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Neutrino-dominated accretion flows as the central engine of gamma-ray bursts

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Abstract

Neutrino-dominated accretion flows (NDAFs) around rotating stellar-mass black holes (BHs) are plausible candidates for the central engines of gamma-ray bursts (GRBs). NDAFs are hyperaccretion disks with accretion rates in the range of around 0.001-10 $M_\odot$ s^{-1}, which have high density and temperature and therefore are extremely optically thick and geometrically slim or even thick. We review the theoretical progresses in studying the properties of NDAFs as well as their applications to the GRB phenomenology. The topics include: the steady radial and vertical structure of NDAFs and the implications for calculating neutrino luminosity and annihilation luminosity, jet power due to neutrino-antineutrino annihilation and Blandford-Znajek mechanism and their dependences on parameters such as BH mass, spin, and accretion rate, time evolution of NDAFs, effect of magnetic fields, applications of NDAF theories to the GRB phenomenology such as lightcurve variability, extended emission, X-ray flares, kilonovae, etc., as well as probing NDAFs using multi-messenger signals such as MeV neutrinos and gravitational waves.

Keywords:
accretion, accretion disks; black hole physics; gamma-ray burst: general; gravitational waves; neutrinos.

1. Introduction

In astrophysics, accretion is a process that matter falls to a central object, which prompts part of gravitational binding energy of the infalling matter converted into heat and radiation due to viscous dissipation. The conservation of angular momentum, however, forces the accreted matter to form an accretion disk around the central object. Accretion disks widely exist in astrophysical systems, such as cataclysmic variable stars, X-ray binaries, protoplanetary disks, active galactic nuclei (AGNs), and gamma-ray bursts (GRBs).

As a fundamental physical model, black hole (BH) accretion disks have been widely studied (see reviews by Frank et al. 2002; Kato et al. 2008; Abramowicz & Fragile 2013; Blaes 2014; Yuan & Narayan 2014). Three classic accretion disk models, namely the Shakura-Sunyaev disk (SSD, Shakura & Sunyaev 1973), the slim disk (Abramowicz et al. 1988), and the advection-dominated accretion disk (ADAF, Narayan & Yi 1994; Abramowicz et al. 1995), have been successfully applied to different systems. The SSD model is geometrically thin, optically thick, and Keplerianly rotating, where the viscous heating is balanced by the radiative cooling. Such a model is very successful in interpreting the high/soft state of X-ray binaries and can be even used to measure the spin of the BH (e.g., Zhang et al. 1997). It is also widely applied to high luminosity AGNs such as quasars. The slim disk model was introduced mainly for systems with super-Eddington accretion, where the disk is geometrically slim and optically thick. The fundamental difference from the SSD model is that the large amount of photons generated by the viscosity cannot escape from the disk. Most of the photons are carried by the accretion flow and finally fall into the BH. In other words, the main cooling mechanism is advection rather than radiation. The slim disk model is often applied to super-Eddington systems such as ultraluminous X-ray sources and narrow line Seyfert 1 galaxies, which is also applied to study cosmology (Wang et al. 2013). Different from the above two models, an ADAF is optically thin and has extremely high temperature. The main cooling mechanism is also advection rather than radiation. The difference from the slim disk is that, the energy advection in an ADAF is related to the internal energy of the flow instead of the photons. The ADAF model has been successfully applied to the low/hard and quiescent states of X-ray binaries and low luminosity AGNs.

Apart from the above three classic accretion models, there are some significant progresses in this field. The advection-dominated inflow outflow solution (ADIOS, Blandford & Begelman 1999) shows that the outflows may have an essential effect on the structure and radiation of the flow. The convection-dominated accretion flow (CDAF, Narayan et al. 2000) includes energy and angular momentum transfers by radially convective process. A luminous hot accretion flow (LHAF, Yuan 2001) can provide both high luminosity and hard photons.

A well-known unified description of different accretion models is in the $\dot{M}$-Σ parameter space (Figure 1), where $\dot{M}$ is the mass accretion rate and Σ is the mass surface density. By including the thermally unstable Shapiro-Lightman-Eardley disk

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