Density profile of ambient circumnuclear medium in Seyfert 1 galaxies

YIJUN WANG (王倚君), 1, 2, 3, 4 ZHICHENG HE (何志成), 3, 4 JUNJIE MAO (毛俊捷), 5, 6 JELLE KAASTRA, 6, 7 YONGQUAN XUE (薛永泉), 3, 4 AND MISSAGH MEHDIPOUR 8

1 Department of Astronomy, Nanjing University, Nanjing 210093, China
2 Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, China
3 CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, China
4 School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, China
5 Department of Physical, Hiroshima University, 1-3-1 Kagamiyama, HigashiHiroshima, Hiroshima 739-8526, Japan
6 SRON Netherlands Institute for Space Research, Niels Bohrweg 4, 2333 CA Leiden, The Netherlands
7 Leiden Observatory, Leiden University, Niels Bohrweg 2, 2300 RA Leiden, The Netherlands
8 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

ABSTRACT

The shape of the ambient circumnuclear medium (ACM) density profile can probe the accretion history of the central supermassive black hole in galaxies and the circumnuclear environment. However, due to the limitation of the instrument resolution, the density profiles of the ACM for most of galaxies remain largely unknown. In this work, we propose a novel method to measure the ACM density profile of active galactic nucleus (AGN) by the equilibrium between the radiation pressure on the warm absorbers (WAs, a type of AGN outflows) and the drag pressure from the ACM. We study the correlation between the outflow velocity and ionization parameter of WAs in each of the five Seyfert 1 galaxies (NGC 3227, NGC 3783, NGC 4051, NGC 4593, and NGC 5548), inferring that the density profile of the ACM is between $n \propto r^{-1.7}$ and $n \propto r^{-2.15}$ ($n$ is number density and $r$ is distance) from 0.01 pc to pc scales in these five AGNs. Our results indicate that the ACM density profile in Seyfert 1 galaxies is steeper than the prediction by the spherically symmetric Bondi accretion model and the simulated results of the hot accretion flow, but more in line with the prediction by the standard thin disk model.

Keywords: Galaxies: Seyfert (1447) — Galaxies: nuclei (609) — Galaxies: ISM (847) — X-rays: galaxies (1822) — Accretion, accretion disks (562)

1. INTRODUCTION

The ambient circumnuclear medium (ACM) in the center of galaxies can probe the accretion history of the central supermassive black hole (SMBH) in galaxies. Different accretion models correspond to different density profiles of the ACM. The classical Bondi accretion (spherically symmetrical accretion; Bondi 1952) predicts that the density profile of the accretion flow is $n \propto r^{-1.5}$ ($n$ is number density and $r$ is distance) within the Bondi radius, and is a constant at larger radii (Frank et al. 2002). The density profile of the hot accretion flow, such as advection-dominated accretion flows (ADAFs; Narayan & Yi 1994; Yuan & Narayan 2014, for a review), is between $n \propto r^{-0.5}$ and $n \propto r^{-1}$ according to simulations (Yuan et al. 2012). The theory of the standard cold, thin accretion disk (Shakura & Sunyaev 1973) predicts that the density profile of the accretion flow is $n \propto r^{-15/8}$ (Frank et al. 2002). The multi-wavelength observations toward the center of the Milky Way (MW) indicated that the density profile of the ACM is $n \propto r^{-1}$ at several hundred Schwarzschild radii (Gillessen et al. 2019), and $n \propto r^{-1.5}$ in the hot gas halo at the kpc scale (Miller & Bregman 2015). Chandra X-ray observations toward the center of M87 and NGC 3115 show that the density profiles of their ACM are $n \propto r^{-1}$ within the Bondi radius (Russell et al. 2015; Wong et al. 2011). However, due to the limitation of the instrument resol-
tion, the density profiles of the ACM for most galaxies are still unknown. One way to infer the density profile of the ACM is through fitting the spectral energy distribution of tidal disruption events (TDEs; a star disrupted by the tidal forces from the SMBH), which can trace the interaction process between the outflows from TDEs and the ACM (Alexander et al. 2016; Eftekhari et al. 2018; Anderson et al. 2020; Alexander et al. 2020). However, TDEs are only detected in a small number of galaxies and are difficult to be identified in active galactic nuclei (AGNs) (Gezari 2021). Besides, for AGNs, the emission from the accretion disk or jet will overshadow the emission from the interaction between outflows and ACM at small scales. In this work, we propose a novel way to estimate the density profile of the ACM in AGNs.

AGNs usually play an important role in forming and driving outflows which might further affect the star formation of their host galaxies (He et al. 2019; Chen et al. 2022; King & Pounds 2015, for a review). These outflows might interact with the ACM. Warm absorbers (WAs) are part of AGN ionized outflows (e.g., Laha et al. 2014), which are detected in roughly half of nearby AGNs (e.g., Reynolds 1997; Kaastra et al. 2000; Tombesi et al. 2013). WAs usually consist of several ionization phases (e.g., Laha et al. 2014) and are located from the accretion disk to the narrow-line region (e.g., Reynolds & Fabian 1995; Elvis 2000; Blustin et al. 2005). WAs have the outflowing velocities up to a few thousand of km s$^{-1}$ (e.g., Kaastra et al. 2000; Ebrero et al. 2013), and are considered to be driven by radiation pressure (e.g., Proga & Kallman 2004), magnetic forces (e.g., Blandford & Payne 1982; Fukumura et al. 2010), or thermal pressure (e.g., Begelman et al. 1983; Mizumoto et al. 2019).

For the radiatively driven outflowing mechanism, the outflow momentum rate $P_{\text{out}}$ ($\propto n_{\text{H}}r^2v_{\text{out}}^2$) approximates to the momentum flux of the radiation field $P_{\text{rad}}$ ($\equiv L_{\text{bol}}/c$) (Gofford et al. 2015), which can produce a simple scaling relation of $v_{\text{out}} \propto \xi^{0.5}$ (Tombesi et al. 2013). For the magneto-hydrodynamically (MHD) driven outflowing mechanism, Fukumura et al. (2010) suggested a few scaling relations between $v_{\text{out}}$, $r$, and $\xi$: $v_{\text{out}} \propto r^{-\frac{1}{2}} \propto \xi^{2.165-\frac{3}{7}}$. Behar (2009) indicated that the parameter $q$ is between $\frac{2}{7}$ and 1 for WA outflowing winds in Seyfert galaxies. Therefore, the scaling relation between $v_{\text{out}}$ and $\xi$ in the MHD scenario is estimated to be between $v_{\text{out}} \propto \xi^{0.5}$ and $v_{\text{out}} \propto \xi^{0.7}$ (see Figure 1). However, the observational results show that the index of $v_{\text{out}}-\xi$ relation is usually smaller than 0.5 (e.g., Tombesi et al. 2013; Laha et al. 2014) or see Figure 1 in this work, which cannot be explained by the above models.

Table 1. Basic properties of each object for the six Seyfert galaxies and previously published X-ray data used in this work.

| Source      | Seyfert type | Redshift | WA references          |
|-------------|--------------|----------|------------------------|
| NGC 3227    | Sy1.5        | 0.004    | Wang et al. (2022)     |
| NGC 3783    | Sy1          | 0.010    | Fu et al. (2017)       |
| NGC 4051    | Sy1.5        | 0.002    | Lobban et al. (2011)   |
| NGC 4593    | Sy1          | 0.008    | Ebrero et al. (2013)   |
| NGC 5548    | Sy1.5        | 0.017    | Ebrero et al. (2016)   |
| NGC 7469    | Sy1.2        | 0.016    | Mehdipour et al. (2018) |

Note—Seyfert type and redshift of each object are obtained from the NASA/IPAC Extragalactic Database (NED). X-ray data: $^1$XMM-Newton; $^2$Chandra.

In this work, we consider that WAs are in a pressure equilibrium state, which means that the radiation pressure on the WAs is comparable to the drag pressure from the ACM. With that, we will use the fitting results for the $v_{\text{out}}-\xi$ relation of WAs to infer the shape of the density profile of the ACM in AGNs. The structure of this work is shown as follows. The method that is applied to infer the density profile of the ACM in AGNs is described in Section 2. In Section 3, we introduce the historical data that are used in this work. In Section 4, we show the fitting results of the observational data, which are further used to infer the density profile of the ACM in AGNs. In Section 5, we discuss the scope of application of our method. Finally, we summarize our conclusions in Section 6.

2. METHOD

The outflows in AGN might be driven by multiple mechanisms, for simplicity, we only consider the radiatively driven outflowing mechanism in this work. The radiation pressure from the AGN radiation on the WA gas (Mo et al. 2010) is

$$P_{\text{rad}} = \frac{L_{\text{ion}}}{4\pi r^2 c},$$

where $L_{\text{ion}}$ is the ionizing luminosity over 1–1000 Ryd, $r$ is the radial distance of the absorbing gas to the central engine, and $c$ is the speed of light. The drag pressure (Batchelor 2000) produced by the ACM on the WAs is

$$P_D = \frac{1}{2} C_Dn_{\text{ACM}}m_p v_{\text{out}}^2,$$

where $C_D$ is the drag coefficient which is probably equal to 1 for compressible gas or clouds, $n_{\text{ACM}}$ is the number
Figure 1. The correlation between the outflow velocity ($v_{\text{out}}$) and ionization parameter ($\xi$) for the following six Seyfert 1 galaxies: NGC 3227 (orange solid circles in the left panel), NGC 3783 (red solid circles and black squares in the right panel), NGC 4051 (green squares in the left panel), NGC 4593 (pink hollow circles in the left panel), NGC 5548 (blue triangles in the left panel), and NGC 7469 (sky-blue diamonds in the right panel). The observational data are from the previously published papers: Wang et al. (2022) (W22), Fu et al. (2017) (F17), Mao et al. (2019) (MJ19), Lobban et al. (2011) (L11), Ebrero et al. (2013) (E13), Ebrero et al. (2016) (E16), and Mehdipour et al. (2018) (MM18). The dashed lines represent the best-fit linear models. The best-fit linear model for NGC 7469 cannot be constrained (see Table 2), so only the observational data are shown here. The gray dashed lines in the top left corner of the left panel represent the predicted correlations of radiation-driven and MHD-driven outflowing mechanisms.

density of the ACM, and $m_p$ is the proton mass. The outflowing velocities of WAs are nearly constant during several years (e.g., Silva et al. 2018). In this work we assume that WAs are in a pressure equilibrium state where the radiation pressure on the WAs is comparable to the drag pressure from the ACM:

$$P_{\text{rad}} \simeq P_D.$$  

(3)

According to Tarter et al. (1969), the ionization parameter of WAs can be defined by

$$\xi = \frac{L_{\text{ion}}}{n_e r^2},$$  

(4)

where $n_e$ is the electron number density of the WA gas. We assume that the electron number densities of the WAs gas and the ACM follow the power-law distributions:

$$n_e = n_{e,0} \left( \frac{r}{r_0} \right)^{-m},$$  

$$n_{\text{ACM}} = n_{\text{ACM},0} \left( \frac{r}{r_0} \right)^{-k},$$  

(5)

where $r_0$ is the launching radius of the WA cloud, $n_{e,0}$ is the number density of WA cloud at $r_0$ and $n_{\text{ACM},0}$ is the number density of the ACM at $r_0$. Therefore, combining Equations 4–5, we can obtain a correlation between $\xi$ and $v_{\text{out}}$:

$$v_{\text{out}} = \left[ \frac{L_{\text{ion}}}{2\pi m_p c} \frac{n_{e,0}}{n_{\text{ACM},0}} \frac{k-2}{r_0} \right]^{1/2} \left( \frac{m-2}{k-2} \right)^{1/2} \xi^{k-2}.$$  

(6)

3. DATA AND FITTING

In order to describe the correlation between $v_{\text{out}}$ and $\xi$ of WAs for the observational data in individual AGN (see Equation 6), high-resolution X-ray spectra and at least four WA components are required. Finally, we collect the parameters of WAs from the previously published papers for the following six Seyfert 1 galaxies (see Table 1):

– NGC 3227: Wang et al. (2022) found four WA components using the XMM-Newton spectra data.

– NGC 3783: Fu et al. (2017) found five WA components through fitting the XMM-Newton spectra, while Mao et al. (2019) found nine WA components using both the XMM-Newton and Chandra data.
Table 2. Best-fit parameters of $\log[v_{\text{out}} \text{ (km s}^{-1})] = a \times \log[\xi \text{ (erg cm s}^{-1})] + b$ using LINMIX, ODR, and BCES methods, and index $k$ of the density profile of the ACM.

| Sources | Data     | $\log[v_{\text{out}} \text{ (km s}^{-1})] = a \times \log[\xi \text{ (erg cm s}^{-1})] + b$ | $k = 2a(m-2) + 2$ |
|---------|----------|-----------------------------------------------------------------------------------------------|------------------|
|         |          | LINMIX                        | ODR             | BCES            |
| NGC 3227 | W22     | $a \leq 0.24$ | $0.25 \pm 0.11^\dagger$ | $0.35 \pm 0.10$ | $1.71 \pm 0.13$ |
|         |          | $b \leq 2.15$ | $2.16 \pm 0.29$ | $1.93 \pm 0.32$ | |
| NGC 4051 | L11     | $a \leq 0.18$ | $0.20 \pm 0.10$ | $0.03 \pm 0.09$ | $1.78 \pm 0.07$ |
|         |          | $b \leq 2.06$ | $2.09 \pm 0.58$ | $2.33 \pm 0.19$ | |
| NGC 4593 | E13     | $a \leq 0.18$ | $0.27 \pm 0.24$ | $0.18 \pm 0.10^\dagger$ | $1.79 \pm 0.11$ |
|         |          | $b \leq 2.06$ | $2.09 \pm 0.58$ | $2.33 \pm 0.19$ | |
| NGC 5548 | E16     | $a \leq 0.18$ | $0.27 \pm 0.24$ | $0.18 \pm 0.10^\dagger$ | $1.79 \pm 0.11$ |
|         |          | $b \leq 2.06$ | $2.09 \pm 0.58$ | $2.33 \pm 0.19$ | |
| NGC 7469 | MM18    | $a \leq 0.64$ | $-0.06 \pm 0.20$ | $0.06 \pm 0.19$ | $\cdots$ |
|         |          | $b \leq -0.56$ | $2.88 \pm 0.55$ | $2.54 \pm 0.47$ | |
| Total   |          | $a \leq 0.24^\dagger$ | $0.20 \pm 0.03$ | $0.26 \pm 0.06$ | $1.78 \pm 0.02$ |
|         |          | $b \leq 2.37 \pm 0.05$ | $2.36 \pm 0.07$ | $2.25 \pm 0.16$ | |

Note—$^\dagger m = 1.42$ is obtained for a sample of 35 Seyfert 1 galaxies from Tombesi et al. (2013) using the absorption measure distribution. The fitting results followed by “$^\dagger$” are used to calculate the index $k$ and are plotted in Figure 1. The observational data are from the previously published papers: Wang et al. (2022) (W22), Fu et al. (2017) (F17), Mao et al. (2019) (MJ19), Lobban et al. (2011) (L11), Ebrero et al. (2013) (E13), Ebrero et al. (2016) (E16), and Mehdipour et al. (2018) (MM18). The data of NGC 3227, NGC 4051, NGC 4593, and NGC 5548 are also fitted together as a reference (see “NGC 3227 & 4051 & 4593 & 5548” in the “Total”).

We mainly use LINMIX$^1$ method (Kelly 2007) to fit the observational data. The LINMIX method performs the linear regression based on a Bayesian approach, which runs a Markov-chain-Monte-Carlo algorithm to calculate the posterior distribution and can account for measurement errors on both variables in the fit. However, for NGC 3227 and NGC 4593, this method can only give an upper limit for the parameters (see Table 2). Therefore, we also use the following two methods as supplements: Orthogonal Distance Regression$^2$ (ODR; Boggs et al. 1989), and bivariate correlated errors and intrinsic scatter$^3$ (BCES; Akritas & Berghady 1996; Nemmen et al. 2012). Both of these two methods can also deal with measurements errors on both variables. The BCES method is a weighted least squares estimator, and the ODR method uses the least squares method to minimize the weighted orthogonal distance from the data to

$1$ https://linmix.readthedocs.io/en/latest/src/linmix.html
$2$ https://docs.scipy.org/doc/scipy/reference/odr.html
$3$ https://github.com/rsnemmen/BCES
driven outflowing mechanism. The $v_{\text{out}} - \xi$ relation of NGC 7469 cannot be constrained, so its ACM density profile will not be discussed further (see Table 2), and its observational data are shown in Figure 1 as a reference.

The number density distribution of WAs can be estimated by the absorption measure distribution (Holczer et al. 2007; Behar 2009). Tombesi et al. (2013) estimated that $m = 1.42$ for WAs in a sample of 35 Seyfert 1 galaxies. Combining Equation 8 and $m = 1.42$ (Tombesi et al. 2013), the density profiles of the ACM in these Seyfert 1 galaxies are estimated to be between $n \propto r^{-1.7}$ and $n \propto r^{-2.15}$ (see Table 2) from 0.01 pc to pc scales, or even larger scales (the distance range of WAs). Both Tombesi et al. (2013) and Laha et al. (2014) investigated the correlation between $v_{\text{out}}$ and $\xi$ for WAs in a large AGN sample, which obtained $a = 0.31$ and $a = 0.12$, respectively. Therefore, index of $k$ is 1.64 and 1.82 for Tombesi et al. (2013) and Laha et al. (2014), respectively. Our results are similar to those in AGN samples. The density profile indexes $k$ of the ACM in the five Seyfert 1 galaxies of our sample (NGC 3227, NGC 3783, NGC 4051, NGC 4593, and NGC 5548) are within the range of $k$ for the ACM in TDEs (between $-1$ and $-2.5$; Alexander et al. 2020) (see Figure 2).

The density profile of the ACM within the Bondi radius might be connected to the accretion models. The Bondi radius can be expressed by $r_B = 2GM_{\text{BH}}/c_s^2$, where $M_{\text{BH}}$ is the SMBH mass and $c_s$ is the sound speed at infinity (Bondi 1952). For simplicity, we assume that the sound speeds at infinity of our sample are similar to that of M87 ($r_B = 0.11$–0.22 kpc with $M_{\text{BH}} = 3.5 \times 10^6 M_{\odot}$; Russell et al. 2015) and Sgr A* ($r_B = 0.4$ pc with $M_{\text{BH}} = 4 \times 10^6 M_{\odot}$; Li et al. 2015). Thus, according to the average $M_{\text{BH}}$ of our sample ($\sim 10^7 M_{\odot}$; Benz & Katz 2015), the Bondi radii of our sample might be between 0.5 pc and 1 pc. Warm absorbers can exist from the scale within the Bondi radius (e.g., Ebrero et al. 2016; Wang et al. 2022) to the kpc scale (Laha et al. 2021). Although the large scale might not be associated with the accretion flow, given that most of the WAs in our sample might be located within or around the Bondi radius (e.g., Ebrero et al. 2016; Wang et al. 2022), we can briefly compare the density profiles between the ACM and the accretion flow here. The indexes $k$ of the five Seyfert 1 galaxies are larger than the predicted value by the spherically symmetrical Bondi accretion model ($-1.5$; Frank et al. 2002) and the simulated results of the hot accretion flow (between $-0.5$ and $-1.0$; Yuan et al. 2012), but relatively consistent with the prediction by the standard thin disk model ($-15/8$; Frank et al. 2002) (see Figure 2).

![Figure 2. The distribution of the ACM density profile index $k$ for the five Seyfert 1 galaxies (NGC 3227, NGC 4051, NGC 4593, NGC 5548, and NGC 3783) in this work (blue histogram). The green dashed line represents the predicted index by the standard thin disk model (Frank et al. 2002). The purple dash-dotted line represents the predicted index by the Bondi accretion model (Frank et al. 2002). The red region represents the predicted range of the index by the hot accretion flow simulations (Yuan et al. 2012). The yellow region represents the observational range of the index in TDEs (Alexander et al. 2020).](image-url)
5. DISCUSSIONS

5.1. Acceleration timescale required before equilibrium

To verify whether the assumption about the pressure equilibrium is feasible, we firstly estimate the acceleration timescale before reaching equilibrium of WA outflows. Under the action of the radiation pressure and drag pressure, the motion equation of the WA clouds is

\[ \frac{vdv}{dr} = \frac{f_L L_{\text{ion}}}{4\pi N_H m_p r^2} - \frac{C_D n_{\text{ACM}}}{2 N_H} v^2, \]  

(9)

where \( f_L \) is the fraction of the ionizing luminosity being absorbed or scattered by the WA cloud, which is about 2% according to Grafton-Waters et al. (2020) and Wang et al. (2022) and \( m_p \) is the mass of proton. The average ionizing luminosity of the sources in our sample is \( 5 \times 10^{43} \, \text{erg s}^{-1} \). We simply set a constant column density to be \( N_H = 10^{22.5} \, \text{cm}^{-2} \), which is the maximum \( N_H \) for WAs obtained in AGN samples (Tombesi et al. 2013; Laha et al. 2014). As shown in Figure 3, we calculate the acceleration timescale for the launching radii \( r_0 \) of 0.001 pc and 0.01 pc, with \( n_{\text{ACM}} \) being 0 cm\(^{-3} \), 100 cm\(^{-3} \), and 1000 cm\(^{-3} \). For the WA component that is close to the SMBH, the typical acceleration distance might be about 0.01 pc and the typical acceleration timescale might be about 10 years (see the left two panels of Figure 3), while the existence distance of this WA component might be larger than 0.01 pc (Laha et al. 2021), which means that its existence timescale might be longer than its acceleration timescale. For the WA component that is relatively farther, the typical acceleration distance might be about 0.05 pc and the typical acceleration timescale might be about 100 years (see the right two panels of Figure 3), while the existence distance of this WA component is larger than 0.05 pc (e.g., Ebrero et al. 2016; Wang et al. 2022), which indicates that its acceleration timescale might be shorter than the existence timescale. These imply that the lifetimes of WAs are much larger than the acceleration timescales. These results indicate that WAs can stay in an equilibrium state during the most periods of their life.

5.2. Imbalance caused by AGN variabilities

The AGN variabilities can break the equilibrium state of WAs. Assuming the central luminosity changes from \( L \) to \( L' = (1+f)L \), the radiation pressure acting on each component of WAs along the line of sight will become \( P'_{\text{rad}} = (1+f)P_{\text{rad}} \) one by one. According to Equations. 1 and 2, then we can easily find that \( P'_{\text{rad}} = (1+f)P_{\text{D}} \) for each component of WAs. This means that the variability only has an impact on the estimation for the coefficient of Eq. 6 rather than the index. That is to say, even if the AGN variabilities are considered, the estimation for the index of the ACM density profile will not be affected.
6. SUMMARY

In this work, we propose a novel method to measure the ACM density profile by the equilibrium between the radiation pressure on the WA outflows and the drag pressure from the ACM for the following six Seyfert 1 galaxies: NGC 3227, NGC 3783, NGC 4051, NGC 4593, NGC 5548, and NGC 7469.

We study the correlation between outflow velocity and ionization parameter of the WAs in five Seyfert 1 galaxies of our sample (NGC 3227, NGC 3783, NGC 4051, NGC 4593, and NGC 5548). According to the fitting results of the $v_{\text{out}} - \xi$ relation, we infer that the density profile of the ACM is between $n \propto r^{-1.7}$ and $n \propto r^{-2.15}$ from 0.01 pc to pc scales in these five AGNs. The indexes of the ACM density profiles in these five Seyfert galaxies are within the range of the indexes in TDEs. Our results indicate that the ACM density profile in Seyfert 1 galaxies is steeper than the prediction by the spherically symmetric Bondi accretion model and the simulation results of the hot accretion flow, but more in line with the prediction by the standard thin disk model.

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REFERENCES

Akritas, M. G., & Bershady, M. A. 1996, ApJ, 470, 706, doi: 10.1086/177901
Alexander, K. D., Berger, E., Guillochon, J., Zauderer, B. A., & Williams, P. K. G. 2016, ApJL, 819, L25, doi: 10.3847/2041-8205/819/2/L25
Alexander, K. D., van Velzen, S., Horesh, A., & Zauderer, B. A. 2020, SSRv, 216, 81, doi: 10.1007/s11214-020-00702-w
Anderson, M. M., Mooley, K. P., Hallinan, G., et al. 2020, ApJ, 903, 116, doi: 10.3847/1538-4357/abb94b
Batchelor, G. K. 2000, An Introduction to Fluid Dynamics
Begelman, M. C., McKee, C. F., & Shields, G. A. 1983, ApJ, 271, 70, doi: 10.1086/161178
Behar, E. 2009, ApJ, 703, 1346, doi: 10.1088/0004-637X/703/2/1346
Bentz, M. C., & Katz, S. 2015, PASP, 127, 67, doi: 10.1086/679601
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883, doi: 10.1093/mnras/199.4.883
Blustin, A. J., Page, M. J., Fuerst, S. V., Branduardi-Raymont, G., & Ashton, C. E. 2005, A&A, 431, 111, doi: 10.1051/0004-6361:20041775
Boggs, P. T., Donaldson, J. R., Byrd, R. h., & Schnabel, R. B. 1989, ACM Trans. Math. Softw., 15, 348364, doi: 10.1145/76909.76913
Bondi, H. 1952, MNRAS, 112, 195, doi: 10.1093/mnras/112.2.195
Chen, Z., He, Z., Ho, L. C., et al. 2022, Nature Astronomy, doi: 10.1038/s41550-021-01561-3
Ebrero, J., Kaastra, J. S., Kriss, G. A., de Vries, C. P., & Costantini, E. 2013, MNRAS, 435, 3028, doi: 10.1093/mnras/stt1497
Ebrero, J., Kaastra, J. S., Kriss, G. A., et al. 2016, A&A, 587, A129, doi: 10.1051/0004-6361/201527808
Eftekhari, T., Berger, E., Zauderer, B. A., Margutti, R., & Alexander, K. D. 2018, ApJ, 854, 86, doi: 10.3847/1538-4357/aaa8e0
Elvis, M. 2000, ApJ, 545, 63, doi: 10.1086/317778
Frank, J., King, A., & Raine, D. J. 2002, Accretion Power in Astrophysics: Third Edition
Fu, X.-D., Zhang, S.-N., Sun, W., Niu, S., & Ji, L. 2017, Research in Astronomy and Astrophysics, 17, 095, doi: 10.1088/1674-4527/17/9/95
Fukumura, K., Kazanas, D., Contopoulos, I., & Behar, E. 2010, ApJ, 715, 636, doi: 10.1088/0004-637X/715/1/636
Gezari, S. 2021, Annual Review of Astronomy and Astrophysics, 59, null, doi: 10.1146/annurev-astro-111720-030029
Gillessen, S., Plewa, P. M., Widmann, F., et al. 2019, ApJ, 871, 126, doi: 10.3847/1538-4357/aaa4f8
Gofford, J., Reeves, J. N., McLaughlin, D. E., et al. 2015, MNRAS, 451, 4169, doi: 10.1093/mnras/stv1207
Grafton-Waters, S., Branduardi-Raymont, G., Mehdipour, M., et al. 2020, A&A, 633, A62, doi: 10.1051/0004-6361/201935815
He, Z., Wang, T., Liu, G., et al. 2019, Nature Astronomy, 3, 265, doi: 10.1038/s41550-018-0669-8
Holczer, T., Behar, E., & Kaspi, S. 2007, ApJ, 663, 799, doi: 10.1086/518416
Kaastra, J. S., Mewe, R., Liedahl, D. A., Komossa, S., & Brinkman, A. C. 2000, A&A, 354, L83.
https://arxiv.org/abs/astro-ph/0002345
Kelly, B. C. 2007, ApJ, 665, 1489, doi: 10.1086/519947
King, A., & Pounds, K. 2015, ARA&A, 53, 115, doi: 10.1146/annurev-astro-082214-122316
Laha, S., Guainazzi, M., Dewangan, G. C., Chakravorty, S., & Kembhavi, A. K. 2014, MNRAS, 441, 2613, doi: 10.1093/mnras/stu669
Laha, S., Reynolds, C. S., Reeves, J., et al. 2021, Nature Astronomy, 5, 13, doi: 10.1038/s41550-020-01255-2
Li, Y.-P., Yuan, F., & Wang, Q. D. 2015, ApJ, 798, 22, doi: 10.1088/0004-637X/798/1/22
Lobban, A. P., Reeves, J. N., Miller, L., et al. 2011, MNRAS, 414, 1965, doi: 10.1111/j.1365-2966.2011.18513.x
Mao, J., Mehdipour, M., Kaastra, J. S., et al. 2019, A&A, 621, A99, doi: 10.1051/0004-6361/201833191
Mehdipour, M., Kaastra, J. S., Costantini, E., et al. 2018, A&A, 615, A72, doi: 10.1051/0004-6361/201832604
Miller, M. J., & Bregman, J. N. 2015, ApJ, 800, 14, doi: 10.1088/0004-637X/800/1/14
Mizumoto, M., Done, C., Tomaru, R., & Edwards, I. 2019, MNRAS, 489, 1152, doi: 10.1093/mnras/stz2225
Mo, H., van den Bosch, F. C., & White, S. 2010, Galaxy Formation and Evolution
Narayan, R., & Yi, I. 1994, ApJL, 428, L13, doi: 10.1086/187381
Nemmen, R. S., Georganopoulos, M., Guiric, S., et al. 2012, Science, 338, 1445, doi: 10.1126/science.1227416
Proga, D., & Kallman, T. R. 2004, ApJ, 616, 688, doi: 10.1086/425117
Reynolds, C. S. 1997, MNRAS, 286, 513, doi: 10.1093/mnras/286.3.513
Reynolds, C. S., & Fabian, A. C. 1995, MNRAS, 273, 1167, doi: 10.1093/mnras/273.4.1167
Russell, H. R., Fabian, A. C., McNamara, B. R., & Broderick, A. E. 2015, MNRAS, 451, 588, doi: 10.1093/mnras/stv954
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 500, 33
Silva, C. V., Costantini, E., Giustini, M., et al. 2018, MNRAS, 480, 2334, doi: 10.1093/mnras/stv1938
Tarter, C. B., Tucker, W. H., & Salpeter, E. E. 1969, ApJ, 156, 943, doi: 10.1086/150026
Tommasi, F., Cappi, M., Reeves, J. N., et al. 2013, MNRAS, 430, 1102, doi: 10.1093/mnras/sts692
Wang, Y., Kaastra, J., Mehdipour, M., et al. 2022, A&A, 657, A77, doi: 10.1051/0004-6361/202141599
Wong, K.-W., Irwin, J. A., Yukita, M., et al. 2011, ApJL, 736, L23, doi: 10.1088/2041-8205/736/1/L23
Yuan, F., & Narayan, R. 2014, ARA&A, 52, 529, doi: 10.1146/annurev-astro-082812-141003
Yuan, F., Wu, M., & Bu, D. 2012, ApJ, 761, 129, doi: 10.1088/0004-637X/761/2/129