Neutrino-cooled Accretion Disks As the Central Engine of Gamma-ray Bursts

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Abstract. Neutrino-cooled hyperaccretion disks around stellar mass black holes are plausible candidates for the central engine of gamma-ray bursts. We calculate the one-dimensional structure and the annihilation luminosity of such disks. The resulting neutrino annihilation luminosity is still likely to be adequate for gamma-ray bursts, and it is ejected mainly from the inner region of the disk and has an anisotropic distribution.

Keywords: accretion, accretion disks - black hole - gamma rays: bursts - neutrinos
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INTRODUCTION

Neutrino-cooled accretion disks around stellar mass black holes are plausible candidates for the central engine of gamma-ray bursts.In this paper we try to refine our previous results of the structure and luminosity of such disks by considering the relevant microphysics more completely and more accurately.

PHYSICS OF NEUTRINO-COOLED ACCRETION DISKS

We limit the central accreting black hole to be a non-rotating one, its general relativistic effect is simulated by the well-known Paczyński & Wiita (1980) potential. Accretion in the disk is driven by viscous stress. The cooling rate is crucially different from that of normal accretion disks, it has three contributions(the cooling rate due to photodisintegration of α-particles ,the advection and the neutrino loss). The equation of state is also very different , as the contributions to the pressure from degenerate electrons and from neutrinos should be included. We take great care to calculate the neutrino optical depth and the electron fraction. We make a careful distinction between the total nucleon number densities $n_{\rm n}$, $n_{\rm p}$ and the free nucleon number densities $\tilde{n}_{\rm n}$,$\tilde{n}_{\rm p}$, so that the composition of the disk matter can be exactly described by fractions $Y_{\rm e}$, $Y_{\rm p}$, $Y_{\rm n}$, and Y_α ; we propose a new bridging formula for $Y_{\rm e}$ from the β-equilibrium condition, which is applicable to both the neutrino optically thin and optically thick regimes(Yuan 2005).

Figure 1 shows the composition of disk matter. In the outer region between $R = 500R_g$ and $R \sim 200R_g$, almost all α-particles are not disintegrated, so that the α-particles fraction Y_α keeps to be ~ 0.25, the electron fraction $Y_{\rm e}$ keeps to be ~ 0.5, and the free proton fraction $Y_{\rm p}$, the free neutron fraction $Y_{\rm n}$, and the free nucleon fraction $X_{\rm nuc}$ are all keeping ~ 0. From $R \sim 200R_g$ inwards, the disintegration of α-particles causes Y_α

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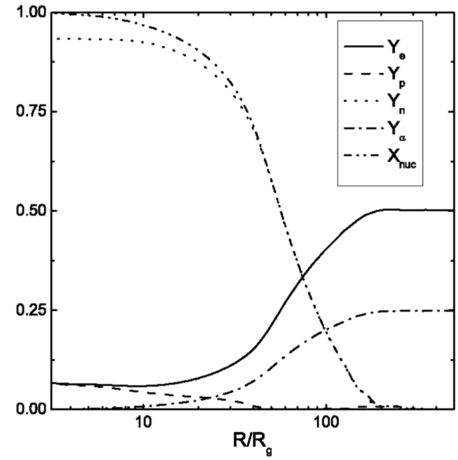

FIGURE 1. Electron fraction $Y_{\rm e}$, free proton fraction $Y_{\rm p}$, free neutron fraction $Y_{\rm n}$, α-particle fraction Y_α , and free nucleon fraction $X_{\rm nuc}$ as functions of R, with the black hole mass M = $3M_{\rm sun}$, mass accretion rate $\dot{M}$ = $1M_{\rm sun}$ s^{-1}, viscosity parameter α =0.1,and the accreted specific angular momentum $j = 1.8cR_g$ (Liu et al. 2007).

to decreases and $X_{\rm nuc}$ to increase dramatically. Because of the neutronization processes favored by high temperature, $Y_{\rm n}$ greatly exceeds $Y_{\rm p}$, and $Y_{\rm e}$ decreases accordingly. In the innermost region $R < 10R_g$, α-particles are almost fully disintegrated, i.e., $Y_\alpha \sim 0$, $X_{\rm nuc} \sim 1$; and the neutronization makes $Y_{\rm n}$ larger than 0.9, and $Y_{\rm p}$ and $Y_{\rm e}$ smaller than 0.1.

NEUTRINO RADIATION AND ANNIHILATION LUMINOSITIES

We calculate the neutrino luminosity L_ν and the neutrino annihilation luminosity $L_{\nu\bar{\nu}}$. Figure 2 shows L_ν (the thick dashed line) and $L_{\nu\bar{\nu}}$ (the thick solid line) with varying $\dot{M}$ ($M = 3M_{\rm sun}$, $\alpha = 0.1$, and $j = 1.8cR_g$ are kept). For comparison, these two luminosities calculated in our previous work (Gu et al. 2006), where the electron degeneracy was not correctly considered and $Y_{\rm e}$ was taken to be equal to 0.5, are also given in the figure by the thin dashed line and thin solid line, respectively. It is clear that the electron degeneracy and the lower $Y_{\rm e}$ resulted from the neutronization processes indeed suppress the neutrino emission considerably, the resulting L_ν and $L_{\nu\bar{\nu}}$ are reduced by a factor $\sim 30\% - 70\%$ comparing with their overestimated values in Gu et al. (2006). Even so, the correct $L_{\nu\bar{\nu}}$ is still well above 10^{50} ergs s^{-1} provided $\dot{M} \sim 1M_{\rm sun}$ s^{-1}, and reaches to $\sim 10^{52}$ ergs s^{-1} when $\dot{M} \sim 10M_{\rm sun}$ s^{-1}. Therefore, based on the energy consideration, neutrino-cooled accretion disks can work as the central engine of GRBs. Note that our

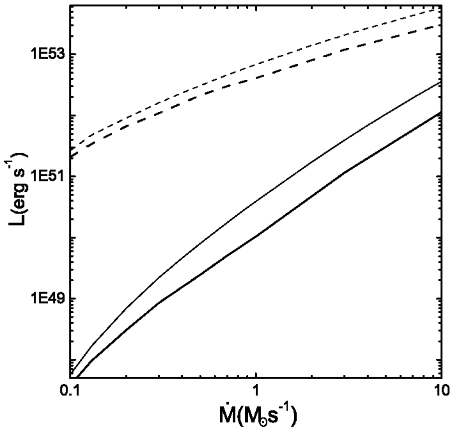

FIGURE 2. Neutrino radiation luminosity L_ν (the thick dashed line) and neutrino annihilation luminosity $L_{\nu\bar{\nu}}$ (the thick solid line) for varying $\dot{M}$. The overestimated L_ν (the thin dashed line) and $L_{\nu\bar{\nu}}$ (the thin solid line) taken from Gu et al. (2006) are also given. The constant parameters M, α, and j are the same as in Fig. 1(Liu et al. 2007).

calculations are for a nonrotating black hole, both Popham et al. (1999) and Chen & Beloborodov (2006) have shown that a spinning (Kerr) black hole will enhance the neutrino radiation efficiency, this only strengthens our conclusion here. Perhaps the main limitation of our calculations here is that they are one-dimensional.

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