Black Hole Winds at All Scales
Proceedings IAU Symposium No. 378, 2024
G. Bruni, M. Diaz Trigo, S. Laha & K. Fukumura, eds.
doi:10.1017/S1743921323003241

Check for updates

Outflows from black hole accretion flows with various accretion rates

De-Fu Bu and Feng Yuan

Shanghai Astronomical Observatory, Chinese Academy of Sciences,
80 Nandan Road, Shanghai 200030, China
email: dfbu@shao.ac.cn, fyuan@shao.ac.cn

Abstract. Both observations and theoretical studies have convincingly shown that outflows (i.e., wind and jet) are common phenomena from black hole accretion systems with various accretion rates, although the physical driving mechanisms are not exactly same for different accretion modes. Outflows are not only important in the dynamics of black hole accretion, but also play an important role in AGN feedback; therefore it is crucial to investigate their main physical properties including mass flux and velocity. In this paper we summarize recent studies in investigating the properties and driving mechanisms from black hole accretion flows with various accretion rates.

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

1. Introduction

Depending on the value of the accretion rate, black hole accretion flow can be divided into two modes, i.e., the hot accretion flow and cold accretion disk (Yuan & Narayan 2014). The cold flow can be further divided into the standard thin disk and super-Eddington accretion flow, bounded by the Eddington accretion rate.

For hot accretion flow, due to the high specific energy of gas, outflow is speculated to be present (Narayan & Yi 1994). The pioneer global numerical simulation of hot accretion flow show that the mass accretion rate decreases inwards (Stone et al. 1999). Two models have been proposed to interpret this result. In the convection-dominated accretion flow (CDAF; Narayan et al. 2000), it is believed that the convective motion of the accretion flow results in the inward decrease of accretion rate. In the alternative adiabatic inflow-outflow model, it is believed that strong wind is present and takes away mass (ADIOS; Blandford & Begelman 1999). To solve this puzzle, Yuan et al. (2012; see also Narayan et al. 2012) have performed numerical simulations of accretion flows and analyzed the simulation data. They systematically compare the properties of "inflow" and "outflow" and find that the properties of "outflow" is systematically different from those of "inflow". Moreover, it is found that the magnetized hot accretion flow is convectively stable. These results make Yuan et al. (2012) conclude that strong wind must be present. For the cold thin disk, both the line force and magnetic field can drive strong wind (e.g., Proga et al. 2000). Super-Eddington accretion flow is believed to have strong outflows as well (e.g., Sadowski et al. 2016).

Wind plays an important role in the physics of black hole accretion because it can transfer angular momentum and change the density profile of accretion flow and subsequently its radiation. Moreover, recent studies find that wind likely plays a crucial role in active galactic nuclei feedback (e.g., Yuan et al. 2018). In the following, we review the current studies of wind properties and driving mechanisms for both hot and cold accretion modes.

© The Author(s), 2024. Published by Cambridge University Press on behalf of International Astronomical Union.

https://doi.org/10.1017/S1743921323003241 Published online by Cambridge University Press

2. Outflows from black hole accretion flow

2.1. *Outflows from hot accretion flow*

We have studied the properties of outflows from hot accretion flows by performing GRMHD simulations of both SANE and MAD around black holes with different spins, i.e., SANE00 ($a = 0$), SANE98 ($a = 0.98$), MAD00 ($a = 0$) and MAD98 ($a = 0.98$) (Yuan et al. 2015; Yang et al. 2021). We find that winds are always present regardless of the black hole spin and magnetic field strength. The mass flux of wind increases with radius,

$$\dot{M}_{\rm w} = \left(\frac{r}{R_0}\right)^s \dot{M}_{\rm BH} \tag{2.1}$$

where $\dot{M}_{\rm BH}$ is the accretion rate at the black hole horizon. For models SANE00, SANE98, MAD00, and MAD98, the values of (R_0, s)= $(20r_s, 1)$, $(15r_s, 1.16)$, $(55r_s, 1.54)$, $(30r_s, 1.26)$, respectively, with r_s being the Schwarzschild radius. Therefore, given a same black hole accretion rate and beyond a certain radius, the mass flux of wind is stronger when the magnetic field is stronger. This is because the magnetic pressure gradient force is found to be important in driving wind. We would like to mention that the mass flux is obtained by using the trajectory approach, i.e, we follow the motion of the wind particles. The usually adopted "time-average" approach in literature is found to underestimate the mass flux by a factor of 2-6 (Yuan et al. 2015; Yang et al. 2021, 2023).

The mass flux-weighted poloidal velocity of wind $v_{\rm p}(r)$ as a function of radius r is found to be proportional to the local Keplerian speed $v_{\rm K}$, i.e., $v_{\rm p} = \alpha v_{\rm K}$, with α being in the range of $0.2 - 0.66$. The decrease of the velocity with increasing radius is because wind produced at larger radii has smaller velocities (Yuan et al. 2015). The Bernoulli parameter of wind is not a constant, but keep increasing outward, which is because the accretion flow is not in strictly steady state and inviscid, but turbulent (Yuan et al. 2015).

It is found that wind can only be produced within the outer boundary of accretion flow, i.e., the Bondi radius (Bu 2016). The large-scale dynamics of wind beyond the outer boundary of accretion flow is studied in Cui & Yuan (2020) and found that wind can escape the gravity of the black hole and reach large scales.

Yang et al. (2021) also studied the properties of jet powered by the Blandford-Znajek mechanism and made comparison with wind. They find that the momentum flux of wind is comparable to that of jet, but the power of jet is roughly an order of magnitude higher than wind. These results, combined with the fact that the opening angle of wind is much larger than that of jet, imply the importance of wind in AGN feedback. The driven mechanism of wind and jet is also studied in Yuan et al. (2015) and Yang et al. (2021). Wind is found to be driven by a combination of gas pressure gradient force, magnetic pressure gradient force and centrifugal force; while jet is mainly accelerated by the magnetic pressure gradient force.

There are growing observational evidences for wind from hot accretion flows (see reviews in Yang et al. 2021). Observations of the low-luminosity active galactic nuclei M81 find blue-shifted and red-shifted iron emissions lines. By running MHD numerical simulations and comparing to the observational data, Shi et al. (2021) find that the emission lines come from wind launched from the hot accretion flow in M81, providing the first direct evidence of wind. As an example of wind-ISM interaction, the *Fermi* bubbles detected in the Galactic center may be inflated by wind from the hot accretion flow in Sgr A* (Mou et al. 2014).

https://doi.org/10.1017/S1743921323003241 Published online by Cambridge University Press

2.2. *Wind from a cold thin disk*

In the MHD disk wind model, in order to simplify the equations, isothermal or adiabatic equation of states is usually adopted in literature. Wang et al. (2022) recently study the wind production from a thin disk by performing two-dimensional MHD simulations based on realistic energy equations. They find that the wind properties strongly depend on the treatment of thermodynamics. The isothermal and adiabatic models underestimate the wind power and overestimate the wind temperature. Additionally, the isothermal and adiabatic assumptions erase the local structure of disc winds.

Wang et al. 2022 also compare their simulation results with the observations of UFOs. The observed UFOs have velocity higher than 10^4 km/s; the ionization parameter is in the range $2.5 < \log \xi < 5.5$; the column density is in the range $22 < \log N_H < 24$. Not all winds found by Wang et al. (2022) meet the conditions of the observed UFOs. They pick up wind that satisfy the conditions of UFOs and find that in the model considering realistic radiative cooling and heating, the wind that satisfying the condition of UFOs covers the region between $\theta = 4.7$ and $45.6°$. The corresponding solid angle $\Omega \sim 3.85$; the fraction of Ω to a whole sphere, $\Omega/4\pi \sim 30.6$ percent. It is close to the lower limit of the fraction of UFO in AGNs.

Wang et al. (2022) also calculate the mass flux, momentum flux, and kinetic power of UFOs found in their simulations and compare them to observations of UFOs. They find that inside $600 r_s$, the mass flux, momentum flux and kinetic power of UFOs found in the simulations are well consistent with those of the observed UFOs. However, a cutoff at 600 r_s is found. Beyond $600 r_s$, there is no wind in the simulations satisfying the condition of the observed UFOs. Combining the ionization parameter and the temperature of our simulations, they find that the reason of the missing UFOs at large radii is the ionization state is too low. On the other hand, it has been reported that the UFOs can exist at $10^2 - 10^4 r_s$ (Gofford et al. 2015). Thus, some physics might be missing in MHD disc winds models. A plausible conjecture for the missing physics would be line force. As the winds are sparse and cool, line force might operate on the winds to change their properties. It is thus important to study wind by combining magnetic field and line force.

2.3. *Outflows from super-Eddington accretion flows*

Using the virtual particle trajectory approach proposed in Yuan et al. (2015), Yang et al. (2023) have investigated the properties of wind and jet launched from a magnetically arrested accretion flow with $\dot{M}_{\rm BH} = 12\dot{M}_{\rm Edd}$ around a black hole with $M_{\rm BH} = 10^6 M_\odot$ and $a = 0.8$. Consistent with previous studies, they find that strong wind can be launched from the super-Eddington accretion flow. Due to the presence of outflow, the mass accretion rate decreases with decreasing radius $\dot{M} \propto r^{0.39}$. The mass flux of wind as a function of accretion rate and radius can be described by,

$$\dot{M}_{\rm w} = \left(\frac{r}{45 r_s}\right)^{0.83} \dot{M}_{\rm BH} \tag{2.2}$$

Different from the case of hot accretion flows, the velocity of wind is found to be a constant of radius, which is ∼15 percent of the speed of light. Such a difference is because of the additional acceleration force in the case of super-Eddington accretion flow, i.e., the radiation force. They have also compared the momentum flux and kinetic power of wind with jet and found that the momentum flux of wind is 1.2 times that of jet while the kinetic power of jet is 2.5 times of that of wind.

The driving mechanism of wind and jet is also studied in Yang et al. (2023). In the case of jet, the force is fully dominated by the Lorentz force. In the case of wind, the results are a bit complicated, depending on locations. In the wind region close to the surface of the

https://doi.org/10.1017/S1743921323003241 Published online by Cambridge University Press

accretion flow, the optical depth is large and the radiation and gas are strongly coupled, so the radiation force and the Lorentz force are comparable and both of them play important roles in the acceleration of wind. Well above the main body of the accretion flow, the optical depth becomes smaller. In this location, compared to the Lorentz force, the radiation force becomes less important in accelerating the wind and is the secondarily important force.

3. Summary

The driving mechanism and main properties of wind and jet are studied by performing (radiative) MHD numerical simulations of accretion flows with various accretion rates around black holes with various spin values. Such studies are performed by the trajectory approach, which can give more exact result compared to the widely adopted time average approach.

For hot accretion flow, the mass flux and velocity as a function of black hole accretion rate and black hole spin for both SANE and MAD are presented and compared to jet. The wind is accelerated by the combination of gas pressure gradient force, magnetic pressure gradient force and centrifugal force; while jet is mainly accelerated by the magnetic pressure gradient force.

In the case of wind launched from a thin disk, we only focus on magnetically driven wind. We find that it is important to adopt a realistic energy equation. In addition, the MHD wind model alone can not interpret the observed ultra-fast outflows, suggesting that we need to combine other mechanisms such as line force.

Strong wind is found in the case of super-Eddington accretion flows and the main properties of wind are presented and compared to jets. The speed of wind is found to be roughly a constant and independent of radius. Lorentz force is found to play an important role in accelerating wind and jet. Close to the surface of the accretion flow, radiation force is found to play a comparable role with Lorentz force in driving wind.

References

Blandford, R., & Begelman, M. 1999, *MNRAS*, 303, L1

Bu, D., Yuan, F., Gan, Z., & Yang, X. 2016, *ApJ*, 823, 90

Cui, C., & Yuan, F. 2020, *ApJ*, 890, 81

Gofford, J. et al. 2015, *MNRAS*, 451, 4169

Mou, G., Yuan, F., Bu, D., Sun, M., & Su, M. 2014, *ApJ*, 790, 109

Narayan, R., & Yi, I. 1994, *ApJ*, 428, L13

Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2000, *ApJ*, 539, 798

Narayan, R., Sadowski, A., Penna, R. F., & Kulkarni, A. K. 2012, *MNRAS*, 426, 3241

Proga, D., Stone, J. M., & Kallman, T. R. 2000, *ApJ*, 543, 686

Sadowski, A., Lasota, J., Abramowicz, M. A. & Narayan, R. 2016, *MNRAS*, 456, 3915

Shi, F., Li, Z., Yuan, F., & Zhu, B. 2021, *NatAs*, 5, 928S

Stone, J. M., Pringle, J. E., & Begelman, M. 1999, *MNRAS*, 310, 1002

Wang, W., Bu, D., & Yuan, F. 2022, *MNRAS*, 513, 5818

Yang, H., Yuan, F., Yuan, Y., & White, C. J. 2021, *ApJ*, 914, 131

Yang, H., Yuan, F., Kwan, T., & Dai, L. 2023, *MNRAS*, arXiv:2211.10710

Yuan, F., Bu, D., & Wu, M. 2012, *ApJ*, 761, 130

Yuan, F., & Narayan, R. 2014, *ARA&A*, 52, 529

Yuan, F., Gan, Z., Narayan, R., Sadowski A., Bu, D., & Bai, X. 2015, *ApJ*, 804, 101

Yuan, F., Yoon D., Li, Y., Gan, Z., Ho, L. C., Guo, F. 2018, *ApJ*, 857, 121

https://doi.org/10.1017/S1743921323003241 Published online by Cambridge University Press