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Hyper-Eddington accretion in GRB(*)

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Summary. — Popular models of the GRB origin associate this event with a cosmic explosion, birth of a stellar mass black hole and jet ejection. Due to the shock collisions that happen in the jet, the gamma rays are produced and we detect a burst of duration up to several tens of seconds. This burst duration is determined by the lifetime of the central engine, which may be different in various scenarios. Characteristically, the observed bursts have a bimodal distribution and constitute the two classes: short ($t < 2\,\mathrm{s}$) and long bursts. Theoretical models invoke the mergers of two neutron stars or a neutron star with a black hole, or, on the other hand, a massive star explosion (collapsar). In any of these models we have a phase of disc accretion onto a newly born black hole: the disc is formed from the disrupted neutron star or fed by the material fallback from the ejected collapsar envelope. The disc is extremely hot and dense, and the accretion rate is orders of magnitude higher than the Eddington rate. In such physical conditions the main cooling mechanism is neutrino emission, and one of possible ways of energy extraction from the accretion disc is the neutrino-antineutrino annihilation.

PACS `97.10.Gz` – Accretion and accretion disks.
PACS `97.60.Lf` – Black holes.
PACS `98.70.Rz` – γ-ray sources; γ-ray bursts.

1. – Disc model

The accretion disc model (Janiuk *et al.* 2004) is built using the continuity equation, angular momentum conservation and thermal balance. We follow the long-term, thermal-viscous evolution of the disc by means of the time dependent numerical code. We assume that:

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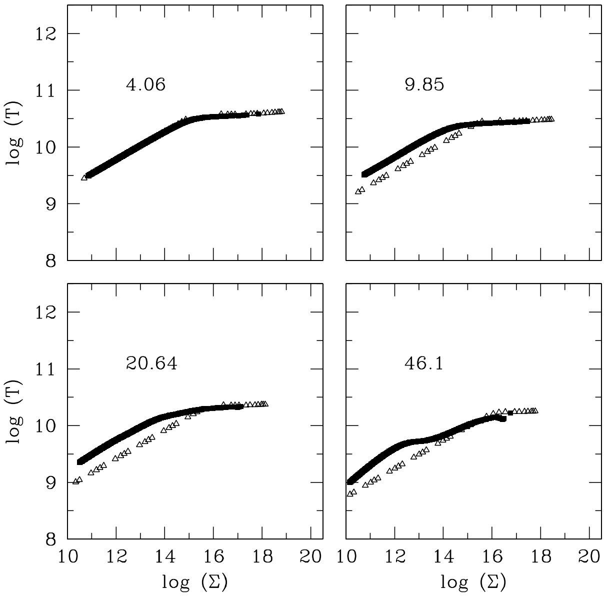

Fig. 1. – The local solutions of disc model on the surface density *vs.* temperature plane, for several exemplary values of radial location in the disc ($x = R/R_{\rm Schw}$ given in each panel). Open triangles are the stationary solutions, while solid squares are time-dependent solutions.

- Heating of material in the disc is due to the viscous energy dissipation. In the α-disc the viscous stress tensor (*i.e.* its $r\phi$ component) is proportional to the pressure. Viscosity is parameterized with constant α.

- Disc cooling is, initially, mainly due to the neutrino emission. Photons are totally trapped in the opaque disc; as the material gradually cools down, the dominating cooling meachanism is advetion (radial energy transport). The radiative cooling starts to be comparable to advection only in the very last stages of disc evolution.

- Disc is in hydrostatic equilibrium. The total pressure includes: gas, radiation (with contribution from electron-positron pairs) and degenerate electrons. Also, when the disc is optically thick to neutrinos, we add the neutrino pressure.

2. – Neutrino emission and absorption mechanisms

In the temperatures ranging from 10^{10} to 10^{11} K and densities of order 10^{10}–10^{12} g cm^{-3} (fig. 1) the processes listed in table I lead to significant neutrino emission (Popham, Woosley and Fryer 1999).

All of these have an inverse process, which is the source of neutrino absorption (Di Matteo *et al.* 2002). Also, the contribution to the overall neutrino opacity comes from scattering on nucleons.

TABLE I. – *Neutrino emission processes.*

Neutronization	e^+e^- capture on nucleons	$p + e^- \rightarrow n + \nu_e,\ \ n + e^+ \rightarrow p + \bar{\nu}_e$
Thermal emission	e^+e^- pair annihilation	$e^+ + e^- \rightarrow \nu + \bar{\nu}$
	Bremsstrahlung	$n + n \rightarrow n + n + \nu + \bar{\nu}$
	plasmon decay	$\gamma \rightarrow \nu + \bar{\nu}$

3. – Results

3˙1. *Short burst.* – A short burst is simulated in the model with no external matter supply to the accretion disc. The outer boundary condition allows for a certain range of disc expansion, in order to keep the angular momentum conserved. The timescale of accretion, during which the neutrino emission is at a significant level, is in good agreement with short bursts' duration. For the initial accretion rate of 1 $M_\odot$/s we obtain the neutrino luminosity $L > 10^{53}$ erg/s (see fig. 2). If we include the neutrino pressure in the viscous heating there is a luminosity excess at the beginning of the evolution (maximum about $T = 20$ ms). This is in good agreement with the results of the NS-NS merger simulations (Lee *et al.* 2004).

3˙2. *Long burst.* – A long burst is simulated in the model with non-zero outer boundary condition, which is imposed by the external supply of material to the disc. The external accretion rate decreases with time, according to the prescription $M \sim t^{-5/3}$, derived for the material fallback in supernova SN 1987A (Chevalier 1989). As a result, the burst duration in this collapsar scenario (MacFadyen and Woosley 1999) is much longer than in the merger case, and the neutrino luminosity decreases below 10^{50} erg/s after about 15 s.

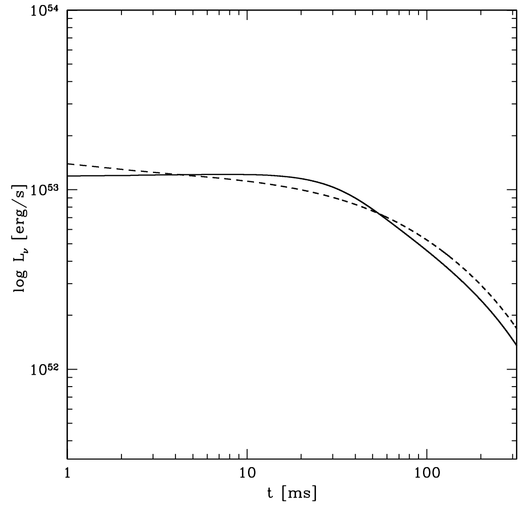

Fig. 2. – The neutrino luminosity of the remnant torus, evolving with zero external matter supply (consistently with compact binary merger scenario). The luminosity drops below 10^{50} erg/s after $\sim$ 1.5–1.0 s, depending on whether the disc was optically thick (solid line), or thin (dashed line) to neutrinos.

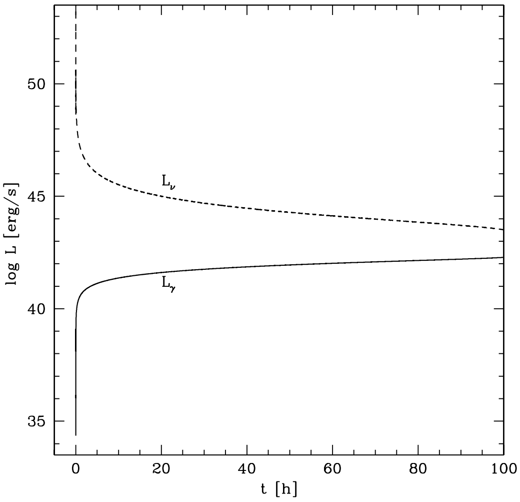

Fig. 3. – Long-term evolution of photon (solid line) and neutrino (dashed line) luminosities of the remnant torus, fed by the material fallback at its outer edge, consistently with the collapsar scenario.

After a few hours of the disc evolution the neutrino cooling decreases significantly, and the radiative cooling becomes comparable to advection. Disc starts to be transparent to photons and the X-ray luminosity rapidly increases (fig. 3), remaining very high for the following couple of days, up to the moment when neutrinos are less efficient in cooling than photons ($L_\gamma > L_\nu$). In principle, this X-ray flux could power the emission lines in the GRB afterglow. However, in our model the X-ray luminosity emitted after a few days of disc evolution is still lower than the value required to power the lines, and probably some additional mechanism should be considered in this case.

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