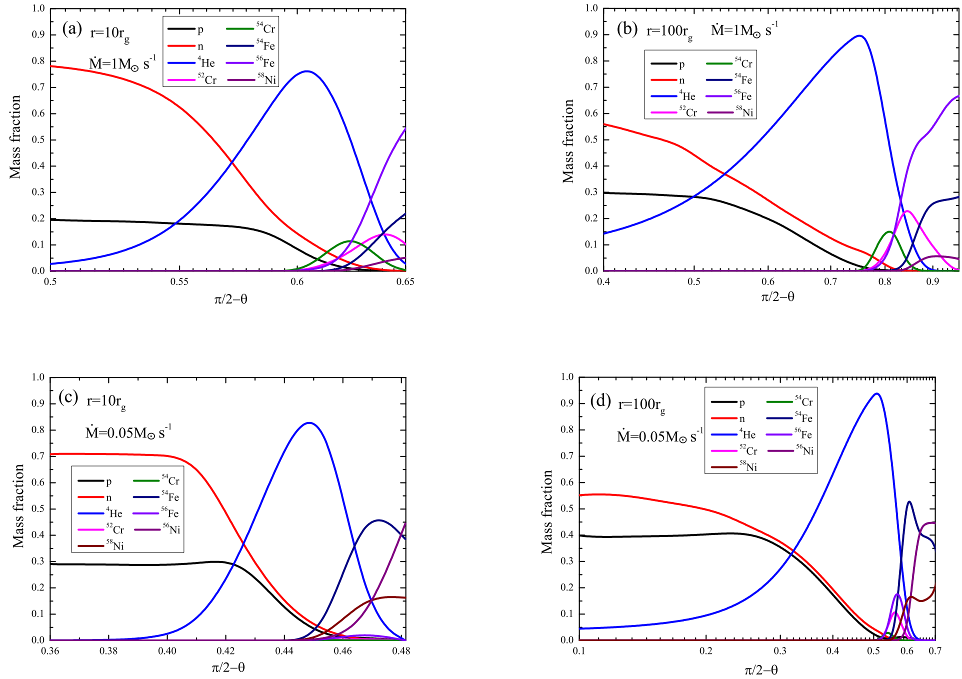

Figure 2. Variations of the mass fraction of the main elements with θ at $r = 10r_g$ and $100r_g$ for $\dot{m} = 0.05$ and 1.

the change of the electron fraction is inversely associated with the accretion rate and radius when the free baryons dominate.

3 Discussion

Supernova light curve bumps have been observed in the optical afterglow of some long-duration GRBs, which is driven by the decay of ^{56}Ni [14]. How to produce massive ^{56}Ni in GRBs associated with supernovae is a major problem which remains unsolved. Moreover, the detection of Fe Kα X-ray lines can play an important role in understanding the nature of GRBs [15]. The observations of some X-ray afterglows with *Beppo-SAX*, *ASCA*, and *Chandra* have revealed strong Fe Kα emission lines [16].

We have described self-consistently how to produce ^{56}Ni, ^{56}Fe and other nuclei in the central region of GRBs with the NDAF model. Actually, [6] revisited the vertical structure of NDAFs and showed that the possible outflow may appear in the outer region of the disk according to the calculations of the vertical distribution of the Bernoulli parameter. ^{56}Ni existed in the outflows from the surface of NDAF with the low mass accretion rate may be the most important source of the long-GRB ^{56}Ni production. Analogously, iron and other heavy nuclei may also form the outflow injecting into external environment in GRBs. The NDAF model with outflows is necessary to be constructed for further theoretical explanation of the bumps in the optical light curve of core-collapse supernovae (see Figure 3).

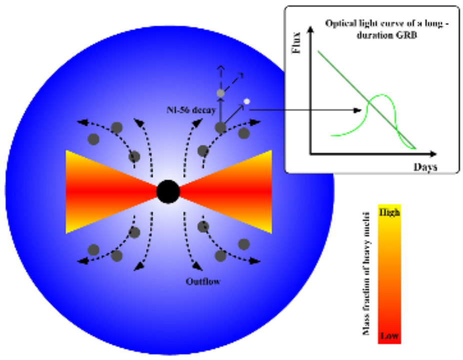

Figure 3. Schematic picture of a Nickel factory in the collapsar.

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