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Instabilities in the Gamma Ray Burst central engine. What makes the jet variable?

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Abstract. Both types of long and short gamma ray bursts involve a stage of a hyper-Eddington accretion of hot and dense plasma torus onto a newly born black hole. The prompt gamma ray emission originates in jets at some distance from this 'central engine' and in most events is rapidly variable, having a form of sipkes and subpulses. This indicates at the variable nature of the engine itself, for which a plausible mechanism is an internal instability in the accreting flow. We solve numerically the structure and evolution of the neutrino-cooled torus. We take into account the detailed treatment of the microphysics in the nuclear equation of state that includes the neutrino trapping effect. The models are calculated for both Schwarzschild and Kerr black holes. We find that for sufficiently large accretion rates ($>\sim 10 M_{\odot}$ s^{-1} for non-rotating black hole, and $>\sim 1 M_{\odot}$ s^{-1} for rotating black hole, depending on its spin), the inner regions of the disk become opaque, while the helium nuclei are being photodissociated. The sudden change of pressure in this region leads to the development of a viscous and thermal instability, and the neutrino pressure acts similarly to the radiation pressure in sub-Eddington disks. In the case of rapidly rotating black holes, the instability is enhanced and appears for much lower accretion rates. We also find the important and possibly further destabilizing role of the energy transfer from the rotating black hole to the torus via the magnetic coupling.

Keywords. physical data and processes: accretion, black hole physics, instabilities, neutrinos, nuclear reactions, gamma-rays:bursts

1. Introduction

Roughly 80 per cent of the observed gamma ray bursts exhibit a substructure in their time profiles and the timescales of the sub-pulses are about 10^3-10^4 times shorter than the total duration of the event, estimated by T_{90} (see Piran (2005) for a review). This effect is most probably connected with the rapidly variable conditions within the jet plasma, such as the Lorentz factor. Therefore, since the energy input into the jet is required to vary, the activity of the central engine that produces this energy should not be stationary but rather change in much shorter timescale than the engine lifetime.

The central engine of the gamma ray burst is presumably a newly born black hole, surrounded by an accretion disk built from either a remnant of the disrupted companion star in the compact binary system, or the fallback material from the hypernova envelope. Such disk is extremely hot and dense due to the large accretion rate which can be on the order of 0.1 up to a few solar masses per second. Such physical conditios make the plasma totally opaque to photons and partially opaque to neutrinos (Di Matteo *et al.* 2002), which are produced in the nuclear reactions and provide a source of cooling to the disk (Popham *et al.* 1999).

The gravitational instability of the outer parts of the hyperaccreting disk in the GRB central engine was suggested first by Perna *et al.* (2006) and studied in the numerical model of Chen & Beloborodov (2007). Such instability may be a source for the late time activity and longer duration flares from the central engine. The prompt emission however is more plausibly explained with the instability discussed in Janiuk *et al.* (2007), and more recently in Janiuk & Yuan (2010), which arises in the regions of the disk closest to the central black hole.

2. Instability mechanism

The time dependent model of the hyperaccreting disk in the GRB central engine, presented in Janiuk *et al.* (2004), was based on a simplified equation of state, where the total pressure was given by a sum of the ideal gas, radiation and degenerate electron pressure. The more elaborate EOS, used in Janiuk *et al.* (2007), invokes self-consistently a chemical equilibrium of species such as protons, neutrons, electron-positron pairs and alpha particles. The reaction rates are computed under the assumption of beta equilibrium and charge neutrality, and the neutrino opacities are due to their absorption and scattering. To the total pressure contribute both partially trapped neutrinos and alpha particles, which are continuously photodissociated and recombinated in the plasma.

As results from our first calculations, at very high accretion rates, which for a non-rotating black hole should be at least 10 $M_{\odot}$ s^{-1}, a thermal instability arises in the innermost disk region close to the inner edge. This instability is associated with helium photodisintegration, which was found to lead to the local accretion rate fluctuations already by e.g. MacFadyen & Woosley (1999). What can be seen from our Fig. 1, bottom panel, the helium photodissociacion in a narrow strip of the accreting disk leads to a phase

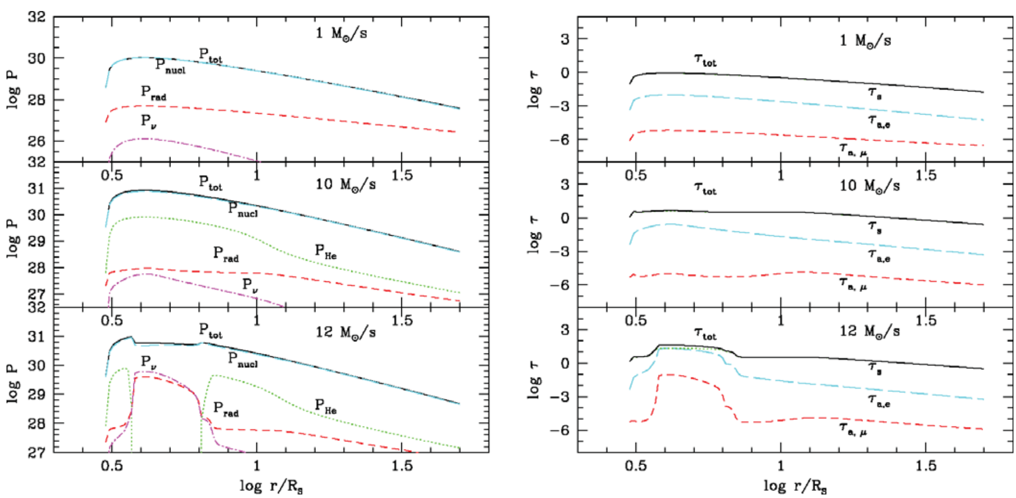

Figure 1. Radial profiles of the total pressure and its components: nuclear, helium, neutrino and radiation pressure (left), and neutrino total opacity and its components due to absorption, for muon and electron neutrinos, and scattering (right). The models were computed for a non-rotating black hole, with three values of accretion rate, as indicated in the panels. The black hole mass is 3 $M_{\odot}$ and viscosity $\alpha = 0.1$

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transition in the nuclear material. Due to this transition, the vanishing helium pressure is compensated by the neutrino pressure. The plasma becomes opaque to neutrinos and the neutrino absorption optical depths increase locally for both muon and electron flavor species. However, the net total pressure drops somewhat in the unsstable region and the resulting density profile in the disk is inversed. The unstable strip is much hotter and less dense than its surroundings. This leads to a faster replenishing of the strip than would be implied by the constant accretion rate in a stable situation. The accretion rate varies in both time and radius, which in turn leads to the neutrino luminosity variations and variable energy output from the disk.

The instability mechanism is much similar to the well known radiation pressure instability, operating in the accretion disks of microquasars and AGN (e.g., Janiuk *et al.* (2002)). In case of gamma ray burst disks, the role of radiation is taken by the neutrino pressure, which has a similar dependency on temperature. However, the mechanism stabilizing the disk in its hot phase, which in the radiation pressure dominated disk is due to advection, is not sufficient in the neutrino cooled disks.

3. Effect of black hole rotation and its energy extraction via magnetic fields

The accretion rates needed for the thermal instability to appear do not have to be extremely large if the disk surrounds a rotating black hole. Such a black hole would be a natural outcom e.g. of a collapsing Wolf Rayet star with a rapid rotation and is much more plausible for powering the GRB jets than a Schwarzschild black hole. As estimated in Janiuk *et al.* (2008), the longest duration GRBs require for their lifetimes large black hole spins, $a > 0.9$. This is because otherwise the realistic distributions of angular momentum within the collapsing envelope do not provide a sufficient condition for a long duration central engine lifetime.

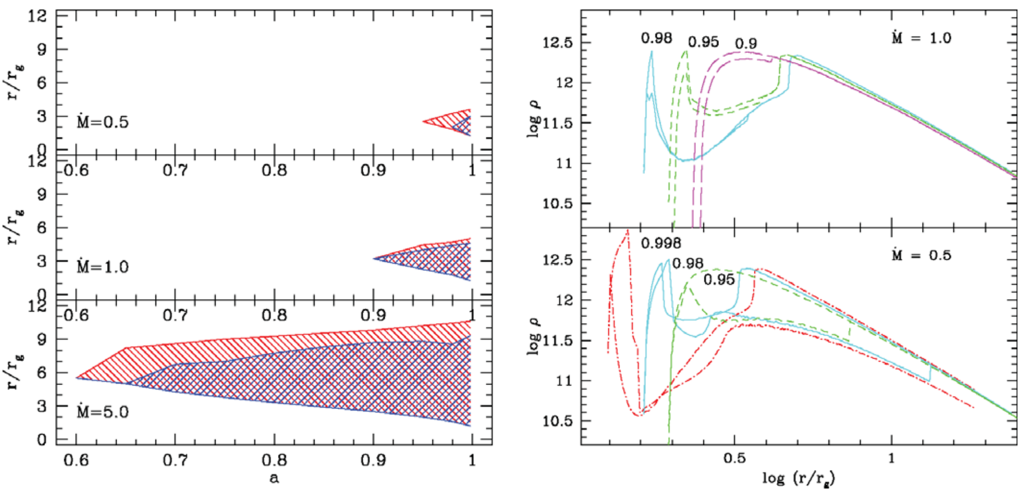

Figure 2. Extension of the unstable zones, depending on the black hole spin (left), and radial density profiles (right). The values of the accretion rate are marked in the panels and the black hole mass is $4M_{\odot}$. The visocsity in the left figure is $\alpha = 0.1$ (line shades regions) or $\alpha = 0.3$ (cross-shaded). The right figure is for $\alpha = 0.1$, and the spin parameters are indicated at the top of each line. The thicker lines show the results for the disk magnetically coupled with a rotating black hole and the thinner lines are for neglected magnetic coupling.

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In Figure 2 we show that the thermal instability occurs in the Kerr black hole disks at quite low accretion rates, e.g. at 0.5 $M_{\odot}$ s^{-1}, as is plausible for the collapsar scenario, or a few $M_{\odot}$ s^{-1}, as more plausible in case of merging neutron stars. This result slightly depends on the adopted disk viscosity (α parameter) and is very sensitive to the black hole spin.

The additional effect which needs to be taken into account in case of the Kerr black hole, is the transfer of its rotational energy to the disk and vice-versa. In other words, the black hole can be spun up by accretion, or spun down if the angular velocity in the inner radii of the differentially rotating disk exceeds that of the black hole. The energy transfer proceeds via the closed magnetic field lines and leads to the additional torque due to the black hole coupling (Wang *et al.* 2002). At the same time, the open magnetic field lines can transfer the black hole rotation energy to the remote load and power the jet via the Blandford - Znajek process. We found that such a coupling does not stabilize the disk against the thermal instability discussed above. The unstable region can be shrunken but also shifted outwards, while the density drop in this region can even be deeper. Another effect is, that in case of the stable disk with a moderate neutrino pressure and some helium nuclei, the additional heating due to the rotating black hole coupling may lead to another type of unstable behaviour (Lei *et al.* 2009).

4. Conclusions

According to our results, the longest duration GRBs are powered by the fast rotation of the black hole. They sould be rapidly variable at the beginning of their prompt emission, due to the instabilities in the accretion process. Later on, the accretion rate drops and the black hole spins down, so that the instability is no longer operating and the burst profile will smoothen. On the other hand, also a moderately rotating black hole can be produced after the hypernova collapse. If the accretion rate is large, the black hole spin up may later allow for sufficient conditions for the instability. The GRB observed properties may therefore serve to test the role of black hole spin in the jet production in accreting black hole systems, other than X-ray binaries and AGN (Fender *et al.* 2010).

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Discussion

Koide: You noted the energy transport from the rotating black hole to the disk through the closed magnetic field lines. As far as we assume ideal MHD or a force-free condition, it is difficult to store the energy in the disk. I think the energy extracted from the black hole is stored in magnetic field outside the disk, where the magnetic configuration changes. Could you comment on this issue?

Janiuk: The disk plasma is fully ionized so we assume the disk to be perfectly conducting and the magnetic filed lines frozen in. When the accretion proceeds, the field lines are advected and its configuration indeed may be changed. Our assumption is in fact a steady state approximation.