Neutrino Cooled disk in GRB central engine

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Abstract.
At the extreme densities and temperatures typical of the central engine of GRBs, the accreting torus is cooled mainly by advection and by neutrino emission. The latter process is dominated by electron and positron capture onto nucleons (β reactions). We calculate the reaction rates and the nuclear composition of matter, assuming that the torus consists of helium, electron-positron pairs, free neutrons and protons. After determining the equation of state and solving for the disk structure for a given initial accretion rate, we subsequently follow its time evolution. We find that, for accretion rates of the order of 10 M⊙/s, likely typical for the early stages of the accretion event, the disk becomes unstable, giving rise to variable energy output. This instability may play an important role for producing internal shocks.

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INTRODUCTION

The enormous power that is released during the gamma-ray burst explosion indicates that a relativistic phenomenon must be involved in creating GRBs ([1]). Whether GRBs are the end-result of a compact binary merger (e.g. NS-NS or NS-BH), or the collapse of a massive star, a dense, a hot torus likely forms around a newly born black hole ([2]).

The steady-state model of a hyperaccreting torus optically thin to neutrinos was proposed e.g. in [3], [4], and the calculations were performed for accretion rates $\dot{M} \leq 1 M_\odot/s$. The effects of neutrino opacities and trapping were introduced in [5].

Since the accretion process is extremely rapid and hence a transient event, it is best studied by means of a time-dependent disk model ([6]). The initial accretion rates in the torus can be as high as 10 $M_\odot/s$, and then rapidly decrease with time. The time-dependent disk model can be regarded as complementary to the studies of binary mergers or collapsars, for which the 2D numerical simulations were presented by e.g. [7], [8]. Here we present new results, based on the detailed calculations of the equation of state (EOS) and the chemical composition of the nuclear matter.
MODEL

For a given accretion rate, we determine the structure of the disk from the ‘steady-state’
equations by imposing the balance between viscous heating (\(\alpha\)-prescription) and cooling
due to advection, radiation and neutrino emission. The neutrino emission mechanisms
are: (i) Electron - positron capture on nucleons and \(\beta\)-decay. These reactions are:
\[ p + e^- \rightarrow n + \nu_e, \quad n + e^+ \rightarrow p + \bar{\nu}_e, \quad n \rightarrow p + e^- + \bar{\nu}_e \]
(ii) Annihilation of electron-positron pairs:
\[ e^- + e^+ \rightarrow \nu_i + \bar{\nu}_i \]
(iii) Nucleon Bremsstrahlung:
\[ n + n \rightarrow n + n + \nu_i + \bar{\nu}_i \]
(iv) Plasmon decay due to the interaction with electron gas:
\[ \tilde{\gamma} \rightarrow \nu_e + \bar{\nu}_e. \]

Each of the above neutrino emission process has the reverse process, that is the source
of neutrino absorption. In addition, the free escape of neutrinos from the disc is limited
by scattering. Therefore we calculate the absorptive and scattering optical depths for
neutrinos, and include in the calculations concerning a non-zero neutrino pressure and
entropy components.

The equation of state is calculated numerically for a given temperature and density,
which is subsequently iterated in a grid of radii. We assume that the torus consists of
helium, electron-positron pairs, free neutrons and protons. The chemical potentials
of the species are calculated from the chemical equilibrium condition. For a given baryon
number density, \(n_b = (n_p + n_n)/X_{\text{nuc}}\), the chemical potentials of neutrons, protons and
electrons are calculated from the transition reaction rates between neutrons and protons,
using the conditions for the conservation of baryons and charge neutrality.

Having computed the initial state we allow the density and temperature to vary with
time. We solve the time-dependent conservation equations for mass, angular momen-
tum and energy. The advection term is included in the energy equation via the radial
derivatives.

RESULTS

For sufficiently large accretion rates, \(M \geq 1M_\odot/s\) neutrino trapping limits the neutrino
cooling rate and the central regions of the disk become advection-dominated. The
temperature profile (see Fig. 1) for 1 \(M_\odot/s\) is similar to that from \[3\] and \[5\] but the
density profile is steeper than found in previous models. For 10 \(M_\odot/s\) we found a distinct
branch of solutions that is unstable due to the helium photodisintegration, which is
intrinsically incorporated in our EOS calculations.

Electron fraction
This is defined as: \(Y_e = \frac{n_{e^-} - n_{e^+}}{n_b}\). For a given the temperature, the electron fraction
changes with increasing baryon number density (Fig. 2). At high densities, \(Y_e\) roughly
equals 0.5, because the torus consists of plenty of ionized helium and some electrons
(the ratio of photon to baryon is small). As the density decreases, helium starts to
dissolve into free neutrons and protons. After that, the electron fraction begins to adjust
to satisfy the beta-equilibrium in the gas. For high temperatures the positrons appear, as
the electrons become non-degenerate; positron capture by neutrons again increases \(Y_e\).

In the time-dependent calculations, initially \(Y_e\) remains small in the innermost disc.
Then it starts to increase with time, due to the disk evolution and gradual drop in
accretion rate, density and temperature.
FIGURE 1. Density and temperature profiles in the disk, for accretion rates of $10 M_\odot/s$ (upper line) and $1 M_\odot/s$ (bottom line).

FIGURE 2. Left: Electron fraction as a function of baryon number density, for 3 various temperatures: $10^{10}, 5 \times 10^{10}$, and $10^{11}$. Right: Electron fraction as a function of time, at several radii in the accretion disk: 4.06, 6.64, 9.85, 20.06, 35.37, 42.37, and 46.10 $R_{\text{Schw}}$.

Stability of the disk
For $M \approx 10 M_\odot/s$ the disk becomes unstable below $10 R_S$ (Fig. 3). Here helium is almost completely photodisintegrated while the electrons become non-degenerate again. For this high accretion rate, the electron fraction rises inwards in the disk. Under these physical conditions the energy balance is affected, leading to the thermal and viscous instability (as demonstrated in the stability curves).

The disk instability leads to fluctuations and a variable accretion rate. This in turn may cause a variable energy output in the jet, and hence a variable Lorentz factor $\Gamma$. This is a fundamental ingredient in order to obtain internal shocks. This type of instability was
FIGURE 3. Left: stability curves on the accretion rate vs. surface density plane, for several chosen radii in the disc: $3.01R_S$, $4.06R_S$, $5.27R_S$ and $11.69R_S$. Right: Fluctuations of the accretion rate at $10R_S$ due to the disk instability.

already found in collapsar simulations ([7]).

SUMMARY

We model the central engine of a GRB with a hyperaccreting disk, cooled by neutrino emission and advection of energy onto the central stellar mass black hole. The equation of state is determined under the assumption of the $\beta$ equilibrium. The chemical composition of matter includes free protons, neutrons, electrons and positrons, as well as helium nuclei. Neutrinos are trapped in the disk due to absorption and scattering on nucleons, and for accretion rates $\dot{M} \geq 1M_\odot/s$ the advective cooling in the inner disk parts is relatively more important. The electron fraction in the disk is much lower than 0.5. The presence of helium nuclei and electron-positron pairs is crucial for the occurrence of an instability in the inner disk.

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