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ORIGINAL ARTICLE

Revisiting vertical structure of neutrino-dominated accretion disks: Bernoulli parameter, neutrino trapping and other distributions

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Abstract We revisit the vertical structure of neutrino-dominated accretion flows (NDAFs) in spherical coordinates with a new boundary condition based on the mechanical equilibrium. The solutions show that NDAF is significantly thick. The Bernoulli parameter and neutrino trapping are determined by the mass accretion rate and the viscosity parameter. According to the distribution of the Bernoulli parameter, the possible outflow may appear in the outer region of the disk. The neutrino trapping can essentially affect the neutrino radiation luminosity. The vertical structure of NDAF is like a "sandwich", and the multilayer accretion may account for the flares in gamma-ray bursts.

Keywords Accretion · Accretion disks · Black hole physics · Gamma rays: bursts

1 Introduction

Neutrino-dominated accretion flows (NDAFs) involve a stellar black hole of 2∼10 $M_\odot$, accreting with a hypercritical rate, in the range of 0.01∼10 $M_\odot\,\mathrm{s}^{-1}$. In the past decade, a number of studies have investigated this model (e.g. Popham et al. 1999; Narayan et al. 2001; Kohri and Mineshige 2002; Di Matteo et al. 2002; Rosswog et al. 2003; Kohri et al. 2005; Lee et al. 2005; Gu et al. 2006; Chen and Beloborodov 2007; Janiuk et al. 2007; Kawanaka and Mineshige 2007; Liu et al. 2007, 2008, 2010a, 2010b). The model can provide a good understanding both the energetics of gamma-ray bursts (GRBs) and the processes of making the relativistic and baryon-poor fireballs by neutrino annihilation or magnetohydrodynamic processes (see e.g. Popham et al. 1999 and Di Matteo et al. 2002 for references).

In cylindrical coordinates, Gu and Lu (2007) discussed the underlying importance of taking the explicit form of the gravitational potential for calculating slim disk solutions, and pointed out that the Hōshi form of the potential (Hōshi 1977) is valid only for geometrically thin disks with $H/R \lesssim 0.2$. Liu et al. (2008) found that NDAFs have both a maximal and a minimal possible mass accretion rate at their each radius, and presented a unified description of all the three known classes of optically thick accretion disks around black holes, namely Shakura-Sunyaev disks, slim disks, and NDAFs. These two works are, however, based on the simple one-zone vertical hydrostatic equilibrium. Furthermore, Gu et al. (2009) revisited the vertical structure of advection-dominated accretion disks in spherical coordinates and showed that those disks should be geometrically thick rather than being slim. As a continuation, Cai et al. (2010) found an analytic relation $c_{s0}/v_K\Theta = [(\gamma-1)/2\gamma]^{1/2}$ for the vertical mechanical equilibrium, where c_{s0} is the sound speed on the equatorial plane, v_K is the Keplerian velocity, Θ is the half-opening angle of the flow, and γ is the adiabatic index. However, the detailed radiation cooling was not considered in that work, and therefore no thermal equilibrium solution was established. Thus, Liu et al. (2010a) presented the vertical structure of NDAF calculating with the numerical method of Gu et al. (2009). We found the luminosity of neutrino annihilation is enhanced by one or two orders of magnitude. The empty funnel along the rotation axis can naturally explain the neutrino annihilable ejection.

The Bernoulli parameter, defined as the summation of kinetic energy, potential energy and enthalpy of the accreting gas, is an essential quantity in accretion flows since it can be used to measure the possibility of arising outflows or

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