Perseus in Sicily: From Black Hole to Cluster Outskirts
Proceedings IAU Symposium No. 342, 2018
K. Asada, E. de Gouveia Dal Pino, M. Giroletti,
H. Nagai & R. Nemmen, eds.

doi:10.1017/S1743921318007755

The wind production from black hole hot accretion flow

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Abstract. Observations of low luminosity active galactic nuclei (LLAGNs) and the hard state of black hole X-ray binaries (BHBs) show that the wind exists. Black hole in LLAGNs and hard state of BHBs accretes gas in hot accretion mode. In this paper, we first use magnetohydrodynamic (MHD) simulations of hot accretion flow around a black hole to study the origin of the wind. We find that the wind is driven by the combination of gradients of gas and magnetic pressure and centrifugal forces. Second, we use simulations with focus on the region around Bondi radius to study whether the wind can be generated outside Bondi radius. In the simulation studying hot accretion flow around Bondi radius, in addition to the black hole gravity, we also take into account the gravity of nuclei stars. We find that the wind can not be generated outside Bondi radius. The absence of the wind is due to the change of gravity potential.

Keywords. accretion, accretion discs, black hole physics, hydrodynamics

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1. Introduction

Hot accretion flow is originally proposed and studied analytically by vertically integrated one-dimensional method (e.g., Narayan & Yi 1994). Later on, intensive numerical simulations have been performed to study hot accretion flows. One of the most important findings is that the mass inflow rate is not a constant of radius, it decreases inward (e.g., Stone, Pringle & Begelman 1999).

What is the reason for the inward decrease of mass inflow rate? Two models have been proposed. In the adiabatic inflow-outflow solution (ADIOS; Blandford & Begelman 1999), it is assumed that the wind is present at any radii. The wind takes away mass, therefore, the mass accretion rate decreases inwards. The other model is the convection-dominated accretion flow (CDAF; Narayan *et al.* 2000; Quataert & Gruzinov 2000). This model is based on an assumption that hot accretion flow is convectively unstable. In this model, it is believed that with accretion, more and more gas is locked in convective eddies which are doing convective motions. Gas is locked in convective eddies and can not fall onto the black hole. Therefore, the mass inflow rate decreases inwards.

In Yuan *et al.* (2012), we performed both hydrodynamic (HD) and MHD simulations to study which model is correct. We first analyze the convective stability of an MHD flow. We find that the accretion flow is convectively stable. We also compare various properties of both inflow and outflow. If the CDAF model is correct, the inflow and outflow rates are due to convective turbulent fluctuations. We should expect that the properties of inflow and outflow should roughly be the same. However, we find that the properties of inflow and outflow (including velocities, temperature, Bernoulli parameter) are significantly different. Based on these results, we conclude that the inward decrease of mass inflow rate is because of the wind.

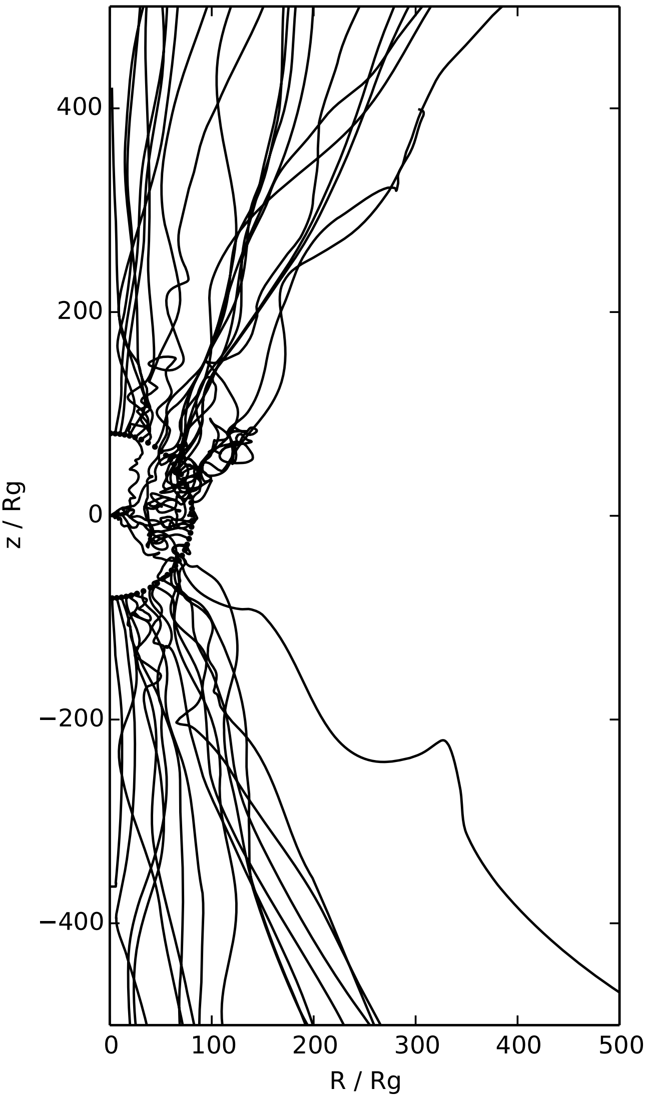

Figure 1. Trajectories of “test particles”. The wind is present in the coronal region. The inflow is around the equatorial plane.

2. The wind properties study by trajectory method

In Yuan *et al.* (2012), the conclusion that the wind is present is based on indirect argument. Therefore, it is necessary to show the existence of the wind in a more direct way.

In Yuan *et al.* (2015), we use the“trajectory” method to study the wind. Trajectory is related to the Lagrangian description of fluid. Trajectory is obtained by following the motion of fluid elements at consecutive times. It is different from the streamline. Streamline is associated with the Euler description of fluid, obtained by connecting the velocity vectors of adjacent fluid elements at a given time. Trajectory is only equivalent to streamline for strictly steady motion, which is not the case for accretion flow since it is always turbulent.

Fig. 1 shows the trajectories of some “test particles” originated from 80 Rs (Rs is Schwarzschild radius). In this figure, the black hole is located at $R = z = 0$. It is clear

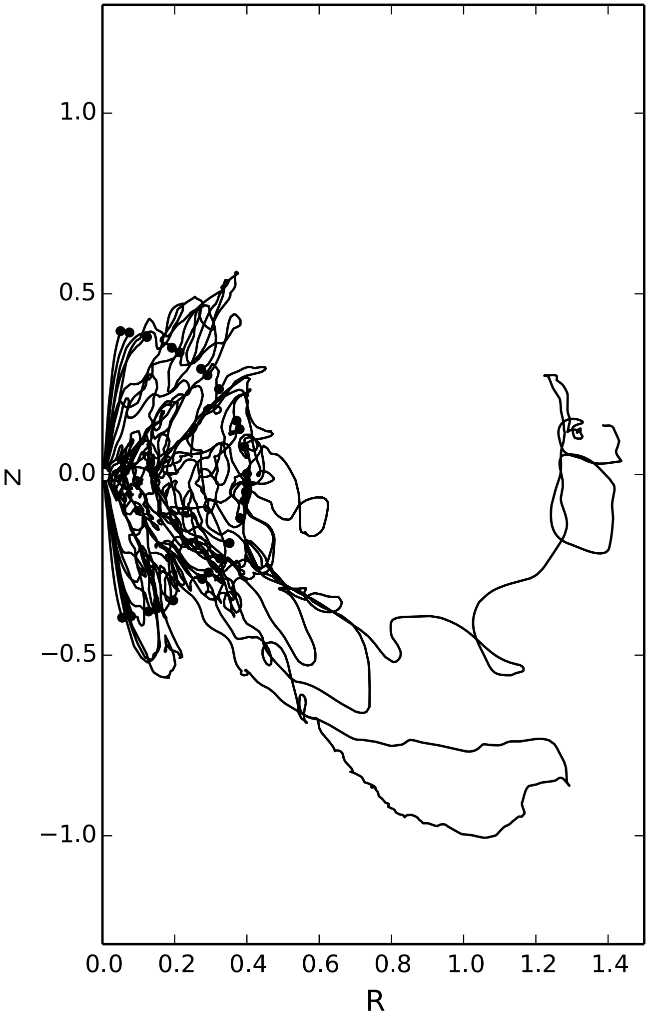

Figure 2. Trajectories of "test particles" for simulations around the Bondi radius. Almost all of the "test particles" are doing turbulent motions. There is no wind.

that the inflow is around the equatorial plane. The wind is present at the coronal region. The wind is driven by the combination of gradients of gas pressure and magnetic pressure and centrifugal forces. The mass flux of the wind can be described by a power law function of radius

$$\dot{\mathrm{M}}_{\mathrm{wind}}(r) = \dot{\mathrm{M}}_{\mathrm{BH}} \left(\frac{r}{20Rs} \right) \tag{2.1}$$

3. Can the wind be generated beyond Bondi radius?

The above mentioned works only focus on the region close to the black hole. From Equation (2.1), we know that most of the wind comes from the region of large radius. Then a question is that how large the value of r can be in Equation (2.1). To answer it, we have to study the accretion flow far away from the black hole. In Bu *et al.* (2016a; 2016b), we studied the accretion from around the Bondi radius. Around the Bondi radius, the gravitational potential of nuclear star cluster is important and has been taken into account. Therefore, around the Bondi radius, in our simulations, we have both the black hole and the nuclear star cluster gravities.

The dispersion velocity of the nuclear stars is roughly a constant with radius (e.g., Kormendy & Ho 2013). So, the potential of the star cluster is

$$\psi_{\rm star}(r) = \sigma^2 \ln(r) + C \tag{3.2}$$

σ is the dispersion of velocity. For a 10^8 solar mass black hole, $\sigma \sim 200{\rm kms}^{-1}$. C is a constant. The radial profile of nuclear star potential is much flatter than that of the black hole. Therefore, the total potential (nuclear star's + black hole) is much flatter than that of black hole.

We find that in this case, the mass inflow rate also decreases inward. We use trajectory method to study whether the wind exists. Fig. 2 shows the result. We find that all of the "test particles" are doing turbulent motions. There is no wind. We speculate that the absence of the wind is due to the change of the radial profile of the gravitational potential.

The wind can not be generated "locally" outside the Bondi radius. However, we note that the wind generated inside the Bondi radius can move to the region outside the Bondi radius and interact with the interstellar medium.

4. Implications

There are also some analytical works that study the wind from accretion disks (e.g. Li & Cao 2009; Xie *et al.* 2008; Bu *et al.* 2009; Bu & Mosallanezhad 2018; Abbassi *et al.* 2010; Chen *et al.* 2012; Li & Begelman 2014; Gu 2015; Cao 2016). The topic of the wind is interesting because it is now widely believed that AGN feedback plays an important role in the evolution of their host galaxies (e.g., Ciotti & Ostriker 2001, 2007; Gan *et al.* 2014; Yuan *et al.* 2018). The wind can push away the gas outside an AGN. This can reduce the feeding rate of the central black hole. Also, the star formation rate may be changed.

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