Nucleosynthesis in black hole accretion flows feeding short GRBs

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We model the nucleosynthesis in black hole accretion disks (and it's neighboring region) at the base of a gamma ray burst. The result is abundant production of light isotopes, as well as heavier elements with mass numbers in the range $A \sim 60 - 80$, which corresponds to the first maximum of nuclide production in the process of rapid neutron capture (r-process). Isotopes are created mainly on the surface of accretion disk and in the area beyond it, where they are carried by the magnetized, neutrino-driven wind.

1 Introduction

Gamma ray bursts (GRBs) are extremely energetic explosions observed in distant parts of the Universe (other galaxies). During a collapse of a massive star into a black hole in a supernova process such a long burst can be observed, providing the progenitor star has enough angular momentum to form an accretion disk around a black hole. Short GRBs are associated with mergers of binary neutron stars. Transient jets are generated by GRB central engine, which is composed of a newly formed black hole, surrounded by a remnant disk.

This work focuses on modeling the production of heavy nuclides in the plasma accreting onto a black hole at the base of GRB.The velocity of nuclear reactions is highly dependent on temperature and density of the media, as well as the proton-baryon ratio presented as electron fraction. In this work the first results of space distribution of selected isotopes, based on quasi-static model (with condition of nuclear statistical equilibrium, NSE) will be presented.

2 Model

The accretion disk around a black hole is modeled with the following parameters: mass of a black hole $M_{\rm BH}$, its accretion rate (rate of matter falling into black hole) and BH dimensionless spin, a. Typical parameters are $M_{\rm BH} = 3M_{\odot}$, $\dot{M} = 0.1 M_{\odot}{\rm s}^{-1}$, and $a = 0.6$, however we examine also a range of values for which the results of nucleosynthesis might provide constraints on the black hole's parameters (Janiuk, 2017).

From the steady state based on above parameters, we follow the dynamical evolution of the disk by solving continuity and momentum-energy conservation equations:

$$(\rho u_\mu)_{;\nu} = 0; \qquad T^\mu_{\nu;\mu} = 0 \tag{1}$$

where

$$\begin{aligned} T^{\mu\nu} &= T^{\mu\nu}_{gas} + T^{\mu\nu}_{EM} \\ T^{\mu\nu}_{gas} &= \rho h u^\mu u^\nu + p g^{\mu\nu} = (\rho + u + p) u^\mu u^\nu + p g^{\mu\nu} \\ T^{\mu\nu}_{EM} &= b^2 u^\mu u^\nu + \frac{1}{2} b^2 g^{\mu\nu} - b^\mu b^\nu ; b^\mu = u^*_\nu F^{\mu\nu} \end{aligned} \tag{2}$$

and u^μ is the four-velocity of gas, u denotes internal energy density, b^μ is magnetic four-vector, F is electromagnetic stress tensor, in the force-free approximation ($E_\nu = u^\nu F^{\mu\nu} = 0$). Here the models were evolved until the time $t_\mathrm{f} = 2000$ M (geometrical units).

The effect important for the state of accretion disk is neutrino cooling. The neutrinos of three flavours are emitted via the electron or positron capture, electron-positron pair annihilation, nucleon bremsstrahlung, and plasmon decay. The equation of state in the plasma is based on equilibrium of these nuclear reactions, which, when reached, defines the proton-to-baryon density ratio Y_e:

$$Y_\mathrm{e} = \frac{1}{1 + \frac{n_\mathrm{n}}{n_\mathrm{p}}} = \frac{n_{\mathrm{e}^-} - n_{\mathrm{e}^+}}{n_\mathrm{b}} \tag{3}$$

The model was evaluated for three spin values: $a_A = 0.6$, $a_D = 0.9$ i $a_E = 0.98$. The quantities which drive the nucleosynthesis rates are temperature, density and electron fraction Y_e. Their values are saved at the two-dimensional grid at t_f.

Nucleosynthesis of isotopes was computed from above described grid with use of NSE modules and thermonuclear reaction network code (Meyer, 2012). The numerical methods applied there are described in detail in literature (Wallerstein et al., 1997). For each area element of the space the nuclear reaction network is computed and abundances of specific isotope species are evaluated. They are evolved until the nuclear statistical equilibrium is reached. The resulting abundances are distributed in the isotopic structure of the accretion disc and it's neighbourhood region.

3 Results

The space distribution of isotopes for specific time-step is dependent on the dimensionless spin a. The main regions of their concentration are the accretion disk itself and, in even greater abundance, its neighboring area under the influence of the disk wind. The greater value of the spin the larger both the distance and the scope of the angle in which the elements are present.

Analysis of integrated fraction of mass allows the evaluation of influence of the spin parameter on the quantitative contribution of isotopes in accretion disk, as modeled in range of $500 r_\mathrm{g}$ from the black hole. In the probed range of dimensionless spin the trend is visible: despite qualitative variations in distribution of specific isotopes with the same mass number, their integrated mass is approximately the same.

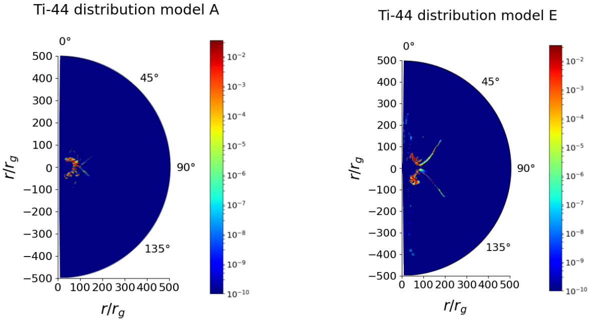

Fig. 1: Space distribution of the stable isotope Ti-44 in the outflow from the accretion disc presented for two values of dimensionless spin, $a_A = 0.6$, $a_E = 0.98$, expressed as normalized mass fraction of created isotopes.

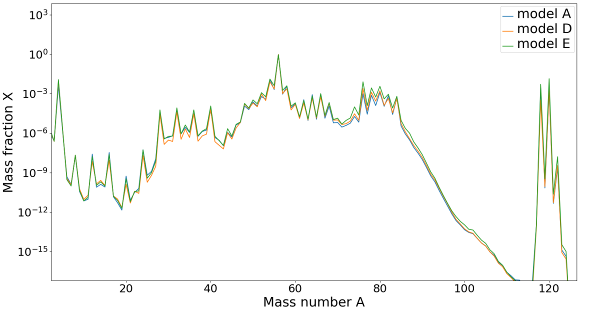

Fig. 2: Distribution of isotopes integrated over the volume, in the function of their mass number A. Parameters of the model: $M_{\rm BH} = 3M_{\odot}$, and three spin values: $a_A = 0.6$, $a_D = 0.9$ i $a_E = 0.98$. Among the heavy isotopes, above the level of Iron, the characteristic peaks for mass numbers close to 60 and 80 are notable. They correspond to the first r-process maximum. The next maximum is present at around $A \sim 120$, while the $A \sim 195$ is also expected (Wu et al., 2016).

4 Conclusions

The NSE model does not predict the synthesis of significant amount of isotopes with mass number larger then 120. However, the creation of meaningful amount of light elements and heavy isotopes such as Mn-53, Ni-56, Fe-58, Co-63 and Ge-76 was established, as well as isotopes connected with the next r-process maximum - Krypton and Strontium. These isotopes may be important in the chemical enrichment of the Universe, e.g., in the evolution of globular clusters (Wünsch et al., 2017)

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