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Nucleosynthesis inside accretion disks and outflows formed during core collapse of massive stars

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Abstract. We investigate nucleosynthesis inside the gamma-ray burst (GRB) accretion disks and in the outflows launched from these disks mainly in the context of Type II collapsars. We report the synthesis of several unusual nuclei like ^{31}P, ^{39}K, ^{43}Sc, ^{35}Cl and various isotopes of titanium, vanadium, chromium, manganese and copper in the disk. We also confirm the presence of iron-group and $\alpha-$elements in the disk, as shown by previous authors. Much of these heavy elements thus synthesized are ejected from the disk and survive in the outflows. While emission lines of several of these elements have been observed in the X-ray afterglows of GRBs by BeppoSAX, Chandra, XMM-Newton etc., Swift seems to have not found these lines yet.

Keywords : accretion, accretion discs – gamma-rays: bursts – nuclear reactions, nucleosynthesis, abundance

1. Introduction

We plan to investigate nucleosynthesis in the accretion disks formed by the Type II collapsars where the accretion rate ($\dot{M}$) is: $0.0001 M_\odot s^{-1} \lesssim \dot{M} \lesssim 0.01 M_\odot s^{-1}$, when $M_\odot$ indicates solar mass, as this regime is the ideal site for the synthesis of heavy elements. These disks are predominantly advection dominated. However, neutrino cooling becomes important in the inner disk where the temperature and density are higher. We also consider nucleosynthesis in the outflows from these disks and report that many of the heavy elements thus synthesized in the disk do survive in the outflow. Moreover, depending on the abundance of ^{56}Ni synthesized in the outflow, we can predict whether the outflow will lead to an observable supernova explosion or not.

2. Disk and outflow models

The accretion disk formed in a Type II collapsar is modeled within the framework suggested by Kohri et al. (2005) where the electron degeneracy pressure and the evolving

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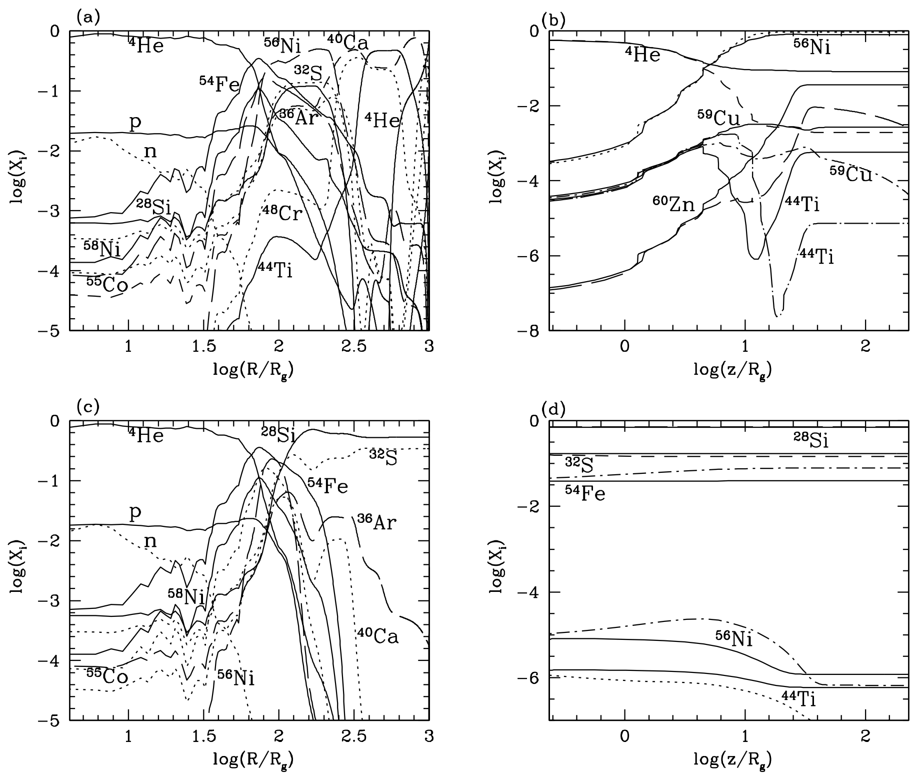

Figure 1. (a) & (c) Zones characterized by dominant elements in the disk with He-rich and Si-rich abundance at the outer disk respectively. (b) & (d) Abundance evolution in the outflow from $R_{ej} \sim 40R_g$ of the disk in (a), from $R_{ej} \sim 180R_g$ of the disk in (c) respectively. In both (b) and (d) solid lines correspond to the higher velocity of ejection and other lines to lower velocity, in each set.

neutron to proton ratio are appropriately calculated. Height-averaged equations based on a pseudo-Newtonian framework as suggested by Mukhopadhyay (2002) is used . Following Fujimoto et al. (2004), we adopt a spherically expanding, one-dimensional and adiabatic outflow model to investigate nucleosynthesis in the outflow. Since $\dot{M}$ is very high, it is always possible that the matter may get deposited onto the accretion disk which favors outflow. Outflows may also be due to magnetic centrifugal force and viscosity. We use well tested nuclear network code as has been used by Mukhopadhyay & Chakrabarti (2000). We have modified this code further by increasing the nuclear network and including reaction rates from the JINA Reaclib Database, https://groups.nscl.msu.edu/jina/reaclib/db/ Cybert et al. (2010). We use He-rich and Si-rich abundances as the initial conditions of nucleosynthesis at the outer disk. We also consider outflow from various radii of ejection, R_{ej}, with $R_{ej} < 200R_g$, R_g being Schwarzschild radius and evaluate the abundance evolution in the outflow assuming the initial composition the same as in the accretion disk at R_{ej}.

3. Nucleosynthesis inside accretion disks and outflows

Fig. 1(a) and Fig. 1(c) illustrate the abundance evolution in the accretion disk around a $3M_\odot$ Schwarzschild black hole accreting at $\dot{M} = 0.001M_\odot s^{-1}$, with the viscosity parameter $\alpha = 0.01$ and the composition of the accreting gas at the outer disk similar to the pre-supernova He-rich and Si-rich layer respectively. They depict that the disks comprise of several zones characterized by dominant elements. In Fig. 1(a) the region $\sim 1000 - 300R_g$, is mainly the ^{40}Ca, ^{44}Ti and ^{48}Cr rich zone. This is because unburnt ^{36}Ar undergoes α-capture reaction to give rise to ^{40}Ca through $^{36}\mathrm{Ar}(\alpha,\gamma)^{40}$Ca, which undergoes partial α-capture to give rise to ^{44}Ti and ^{48}Cr. Inside this region, the temperature and density in the disk favor complete photodisintegration of ^{44}Ti and ^{48}Cr resulting in the formation of ^{40}Ca, ^{36}Ar, ^{32}S and ^{28}Si, as is evident from Fig. 1(a). Subsequently, ^{28}Si and ^{32}S start burning, which favors formation of iron-group elements via *photodisintegration rearrangement* reactions Clayton (1968). Therefore, in the range $\sim 300-80R_g$, there is a zone overabundant in ^{56}Ni, ^{54}Fe, ^{32}S and ^{28}Si. Inside this zone, all the heavy elements photodisintegrate to ^{4}He, neutron and proton. In Fig. 1(c) the disk has a huge zone rich in ^{28}Si and ^{32}S extending from $1000R_g$ to $250R_g$. Inside this radius, silicon burning commences and soon the disk becomes rich in ^{54}Fe, ^{56}Ni and ^{58}Ni. Inside $\sim 70R_g$, all the heavy elements again get photodisintegrated to $\alpha-$s and free nucleons. Another remarkable feature in the He-rich and Si-rich disks is that inside $\sim 100R_g$, the abundances of various elements start becoming almost identical as if once threshold density and temperature are achieved, the nuclear reactions follow only the underlying disk hydrodynamics. Banerjee & Mukhopadhyay (2013) gives the details of the nuclear reactions. On increasing $\dot{M}$ ten times we find that the individual zones in both disks shift outward retaining similar composition as is in the low $\dot{M}$ cases described above.

Next we consider outflow from $40R_g$, which lies in the He-rich zone of the aforementioned He-rich disk. The abundance evolution in the outflow is shown in Fig. 1(b). We find that ^{56}Ni is copiously synthesized along with isotopes of copper and zinc. Presence of ^{56}Ni in the outflow signifies that it will result in an observable supernova explosion. Fig. 1(b) also depicts that on changing the initial velocity of ejection the final abundances of the nucleosynthesis products change significantly. More ^{56}Ni is synthesized when the velocity of ejection is low (see Fig. 1(b)) because then the temperature drops slowly in the ejecta which facilitates greater recombination of alphas to nickel. Fig. 1(d) depicts the abundance evolution in the outflow from $180R_g$ of the above mentioned Si-rich disk. We choose this radius of ejection because outflow from the He-rich zone yields similar results as in Fig. 1(b). Outflow from the Si-rich zone remains rich in ^{28}Si and ^{32}S. ^{56}Ni is hardly synthesized and there will be no observable supernova explosion.

4. Summary and conclusions

Apart from the synthesis of iron-group and $\alpha-$elements we report for the first time, to the best of our knowledge, that several unusual nuclei like ^{31}P, ^{39}K, ^{43}Sc, ^{35}Cl and various uncommon isotopes of titanium, vanadium, chromium, manganese and copper are synthesized in the disk. Several of these heavy elements survive in the outflow from these disks, and when ^{56}Ni is abundantly synthesized in the outflow, there is always a supernova explosion.

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