The effects of large-scale magnetic fields on the model for repeating changing-look AGNs

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**ABSTRACT**

Periodic outbursts are observed in several changing-look (CL) active galactic nuclei (AGNs). Sniegowska et al. (2020) suggested a model to explain the repeating CL in these AGNs, where the periodic outbursts are triggered in a narrow unstable zone between an inner ADAF and outer thin disk. In this work, we intend to investigate the effects of large-scale magnetic fields on the limit cycle behaviors of CL AGNs. The winds driven by magnetic fields can significantly change the structure of thin disk by taking away the angular momentum and energy of the disk. It is found that the period of outburst in repeating CL AGNs can be substantially reduced by the magnetic fields. Conversely, if we keep the period unchanged, the outburst intensity can be raised for several times. These results can help to explain the observational properties of multiple CL AGNs. Besides the magnetic fields, the effects of transition radius $R_{tr}$, the width of transition zone $\Delta R$ and Shakura-Sunyaev parameter $\alpha$ are also explored in this work.

**Keywords:** accretion disks — instabilities: active — galaxies: Seyfert — quasars: magnetic fields

1. INTRODUCTION

Active galactic nuclei (AGNs) can be classified into type 1 and type 2 based on the appearance or disappearance of broad emission lines (Seyfert 1943), which is usually explained as whether broad emission line region (BLR) is obscured by torus or not in AGN unified model (e.g., Antonucci 1993). Some AGNs have been reported that their types change on timescales of months to years for many years, i.e., from type 1 to 2 (e.g., Penton & Perez 1984; Elitzur et al. 2014), or from type 2 to 1 (e.g., Khachikian & Weedman 1971; Kotrebi et al. 2019), or even experience multiple changes (e.g., McElroy et al. 2016; Wang et al. 2020). These sources are the so-call changing-look AGNs (CL AGNs) and have attracted more and more attention in recent years. Up to 100 CL AGNs have been discovered so far (e.g., Parker et al. 2016; Gezari et al. 2017; Yang et al. 2018; MacLeod et al. 2019; Wang et al. 2020).

The physical origin of CL AGNs is still under debate. The first direct explanation is that BLR is obscured by clouds crossing over our line of sight (e.g., Goodrich 1989; Tran et al. 1992; Elitzur 2012). However, both the low polarization level and strong variability of infrared (IR) emissions in CL AGNs don’t support this scenario (MacLeod et al. 2016; Sheng et al. 2017; Hutsemékers et al. 2019). Tidal disruption events (TDEs) is also a possible mechanism for some CL AGNs (Merloni et al. 2015; Kawamuro et al. 2016; Ricci et al. 2020), but other CL AGNs may be not triggered by TDEs (e.g., Alloin et al. 1986; Rumoe et al. 2016; Wang et al. 2020). Besides these two mechanisms, change of mass accretion rate seems to be the most promising candidate for CL AGNs as suggested by recent works (e.g. Elitzur et al. 2014; Ross et al. 2018; Liu et al. 2019; Sniegowska et al. 2020). However, the viscous timescale of a thin disk corresponding with variable accretion rate is found to be inconsistent with observed timescale of CL AGNs (e.g. Gezari et al. 2017; Stern et al. 2018). This problem can be qualitatively resolved when taking the large-scale magnetic field into account (Dexter & Begelman 2019), or considering the instability of accretion disk (Sniegowska et al. 2020). Lastly, the close binaries of supermassive black holes with high eccentric-
ities has also been suggested to be a possible model for CL AGNs recently (Wang & Bon 2020).

For CL AGNs with periodic or quasi-periodic outbursts, the outburst mechanism should be related to some kind of instability. The inner region of a thin disk, which is dominated by radiation pressure, is known to be both thermally and viscously unstable (Shakura & Sunyaev 1973; Shakura & Sunyaev 1976), unless other factors are included, such as, convection, turbulence, or magnetic field (Goldman & Wandel 1995; Zheng et al. 2011; Li & Begelman 2014; Yu et al. 2015). Sniegowska et al. (2020) proposed an ingenious model to explain the repeating CL AGNs. In order to decrease the viscous timescale, the instable region is limited to a narrow zone between outer thin disk dominated by gas pressure and inner advection-dominated accretion flows (ADAF). This toy model can qualitatively repeat the observed multiple outbursts. In observations, relativistic jets are discovered in many AGNs (e.g., see a review in Blandford et al. 2019 and references therein), where large-scale magnetic fields play a key role in the popular mechanism launching relativistic jets (Blandford & Znajek 1977; Hawley et al. 2015). Winds are also found to be present in a significant fraction of AGNs through the observation of blue-shift absorption/emission lines (e.g., Matthews et al. 2020). Except for radiation pressure and line-driven (e.g., Proga et al. 2000; Proga & Kallman 2004), large-scale magnetic fields can also drive disk winds in some AGNs (e.g., Blandford & Payne 1982; Camenzind 1986; Cao 2014). The magnetic accelerated winds can significantly change the structure of disk by taking away both the angular momentum and energy. The former will decrease disk temperature and the latter can improve radial velocity of disk (Li & Begelman 2014). Therefore, we anticipate that large-scale magnetic fields can affect both the period and outburst amplitude of disk instability. In this work, we will investigate the effects of magnetic fields on the model produced by Sniegowska et al. (2020) and on repeating CL AGNs.

2. MODEL

The inner region of a thin disk is known to be unstable (Shakura & Sunyaev 1973; Shakura & Sunyaev 1976). Based on this phenomenon, Sniegowska et al. (2020) proposed a possible mechanism for the multiple CL AGNs, where they assumed that the accretion flow is composed of an inner ADAF and outer thin disk. The radiation-dominated region of a thin disk will shrink when mass accretion rate decreases, in the mean while an inner ADAF will appear. A specific mass accretion rate $\dot{m}_{\text{inst}}$ may be present, for which the inner ADAF will coincide with the outer radius of instable region in a thin disk (see Sniegowska et al. 2020 for details). When the accretion rate $\dot{m}$ is slightly higher than $\dot{m}_{\text{inst}}$, a small instable belt ($\Delta R$) will emerge between outer gas-dominated disk and inner ADAF. Because the belt is very narrow ($\Delta R \ll R$), its viscous timescale can be decreased to match the observed timescale of CL AGNs. The irradiation of inner ADAF on outer thin disk is also included in (Sniegowska et al. 2020), where the radiative efficiency is simply adopted to be 10 percent (Bisnovatyi-Kogan & Lovelace 1997; Ferreira & Petrucci 2011; Hirotani 2018).

In this work, we study the effects of magnetic fields on the model suggested by Sniegowska et al. (2020). As shown in figure 1, large-scale magnetic fields are assumed to thread not only on the radiation-dominated belt but also on the outer gas-dominated disk.

![Figure 1](SS_disk.png)

**Figure 1.** The schematic picture of our model. The intermediate zone is unstable, locating between an inner ADAF and outer gas-dominated thin disk, where the irradiation from inner ADAF is included.

2.1. Model for outer thin disk dominated by gas pressure

At first, we present the equations for outer thin disk region threaded by large-scale magnetic fields. In all the calculations, we adopt pseudo-Newtonian potential (Paczyński & Wiita 1980) and $\alpha P$ prescription for viscosity. Following Li & Begelman (2014), the continuity equation is given by

$$\frac{dM}{dR} + 4\pi R \dot{m}_{w} = 0,$$

(1)

where $\dot{m}_{w}$ is the mass loss rate from unit surface area of disk. $\dot{m}_{w}$ can be gotten from

$$\dot{m}_{w} = \frac{B_{p} B_{z}}{4\pi \Omega_{k} R} \mu,$$

(2)

where $\mu$ is the dimensionless, mass loading parameter of the outflow (Cao & Spruit 2013), in this work we adopt $\mu = 0.001$ for fast moving winds with low mass-loss rates (Ogilvie & Livio 1998; Cao 2002). Here $B_{p}$
where $\beta_{\text{accretion disk}}$ is given as

$$T_m \approx B_{\text{pol}} B_{\text{vert}} R / 2\pi,$$

where $T_m$ is the magnetic torque exerted on accretion disk. The magnetic torque exerted on the accretion flow is (Li & Begelman 2014)

$$T_m = B_{\text{pol}} B_{\text{vert}} R / 2\pi,$$

which can also be given through the outflows (Cao & Spruit 2013)

$$T_m = (3/4\pi) R B_{\text{pol}}^2 \mu \left( 1 + \mu^{2/3} \right).$$

Combining the equation (4) and (5) we can derive

$$B_{\text{pol}} / B_{\text{vert}} = (3/2) \mu \left( 1 + \mu^{2/3} \right),$$

in the case of $\mu = 0.001$, the toroidal component of magnetic field $B_{\text{pol}} = 0.15 B_{\text{vert}}$. The total pressure of accretion disk is given as

$$P = (1 + 1/\beta_{\text{adv}}) (P_{\text{gas}} + P_{\text{rad}}),$$

where $\beta_{\text{adv}} = (P_{\text{gas}} + P_{\text{rad}}) / (B^2/8\pi)$. The gas pressure $P_{\text{gas}}$ and radiation pressure $P_{\text{rad}}$ are given by $P_{\text{gas}} = 2\rho k T / m_H$ and $P_{\text{rad}} = a T^4 / 3$, respectively.

The energy equation can be calculated with

$$\nu \Sigma R^2 \left( \frac{d\Omega_k}{dR} \right)^2 + L_* (1 - a_*) (H_* + \dot{q}_H) = \frac{8acT^4}{3\pi},$$

where $\nu$ is the viscosity coefficient and $\Sigma = 2\rho H$ is the surface density. The optical depth is given by $\tau = \kappa \Sigma / 2$, where $\kappa$ is the opacity. The second in the left side of equation represents the irradiation from inner ADAF. $L_*$, $H_*$, $a_*$ and $\dot{q}_H$ correspond to the luminosity of irradiation, height of irradiation source, albedo and an index for $H/R \propto R^{\beta_2}$, respectively (see Liu et al. 2016 for details). With above equations (1), (3), (7) and (8), we can get steady solutions for outer thin disk.

2.2. Model for transition zone dominated by radiation pressure

The winds driven by magnetic fields can take away the mass, angular momentum and energy from accretion disk. Therefore, we need to revise the model produced by Śniegowska et al. (2020). Following their work, we assume that the inflow rate from outer thin disk to the transition zone is constant and that the evaporation rate from transition zone to inner ADAF is proportional to the scale-height and surface density of transition zone. This evaporation rate can be written as:

$$\dot{M} = \dot{M}_0 \frac{H}{H_0} \frac{\Sigma}{\Sigma_0},$$

where $\dot{M}_0$, $H_0$ and $\Sigma_0$ are the inflow rate from outer zone to transition zone, scale-height and surface density of transition zone at equilibrium state, respectively. With $\dot{M}$, the time evolution equation of surface density can be revised as

$$\frac{d\Sigma}{dt} = \frac{\dot{M}_0 - \dot{M} - 4\pi \rho \dot{m}_w \Delta R}{2\pi R \dot{\Delta} R},$$

where $\Delta R$ is the width of transition zone.

The general form of time evolution equation for energy is

$$\Sigma T \frac{ds}{dt} = Q^+ - Q^-,$$

where $Q^+$ and $Q^-$ are the viscous heating rate and radiative cooling rate, respectively. From the first law of thermodynamics, we have

$$T ds = dq = \left( \frac{\partial u}{\partial T} \right)_T dT + \left( \frac{\partial u}{\partial \rho} \right)_T \frac{P}{\rho^2} d\rho,$$

where $s$ is the entropy. Including energy of magnetic fields, the internal energy $u$ can be written as

$$u = \frac{3P_{\text{gas}}}{2\rho} + \frac{a T^4}{\rho} + B^2 / 8\pi \rho.$$
where $Q_{\text{adv}} = M PH / 2\pi R \Delta R \Sigma$ is the advection cooling rate (see Sniegowska et al. 2020).

3. NUMERICAL RESULTS

In this section, we start to investigate the effects of magnetic fields on the limit cycle behaviors of transition zone through equations (10) and (15). The albedo $\alpha_* = 0.3$, $H_* = 10 R_g$ ($R_g = 2GM/c^2$) and $q_* = 0.3$ are always adopted when calculating the irradiation from ADAF. Given the black hole mass $M$, the external accretion rate of transition zone $\dot{m}$ ($= M/\dot{M}_{\text{Edd}}$, $\dot{M}_{\text{Edd}} = 48\pi GMm_H/\sigma_T c^2$), the Shakura-Sunyaev parameter $\alpha$, the position of transition zone $R_{\text{tr}}$, the width of transition zone $\Delta R$ and the parameter of magnetic field $\beta_1$, we can numerically solve the equations (10) and (15).

The winds driven by large-scale magnetic fields can reduce the temperature of disk by taking away its energy, which will affect the instability of disk (Li & Begelman 2014). In figure 2, we present how the transition radius varies with the strength of magnetic field. The blue solid line shows the radius between an inner ADAF and outer thin disk, which is given by $R_{\text{ADAF}} = 2 \alpha_{g,1} \dot{m}^{-2} R_g$ in Sniegowska et al. (2020). It is found that the outer radius of inner thin disk dominated by radiation pressure decreases with increasing magnetic field strength, resulting on a smaller transition radius ($R_{\text{tr}}$, the point of intersection between the blue line and other lines). However, this issue can be somewhat overcome when considering the effects of magnetic fields on $\alpha$. The value of $\alpha$ is found to increase with increasing magnetic field strength, leading to a higher $R_{\text{ADAF}}$ (e.g., Bai & Stone 2013; Salvesen et al. 2016).

![Figure 2. The outer radius of inner thin disk dominated by radiation pressure as functions of mass accretion rate, where the black hole mass $M = 10^7 M_\odot$ and $\alpha = 0.04$ are adopted. The blue line is the radius between ADAF and outer disk. the red cross, green triangle and yellow circle represent $\beta_1 = \infty$, 1000, 500, respectively.](image2)

![Figure 3. The light curves correspond to the parameters in group number 1, 2, 3, 4 and 5. The red dash line represents the light curve of the default parameters (group 1) and the blue solid lines represent the light curves of other group. Left panel: the comparison of light curves with different magnetic field strength (group 2 and 3). Right panel: the comparison of light curves with different $\Delta R$ and magnetic field strength (group 4 and 5).](image3)

Table 1. Detailed parameter of our calculations

| Number | $\alpha$ | $\dot{m}$ | $R_{\text{tr}}/R_g$ | $\Delta R/R_g$ | $\beta_1$ | $L_{\max}/L_{\min}$ |
|--------|---------|---------|--------------------|----------------|----------|--------------------|
| 1      | 0.04    | 0.048   | 30                 | 0.1            | $\infty$ | 7.93               |
| 2      | 0.04    | 0.240   | 30                 | 0.1            | 500      | 7.17               |
| 3      | 0.04    | 0.138   | 30                 | 0.1            | 1000     | 9.44               |
| 4      | 0.04    | 0.225   | 30                 | 0.47           | 500      | 50.38              |
| 5      | 0.04    | 0.133   | 30                 | 0.28           | 1000     | 31.71              |
| 6      | 0.04    | 0.065   | 40                 | 0.1            | $\infty$ | 5.27               |
| 7      | 0.04    | 0.084   | 50                 | 0.1            | $\infty$ | 3.77               |
| 8      | 0.06    | 0.045   | 30                 | 0.1            | $\infty$ | 8.68               |
| 9      | 0.1     | 0.042   | 30                 | 0.1            | $\infty$ | 9.84               |

In order to investigate the effects of magnetic field and other parameters on the limit cycle behavior of transition zone, we provide nine group of parameters (see table 1). The parameters in group 1 are the default values in our calculations, while parameters in other group are just slightly modified. In all the calculations in table 1, the black hole mass $M = 10^7 M_\odot$ is always adopted.

The strength of magnetic fields ($\beta_1$) and the width of transition zone ($\Delta R$) are found to the limit cycle behaviors more significantly than other parameters. The period of disk light curve decreases fast with increas-
ing strength of magnetic field (decreasing $\beta_1$) as shown in the left panel of figure 3, while the shape of light curves are quite similar. If we keep the period of light curve as constant, $\Delta R$ is required to increase with decreasing $\beta_1$ (right panel of figure 3). In this case, it is found that the outburst intensity $(L_{\text{max}}/L_{\text{min}})$ significantly increases with decreasing $\beta_1$. Notably, when tuning the parameter $\beta_1$, we just increase the mass accretion to ensure that the position of transition radius $R_{\text{tr}}$ is roughly constant, while its width $\Delta R$ is assumed to remain unchanged for simply (group 2 and 3). The detailed calculation of $\Delta R$ should be carried out by considering the effects of large-scale magnetic fields on the heating and cooling process in ADAF, which is beyond the scope of this work.

The position of transition zone $R_{\text{tr}}$ and $\alpha$ can just slightly change the limit cycle behavior of transition zone (figure 4). The increasing $R_{\text{tr}}$ will lead to larger period and smaller outburst intensity simultaneously, as shown in the left panel of figure 4. However, increasing $\alpha$ can only increase the period of light curve (right panel of figure 4).

4. CONCLUSIONS AND DISCUSSION

In this work, we construct a new model to investigate the effects of large-scale magnetic fields on the model produced by Sniegowska et al. (2020). The presence of magnetic fields can greatly reduce the period of outburst in multiple CL AGNs. However, if the period is remained the same, the outburst intensity will increase for several times (see figure 3). Besides magnetic fields, the width of transition zone ($\Delta R$), the position of transition zone $R_{\text{tr}}$ and $\alpha$ can all change the limit cycle behaviors of transition zone. The large-scale magnetic fields adopted is very weak in our model. In case of strong magnetic fields, where MRI process will be suppressed (Narayan et al. 2003), reconnecting tearing instabilities may be responsible for the transport of angular momentum and produce the outburst in observations (de Gouveia Dal Pino et al. 2010; Ebrahimi & Prager 2011).

The formation mechanism of large-scale magnetic fields in a standard thin disk is still an open issue so far. There are mainly two candidates currently. Firstly, the weak large-scale magnetic fields locating in outer region of a thin disk is difficult to be effectively dragged inward because the diffusive speed of magnetic field is found to be faster than its advection speed (van Ballegooijen 1989; Lubow et al. 1994). However, this problem may be solved when considering the effect of winds accelerated by magnetic fields. The strong winds driven by magnetic fields can greatly improve the advection speed by taking away most of angular momentum in a thin disk. Even for a very weak magnetic fields ($\beta_1 > 100$), the initial magnetic fields can be effectively magnified (Cao & Spruit 2013; Li & Begelman 2014). Secondly, the dynamo process from magnetorotational instability (MRI) (Balbus & Hawley 1991) can also generate the large-scale magnetic fields, as suggested from both the shearing box and global simulations (e.g., Sądowski et al. 2015; Ebrahimi & Blackman 2016; Bhat et al. 2016).

Our model can help to explain the observational properties of periodic repeating CL AGNs. For example, the fluxes in CL AGN NGC 1566 appear obvious periodicity (Alloin et al. 1986). However, the outburst intensity of NGC 1566 is different in each outburst, which may be caused by the variation of magnetic field strength. As shown in figure 3, the outburst intensity can increase 6 times when considering a weak magnetic fields ($\beta_1 = 500$). GSN 069 is another CL AGNs showing periodic light curve, whose period is about 9 hours (Miniutti et al. 2019). In order to get such a short period, Sniegowska et al. (2020) suggested that a small transition radius ($R_{\text{tr}}$) and a big $\alpha$ are necessary. The presence of magnetic field can be in favor of shortening its period.

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REFERENCES

Alloin, D., Pelet, D., Phillips, M. M., Fosbury, R. A. E., & Freeman, K. 1986, The Astrophysical Journal, 308, 23, doi: 10.1086/164475
Antonucci, R. 1993, Annual Review of Astronomy and Astrophysics, 31, 473, doi: 10.1146/annurev.aa.31.090193.002353
Bai, X.-N., & Stone, J. M. 2013, ApJ, 767, 30, doi: 10.1088/0004-637X/767/1/30
Baldassare, S. A., & Hawley, J. F. 1991, ApJ, 376, 214, doi: 10.1086/170270
Bhat, P., Ebrahimi, F., & Blackman, E. G. 2016, MNRAS, 462, 818, doi: 10.1093/mnras/stw1619
Bisnovatyi-Kogan, G. S., & Lovelace, R. V. E. 1997, The Astrophysical Journal Letters, 486, L43, doi: 10.1086/310826
Blandford, R. D., & Payne, D. G. 1982, Monthly Notices of the Royal Astronomical Society, 199, 883, doi: 10.1093/mnras/199.4.883
Blandford, R. D., & Znajek, R. L. 1977, Monthly Notices of the Royal Astronomical Society, 179, 433, doi: 10.1093/mnras/179.3.433
Camenzind, M. 1986, A&A, 156, 137
Cao, X. 2002, MNRAS, 332, 999, doi: 10.1046/j.1365-8711.2002.05375.x
—. 2014, ApJ, 783, 51, doi: 10.1088/0004-637X/783/1/51
Cao, X., & Spruit, H. C. 2013, ApJ, 765, 149, doi: 10.1088/0004-637X/765/2/149
Cao, X., & Spruit, H. C. 2013, The Astrophysical Journal, 765, 149, doi: 10.1088/0004-637X/765/2/149
de Gouveia Dal Pino, E. M., Piovezan, P. P., & Kadowaki, L. H. S. 2010, A&A, 518, A5, doi: 10.1051/0004-6361/200913462
Dexter, J., & Begelman, M. C. 2019, MNRAS, 483, L17, doi: 10.1093/mnrasl/sly213
Ebrahimi, F., & Blackman, E. G. 2016, MNRAS, 459, 1422, doi: 10.1093/mnras/stw724
Ebrahimi, F., & Prager, S. C. 2011, ApJ, 743, 192, doi: 10.1088/0004-637X/743/2/192
Elitzur, M. 2012, The Astrophysical Journal Letters, 747, L33, doi: 10.1088/2041-8205/747/2/L33
Elitzur, M., Ho, L. C., & Trump, J. R. 2014, Monthly Notices of the Royal Astronomical Society, 438, 3340, doi: 10.1093/mnras/stt2445
Ferreira, J., & Petrucci, P. O. 2011, 275, 260, doi: 10.1017/S1743921310016121
Gezari, S., Hung, T., Cenko, S. B., et al. 2017, The Astrophysical Journal, 835, 144, doi: 10.3847/1538-4357/835/2/144
Goldman, I., & Wandel, A. 1995, ApJ, 443, 187, doi: 10.1086/175513
Goodrich, R. W. 1989, The Astrophysical Journal, 342, 224, doi: 10.1086/167586
Hawley, J. F., Fendt, C., Hardcastle, M., Nokhrina, E., & Tschekhovskoy, A. 2015, arXiv:1508.02546 [astro-ph], doi: 10.1007/s11214-015-0174-7
Hirotani, K. 2018, Galaxies, 6, 122, doi: 10.3390/galaxies6040122
Hutsemékers, D., González, B. A., Marin, F., et al. 2019, A&A, 625, A54, doi: 10.1051/0004-6361/201834633
Janiuk, A., Czerny, B., & Siemiginowska, A. 2002, ApJ, 576, 908, doi: 10.1086/341804
Katebi, R., Chornock, R., Berger, E., et al. 2019, Monthly Notices of the Royal Astronomical Society, 487, 4057, doi: 10.1093/mnras/stt1552
Kawamuro, T., Ueda, Y., Shidatsu, M., et al. 2016, Publications of the Astronomical Society of Japan, 68, 58, doi: 10.1093/pasj/psw056
Khachikian, E. Y., & Weedman, D. W. 1971, The Astrophysical Journal Letters, 164, L109, doi: 10.1086/180701
Li, S.-L., & Begelman, M. C. 2014, ApJ, 786, 6, doi: 10.1088/0004-637X/786/1/6
Liu, H., Li, S.-L., Gu, M., & Guo, H. 2016, Mon. Not. R. Astron. Soc. Lett., 462, L56, doi: 10.1093/mnrasl/slw123
Liu, H., Wu, Q., Lyu, B., & Yan, Z. 2019, arXiv e-prints, arXiv:1912.03972. https://arxiv.org/abs/1912.03972
Lubow, S. H., Papaloizou, J. C. B., & Pringle, J. E. 1994, MNRAS, 267, 235, doi: 10.1093/mnras/267.2.235
MacLeod, C. L., Ross, N. P., Lawrence, A., et al. 2016, Mon. Not. R. Astron. Soc., 457, 389, doi: 10.1093/mnras/stv2997
MacLeod, C. L., Green, P. J., Anderson, S. F., et al. 2019, The Astrophysical Journal, 874, 8, doi: 10.3847/1538-4357/ab05e2
Matthews, J. H., Knigge, C., Higginbottom, N., et al. 2020, MNRAS, 492, 5540, doi: 10.1093/mnras/staa136
McElroy, R. E., Husemann, B., Cromm, S. M., et al. 2016, Astronomy and Astrophysics, 593, L8, doi: 10.1051/0004-6361/201629102
Merloni, A., Dwelly, T., Salvato, M., et al. 2015, Monthly Notices of the Royal Astronomical Society, 452, 69, doi: 10.1093/mnras/stv1095
Miniutti, G., Saxton, R. D., Giustini, M., et al. 2019, Nature, 573, 381, doi: 10.1038/s41586-019-1556-x
Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2003, PASJ, 55, L69, doi: 10.1093/pasj/55.6.L69
Ogilvie, G. I., & Livio, M. 1998, ApJ, 499, 329, doi: 10.1086/305636
Paczynsky, B., & Wiita, P. J. 1980, A&A, 500, 203
Parker, M. L., Komossa, S., Kollatschny, W., et al. 2016, Monthly Notices of the Royal Astronomical Society, 461, 1927, doi: 10.1093/mnras/stw1449
Penston, M. V., & Perez, E. 1984, Monthly Notices of the Royal Astronomical Society, 211, 33P, doi: 10.1093/mnras/211.1.33P
Proga, D., & Kallman, T. R. 2004, ApJ, 616, 688, doi: 10.1086/425117
Proga, D., Stone, J. M., & Kallman, T. R. 2000, ApJ, 543, 686, doi: 10.1086/317154
Ricci, C., Kara, E., Loewenstein, M., et al. 2020, arXiv:2007.07275 [astro-ph], doi: 10.3847/2041-8213/ab91a1
Ross, N. P., Ford, K. E. S., Graham, M., et al. 2018, Monthly Notices of the Royal Astronomical Society, 480, 4468, doi: 10.1093/mnras/sty2002
Runnoe, J. C., Cales, S., Ruan, J. J., et al. 2016, MNRAS, 455, 1691, doi: 10.1093/mnras/stv2385
Salvesen, G., Simon, J. B., Armitage, P. J., & Begelman, M. C. 2016, MNRAS, 457, 857, doi: 10.1093/mnras/stw029
Seyfert, C. K. 1943, The Astrophysical Journal, 97, 28, doi: 10.1086/144488
Shakura, N. I., & Sunyaev, R. A. 1973, Astronomy and Astrophysics, 24, 337. http://adsabs.harvard.edu/abs/1973A%26A....24..337S
Shakura, N. I., & Sunyaev, R. A. 1976, MNRAS, 175, 613, doi: 10.1093/mnras/175.3.613
Sheng, Z., Wang, T., Jiang, N., et al. 2017, ApJL, 846, L7, doi: 10.3847/2041-8213/aa85de
Sądowski, A., Narayan, R., Tchekhovskoy, A., et al. 2015, MNRAS, 447, 49, doi: 10.1093/mnras/stu2387
Sniegowska, M., Czerny, B., Bon, E., & Bon, N. 2020, arXiv e-prints, 2007, arXiv:2007.06441.
http://adsabs.harvard.edu/abs/2020arXiv200706441S
Stern, D., McKernan, B., Graham, M. J., et al. 2018, ApJ, 864, 27, doi: 10.3847/1538-4357/aac726
Tran, H. D., Osterbrock, D. E., & Martel, A. 1992, The Astronomical Journal, 104, 2072, doi: 10.1086/116382
van Ballegooijen, A. A. 1989, Magnetic Fields in the Accretion Disks of Cataclysmic Variables, ed. G. Belvedere, Vol. 156, 99, doi: 10.1007/978-94-009-2401-7_10
Wang, J., Xu, D. W., Sun, S. S., et al. 2020, arXiv:2003.09613 [astro-ph], doi: 10.3847/1538-3881/ab85cc
Wang, J., Xu, D. W., & Wei, J. Y. 2020, ApJ, 901, 1, doi: 10.3847/1538-4357/abaa48
Wang, J.-M., & Bon, E. 2020, arXiv:2010.04417 [astro-ph]. http://arxiv.org/abs/2010.04417
Yang, Q., Wu, X.-B., Fan, X., et al. 2018, The Astrophysical Journal, 862, 109, doi: 10.3847/1538-4357/aaca3a
Yu, X.-F., Gu, W.-M., Liu, T., Ma, R.-Y., & Lu, J.-F. 2015, ApJ, 801, 47, doi: 10.1088/0004-637X/801/1/47
Zheng, S.-M., Yuan, F., Gu, W.-M., & Lu, J.-F. 2011, ApJ, 732, 52, doi: 10.1088/0004-637X/732/1/52