The low angular momentum in the collapsar: how long is a gamma ray burst?

Agnieszka Janiuk[1] and Daniel Proga[1]

[1]Department of Physics and Astronomy, University of Nevada, Las Vegas

(e-mail: ajaniuk@physics.unlv.edu)

Abstract

The collapsar model is the most promising scenario to explain the huge release of energy associated with long duration gamma-ray-bursts. Within this scenario GRBs are believed to be powered by accretion through a rotationally support torus or by fast rotation of a compact object. In both cases then, rotation of the progenitor star is one of the key properties because it must be high enough for the torus to form, the compact object to rotate very fast, or both. Here, we check what rotational properties a progenitor star must have in order to sustain torus accretion over relatively long activity periods as observed in most GRBs

Method

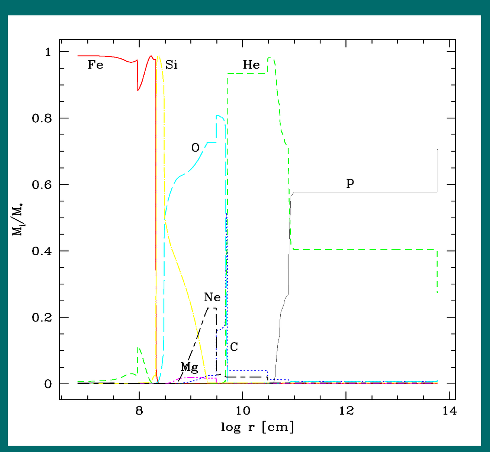
In the initial conditions, we use the spherically symmetric model of the 25 M_{Sun} pre-supernova (Woosley \& Weaver 1995).

We parameterize the distribution of specific angular momentum within a star to be either a function of the polar angle θ (simplest case; models A and B), or a function of both radius r and θ (models C and D).

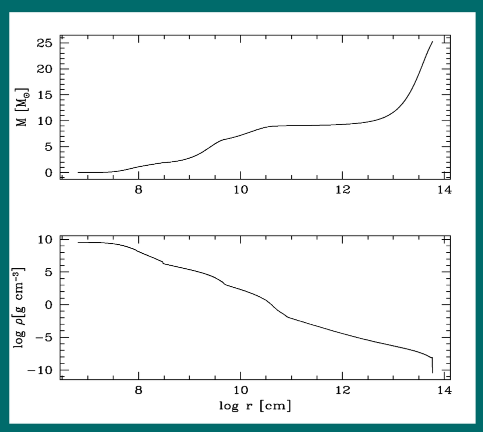
Initially, the mass of the black hole is given by the mass of the iron core of the star. Only the fraction of envelope mass with $l_{spec>}$ > $l_{crit} = 2R_S c$ (R_S is a Schwarzschild radius) is able to form a torus. As the collapse proceeds, l_{crit} will be a function of the increasing black hole mass.

We iteratively compute the mass of the envelope with $l_{spec>} > l_{crit}$, and determine the duration of GRB driven by torus accretion.

Pre-SN model: iron core + envelope



Chemical composition (data from Woosley & Weaver 1995)



Density and mass distribution in the pre-supernova star

The thick torus may form during the collapse of a massive, rotating star, if the specific angular momentum is larger than the critical value:

$$l_{crit} = 2 R_S c$$

R_S is the Schwarzschild radius and depends on the BH mass:

$$R_S = 2GM_{BH}/c^2$$

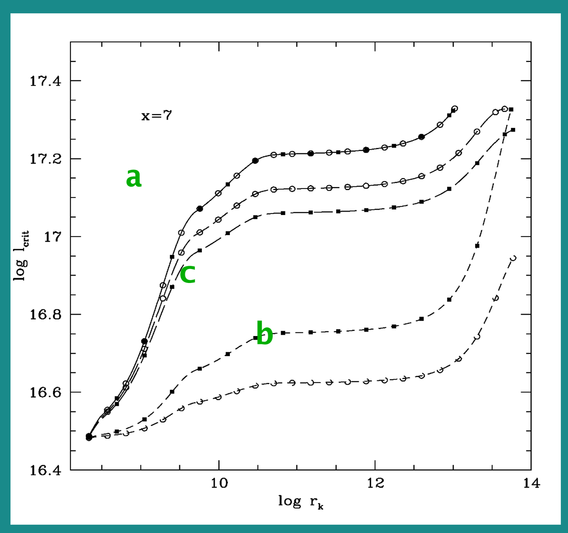
The black hole mass is initially the mass of the iron core:

$$M^0_{BH} = M_{core}$$

The black hole mass increases during the collapse:

$$M_{BH} = M^0_{BH} + M_{accr}$$

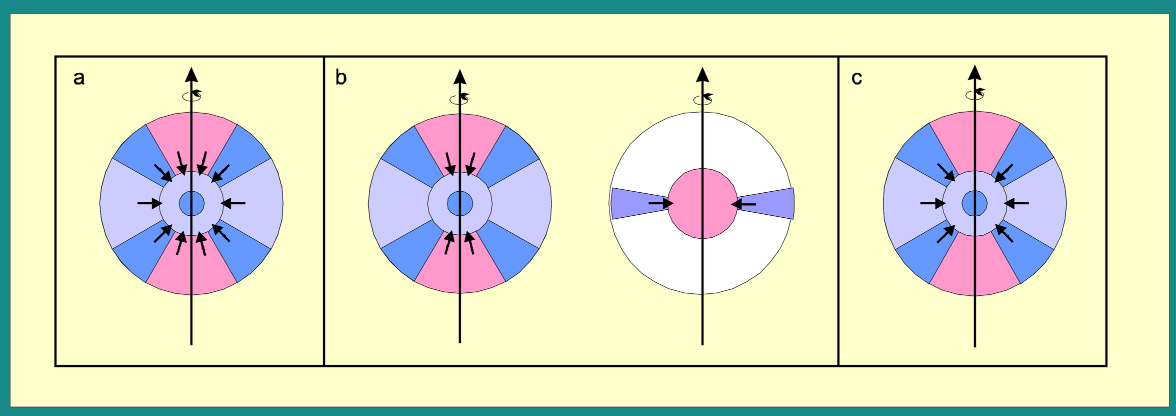
Critical angular momentum increases during the collapse



l_{crit} during the collapse of subsequent shells. The function depends on the initial normalization (here shown for x=7).

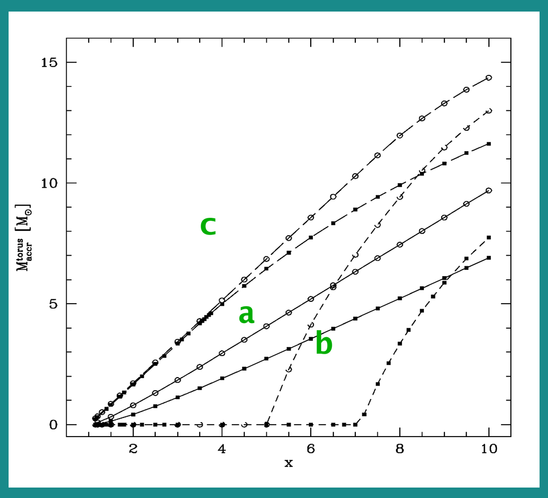
- During the collapse l_{crit} is a function of M_{BH}, so the *procedure is iterative*
- The larger l_{crit}, the less material in the envelope is capable of forming the rotationally supported torus
- When there is no torus, the GRB is finished (we assume that the jet is accretion powered)

How the black hole grows during the stellar collapse?

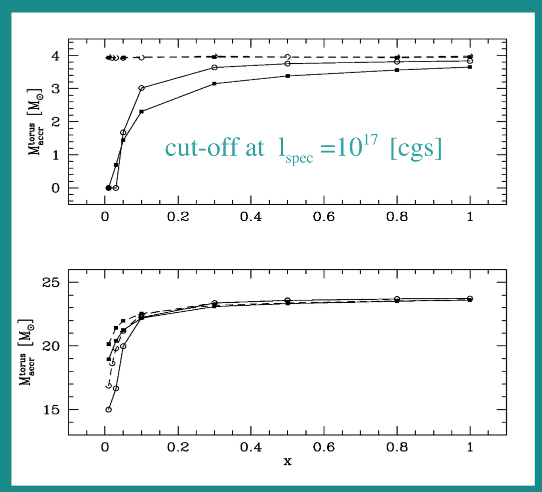


We calculate the evolution of the collapsar, starting from the BH mass equal to that of an iron core, and adding the mass to the black hole (non-homologous accretion). How much mass is added, depends on the accretion scenario: a – uniform accretion; b: first the polar regions are evacuated and then the torus accretes; c – only the torus accretes.

Results



Rotation depends only on (models A and B): 3 scenarios (a,b,c)



l_{spec} depends on and radius (models C and D). Accretion scenarios a and c; with and without cut-off on l_{spec}

How long is a GRB?

We simplify the problem by assuming *a constant accretion rate,* on the order of 0.5 M_{Sun}/sec.

The GRB duration is proportional to the mass accreted onto BH through the torus. This is a function of initial normalization of l_{spec} and depends on the model of pre-SN rotation. For the more realistic models we studied, we obtain between 4 and 15 M_{Sun} accreted, which corresponds to the GRB duration of t=8-30 seconds.

How the pre-collapse star rotates?

$$l_{spec} = l_0 f(\theta). \quad (1)$$

$$f(\theta) = 1 - |\cos\theta| \quad (\text{model } \mathbf{A}) \quad (2)$$

$$f(\theta) = \sin^2\theta \quad (\text{model } \mathbf{B}) \quad (3)$$

$$l_{spec} = l_0 g(r) f(\theta), \quad (4)$$

$$l_{spec} = x l_{crit} (\frac{r}{r_{core}})^2 \sin^2\theta \quad (\text{model } \mathbf{C}) \quad (5)$$

$$l_{spec} = x\sqrt{8GM_{core} r} \sin^2\theta \quad (\text{model } \mathbf{D}) \quad (6)$$

In models C and D we take into account the rigid rotation (with a possible cut-off on l_{spec}) or a constant ratio of centrifugal to gravitational forces

The results are sensitive to the initial normalization, $x=l_0/l_{crit}(M^0_{BH})$. We took the values between x=0.01 and 10.

Conclusions

We showed that simple estimates of the total mass available for torus formation and consequently the duration of a GRB are only upper limits. We revised these estimates by taking into account the long term effect that as the compact object accretes mass, the minimum specific angular momentum needed for torus formation increases. This in turn leads to a smaller fraction of the stellar envelope that can form a torus.

We demonstrated that this effect can lead to a significant reduction of the total energy and overall duration of a GRB event. This can hardly be mitigated by assuming that the progenitor star rotates faster than in our model, because our assumed rotation is already high compared to observational and theoretical constraints.

References

Janiuk A., Proga D., 2007, ApJ, submitted

Proga D., MacFadyen A.I., Armitage, P.J., Begelman, M.C., 2003, ApJ, 599, L5

Woosley S.E., Weaver T.A., 1995, ApJS, 101, 181