ACCRETION AND OUTFLOW FROM A MAGNETIZED, NEUTRINO COOLED TORUS AROUND THE GAMMA RAY BURST CENTRAL ENGINE

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ABSTRACT

We calculate the structure and short-term evolution of a gamma ray burst central engine in the form of a turbulent torus accreting onto a stellar mass black hole. Our models apply to the short gamma ray burst events, in which a remnant torus forms after the neutron star-black hole or a double neutron star merger and is subsequently accreted. We study the 2-dimensional, relativistic models and concentrate on the effects of black hole and flow parameters as well as the neutrino cooling. We compare the resulting structure and neutrino emission to the results of our previous 1-dimensional simulations. We find that the neutrino cooled torus launches a powerful mass outflow, which contributes to the total neutrino luminosity and mass loss from the system. The neutrino luminosity may exceed the Blandford-Znajek luminosity of the polar jets and the subsequent annihilation of neutrino-antineutrino pairs will provide an additional source of power to the GRB emission.

Subject headings: accretion, accretion disks; black hole physics; magnetohydrodynamics (MHD); neutrinos; relativistic processes; gamma ray burst:general

1. INTRODUCTION

Gamma Ray Bursts (GRB), known for about forty years [Klebesadel et al. 1973], are extremely energetic transient events, visible from the most distant parts of the Universe. They last from a fraction of a second up to a few hundreds of seconds and are isotropic, non-recurrent sources of gamma ray radiation (10 keV - 20 MeV). Short gamma ray bursts were distinguished in the KONUS data by [Mazets & Golentski 1981] and further by [Kouveliotou et al. 1993]. The energetics of these events points to a cosmic explosion as a source of the burst, associated with the compact objects such as black holes and neutron stars. The short timescales and high Lorentz factors of the gamma ray emitting jets are most likely produced in the process of accretion of rotating matter that supports the rotating torus.

Accretion of magnetized torus onto a black hole with a range of spin parameters was studied by [De Villers et al. 2003; McKinney & Gammie 2004] and applied to the long gamma ray bursts [Nagataki 2009]. The relativistic simulations of accretion flows with an ideal gas equation of state were studied e.g., by [Hawley & Krolik 2006] and McKinney & Blandford 2009 and recently more sophisticated models with a realistic EOS were proposed by Barkov & Komissarov 2008, 2010 and Barkov 2008; Barkov & Baushev 2011.

This central engine gives rise to the most powerful jets (Zhang & Meszaros 2004; Piran 2005; Gehlers et al. 2009; Metzger 2010, Gehlers et al. 2009, Metzger 2010). Despite the existence of still unsolved problems, such as the composition of the outflows, the emission mechanisms creating the gamma rays, or the form of energy that dominates the jet (i.e. kinetic or Poynting flux), the jets themselves are believed to be powered by accretion and rotation of the central black hole. In this process, the strong large-scale magnetic fields play a key role in transporting the energy to the jets (McKinney 2006; Tchekhovskoy et al. 2008; Dexter et al. 2012).

In addition to the magneto-rotational mechanism of energy extraction, the annihilation of neutrino-antineutrino pairs, emitted from the accreting torus, may provide some energy reservoir available in the polar regions to support jets. The neutrinos are produced in central engines of both short and long GRBs, the latter being modeled in the frame of the collapsing massive star scenario (Woosley 1993; Paczynski 1998). The recent numerical simulations of the hypernovae aimed to capture the effects of both MHD and neutrino transport in the supernova explosion modeling (Burrows et al. 2007), using a flux-limited neutrino diffusion scheme in the Newtonian dynamics. The general relativistic simulations by Shibata et al. 2007 on the other hand, consider the neutrino cooling of the accreting torus around the black hole and capture the neutrino-trapping effect in a qualitative way.

In this work, we study the central engine, composed of a stellar mass, rotating black hole and accreting torus that has formed from the remnant matter at the base of the GRB jet. We start from an axially symmetric, configuration of matter filling the equipotential surfaces around a Kerr black hole [Fishbone & Moncrief 1976].

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Abramowicz et al. (1978), assuming an initial poloidal magnetic field. The MHD turbulence amplifies the field and leads to the transport of angular momentum within the torus. In the dynamical calculations, we use a realistic equation of state while we account for the neutrino cooling (Yuan 2005; Janiuk et al. 2007). We study the evolution and physical properties of such an engine, its neutrino luminosity and production of a wind and outflow from the polar regions. Our calculations are 2-D and relativistic, therefore this work is a generalization of the model presented in Janiuk et al. (2007); Janiuk & Yuan (2010), where a simpler steady-state, 1-dimensional model of a torus around a rotating black hole was analyzed, using approximate correction factors to the pseudo-Newtonian potential that allowed to mimic Kerr metric. The microphysics however is currently described using the EOS from that work and neutrino cooling is incorporated into the HARM scheme via the cooling function. The total pressure invoked to compute the cooling is contributed by the free and degenerate nuclei, electron-positron pairs, helium, radiation and partially trapped neutrinos. This allows us to compute the optical depths for neutrino absorption and scattering and the neutrino emissivities in the optically thin or thick plasma.

The article is organized as follows. In §2 we describe our model, the initial conditions, the dynamical evolution of the system and the assumed chemical composition as well as the processes responsible for energy losses via neutrino cooling. In §3 we present the results, describing the effects of (i) black hole mass (ii) its spin (iii) torus mass, and (iv) magnetic field strength. We also discuss the effect of neutrino cooling on the torus structure, in comparison with the reference model with such cooling neglected. Finally, we compare our results with the 1-D simulations of the vertically averaged torus, emphasizing the effects of 2-dimensional computations. We discuss the results in §4.

2. MODEL OF THE HYPERACCRETING DISK

The model computations are based on the axisymmetric, general relativistic MHD code HARM-2D, described by Gammie et al. (2003) and Noble et al. (2006). The nuclear equation of state is discussed in detail in Janiuk et al. (2007). The goal of our calculations is to investigate the overall structure of a magnetized, turbulent accretion disk in which nuclear reactions take place and the gas looses energy via neutrino cooling, and in particular to expand our previous 1-dimensional models based on α viscosity, to the case of 2-D GRMHD.

2.1. Initial conditions and dynamical model

We start the numerical calculations from the equilibrium model of a thick torus around a spinning black hole as introduced by Fishbone & Moncrief (1976) and Abramowicz et al. (1978). The parameters of the model are the central black hole mass, $M_{\text{BH}} = 3 - 10M_\odot$, the dimensionless spin of the black hole, $a = 0.8 - 0.98$, and the total mass of the surrounding gas, $M_{\text{torus}} = 0.1 - 2.5M_\odot$ (see Table 1 for the list of models). We seed the torus with a poloidal magnetic field (magnetic field lines follow the constant density surfaces); the strength of the initial magnetic field is normalized by the gas to magnetic pressure ratio at the pressure maximum of the initial structure of the disk ($\beta = P_{\text{gas}}/P_{\text{mag}} = 5 - 100$). In the dynamical calculations, we use $P = (\gamma - 1)u$ equation of state with the adiabatic index $\gamma = 4/3$. To follow the evolution of the gas dynamics near a black hole we use a numerical MHD code HARM-2D. The numerical code is designed to solve magnetohydrodynamic equations in the stationary metric around a black hole.

In this work, we modify the MHD code to account for the chemical composition of the nuclear matter accreting onto black hole in the GRB environment (described in more detail in §2.2). At each time moment of the simulation we calculate the gas nuclear composition assuming the balance of nuclear equilibrium reactions. This gives us expected neutrino cooling rates which we incorporate into the code. After each time step of the dynamical evolution the total internal energy of gas is reduced by $Q_\nu \Delta t$ factor using an explicit method with $n$-sub-cycles. The procedure for calculating the neutrino cooling takes into account the change of the gas internal energy in the comoving frame, which is a correct relativistic approach. We do not account for the neutrino transfer though, and the effects like the gravitational redshift are neglected.

Our models have numerical resolution of the grid $256 \times 256$ points in $r$ and $\theta$ directions (see also Sect. 3.1.2). The grid is logarithmic in radius and condensed in polar direction towards the equatorial plane, as in Gammie et al. (2003).

2.2. Chemical composition and neutrino cooling

We assume that the neutrino emitting plasma consists of protons, electron-positron pairs, neutrons and helium nuclei. The gas is in beta equilibrium, so that the ratio of protons to neutrons satisfies the balance between forward and backward nuclear reactions.

Neutrinos are formed in the URCA process, electron positron pair annihilation, nucleon - nucleon bremsstrahlung, plasmon decay. These reactions are:

\begin{equation}
\begin{aligned}
p + e^- &\rightarrow n + \nu_e \\
n + e^+ &\rightarrow p + \bar{\nu}_e \\
n &\rightarrow p + e^- + \bar{\nu}_e
\end{aligned}
\end{equation}

and

\begin{equation}
\begin{aligned}
\gamma &\rightarrow ve + \bar{\nu}_e \\
e^- + e^+ &\rightarrow \nu_1 + \bar{\nu}_1
\end{aligned}
\end{equation}

and

\begin{equation}
n + n &\rightarrow n + n + \nu_1 + \bar{\nu}_1.
\end{equation}

For a given temperature and density, the neutrino cooling rate is calculated from the balance between the above reactions, supplemented with the conditions of the conservation of the baryon number and charge neutrality (Yuan 2005; see also Kohri & Mineshige 2002, Chen & Beloborodov 2007, Janiuk et al. 2007).

We assume that the cooling proceeds via electron, muon and tau neutrinos in the plasma opaque to their absorption and scattering. The URCA process and plasmon decay produce the electron neutrinos only, while the other processes produce neutrinos of all flavors. The emissivities of these processes are

\begin{equation}
q_{\text{brems}} = 3.35 \times 10^{27} \rho_2^2 \xi_1^{5.5},
\end{equation}

where $\rho_2$ is the baryon density in units of $10^2 M_\odot$ and $\xi_1$ is the electron fraction.
\[ q_{\text{plasmon}} = 1.5 \times 10^{32} T_4^3 \rho_7^6 e^{-\gamma_p} (1 + \gamma_p) \left( 2 + \frac{\gamma_p^2}{1 + \gamma_p} \right), \]

\[ q_{\nu_e} = q_{\nu_e}^\text{pair} + q_{\nu_e}^\text{brems}, \quad (6) \]

\[ q_{\nu_\mu, \tau} = q_{\nu_\mu, \tau}^\text{pair} + q_{\nu_\mu, \tau}^\text{brems}, \quad (7) \]

and

\[ q_{\text{urca}} = q_{p + e^{-} \rightarrow n + \nu_e} + q_{n + e^{+} \rightarrow p + \nu_e} + q_{n + p + e^{-} \rightarrow n + \nu_e}. \quad (8) \]

the two latter being iterated numerically (the full set of Equations is given in the Appendix of Janiuk et al. 2007). Here \( \rho_{10} \) is the baryon density in the units of \( 10^{10} \) g/cm\(^3\) and \( T_{11} \) is temperature in the units of \( 10^{11} \) K. The emissivities are given in the units of \([\text{erg cm}^{-3}\text{s}^{-1}]\). We neglect here the term of neutrino cooling by photodissociation of helium nuclei, since at the temperatures and densities obtained in the presented models, this term will be practically equal to zero.

The plasma can be opaque to neutrinos, so we use the optical depths, given by the equations derived in Di Matteo et al. 2002:

\[ \tau_{a, \nu_i} = \frac{H}{4 \pi \sigma T^4} q_{a, \nu_i}, \quad (9) \]

where absorption of the electron neutrinos is determined by

\[ q_{a, \nu_e} = q_{\nu_e}^\text{pair} + q_{\nu_e}^\text{brems}, \quad (10) \]

and for the muon and tau neutrinos is given by

\[ q_{a, \nu_{\mu, \tau}} = q_{\nu_{\mu, \tau}}^\text{pair} + \frac{1}{3} q_{\nu_{\mu, \tau}}^\text{brems}. \quad (11) \]

We also account for the neutrino scattering and the scattering optical depth is given by:

\[ \tau_s = \tau_{s, p} + \tau_{s, n}, \quad (12) \]

\[ = 24.28 \times 10^{-5} \left[ \left( \frac{kT}{m_e c^2} \right)^2 H (C_{s, p} n_p + C_{s, n} n_n) \right] \]

where \( C_{s, p} = (4(C_Y - 1)^2 + 5a^2)/24, \) \( C_{s, n} = (1 + 5a^2)/24, \) \( C_Y = 1/2 + 2\sin^2 \theta_C, \) with \( a = 1.25 \) and \( \sin^2 \theta_C = 0.23 \) \cite{Yuan2003} \cite{Reddyetal1998}.

The neutrino cooling rate is finally given by

\[ Q_\nu = \frac{7 \sigma T^4}{4} \sum_{i=e, \mu, \tau} \frac{\tau_{s, i}^{
u_{\tau, i}} + \tau_{s, \nu_{e, \tau}}^{
u_{\tau, i}}}{2} \frac{1}{\sqrt{3}} \frac{1}{\sqrt{3}} \times \frac{1}{H} \text{[erg s}^{-1} \text{cm}^{-3}] \quad (13) \]

and the neutrino luminosity emitted by the plasma is

\[ L_\nu = \int Q_\nu dV \text{[erg s}^{-1}]. \quad (14) \]

where \( dV \) is the unit volume in the Kerr geometry.

The optical depths for absorption and scattering are calculated approximately by assuming the disk vertical thickness equal to the pressure scale-height, \( H = c_s/\Omega_K \), where \( c_s \) is the speed of sound and \( \Omega_K = \sqrt{aM/1.7m_H} (a + r^3/2)^{1/2} \) is the Keplerian frequency \cite{Lopez-Camaraetal2009}. The resulting thickness is roughly proportional to a fraction of the disk radius and the typical ratios are \( H/r \sim 0.3 - 0.5 \).

\[ q_{\nu_{e, \mu, \tau}} = q_{\nu_{e, \mu, \tau}^\text{pair}} + q_{\nu_{e, \mu, \tau}^\text{brems}}. \quad (11) \]

We do not account for the neutrino heating in the jets via the annihilation process, because of large uncertainties in the internal energy computations in the jet.

The neutrino cooling is limited to the torus and wind only, via the density and temperature ranges for which the cooling is operating \( \left(10^9 - 10^{10} \text{ g cm}^{-3}\right) \) and \( \text{and} 10^7 - 10^{12} \text{ K}, \) respectively. Therefore the jets are not shown in the neutrino cooling maps.

3. RESULTS

3.1. Effect of the BH parameters and torus mass on the \( M \) and neutrino luminosity

We studied the models with the black hole mass of \( M_{BH} = 3M_\odot \) or \( M_{BH} = 10M_\odot \), and torus mass was assumed equal to about 0.1, 0.3, 0.7, 1.0 or 2.6 \( M_\odot \) \cite{Table1}. In Figure 1 we show the time evolution of the mass accretion rate onto black hole, for the two values of torus and black hole mass. The average accretion rate onto black hole is not changing much with the black hole spin and is about 0.3-1.0 \( M_\odot \text{s}^{-1} \) for most SBH models. The accretion rate for the first 2-3 milliseconds is very small, and then grows to about 0.2-0.5 \( M_\odot \text{s}^{-1} \) and starts varying. During such flares, it exceeds momentarily 2-5 \( M_\odot \text{s}^{-1} \). These flares are however very short in duration. The mean accretion rate in our models does not exceed 1 \( M_\odot \text{s}^{-1} \).

The magnitude of the flares depends on the black hole spin, and largest is for \( a = 0.8 \) in the small disk models (SBH). The amplitude of flares is by a factor of \( \sim 2 - 3 \) larger for the black hole mass of 10 \( M_\odot \) (LBH). In the LBH models, the case with \( a = 0.9 \) shows higher flares at the early evolution, while the \( a = 0.8 \) model is flaring in the late times. After the time of about \( t = 3000M \), the accretion rate decreases, the flaring ceases and a rather stable value below \( M \lesssim 0.3M_\odot \text{s}^{-1} \) is reached. The late time activity ceases because of the decay of magnetic turbulence characteristic for axisymmetric models.

In Figures 2 and 3 we show the maps of the torus structure calculated in the 2-D model for the black hole mass \( M_{BH} = 3M_\odot \) and 10\( M_\odot \), and torus mass of 0.1\( M_\odot \) and
1.0\,M_\odot$, respectively (models SBH3 and LBH3 in Table 1). The snapshots, taken at the end of the simulation for time $t = 2000\,G_{\text{BH}}/c^3$, present the baryon density $\rho$, gas temperature $T$ and magnetic $\beta$ parameter overplotted with magnetic field lines, as well as the neutrino cooling.

The neutrino luminosity evolution with time is shown in Figure 4 (models with small and large black hole mass). For the black hole mass of 0.1 $M_\odot$, the initial neutrino luminosity calculated using Eq. 13 is about $10^{52}$ erg s$^{-1}$. Then the luminosity gradually grows to over $10^{53}$ erg s$^{-1}$ and peaks at time $t = 0.01$ s, which is equal to about 660 M. For the black hole mass of 10 $M_\odot$ and more massive torus of 1.0 $M_\odot$, the total luminosity is higher and at maximum reaches values almost $10^{54}$ erg s$^{-1}$, at about $t = 0.04$s (equal to about 800 M). At the end of the simulation, the neutrino luminosity is about $2 \times 10^{53}$ in this model and depends mostly on the ratio between the torus and black hole mass. The exact values of $L_\nu$ at the end of the simulation are given in Table 1 for a range of parameters.

The neutrinos are emitted from the torus as well as from the hot, rarefied wind. The luminosity of this wind gives substantial contribution to the total luminosity and it is about 8-13 % for SBH models, and 10-15 % for LBH models, anticorrelating with the black hole spin. This fraction was estimated geometrically, i.e. the wind luminosity was calculated by integrating the emissivities over the volume above and below $30^\circ$ from the mid-plane. The luminosity of the densest parts of the torus, on the other hand, which can be estimated e.g. by weighing the total emissivity by the plasma density, is not more than $10^{48} - 10^{49}$ erg s$^{-1}$, because the opacity for neutrino absorption and scattering in these regions reaches $\tau \sim 0.1$.

The velocity field maps at the end of the simulation, for $M_{\text{BH}} = 3\,M_\odot$ and $M_{\text{BH}} = 10\,M_\odot$ are shown in Figure 5. The figures show results of the models with highest $\beta = 100$ at time $t=4000$ M, so that we could obtain clear polar jets. In the first case, the torus is turbulent, the wind outflow occurs, but most of material is swept back from the outermost regions and finally accretes onto black hole. Some fraction of gas is lost via the hot winds at moderate latitudes. In the second model, the disk winds are sweeping the gas out from the system, both in the equatorial plane and at higher latitudes. We identified the regions of the wind in the computation domain by defining three conditions that must be satisfied simultaneously: (i) the radial velocity of the plasma is positive (ii) the density is smaller than $10^9$ g cm$^{-3}$ and (iii) the gas pressure is dominant, $\beta > 0.1$. The two latter conditions are somewhat arbitrary but they are necessary to distinguish the wind from the turbulent dense torus and from the magnetized jets. The winds are located approximately at radii above $10\,R_g$ and latitudes between about $30^\circ$ - $60^\circ$ and $120^\circ$ - $150^\circ$. The velocity in the wind is 0.005 - 0.18 of the velocity of light (models SBH) and 0.002 - 0.06 (models LBH). In the first case, it is on the order of the escape velocity, while in the second case the winds are bound by the black hole gravity (cf., e.g., McKinney 2006, who found the winds with half opening angles of $\theta = 16 - 45^\circ$ and mildly relativistic velocities). Such large-scale circulations can be determined in the simulations with a much larger radial domain (e.g. Narayan et al. 2012; McKinney, Tchekhovskoy & Blandford 2012).

The effect of the wind is the mass loss from the system. We estimated quantitatively the evolution of the mass during the simulation. The total mass removed from the torus as a function of time, calculated by integrating the density over the total volume, differs significantly from the total mass accreted onto the black hole (i.e. the time integrated mass accretion rate through the inner boundary, subtracted from the initial mass). For models with $M_{\text{BH}} = 3\,M_\odot$, the denser and cooler torus, with smaller gas pressure to magnetic pressure ratio, launches a wind and about 50% of mass is lost through wind, while the rest is accreted onto black hole. However, for the black hole of $10\,M_\odot$, after the wind is launched, it takes away about 75% of mass from the system. In other words, the average mass loss rate in the winds is either equal to or larger (in particular, in LBH models, it may be even 3 times larger) than the accretion rate onto the black hole. The results are weakly sensitive to the black hole spin value.

The physical conditions in the winds are different from those in the torus. The densities are a few orders of magnitude smaller, between $5 \times 10^8$ and $10^9$ g cm$^{-3}$, while the temperatures in the wind are very high, in the range $7 \times 10^8 - 5 \times 10^{10}$ K (in general, the winds in models LBH are slightly hotter and less dense than in SBH). Such high temperatures, above the treshold for electron-positron pair production, $T = m_e c^2 \approx 5 \times 10^9$ K, are the key condition for neutrino emission processes. The neutrino cooling is then efficient and only weakly depends on density. In the clumps with $\rho > 10^8$ g cm$^{-3}$, the nuclear processes lead to neutrino production, while the optical depths for their absorption are very small.

The hot, rarefied, transient polar jets appear as well on both sides of the black hole, as seen in Figure 5 as well as in the maps in Figs. 4 and 9. The limitation of our model is only that here we do not study the neutrino emission in these jets.

In this Section, we show the results of the models where the thickness of the torus is given by the pressure scale-height at the equator. This is about 0.3 times the radius. We also tested the approximate condition for the disk thickness being a fraction of the radius, $H \sim 0.5 r$. We verified that the disk thickness parametrization of neutrino cooling does not affect much the accretion rate onto black hole neither the total luminosity.

3.1.1. Optically thin and thick tori

We find no clear neutrinosphere in the models where the torus to the black hole mass ratio is small and the accretion rate is below $\sim 1\,M_\odot$ s$^{-1}$. In these models, the torus and wind are both optically thin to neutrinos and radiate efficiently. The optical depths due to the scattering and absorption of neutrinos, calculated in the equatorial plane, are shown in Figure 6. As shown in the top and middle panels of the Figure, $\tau_{\nu\nu} \approx 0.15$ in the innermost parts of the torus at the equator, for the model with black hole mass $M_{\text{BH}} = 3\,M_\odot$ and disk mass of 0.1$M_\odot$ (i.e., SBH3 and LBH3). Above the equator, the optical depths are much smaller. Also, the model with back hole mass $M_{\text{BH}} = 10\,M_\odot$ and disk mass of 1.0$M_\odot$ gives small neutrino optical depths, up to about 0.05.
The flow is optically thin to neutrinos for the magnetic field parameter $\beta = 50$ as well as $\beta = 5$. Therefore the neutrino pressure is much less than both the gas and magnetic pressures.

In the bottom panel of the Figure 6, we show the results from the model SBH8, where the torus mass was assumed 1.0$M_\odot$ and the black hole mass was $M_{BH} = 3M_\odot$. The accretion rate onto the black hole was in this case larger than 1.0$M_\odot$s$^{-1}$ and the optical thicknesses to the neutrino absorption and scattering were larger than unity within the inner 3 gravitational radii in the torus equatorial plane. The neutrino luminosity of the plasma is affected by the opacities. However, the neutrino trapping effect that was clearly present in the 1-D models, is now rather subtle and plays a role in the densest, equatorial regions of the torus. In Figure 7 we plot the neutrino luminosity weighted by the plasma density, i.e. $< L_\nu >_p = \int Q_\nu \rho dV / \int \rho dV$. We see, that after the initial conditions of the simulation are relaxed, about 0.01 s for the back hole mass $M_{BH} = 3M_\odot$, the luminosity of the more massive torus drops below the value obtained for the less massive one, optically thin to neutrinos. Still, the total neutrino luminosity of the system is dominated by the optically thin wind, and the total $L_\nu$ of the more massive torus is large (e.g. at $t_{end}$ it is equal to $9 \times 10^{52}$ and $4 \times 10^{53}$ ergs$^{-1}$ respectively; see Table I).

In Figure 8 we show the total neutrino luminosity (i.e. the disk and wind luminosity), in the models with different BH and disk mass. These models are optically thin. In Figure 7 we show the luminosity weighted by the density, which represents the densest parts of the disk, where the optical depths could be larger than 1. The meaning of Fig. 7 is therefore to compare the optically thick and thin models, which have luminosities slightly
Fig. 4.— Total neutrino luminosity as a function of time. The black hole mass is $M_{\text{BH}} = 3\,M_\odot$ and torus initial mass is $M_\text{d} \sim 0.1\,M_\odot$ (bottom panel) and $M_{\text{BH}} = 10M_\odot$ and $M_\text{d} \sim 1.0\,M_\odot$ (top panel). The black hole spin is $a = 0.98$.

Fig. 5.— Velocity fields at the end of the simulation, $t = 4000\,M$, for black hole mass of $3M_\odot$ (left) and $10M_\odot$ (right). Other parameters: spin $a = 0.98$, $\beta = 100$. The torus mass is $M_{\text{torus}} \approx 0.1\,M_\odot$ or $1.0\,M_\odot$, respectively.

different due to neutrino absorption. Still, the luminosities are on the same order of magnitude, after the initial conditions are relaxed. The differences in the initial conditions leading to the luminosity differences are mainly due to a larger size and mass of the disk in the compared models, determined by the initial location of the pressure maximum. After the torus redistributes itself and matter accretes through the black hole horizon, the initial conditions are relaxed.

3.1.2. Resolution tests

As a standard resolution, we use $256 \times 256$ zones in $r$ and $\theta$. For numerical test, we also checked two other resolutions, for the model SBH3. The lowest resolution model was with $128 \times 128$ zones and highest resolution was with $512 \times 512$ zones. We found the increase of total neutrino luminosity with resolution at late times of the evolution, up to a factor of 2 between the two extreme cases. The time averaged neutrino luminosity is equal to $4.74 \times 10^{52}$, $1.04 \times 10^{53}$ and $6.55 \times 10^{52}$ erg s$^{-1}$, for the low, medium and high resolution models, respectively. Also, the relaxation from initial conditions is reached earlier for the largest resolution. For the disk structure, the increase of resolution results in a slight temperature increase and density rise in the inner regions of the torus, because the magneto-rotational turbulence is better resolved and accretion rate is increased. The time dependence of accretion rate onto black hole is finest for highest resolution models. The peaks in the accretion rate are higher, occur earlier during the evolution and continue to the end of simulation.

Fig. 6.— Neutrino optical depths due to absorption on tau and muon neutrinos (dashed lines) and scattering (dotted lines) and total (solid lines), at the end of the simulation for the models with $M_{\text{BH}} = 3M_\odot$ and torus mass $M_{\text{torus}} \sim 1.0M_\odot$ (bottom) $M_{\text{BH}} = 3M_\odot$ and torus mass $M_{\text{torus}} \sim 0.1M_\odot$ (middle), or $M_{\text{BH}} = 10M_\odot$ and $M_{\text{torus}} \sim 1.0M_\odot$ (top). The profiles are taken in the equatorial plane. The black hole spin is $a = 0.98$.

Fig. 7.— Comparison of the optically thin and thick models. Neutrino luminosity weighted by the plasma density, at the end of the simulation. The models are with $M_{\text{torus}} \sim 1.0M_\odot$ (thick solid line) and $M_{\text{torus}} \sim 0.1M_\odot$ (thin dashed line) The black hole mass is $M_{\text{BH}} = 3M_\odot$, spin $a = 0.98$ and magnetization $\beta = 50$. 

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Still, we conclude that it is justified to keep the moderate resolution as the basic one, as it satisfies the balance between accuracy and computation time.

3.2. Effects of the black hole spin

We ran our small and large black hole simulations with three values of the black hole spin parameters, \( a = 0.98, a = 0.9, \) and \( a = 0.8 \). The value of black hole spin is qualitatively not very significant for the average properties of the torus. For the lower spins, the torus is slightly hotter and less magnetized, with the neutrino emissivity being smaller both in the torus and in the wind.

The flaring activity, shown in the Figure 4 and discussed above, is stronger for smaller black hole spins at late times, and the accretion rate onto black hole occasionally reaches 3–4 or even 5–6 \( M_{\odot}s^{-1} \), depending on the black hole to torus mass ratio. The fast spinning black holes launch powerful and steady polar jets. However, the values of the Blandford-Znajek luminosity as given in Table 1 do not differ significantly for our spins (\( a=0.8-0.98 \)). These results should be further verified by the 3-dimensional simulations with a range of grid resolutions.

The mean accretion rate onto the black hole decreases with black hole spin, as given in Table 1. The result is therefore the same as in De Villers et al. (2003), regardless of the neutrino cooling included.

3.3. Effect of the magnetic field

The magnetic field in our simulations was parametrized with initial conditions of \( \beta = P_{\text{gas}}/P_{\text{mag}} \) of a fixed value with a maximum at the pressure maximum radius and zero everywhere outside of the torus.

The mean value of \( \beta \), integrated over the total volume, was at \( t = 0 \) infinite due to such initial conditions, but at the end of the simulation converged to the value assumed for the torus. The mean \( \beta \) weighted by the density was always a bit larger than the total volume integrated beta due to the dominating gas pressure in the disk.

Changing the magnetic field normalization \( \beta \) affects somewhat the resulting structure of the torus. The torus density increases with \( \beta \): the maximum density at the equatorial plane for the torus around a \( 3M_{\odot} \) black hole with \( \beta_{\text{init}} = 50 \) is \( \rho_{\text{max}} \approx 1.5 \times 10^{12} \text{ g cm}^{-3} \), for \( \beta_{\text{init}} = 10 \) it is \( 3.5 \times 10^{11} \text{ g cm}^{-3} \), and for \( \beta_{\text{init}} = 5 \) it is \( 1.5 \times 10^{11} \text{ g cm}^{-3} \) (all results are for \( t = 0.03 \text{ s} \) of the torus evolution; the models we compare are SBH3, SBH4 and SBH5). Similar trend in density is found for other torus to black hole mass ratios. The temperature of the torus is roughly similar for all the \( \beta \) values we tested and \( T_{\text{max}} \approx 1.2 \times 10^{11} \text{ K} \), however the jets are cold only for the highest \( \beta \). The latter might be affected by numerical effects, so we do not analyze the jets structure here.

For the largest \( \beta_{\text{init}} \) we tested, the contrast between the highly magnetized polar jets and weakly magnetized disk is most pronounced. For smaller \( \beta \), we have a region of mildly magnetized flow in the intermediate latitudes. The speed of evolution of the disk also depends on \( \beta \) and the shortest relaxation time is for the model with smallest \( \beta_{\text{init}} \), because the viscous time scale is small in this case. On the other hand, the large \( \beta \) means that the magnetic field is weak and therefore the action of magnetic dynamo most quickly dies out.

![Figure 8: Neutrino luminosity as a function of time, for the neutrino cooled model with black hole mass 3M_\odot and spin a = 0.98, with \( \beta = 100 \).](image)

In Figure 8 we show the neutrino luminosity for \( \beta = 100 \). The general evolution of the luminosity does not depend on \( \beta \), so the maximal neutrino luminosity is reached at time \( t \approx 0.01 \), and then \( L_{\nu} \) slowly decreases. The value of the maximum luminosity exceeds \( 2 \times 10^{53} \text{ erg s}^{-1} \). This value does not depend significantly on \( \beta \) parameter and the differences (see Table 1) should be attributed mainly to numerical uncertainties (see Section 3.1.2).

The Figure 8 shows the simulation up to time 4000 M (model SBHib). For the initial configuration, estimated as the ratio between the total thermal energy and neutrino luminosity, is in this model equal to 0.12 s, while in the models SBH4 and SBH5 (\( \text{beta} = 10 \) and \( \beta = 5 \)), it is equal to \( \tau_{\nu} \approx 0.05 \sim 0.07 \text{ s} \).

3.4. Comparison to the models without neutrino cooling

The torus around the spinning black hole at hyper-Eddington rates is cooled by neutrinos and in the 1-D simulations the neutrino cooling effects were studied e.g., by Janiuk et al. (2007); Chen & Beloborodov (2007). To quantify the effect of neutrino cooling in 2D MHD simulations, we ran a test model with no cooling assumed.

In Figure 9 with a thin dashed line we plot the accretion rate as a function of time for an exemplary model without neutrino cooling. The average accretion rate onto black hole is lower in these models than in the cooled models, for the same black hole spin and magnetic field. Decreasing the \( \beta \) parameter, i.e. increasing the viscosity, results in the increase of the accretion rate, similarly to the \( \alpha \)-disks.

The density of the disk in the models without cooling is smaller in the equatorial plane, the disk being less compact (i.e., less dense and geometrically thicker) and hotter than in the neutrino-cooled disks. The disk with-
neutrino cooling, as shown in the example in Figure 12.

The ratio of neutrino cooling, as shown in the example in Figure 12. The black hole mass is $3 M_\odot$, its spin is $a = 0.98$, and the initial disk mass is $0.1 M_\odot$. The initial magnetic field normalization is $\beta = 10$.

![Fig. 9. — Accretion rate as a function of time, in the models with and without neutrino cooling (solid and dashed lines, respectively). The black hole mass is $3 M_\odot$, its spin is $a = 0.98$, and the initial disk mass is $0.1 M_\odot$. The initial magnetic field normalization is $\beta = 10$.](image1)

The distribution of gas to magnetic pressure in the equatorial plane of the torus in the function of radius, at the end of the simulation ($t_{\text{end}} = 2000M$), for the models with and without neutrino cooling (solid and dashed lines, respectively). The black hole mass is $3 M_\odot$, and its spin is $a = 0.98$, while the initial disk mass is $0.1 M_\odot$, and initial magnetic field normalization is $\beta = 50$.

![Fig. 10. — The ratio of the gas to magnetic pressure in the equatorial plane of the torus in the function of radius, at the end of the simulation ($t_{\text{end}} = 2000M$), for the models with and without neutrino cooling (solid and dashed lines, respectively). The black hole mass is $3 M_\odot$, and its spin is $a = 0.98$, while the initial disk mass is $0.1 M_\odot$, and initial magnetic field normalization is $\beta = 50$.](image2)

out cooling is also more magnetized i.e. the ratio of gas to magnetic pressure, $\beta$, is on average smaller in the disk. This is because the pressure decreases with smaller density, albeit the higher temperatures in the plasma.

The distribution of gas to magnetic pressure in the equatorial plane is shown in Figure 10. The maps of the density, temperature and magnetic field are shown in Figure 11.

Also, the thickness of the torus, measured by the pressure scale height at the equator, is larger in case of no neutrino cooling, as shown in the example in Figure 12. The ratio of $H/r$ is about 0.3-0.5 in the model without neutrino cooling, and it is 0.1-0.3 in the cooled disk (initial approximation of $H = 0.5 r$ was used to compute the neutrino opacities).

To sum up, the mass accretion rate remains similar, but the structure of the disk changes, compared to the torus evolving with no neutrino cooling: the disk is geometrically thinner and more magnetized.

3.5. Comparison with 1-dimensional models

In this section, we quantify the effects of 2-dimensional GR MHD approach with respect to the simplified 1-D neutrino cooled torus model (Janiuk et al. 2007) and compare the 1D and 2D models. The 1-D model is parametrized by the black hole mass, spin and $\alpha$ viscosity. To compare its results with the relaxed model in 2-D simulations, we set these parameters to $3 M_\odot$, 0.98 and 0.1, respectively, which corresponds to the SBH5 2-D model in the Table 1. The accretion rate is taken equal to $0.17 M_\odot s^{-1}$ which is the mean accretion rate computed after evolving the 2-D model.

The structure of the disk in our 1-D model is calculated assuming the zero-torque boundary condition at the marginally stable circular orbit. Its location is dependent on the black hole spin, according to the formulae by Bardeen (1970) (see Janiuk & Yuan (2010) Eq. (17)). This condition is used for standard $\alpha$-disks and does not apply in the MHD simulations. The total mass of the torus, calculated up to $50 r_g$, is computed from integration of the converged surface density profile. The resulting value is of the same order as that assumed in the 2-D calculations by defining the location of the pressure maximum, the difference being mainly due to lower density in the inner $\sim 6 R_g$ of the 2-D model equatorial plane.

The viscosity in the 1-D simulations was parametrized by means of the Shakura & Sunyaev (1973) $\alpha$ constant. In the 2-D model, the viscosity is due to the magnetic turbulence, as parametrized with an initial value of $\beta$ inside the torus and infinite outside it, and then depending on the location and evolving in time.

The angular momentum is transported outwards due to magneto-rotational turbulence. In consequence, no constant value of viscosity is obtained, but after the initial conditions imposed by $\beta_{\text{init}} = P_{\text{gas}}/P_{\text{mag}}$ are relaxed, the system slowly converges to a value $\beta = \alpha (r_g/\beta)^{-1}$, which approximately corresponds to $\alpha$ via the relation $\alpha \approx 1/(2\beta)$. This approximate relation might be verified with a 3-D model of the magneto-rotational instability with Maxwell and Reynolds stresses computed directly.

The 2-dimensional structure of the torus is basically consistent with the results of 1-D models. The results are shown in Figure 13. The equatorial density profiles have the same average slopes and normalisations are within the same order of magnitude, up to $20 r_g$, however they differ due to the types of boundary conditions.

The temperature profiles have the same slopes in 1-D and 2-D equatorial plane. Their relative normalisations differ only slightly and they depend mostly on $\alpha$ value. We note that in the 2-D models the temperature is more sensitive to resolution, as the MHD turbulence is better resolved.

The neutrino cooling profiles in the 1-D and 2-D models are similar within 2 orders of magnitude. At inner parts of the tori the boundary conditions are different, and at outer parts the neutrino emissivity in 2-D model
Fig. 11.— Model without neutrino cooling. The parameters are: $a = 0.98$, $M_{BH} = 3M_\odot$, $\beta_{init} = 50$, $M_{torus} = 0.1M_\odot$. The maps, from left to right, show the distribution of density, temperature, ratio of gas to magnetic pressure with field lines topology, and velocity field. The snapshot is at $t = 0.03$ s since the formation of the black hole.

Fig. 12.— The thickness of the torus in the function of radius, at the end of the simulation, for the models with and without neutrino cooling (solid and dashed lines, respectively). The black hole mass is $3M_\odot$, and its spin is $a = 0.98$, while the initial disk mass is $0.1M_\odot$, and initial magnetic field normalization is $\beta = 50$.

decreases due to drop in density and temperature. Close to the inner edge of the torus, the emissivity in the 2-D model strongly varies, because of the magnetic turbulence and thermal flickering, which was not accounted for in the 1-D model.

4. SUMMARY AND DISCUSSION

We calculated the structure and short-term evolution of a gamma ray burst central engine in the form of a turbulent torus accreting onto a black hole. We studied the models with a range of value of the black hole spin, its mass to the torus mass ratio and magnetization. We found that (i) in the 2-dimensional computations, the neutrino cooling changes the torus structure, making it denser, geometrically thinner and less magnetized; (ii) the total neutrino luminosity reaches $10^{53} - 10^{54}$ erg s$^{-1}$, for the torus to black hole mass ratio 0.03-0.1, and the time of its peak anticorrelates with the black hole spin; (iii) at the end of the simulation, $t \sim 0.03$ or $t \sim 0.1$ s for smaller or larger black hole, the neutrino luminosity is about $10^{52} - 10^{53}$ erg s$^{-1}$, increasing with black hole spin; this is by 1-2 orders of magnitude larger than the Blandford-Znajek luminosity of the jets computed in our models; (iv) the neutrino cooled torus launches a fast, rarefied wind that is responsible for a powerful mass outflow, correlated with the torus to black hole mass ratio; (v) the contribution of the wind to the total neutrino luminosity is on the order of 10% and correlates with its mass; (vi) the density and temperature profiles in the equatorial plane of the 2-dimensional MHD torus are well reproduced by the vertically averaged profiles calculated
in the 1-dimensional α-disk model, however in the latter case the torus is cooler by a factor of 1.5-2; (vii) the neutrino cooling rates are similar for the inner ~ 20 – 30R⊙ in the 1D and 2D calculations. The structure of the central engine we modeled is relevant for any gamma ray burst, the free parameters being mainly the black hole spin and initial magnetic field strength. Without neutrino cooling, all the results scale with the black hole mass and the assumed mass and size of the initial torus. Here we have shown only the short timescale calculations, with no extra inflow of matter to the outer edge of the disk, which would be relevant for the subclass of long GRBs central engines. The internal structure of the torus should not depend on that, as supported e.g. by the recent observations by Swift showing that flares in both short and long GRBs are likely produced by the same intrinsic mechanism (Margutti et al. 2011). In the short GRB models, during the evolution of the post-merger disks the rings of material of a mass between 0.01 and 0.1 M⊙ can fall back from the eccentric orbits. In this way, the neutrino luminosity may brighten a few times on a timescale of > 1 second (Lee et al. 2009). Mass fallback from the stellar envelope material is also a key feature of the collapsar model for the long GRBs.

The mass of the torus assumed in most of our models is about 0.1-1.0 M⊙, when the black hole mass is fixed at 3 or 10 M⊙. A more massive torus, which can form in the center of a massive star as a ‘collapsar’ central engine, would result in accreting a substantial amount of mass and angular momentum onto the black hole. Therefore the evolution of the black hole mass and spin should consistently be taken into account, as shown e.g. by (Janiuk, Moderski & Proga 2008). This is currently neglected in our calculations, and we focus on the torus much less massive than the accreting black hole, M_{torus}/M_{BH} ≤ 0.25. This is still relevant for the compact binary merger scenario.

The initial conditions used in our models, similarly to other simulations, is based on the equilibrium torus solution and embedded magnetic field of a specified topology and strength. The recently simulated mergers of hypermassive neutron stars (e.g. Shibata et al. 2011) follow the evolution of matter and electromagnetic energy ejection during several tens of milliseconds and show that already at this stage the toroidal magnetic field component is developed and relativistic outflows occur. Then, it is expected that the neutron star will eventually collapse to a black hole, after a substantial loss of the angular momentum due to the gravitational wave emission, and the transient torus with a lifetime of about 100 milliseconds will power the GRB engine. Our simulation covers this last stage of the event: obviously conditions for initial magnetic field are mostly artificial at t=0. However, the toroidal field forms in our computations really quickly, i.e. after one orbit, and the evolution of the neutrino luminosity and flares should match then the outcome of the former compact object merger. The black hole-neutron stars merger simulations (for a review see Shibata & Taniguchi 2011) lead mostly to the formation of a massive black hole with a remnant disk of less than 10 % of the total initial mass of the binary. Its density depends on the initial mass ratio and primary BH spin, as well as on the neutron star’s EOS. The final BH spin is determined mostly by its initial value. Overall, the coalescence of high mass ratio binaries with α ≤ 0.75 is a promising channel for a short GRB progenitor, forming a massive disk plus BH system. Our simulations are aimed to realize this scenario. More detailed studies of the dynamical evolution of the post-merger system, with initial conditions based on the direct output of the merger simulations rather than the quasi-steady-state torus, are planned for our future work (see e.g. by Schwab et al. 2012 for the post-merger evolution of binary white dwarfs).

The distribution of the compact binaries from the population synthesis models shows two peaks: double black holes constitute about two-thirds of the popula-

### Table 1

| Model | M_{BH} | α | β_{ini} | t_{end} | M_{torus(t=0)} | M_{torus(t=0)} < M > | M(t_{end}) | L_{BH}^{in} (t_{end}) | L_{BH} (t_{end}) |
|-------|--------|---|---------|--------|----------------|------------------------|-----------|-------------------|-----------------|
| SBH1  | 3      | 0.8| 50      | 0.03   | 0.1           | 0.09                   | 0.45      | 0.10              | 3.70 × 10^{32} | 3.52 × 10^{34} |
| SBH2  | 3      | 0.9| 50      | 0.03   | 0.1           | 0.09                   | 0.40      | 0.13              | 4.63 × 10^{32} | 9.96 × 10^{34} |
| SBH3  | 3      | 0.98| 50    | 0.03   | 0.1          | 0.10                   | 0.31      | 0.14              | 8.89 × 10^{32} | 6.63 × 10^{34} |
| SBH4  | 3      | 0.98| 10    | 0.03   | 0.1          | 0.06                   | 0.86      | 0.22              | 1.25 × 10^{33} | 2.67 × 10^{33} |
| SBH5  | 3      | 0.98| 5     | 0.03   | 0.1          | 0.05                   | 1.01      | 0.66              | 2.93 × 10^{33} | 4.61 × 10^{34} |
| SBH6  | 3      | 0.98| 50    | 0.03   | 0.8          | 0.65                   | 0.78      | 0.42              | 2.9 × 10^{33}  | 7.32 × 10^{33} |
| SBH7  | 3      | 0.98| 50    | 0.03   | 0.3          | 0.27                   | 0.50      | 0.31              | 1.88 × 10^{33} | 1.56 × 10^{34} |
| SBH8  | 3      | 0.98| 50    | 0.03   | 1.0          | 0.87                   | 0.96      | 0.41              | 4.06 × 10^{33} | 3.02 × 10^{34} |
| LBH1  | 10     | 0.8| 50    | 0.1    | 1.0          | 0.86                   | 0.88      | 0.63              | 1.35 × 10^{33} | 1.65 × 10^{34} |
| LBH2  | 10     | 0.9| 50    | 0.1    | 1.0          | 0.88                   | 0.77      | 0.31              | 1.53 × 10^{33} | 3.31 × 10^{34} |
| LBH3  | 10     | 0.98| 50   | 0.1    | 1.0          | 0.90                   | 0.52      | 0.31              | 1.92 × 10^{33} | 2.27 × 10^{34} |
| LBH4  | 10     | 0.98| 10   | 0.1    | 1.0          | 0.72                   | 1.31      | 0.30              | 1.65 × 10^{33} | 9.04 × 10^{34} |
| LBH5  | 10     | 0.98| 5    | 0.1    | 1.0          | 0.58                   | 1.71      | 0.67              | 2.63 × 10^{33} | 6.34 × 10^{34} |
| LBH6  | 10     | 0.98| 50   | 0.1    | 2.7          | 2.27                   | 0.87      | 0.64              | 3.15 × 10^{33} | 1.28 × 10^{34} |
| LBH7  | 10     | 0.98| 50   | 0.1    | 0.4          | 0.32                   | 0.35      | 0.22              | 8.07 × 10^{32} | 1.77 × 10^{34} |
| SBH4  | 3      | 0.98| 10   | 0.15   | 0.1          | 0.04                   | 0.22      | 0.03              | 1.16 × 10^{34} | 1.29 × 10^{34} |
| SBH5  | 3      | 0.98| 5    | 0.15   | 0.1          | 0.031                  | 0.18      | 0.02              | 8.86 × 10^{31} | 7.18 × 10^{30} |
| LBH4  | 10     | 0.98| 10   | 0.5    | 1.0          | 0.59                   | 0.34      | 0.04              | 2.43 × 10^{32} | 2.44 × 10^{32} |
| LBH5  | 10     | 0.98| 5    | 0.5    | 1.0          | 0.47                   | 0.42      | 0.05              | 2.74 × 10^{32} | 3.89 × 10^{30} |
| SBH8b | 3      | 0.98| 100  | 0.06   | 0.1          | 0.03                   | 0.11      | 0.06              | 2.16 × 10^{34} | 3.85 × 10^{39} |
| LBH8b | 10     | 0.98| 100  | 0.2    | 1.0          | 0.85                   | 0.28      | 0.19              | 6.15 × 10^{32} | 1.22 × 10^{31} |
The simulations presented in [Krolik et al. (2005)] show the existence of the polar jet outflows. The authors do not discuss massive winds, as they concentrate mostly on the accretion disk properties. However, McKinney (2006) reports on the existence of winds with moderately relativistic velocities ($\Gamma \sim 1.5$) and half opening angles of 16-45$^\circ$.

The results shown in this work are obtained with a detailed neutrino cooling description in which we have incorporated the chemical composition of nuclear matter where the reactions lead to the neutrino production (Janiuk et al. 2007). The simulations discussed in Dibi et al. (2012) include the radiative cooling for low luminosities and accretion rates, appropriate for the case of radiatively inefficient flows in AGN. The scale height of the disk in their results is affected by the radiative cooling by a factor of 30-50 per cent, however the density and thickness of the inner torus might still be partly affected by the initial conditions assumed in these simulations. Qualitatively, our results are similar to theirs, as the neutrino cooling also leads to the denser and thinner torus inside 10-15 gravitational radii. The 'bump' outside that radius, seen in the final snapshots from our simulations, may partly also be affected by initial conditions. However, the difference may also arise because of a stronger radial dependence of neutrino cooling than it is in the case of photon cooling. Similarly to Dibi et al. (2012), our dynamical model uses a simplified version of EOS. We note that the electrons are degenerate near the disk equatorial plane between the BH horizon and $r \approx 20R_g$, e.g. in the model SBH2. In this small region, the dynamical computations with $\gamma = 4/3$ might not be suitable to describe the degenerate electrons (see Barkov & Komissarov (2008, 2010)). To model degenerate gas one could introduce a new equation of state (e.g. $P = P(\rho_0) \rho_0^\gamma / n$ where $\rho_0$ is the density of the electrons and $n$ is a polytropic index (see Paschalidis et al. 2011; Malone et al. 1975)). The latter however is a mayor change of the numerical scheme since the matter is composed of also partially degenerate and non-degenerate electrons, protons, helium nuclei and neutrons which can still be described by perfect gas law. Moreover, to account for the pressure of photons and neutrinos one would need to follow the evolution of radiation and neutrino energy-momentum tensor coupled to the evolution of matter. Sill, in our present model the energy carried out from the system by the neutrinos does not depend on the EOS used in the interior of the disk and most of the energy is generated in the disk wind. Of course, it is possible that the change of the EOS would influence the wind strength, structure and neutrino luminosity. It would be interesting to explore the wind launching mechanism in this case and we plan to study this in future work.

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