Extreme AGN variability: evidence of magnetically elevated accretion?

Jason Dexter\textsuperscript{1}\textsuperscript{*} and Mitchell C. Begelman\textsuperscript{2,3}
\textsuperscript{1}Max-Planck-Institut f"ur Extraterrestrische Physik, Giessenbachstr. 1, 85748 Garching, Germany
\textsuperscript{2}JILA, University of Colorado and NIST, 440 UCB, Boulder, CO 80309-0440, USA
\textsuperscript{3}Department of Astrophysical and Planetary Sciences, 391 UCB, University of Colorado, Boulder, CO 80309-0391, USA

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Rapid, large amplitude variability at optical to X-ray wavelengths is now seen in an increasing number of Seyfert galaxies and luminous quasars. The variations imply a global change in accretion power, but are too rapid to be communicated by inflow through a standard thin accretion disc. Such discs are long known to have difficulty explaining the observed optical/UV emission from active galactic nuclei. Here we show that alternative models developed to explain these observations have larger scale heights and shorter inflow times. Accretion discs supported by magnetic pressure in particular are geometrically thick at all luminosities, with inflow times as short as the observed few year timescales in extreme variability events to date. Future time-resolved, multi-wavelength observations can distinguish between inflow through a geometrically thick disc as proposed here, and alternative scenarios of extreme re-processing of a central source or instability-driven limit cycles.

Key words: black holes — galaxies: active — variability

1 INTRODUCTION

The standard “thin disc” theory (Shakura & Sunyaev 1973; Novikov & Thorne 1973) explains the high radiative efficiency, luminosity, and spectral peak locations seen from black holes accreting at the Eddington rate. However, it is difficult to reconcile the theory with optical/UV observations of active galactic nuclei (AGN):

- The variability is often nearly simultaneous over a wide range of wavelength, requiring a coordination speed close to the speed of light (Clavel et al. 1991; Krolik et al. 1991), inconsistent with viscous inflow through a thin disc.
- Observed accretion discs are several times larger than predicted, as measured either by quasar microlensing (Morgan et al. 2010) or continuum reverberation (McHardy et al. 2014).
- AGN accretion disc spectra are broader than expected (Zheng et al. 1997; Davis et al. 2007), typically peak around 1000Å (Shull et al. 2012), and do not show the expected $T_{\text{eff}} \sim (\dot{m}/M)^{1/4}$ dependence (Davis et al. 2007; Laor & Davis 2014), where $M$ is the black hole mass and $\dot{m} = 0.1 M c^2/L_{\text{edd}}$ is the dimensionless accretion rate, equivalent to the Eddington ratio $L/L_{\text{edd}}$ for a radiative efficiency $\eta = 0.1$.
- Thin accretion discs should be subject to thermal (Shakura & Sunyaev 1976) and inflow (Lightman & Eardley 1974) instabilities in the inner disc, and should be truncated at large radius by gravitational instability (Shlosman & Begelman 1987; Goodman 2003).

AGN optical/UV variability has typical rms amplitudes of $\approx 10 – 20\%$. Wide field surveys find that up to $\approx 50\%$ of quasars undergo “extreme” variability, where the optical luminosity changes by a factor $\gtrsim 2$ (Rumbaugh et al. 2018). In “changing look” AGN, the broad emission lines appear or disappear, causing transitions between Types 1 and 2 (or 1.8/1.9). Known previously in a few nearby Seyferts (Tobline & Osterbrock 1976; Cohen et al. 1986; Storchi-Bergmann et al. 1995), such events are now also found from luminous quasars in wide-field surveys (MacLeod et al. 2016; Ruan et al. 2016; Yang et al. 2017; Wang et al. 2018) increasing the sample to $\approx 40$ total. The changes in broad line flux correspond to factor $\approx 10$ changes in continuum luminosity, which occur on timescales of a few years (e.g., LaMassa et al. 2015; Gezari et al. 2017). The timescale does not seem to depend on the type of object or whether the luminosity is increasing or decreasing.

Variable obscuration is disfavored for changing look AGN. The obscuring medium would need to have a large size and high speed to cover both the broad line and continuum emission regions. In one case the mid-infrared flux...
decreases, so that obscuring material would have to block the torus (Stern et al. 2018), while in another there is no linear polarization signature (Hutsemékers et al. 2017) as seen in Type 2 AGN. In addition, in the Seyfert galaxy Mrk 1018 a full optical to X-ray SED shows no sign of variable obscuration, but is rather fully consistent with a drop in intrinsic accretion power by a factor $\sim 10$ (McElroy et al. 2016; Husemann et al. 2016) over a few years. The timescales seen in the small sample of changing look events are similar to those of normal (Kelly et al. 2009; MacLeod et al. 2010) and extreme AGN variability, and the extreme objects do not stand out from the overall population except for their large variability amplitudes (Rumbaugh et al. 2018). Therefore, changing look objects may simply be the high amplitude tail of normal AGN variability and not the result of discrete events (e.g., mergers or state transitions, Kim et al. 2018; Noda & Done 2018; Ross et al. 2018). Apparently many or even most AGN can undergo rapid, large amplitude, coordinated luminosity variations, implying a much faster propagation timescale through the accretion disc than predicted: a “viscosity crisis” (Lawrence 2018).

The crisis comes from the fact that in standard theory the disc is expected to be “razor thin,” but that theory is clearly problematic for AGN. Here we estimate inflow times for three alternative disc models (§2) introduced in the literature in order to explain one or more of these tensions between theory and observation. Generically, discs in these scenarios are thicker, leading to shorter inflow times that could help explain extreme AGN variability (§2.4). We show that accretion discs supported vertically by strong magnetic fields (“magnetically elevated discs”) provide a particularly promising explanation, and discuss how time-resolved photometry of changing look events can constrain their physical origin (§3).

## 2 Geometrically Thick AGN Accretion Discs

In the standard thin disc model (Shakura & Sunyaev 1973; Novikov & Thorne 1973), radiation pressure provides the vertical support against gravity at small radius (Krolik 1999),

$$R \lesssim 1000 \alpha^{2/3} \left(\frac{L}{10^{46} \text{ erg s}^{-1}}\right)^{2/21} \left(\frac{\kappa}{k_T} \right)^{20/21} \eta^{2/3} \nu_g,$$

(1)

where $\alpha \approx 0.02$ (Hawley et al. 2011) is the dimensionless viscosity parameter, $\kappa$ is the opacity scaled to the value for Thomson scattering, and $\nu_g = GM/c^2$ is the gravitational radius. Both the predicted and measured (Dai et al. 2010; Blackburne et al. 2014; McHardy et al. 2014) sizes of the X-ray and optical emission regions for $\dot{m} \gtrsim 10^{-2}$ are in the radiation-dominated regions of the disc.

When radiation pressure dominates, the disc is thin, with a constant height $H$ for radii $R$ far from the inner edge:

$$\frac{H}{R} = \frac{3 \kappa}{2 \kappa T} \frac{L}{4 \pi \eta \nu g} \frac{R_{\text{in}}}{R}$$

(2)

where $R_{\text{R}}$ and $R_{\nu}$ are relativistic correction factors (Novikov & Thorne 1973; Krolik 1999) approaching unity at large $r/r_g$ and $R_\text{R} = 0$ at $R/r_g = r_{\text{in}}$ where $r_{\text{in}}$ is the disc inner radius assumed to be the marginally stable orbit.

The inflow time is given as $t_{\text{inflow}} \propto v^2/\nu$, where $v$ is the disc viscosity. In the thin disc framework, this is

$$t_{\text{inflow}} \sim (\Omega \alpha)^{-1} (H/R)^{-1},$$

$$t_{\text{inflow}} \approx 500 \left(\frac{\alpha}{0.02}\right)^{-1} \left(\frac{\kappa}{k_T}\right)^{-2} \left(\frac{\dot{m}}{0.1}\right)^{-2} \left(\frac{R}{50 r_g}\right)^{7/2} \text{ yr},$$

(3)

where the second estimate is for the thin disc model in the radiation pressure supported regime far from the inner edge, and we fix the black hole mass $M = 10^8 M_\odot$ throughout.

This timescale is long at large radii and/or low luminosity, so that changes in the outer optical emission region should be much slower and separated in time from those in the inner UV and X-ray region. Neither should the stress vanish at the inner edge.

Proposed alternative accretion disc models remove inconsistencies in standard theory and help reconcile it with optical/UV observations. The disc structure is generically thicker in these models, leading to shorter inflow times. Here we estimate inflow times of a few such scenarios which hold promise for explaining extreme AGN variability.

### 2.1 Extra Dissipation near the Inner Edge

Shakura & Sunyaev (1973) and Novikov & Thorne (1973) assumed that the stress vanishes at the disc inner edge. This is convenient for calculating disc structure, but leads to singularities in the surface density and scale height which disappear in a more careful treatment of the boundary conditions (Abramowicz et al. 1988; Gammie 1999) and Agol & Krolik (2000) further examined the effects of magnetic torques, which do not vanish at the inner edge.

In Agol & Krolik (2000), the effect is parameterized as an extra radiative efficiency $\Delta \eta$ which contributes to $R_{\text{R}}$:

$$R_{\text{R,AK}} = \frac{C_{\text{in}}^{3/2} \nu g_{\text{in}}}{C R_{\text{in}}^{1/2}} \Delta \eta + R_{\text{R}},$$

(4)

where $C$ is another relativistic correction factor (Agol & Krolik 2000) of order unity and $C_{\text{in}}$ is evaluated at $r_{\text{in}}$. The disc scale height increases significantly when $R_{\text{R,AK}} - R_{\text{R}} \gtrsim 1$ or for $R/r_g < (\Delta \eta C_{\text{in}}/C)^2 r_{\text{in}}$. For a non-spinning black hole, the disc thickness significantly increases for $R_{\text{th}} \lesssim 15, 200 r_g$ for $\Delta \eta = 0.25, 1$. The effects are strongly concentrated near $r_{\text{in}}$ since the extra dissipation term scales as $H \sim R^{1/2}$ instead of $H \sim R^0$ for a thin disc.

### 2.2 UV Line Opacity

The thin disc solution includes free-free and electron scattering opacity. The temperatures of inner AGN discs are similar to those of massive stars, and so line opacity from heavy elements is expected to play an important role. When

---

MNRA 000, 1–5 (2018)
including lines (ignored in the thin disc model), the mean opacity at temperatures $T \sim 10^5$ K is a factor $\approx 2 - 3$ higher than $\kappa_T$ for solar metallicity (Jiang et al. 2015). This can alter the thermal stability of the disc (Jiang et al. 2016), and clearly including it will increase the scale height at least over the range of radii with temperatures near this value.

As in massive stars, line driving could also produce powerful winds (Murray & Chiang 1995; Proga et al. 2000; Proga 2005). Laor & Davis (2014) showed that if the mass loss rate per unit area scaling derived in O stars holds for AGN, the total mass loss rate exceeds the accretion rate inside the radius

$$R_{eq} \approx 41.5 \left(\frac{M}{10^5 M_\odot}\right)^{0.24} \eta^{0.24} r_g.$$  

(5)

In their model, the disc truncates at $R_{eq}$. At smaller radii the disc becomes geometrically thick and optically thin, greatly decreasing the inflow time for $R \lesssim R_{eq}$.

A proper calculation of the scale height from this model would require self-consistently solving for accretion and outflow, whereas currently simulations including the frequency-dependent line opacity treat the thin disc as a boundary condition and ignore its vertical structure (e.g., Proga et al. 2000). Radiation MHD simulations including line opacity are now possible (Jiang et al. 2017), but use a gray opacity. Here we instead use a schematic picture of such a disc to estimate the inflow time. We assume $H/R = 1$ for $R \leq R_{eq}$. The effects of mass loss are highly concentrated near $R_{eq}$ (Laor & Davis 2014), so we adopt a power law scaling of $H/R \sim R^{-\beta}$ and find $\beta$ by matching onto the thin disc value of $H/R$ at $2R_{eq}$.

### 2.3 Magnetically elevated discs

The thin disc model includes gas and radiation pressure but ignores magnetic fields. MHD simulations of small patches of accretion discs (shearing box simulations) generically find that magnetic pressure declines more slowly with height than radiation or gas pressure, and so dominates in the upper atmosphere of the disc (Miller & Stone 2000). Those simulations usually adopt an initial condition with weak or no vertical magnetic field. If it can be efficiently brought to the black hole, the magnetic flux available in the inner parts of galaxies could instead be large. In that case, the toroidal field amplified by the MRI (Balbus & Hawley 1991) can become strong enough to support the disc vertically (Bai & Stone 2013; Salvesen et al. 2016).

The vertical structure of such magnetically elevated discs remains uncertain. In an early one-zone model, Begelman & Pringle (2007) assumed that the toroidal field grows to a limiting field strength beyond which the MRI shuts off (Pessah & Psaltis 2005): $v_A \approx \sqrt{2c_s v_K}$, where $v_A$, $v_K$, and $c_s$ are the Alfvén, orbital, and sound speeds. The gas to magnetic pressure ratio is $\beta \sim c_s/v_K$, which is $\sim H/R$ for a gas pressure supported thin disc and so small.

Begelman et al. (2015) took into account the competition between the generation of toroidal field by MRI and shear — assumed to occur at all heights — and its buoyant escape. Their vertically stratified models agree better with shearing-box simulations (Bai & Stone 2013; Salvesen et al. 2016) and yield a much larger characteristic scale height, even if the Pessah–Psaltis criterion is imposed:

$$\frac{z_2}{R} \approx 0.75\alpha^{-0.5} \eta^{0.4},$$  

(6)

where we have used their height $z_2$ for the elevated MRI-active layer. More recent studies of MRI in the presence of a strong toroidal field, however, show that MRI never completely stabilizes, even for very strong toroidal fields, although it passes through a range of small values (Das et al. 2018). Moreover, shearing-box simulations, which lack toroidal field-line curvature and should be more stable than global simulations with a strong toroidal field (Blaes & Balbus 1994), show no evidence of MRI suppression in the nonlinear state. It seems reasonable to guess that magnetically elevated discs can thicken to $H/R \gtrsim 0.1$ (Begelman & Silk 2017). In the following we will adopt the result of equation 6, as well as constant $H/R = 0.1$ for comparison. The MRI stress also grows with magnetic flux, and in the magnetically elevated case we assume $\alpha = 0.3$. However, $t_{inflow}$ is independent of $\alpha$ when the height is given by equation 6.

### 2.4 Inflow times and extreme AGN variability

Figure 1 shows estimated inflow times (equation 3) for each of these scenarios as a function of $R/r_g$ and $\dot{m}$ for $M = 10^8 M_\odot$ ($t_{inflow} \propto M$). For low accretion rates and large radii, the thin disc inflow time is very long ($\gtrsim 10^5$ years) even when including extra dissipation or possible effects of line-driven outflows (dark gray and purple curves). In both scenarios the inflow time becomes short for $R \lesssim 20r_g$ or $\dot{m} \gtrsim 0.1$ where the added effects become important ($R < R_{th}$ or $R_{eq}$). For intrinsic disc emission at the measured size $R \approx 50r_g$ (Dai et al. 2010; Blackburne et al. 2014; McHardy et al. 2014), changing look AGN in relatively low-luminosity Seyfert galaxies ($\dot{m} \approx 10^{-3}$ to $10^{-2}$) are difficult to explain in these scenarios.

Magnetically elevated discs are geometrically thick over the entire parameter space, leading to very short inflow times (blue). When magnetic pressure supports the disc vertically against gravity, its thermal content (luminosity, temperature) is decoupled from the structure. The scale height and inflow time are not only short, but also relatively insensitive to $\dot{m}$. This provides a natural explanation for the few year timescales seen in changing look AGN at both low and high luminosity.

### 3 DISCUSSION

Extreme AGN variability with factor $2 - 10$ optical/UV/X-ray luminosity changes on $\approx 1 - 10$ year timescales places stringent constraints on accretion theory. In the standard picture of fluctuations propagating through the disc, the propagation timescale must be much shorter than expected: the disc must be geometrically thick. We have shown that three alternative AGN accretion disc models from the literature predict larger scale heights and shorter inflow times than in standard theory. Figure 2 summarizes the results, showing regions in the $\dot{m} (L/L_{Edd})$ and $R/r_g$ parameter space where our estimated $t_{inflow} \lesssim 10$ years in each case, as implied (Pringle 1981) by the $\lesssim 1$ yr timescale for the most rapid
LaMassa et al. 2015). Magnetically elevated discs are a
Morgan et al. 2010). In either a standard thin disc or in-
large amplitude variations seen so far (Gezari et al. 2017).
The red stars schematically show the changing look AGN
Mrk 1018, assuming that the variations are sourced at the
optical emission region is mostly unaffected. UV line opacity could drive a
strong wind and support a thick inner disc. The wind is expected
to be strongest at small radius and high $m$, and again may not
alter the optical emission region. Magnetically dominated discs are
generically geometrically thick, leading to much shorter in-
flow times $\lesssim 10$ years over a wide range of luminosity (blue). The
Begelman et al. 2015 estimate we adopt gives similar results to
a constant $H/R = 0.1$ (dashed orange).

Figure 2. Allowed parameter space ($t_{\text{inflow}} \leq 10$ years, shaded
regions) for changing look AGN as a function of radius and accretion
rate assuming $M = 10^8 M_\odot$. The red stars correspond to
the high and low states of the changing look Seyfert galaxy Mrk
1018 (McElroy et al. 2016). In either a standard thin disc or in-
cluding extra dissipation at the ISCO, the inflow time is long
except in the inner disc at high luminosity ($L/L_{\text{edd}} \gtrsim 0.1$). UV
opacity could further inflate the inner disc, but may not be ef-
factive at the low luminosities of changing look Seyferts or in
the outer optical emission regions. Magnetically dominated discs are
expected to be geometrically thick over a wide range of radius and luminosity (blue, $H/R = 0.1$ dashed orange line for compari-
son) and provide a natural explanation for rapid large amplitude
variability.

Our estimates are heuristic, either taken from past semi-
analytic work (Agol & Krolik 2000; Begelman et al. 2015) or
estimated in toy models based on that work (Laor & Davis
2014). In the case of UV opacity, we have not calculated the
vertical structure, and have ignored the bulk increase in the
total opacity coming from lines (e.g., Jiang et al. 2015). A
calculation of the disc structure and emergent spectrum are
needed to determine whether a magnetically elevated disc
can produce the observed AGN SED, especially at high $m$
where the absorption and effective optical depths may be
small. These improvements are left to future work.

Geometrically thick accretion discs help explain how
large amplitude AGN variability can occur on timescales $\approx 1$
year, but the physical origin of the events remain uncertain.
Scenarios proposed for changing look AGN include insta-
bility driven limit cycles (Ross et al. 2018) or state transi-
tions (Noda & Done 2018), both of which are seen in X-ray
binaries. These scenarios invoke radiation pressure effect,
which we disfavor. Radiation pressure is strongest at high
luminosity and small radius, whereas extreme variability
prefers low luminosity (Rumbaugh et al. 2018) and the
optical emission comes from large radius (Morgan et al. 2010;
McHardy et al. 2014). The short observed timescales can be
explained if the variability is driven entirely by reprocessed
UV/X-ray radiation from the inner disc (Shappee et al. 2014;
LaMassa et al. 2015; Lawrence 2018) and radiation
pressure and outflow will increase the irradiation by thick-
ening the inner disc (Agol & Krolik 2000). However, this
seems disfavored by energetics in Mrk 1018 due to the low X-
ray/UV luminosity (Husemann et al. 2016). In addition, in
all of these scenarios the variability timescale should strongly
depend on luminosity (eq. 3), which has not been seen.

We propose instead that AGN accretion discs are sup-
sported by strong toroidal magnetic fields. Magnetic pres-
sure support leads to a geometrically thick disc whose scale
height is decoupled from its thermal properties. This sup-
presses the thermal instability and leads to a short inflow time at all observed luminosities. In this scenario, the variability mechanism is the same for normal and extreme AGN, with the latter the high amplitude tail of a continuous distribution. Rumbaugh et al. (2018) find that extreme AGN make up ≳ 30 − 50% of the population, and are only distinct in their variability amplitudes (and slightly lower #t). The variability mechanism is likely to either be mass accretion rate or thermal fluctuations (Kelly et al. 2009; Ruan et al. 2014; Hung et al. 2016) which then propagate through the disc to produce changes over a wide spectral range. Magnetically elevated accretion shows large density inhomogeneities (Salvesen et al. 2016) and could support large temperature fluctuations. The same features may produce the observed flat spectra and large sizes in the optical/UV (Dexter & Agol 2011; Hall et al. 2018). For the observed ≈ 1 year timescales, this scenario predicts R ∼ 105r7 for the origin of the variability (figure 2), in the outer disc but within the broad emission line region. The broad line luminosity and width should therefore trace the continuum variations.

A sharp change in mass accretion rate should be seen first in the optical and finally in the UV as it propagates inwards. In the case of extreme reprocessing, the propagation should proceed with high energies leading, while instability-driven heating and cooling fronts can travel in both directions. In this way time-resolved, multi-band photometry during extreme variability events can provide a direct probe of AGN accretion physics.

ACKNOWLEDGEMENTS
JD thanks S. W. Davis and the participants of the 2017 meeting “Unveiling the Physics Behind Extreme AGN Variability” for stimulating discussions. This work was supported by a Sofja Kovalevskaja award from the Alexander von Humboldt foundation. MB acknowledges support from NASA Astrophysics Theory Program grant NNX17AK55G.

REFERENCES
Abramowicz M. A., Czerny, B., Lasota J. P., Szuszkiewicz E., 1988, ApJ, 332, 646
Agol E., Krolik J. H., 2000, ApJ, 528, 161
Bai X.-N., Stone J. M., 2013, ApJ, 767, 30
Balbus S. A., Hawley J. F., 1991, ApJ, 376, 214
Begelman M. C., Pringle J. E., 2007, MNRAS, 375, 1070
Begelman M. C., Silk J., 2017, MNRAS, 464, 2311
Begelman M. C., Armitage P. J., Reynolds C. S., 2015, ApJ, 809, 118
Blackburne J. A., Kochanek C. S., Chen B., Dai X., Chartas G., 2014, ApJ, 789, 125
Blaes O. M., Balbus S. A., 1994, ApJ, 421, 163
Clavel J., et al., 1991, ApJ, 366, 64
Cohen R. D., Rudj R. Y., Puetter R. C., Ake T. B., Foltz C. B., 1986, ApJ, 311, 135
Dai X., Kochanek C. S., Chartas G., Kozlowski S., Morgan C. W., Garmire G., Agol E., 2010, ApJ, 709, 278
Das U., Begelman M. C., Lesur G., 2018, MNRAS, 473, 2791
Davis S. W., Woo J., Blaes O. M., 2007, ApJ, 668, 682
Dexter J., Agol E., 2011, ApJ, 727, L24
Gammie C. F., 1999, ApJ, 522, L57

Gezari S., et al., 2017, ApJ, 835, 144
Goodman J., 2003, MNRAS, 339, 937
Hall P. B., Sarrouh G. T., Horne K., 2018, ApJ, 854, 93
Hawley J. F., Guan X., Krolik J. H., 2011, ApJ, 738, 84
Hung T. C., et al., 2016, ApJ, 833, 226
Huesemann B., et al., 2016, A&A, 593, L9
Hutsi, S., Agis González B., Sluse D., Ramos Almeida C., Acosta Pulido J.-A., 2017, A&A, 604, L3
Jiang Y.-F., Cantieni M., Bildsten L., Quataert E., Blaes O., 2015, ApJ, 813, 74
Jiang Y.-F., Davis S. W., Stone J. M., 2016, ApJ, 827, 10
Jiang Y.-F., Stone J., Davis S. W., 2017, preprint, (arXiv:1709.02845)
Kelly B. C., Bechtold J., Siemiginowska A., 2009, ApJ, 698, 895
Kim D.-C., Yoon I., Evans A., 2018, preprint, (arXiv:1805.05251)
Krolik J. H., 1999, Active galactic nuclei : from the central black hole to the galactic environment. Princeton University Press
Krolik J. H., Horne K., Kallman T. R., Malkan M. A., Edelson R. A., Kass G. A., 1991, ApJ, 371, 541
LaMassa S. M., et al., 2015, ApJ, 800, 144
Laor A., Davis S. W., 2014, MNRAS, 438, 3024
Lawrence A., 2018, Nature Astronomy, 2, 102
Lightman A. P., Eardley D. M., 1974, ApJ, 187, L1
MacLeod C. L., et al., 2010, ApJ, 721, 1014
MacLeod C. L., et al., 2016, MNRAS, 457, 389
McElroy R. E., et al., 2016, A&A, 593, L8
McHardy I. M., et al., 2014, MNRAS, 444, 1469
Miller K. A., Stone J. M., 2000, ApJ, 534, 398
Morgan C. W., Kochanek C. S., Morgan N. D., Falco E. F., 2010, ApJ, 712, 1129
Murray N., Chiang J., 1995, ApJ, 454, L105
Noda H., Done C., 2018, preprint, (arXiv:1805.07873)
Novikov I. D., Thorne K. S., 1973, in Black Holes (Les Astres Occlus). New York: Gordon and Breach
Pessah M. E., Psaltis D., 2005, ApJ, 628, 879
Pringle J. E., 1981, ARA&A, 19, 137
Proga D., 2005, ApJ, 630, L9
Proga D., Stone J. M., Kallman T. R., 2000, ApJ, 543, 686
Ross N. P., et al., 2018, preprint, (arXiv:1805.06921)
Ruan J. J., Anderson S. F., Dexter J., Agol E., 2014, ApJ, 783, 105
Ruan J. J., et al., 2016, ApJ, 826, 188
Rumbaugh N., et al., 2018, ApJ, 854, 160
Salvesen G., Armitage P. J., Simon J. B., Begelman M. C., 2016, MNRAS, 460, 3488
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shakura N. I., Sunyaev R. A., 1976, MNRAS, 175, 613
Shappee B. J., et al., 2014, ApJ, 788, 48
Shlosman I., Begelman M. C., 1987, Nature, 329, 810
Shull J. M., Stevans M., Danforth C. W., 2012, ApJ, 752, 162
Stern D., et al., 2018, preprint, (arXiv:1805.06920)
Storchi-Bergmann T., Eracleous M., Livio M., Wilson A. S., Filippenko A. V., Halpern J. P., 1995, ApJ, 443, 617
Thohle J. E., Osterbrock D. E., 1976, ApJ, 210, L117
Wang J., Xu D. W., Wei J. Y., 2018, ApJ, 858, 49
Yang Q., et al., 2017, preprint, (arXiv:1711.08122)
Zheng W., Kriss G. A., Teller R. C., Grimes J. P., Davidsen A. F., 1997, ApJ, 475, 469

This paper has been typeset from a TeX/LaTeX file prepared by the author.