Evolution of a black hole mass and spin in collapsars for rotating and magnetised pre-supernovae

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Abstract

We investigate the collapsar scenario, in which, according to Woosley (1993) and Paczynski (1998), the long gamma ray bursts (LGRBs) can be explained. The total energetics of explosions observed in the gamma ray band are consistent here with the total binding energy of a pogenitor star. However, the details characteristic for various events, such as their individual duration times, lightcurve profiles, variability, and connection with supernovae of different spectral properties, are still subject of many studies. In our scenario, the evolved progenitor star is collapsing onto a compact core, which forms a spinning black hole. The process of accretion via rotationally supported torus powers the ejection of relativistic jets. Here, the rotational energy of the black hole is presumably transported to the remote jet, which is mediated by magnetic fields. The rotation of pre-supernova star is a key property of the model. In our study, we investigate different types of collapsing stars: magnetized and non-magnetized. We probe the distributions of angular momentum inside the collapsar and the process of spinning up the black hole. Both Kerr parameter, and increasing mass of the black hole, put a constraint for the existence of rotationally supported torus inside the collapsar's envelope.

Tested pre-supernova models

We used pre-supernova models from Woosley et al. (2002), Heger et al. (2000) Heger et al. (2005).ZAMS mass of all those stars was $25M_\odot$. First of them (NR) similarly to the one used in Janiuk and Proga (2008) and Janiuk et al. (2008) did not take into account rotation nor magnetic field during star evolution, its initial metallicity was 10^{-4} solar. There is no mass-loss in this case. In the second one (R) rotation was introduced, this model is affected by the biggest mass-loss leading to pre-supernova mass of $5.62M_\odot$. In the third model (RMF) both rotation and magnetic field is incorporated in evolution. It leads to pre-supernova mass of $12.55M_\odot$. For second and third model initial metallicity was equal to solar. In the Fig.1we present density profiles of used models.

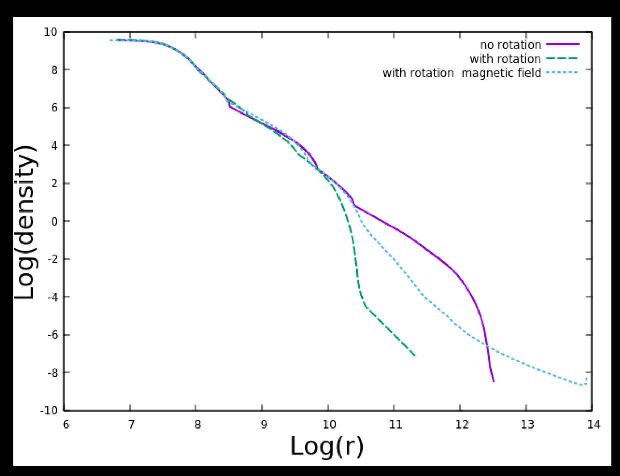

Fig. 1: Density profiles of different pre-supernova models

Models of accretion

Critical specific angular momentum $l_{\rm crit}$ is given by the equation:

$$l_{\rm crit} = \frac{2GM}{c}\sqrt{2 - A + 2\sqrt{1-A}}. \quad (1)$$

Torus can be sustained when there is a matter with $l_{\rm spec} > l_{\rm crit}$.The original distribution of angular momentum was given by:

$$l_{\rm spec} = {\rm x} l_{\rm crit} f(r,\theta)., \quad (2)$$

where $f(r,\theta)$ depend on the model.We examined variety of x values. Every step of mass (M) and angular momentum (J) evolution in our model is given by:

$$M^k = M^{k-1} + \Delta m$$
$$J^k = J^{k-1} + \Delta j,$$
$$\Delta m^k = 2\pi \int_{r_k}^{r_k+\delta r}\int_0^\pi \rho r^2 \sin\theta d\theta dr \quad (3)$$
$$\Delta j^k = 2\pi \int_{r_k}^{r_k+\delta r}\int_0^\pi min[l_{\rm spec}, l_{\rm crit}] \rho r^2 \sin\theta d\theta dr.$$

Thereafter spin parameter A is expressed by the formula: $A = \frac{cJ}{G(M)^2}$. This evolution formula ensure fulfilment of the condition $A < 1$, but do not specify any mechanism of the angular momentum loss. We investigate two accretion scenarios (scenario 1 and 3 accordingly from Janiuk and Proga (2008)). Accretion proceeds through: both torus and the envelope in the first scenario, only torus in the second. Calculations were stopped when there was no matter with $l_{\rm spec} > l_{\rm crit}$. We present examination of four models, with combinations of accretion scenarios and $f(r,\theta)$ formula:

- $f(r,\theta) f(\theta) = 1 - |\cos\theta|$ (A models)
- $f(r,\theta) = \sin^2\theta\sqrt{\frac{r}{r_{in}}}$ (D models)

Models with angular momentum distribution given by function A

In the left panel of Fig. 2 we present evolution of the Kerr spin parameter for the A1 model (i.e., only polar dependence of angular momentum, and homologous accretion). The evolution depends heavily on the pre-supernova star type. Our calculations end when there is no matter which can form torus. Accretion in RMF and NR models tend to end at the same radii. For small x their final A is similar, but with increase of x the difference between final spins grow, RMF leads to higher values. Pre-supernova model R allows the support of torus for higher r. Starting from $\log r \sim 10.5$ accretion almost don't change A, due to a low density in outer most parts of the pre-supernova. For A3 scenario (i.e., only torus accretion), all examined x values lead to rapid growth of A to value 1 and maintaining this value until the end of the accretion. In the right panel of Fig. 2 we present final mass of the black hole as a function of x. Higher x, which corresponds to higher specific angular momentum of the matter, leads to more massive black holes, because accretion in our model can proceed longer.

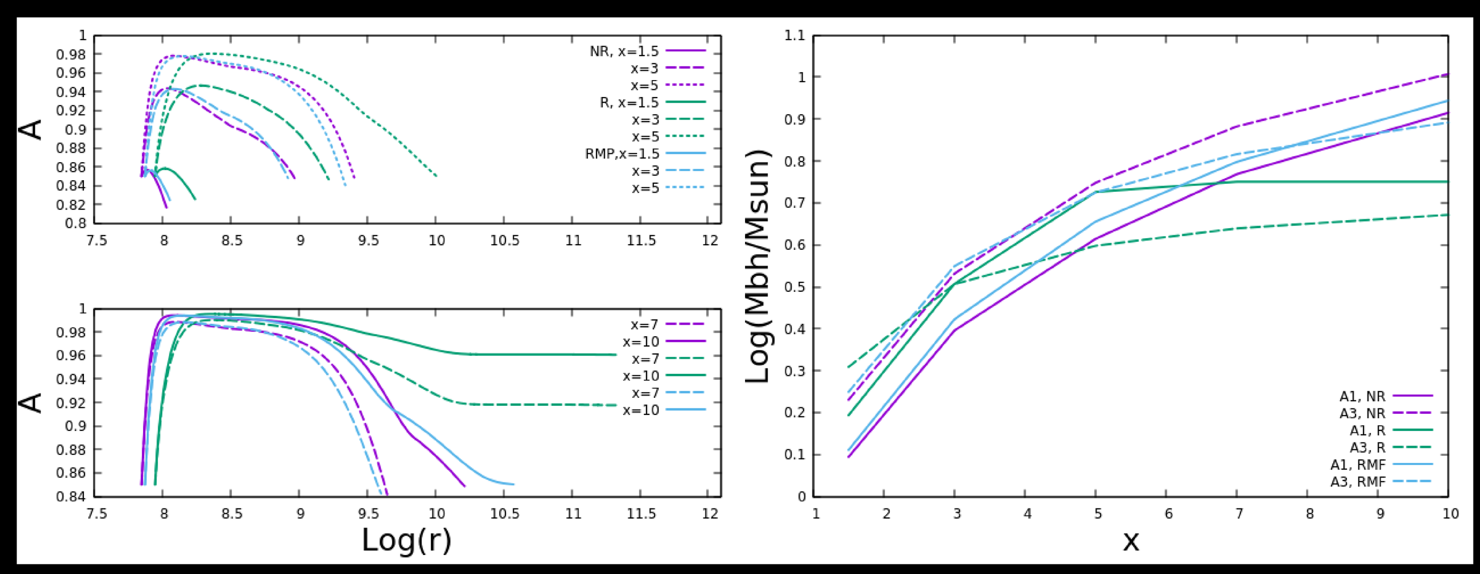

Fig. 2: Left panel: Evolution of the spin parameter for different pre-spernova models and values of x parameter. Right panel: Final mass of the black hole as a function of x parameter.

Models with angular momentum distribution given by function D

In case of model D1 (initial angular momentum distribution depends on radius, and accretion model is homologous), we examined different range of x values. Due to dependence of $l_{\rm spec}$ on $\sqrt{r}$, the x values from A1 model lead to very high initial $l_{\rm spec}$. Therefore, now we examined values in the range $x = [0.05, 1.0]$.
Dependence of the spin of BH on pre-supernova model is similar to the A1 model. In case of small x values, the NR and RMF models are terminated after roughly the same part of the star's envelope has accreted, and they give similar final A values. Situation changes for faster rotation, with $x = 0.9$. For this x value, both NR and RMF models sustain the torus until the outermost part of the star start accrete, and the difference in the radius of termination occurs due to different sizes of the stars (see Fig. 1). In case of pre-supernova model with rotation, the whole star accretes for x larger than 0.5. Evolution of the Kerr parameter is presented in the left panel of Fig. 3. Final mass of the black hole as a function of x is shown in the right panel of Fig. 3

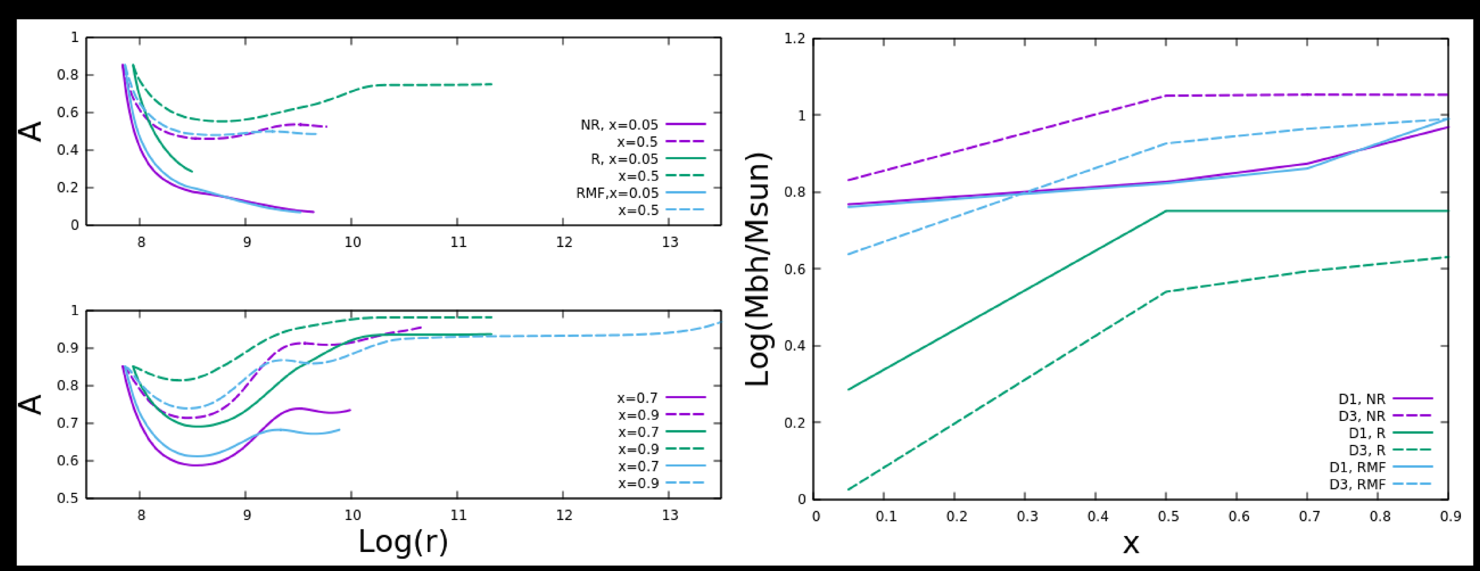

Fig. 3: Left panel: Evolution of the spin parameter for different pre-spernova models and values of x parameter. Right panel: Final mass of the black hole as a function of x parameter.

Summary

★Final black hole masses are in the range between 0.6 and 1.05 $\log(\frac{M_{\rm BH}}{M_\odot})$ depending on the accretion scenario and pre-supernova model.
★In case of spin evolution through consecutive accretion layers, models A1 and D1 gives different shape of the A evolution:
★In case of A1 scenario for every pre-supernova model we observe growth at first and then depending on exact model and x value drop or stabilisation for outer parts of the star.
★On the other hand D1 model gives for every case drop of A at first and then growth for high enough x value.

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