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A Novel Test of Quasar Orientation

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Abstract

The orientation of the disk of material accreting onto supermassive black holes that power quasars is one of most important quantities that are needed to understand quasars—both individually and in the ensemble average. We present a hypothesis for determining comparatively edge-on orientation in a subset of quasars (both radio loud and radio quiet). If confirmed, this orientation indicator could be applicable to individual quasars without reference to radio or X-ray data and could identify some 10%–20% of quasars as being more edge-on than average, based only on moderate resolution and signal-to-noise spectroscopy covering the C IV λ 1549 Å emission feature. We present a test of said hypothesis using X-ray observations and identify additional data that are needed to confirm this hypothesis and calibrate the metric.

Unified Astronomy Thesaurus concepts: Radio quiet quasars (1354); Radio loud quasars (1349); Optical observation (1169); Emission line galaxies (459); X-ray quasars (1821); Metal line absorbers (1032)

1. Introduction

The physics of quasars and active galactic nuclei (AGNs) is primarily governed by three properties of the system: the mass of the black hole, the spin of the black hole, and the accretion rate—with our line-of-sight orientation to the accretion disk also strongly affecting how we see and interpret these systems. Astronomers have gone to great lengths to measure black hole masses for the ≈100 quasars with robust "reverberation mapping" analysis (Peterson 1993) and have constructed empirical "scaling relations" (e.g., Vestergaard & Peterson 2006) that allow astronomers to estimate black hole masses for a much larger sample of AGN/quasars—albeit possibly biased toward objects that lack evidence for strong accretion disk winds (e.g., Richards et al. 2011; Shen 2013).

The situation for black hole spins is much worse. Using measurements of subtle signatures of gravitational redshifts from atomic features present in X-ray data, it has been possible to estimate black hole spin for only ≈2 dozen AGNs (Reynolds 2019). Similarly, the "beam power" of the outflow in strong radio sources has been used in attempt to estimate the spin for only 55 AGNs (Daly 2011). So-called "thermal continuum" fitting procedures (e.g., Capellupo et al. 2015) have shown some promise, but with a high degree of uncertainty and also limited to handfuls of AGNs.

The third parameter, the accretion rate, is historically estimated from the quasar luminosity as $L = \eta \dot{M} c^2$, with the uncertainties inherent to understanding how a monochromatic luminosity translates to a bolometric luminosity and the aforementioned spin dependence that affects η.

Thus, it may be that orientation (while not fundamental to quasar physics itself, but nevertheless fundamental to our ability to understand said physics) is the best measured of these key AGN parameters. Specifically, if we adopt a model where all quasars have essentially the same axisymmetric geometry (with the accretion disk obscured by a dusty toroidal region when observed edge-on; e.g., Elitzur 2012), then we have thousands of examples of so-called "type-2" quasars that are almost certainly observed edge-on (e.g., Zakamska et al. 2003; Reyes et al. 2008). However, for type-2 quasars, *all* of the crucial diagnostics that can be derived from the accretion disk (such as the black hole mass) are gone, rendering the orientation information rather emasculated. Alternatively, it has long been argued that radio spectral index provides a rough orientation estimate for quasars (Orr & Browne 1982; Richards et al. 2001; Van Gorkom et al. 2015), but only ≈5% of quasars from the Sloan Digital Sky Survey (SDSS; York et al. 2000) are even radio-detected by the moderately deep and large-area Faint Images of the Radio Sky at Twenty centimeters (Becker et al. 1995) survey (Ivezić et al. 2002; Kratzer & Richards 2015). Moreover, most radio emission from quasars may have little to do with jets (e.g., Panessa et al. 2019).

In this Letter we hypothesize another orientation measure for quasars that has the potential to be applicable for both radio-loud and radio-quiet quasars. In Section 2 we describe the proposed metric and an experiment that can be applied to test the metric. In Section 3 we present the data for this test. We carry out a test of a prediction in Section 4 and identify shortcomings that suggest the need for additional data. We finish with discussion and conclusions in Section 5.

2. The Hypothesis

In terms of accurately determining one of the key parameters needed to understand the physics of quasars, we argue herein that a promising avenue is the use of absorption and emission features in quasars to identify broad-line quasars with comparatively edge-on line-of-sight orientations.[7] Our proposed orientation indicator is the presence of C IV absorption at

[7] Hereafter we shall use "edge-on" to mean as edge-on as possible without obscuring the accretion disk continuum and the broad-line region.

the systemic redshift of the quasar (which is often *redward* of the peak of the C IV emission line). The background needed to understand the orientation hypothesis for such systems starts with determining the redshifts of quasars very accurately (e.g., Hewett & Wild 2010), removing much of what can be thousands of kilometers per second of uncertainty due to accretion disk winds (Richards et al. 2002; Dix et al. 2020). As a result of that process, it has become clear that what was once thought to be a distribution of C IV absorption-line systems representing "cluster" gas with velocities within $\pm 1000\ \mathrm{km\ s^{-1}}$ of the systemic redshift (Foltz et al. 1986; Anderson et al. 1987) are more likely a combination of outflowing material and "virialized" material that is at much lower velocity (Bowler et al. 2014). Stone & Richards (2019) argued that systems with "zero-velocity associated absorption-line systems" (hereafter AAL0s), may be an orientation indicator for radio-quiet quasars given that (1) in radio-loud quasars these systems are observed preferentially in steep-spectrum radio sources that are presumed to have an edge-on orientation, and (2) that they are just as common in radio-quiet quasars as in radio-loud quasars.

Given the prevalence of C IV absorption due to gas in the halos of galaxies (e.g., Chen et al. 2001; Prochaska et al. 2014; Perrotta et al. 2016)—including our own Milky Way (e.g., Richter et al. 2017)—it might be expected that one should see C IV in absorption at ≈0 velocity in nearly every galaxy unless something has happened to that gas. One reason for said gas not to be there (and causing absorption at the appropriate ionization) is if quasar activity has driven the gas from our line of sight. Arguably, the most likely place for such gas to remain along our line of sight is in a region that is relatively shielded from the accretion disk (and the wind blown from it; e.g., Giustini & Proga 2019), where gas in the halo of the host galaxy might persist. Alternatively, Ganguly et al. (2001) suggested that AALs may represent gas that is "hugging" an equatorial accretion disk wind (likely to be seen more edge-on than not). Thus, whether the gas is associated with the central engine or the host galaxy, AAL0s might be expected to be more common in relatively edge-on orientations. Such an explanation for AAL0s would be consistent with the findings of Stone & Richards (2019) and could provide an orientation indicator for both radio-loud and radio-quiet quasars that exhibit AAL0s.

During the course of an analysis of repeat spectroscopy of quasars from the SDSS Reverberation Mapping (SDSS-RM; Shen et al. 2015) campaign, Rivera et al. (2020) discovered many examples of quasars with AAL0s (10%–20%), which potentially represent a larger fraction of quasars than current estimates of orientation allow. For reference, a symmetric conical distribution of absorbing gas with a 10%–20% covering fraction would correspond to a opening angle of 6°–12° with respect to the plane of the accretion disk (in the absence of toroidal obscuration). If AAL0 systems are indicative of edge-on orientation, the SDSS-RM sample would be a unique sample for an investigation of orientation given the abundance of data on these systems. Specifically, while not all of the SDSS-RM quasars have accurately estimated black hole masses, we can be certain that the time-dependent changes mapped by the SDSS-RM campaign are not caused by changes in the black hole mass and are unlikely to be caused by orientation.

Our hypothesis is that all quasars with AAL0 systems have edge-on orientations, and we suggest a novel test of this hypothesis using X-ray data. This test applies only to a fraction of the AAL0 quasars; however, positive confirmation of an edge-on orientation for this subsample would add confidence to the edge-on hypothesis for the parent sample.

Specifically, in Wu et al. (2011), Luo et al. (2015), and Ni et al. (2018), it was argued that a "slim" accretion disk model (Abramowicz et al. 1988) might be able to explain the observed diversity of X-ray properties of weak-lined quasars (WLQs). WLQs are quasars where Lyα+N V EW $\lesssim$10–15 Å or C IV EW $\lesssim$10 Å (Diamond-Stanic et al. 2009; Shemmer et al. 2009). Figure 18 from Luo et al. (2015) illustrates the empirical problem and its proposed solution. The problem is that WLQs are observed to have X-ray measurements that are sometimes normal (relative to their UV luminosity, given the well-established $L_{\mathrm{UV}} - \alpha_{\mathrm{ox}}$ relationship), but sometimes are X-ray weak. The Luo et al. (2015) model would argue that *all* of the WLQs are hosted by quasars with slim disks that shield the broad-emission-line-region (BELR) gas from being over-ionized by X-ray radiation from the hot corona (see also Giustini & Proga 2019 for a more detailed illustration of how wind strength depends on accretion rate and black hole mass). While the BELR gas is always shielded from the X-ray corona in such slim-disk systems, only more edge-on WLQs would be X-ray weak from our line of sight. For face-on orientations, an Earth-based observer will see the X-ray corona even if the BELR does not. Thus an X-ray indicator of orientation is possible: the geometry of the accretion disk creates a situation conducive to forming WLQs, but the orientation of that disk with respect to our line of sight dictates whether we see such objects as X-ray weak or X-ray normal. It is therefore an important step forward in determining quasar orientation to observe samples of WLQs in the X-ray. Indeed a number of investigations have done just that (e.g., Shemmer et al. 2009, 2010; Wu et al. 2011; Luo et al. 2015; Ni et al. 2018; Marlar et al. 2018).

If AAL0s are indicative of edge-on orientation and if X-ray weakness in quasars is also evidence for edge-on orientation in objects with slim accretion disks, then we might expect both of the following to be true: (1) quasars with AAL0s are more likely to be X-ray weak if they have slim disks, and (2) quasars with slim disks are more likely to be X-ray weak if they have AAL0s. While these two situations sound similar, they are indeed distinct as the first asks about the X-ray properties of all quasars purported to be edge-on (regardless of whether they host a slim disk) and the second asks about quasars with slim disks (regardless of whether they are purported to be edge-on or not.)

3. Data

The SDSS-RM program took dozens of epochs of repeat spectroscopy of 849 broad-line quasars in a 7 deg^2 field of view. This experiment was designed to determine the time delay between continuum and emission-line variations in order to estimate black hole masses using the reverberation mapping technique. Rivera et al. (2020) analyzed the spectra of 133 of these 849 quasars that have 30 or more epochs, with a mean S/N > 6 per pixel over the wavelength interval $3650 < \lambda < 9300$ Å. These data enabled an investigation of how much limited spectrum S/N and intrinsic spectral variability can affect the measurement of C IV equivalent width (EW) and C IV blueshift (see also Sun et al. 2018), which are thought to be indicators of accretion disk winds (Richards et al. 2011). As

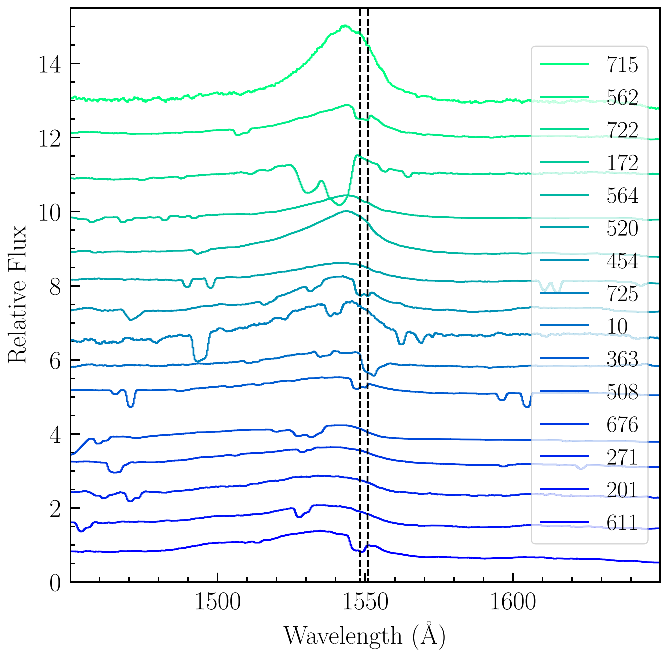

Figure 1. C IV emission-line regions of the 15 highest blueshift sources in our sample. Shown are the median spectra (from all of the SDSS-RM epochs). Five have AAL0s (RMIDs 10, 363, 454, 562, and 611) and are candidates for edge-on orientation. The vertical lines indicate the C IV doublet at λλ1548.202, 1550.744. RMID 722 is a BAL that should be correctly located in terms of C IV blueshift due to the ICA reconstruction process, but is expected to be absorbed in the X-ray. None of these sources are formally WLQs, but the combination of large blueshift and low EQW (for most of the sources shown) are potentially indicative of a slim-disk-like geometry.

there is a degeneracy between C IV EW and blueshift (e.g., quasars with intermediate blueshift or EW can have a large range of the other property; Richards et al. 2011), Rivera et al. (2020) define a hybrid metric, the C IV "distance," as a more robust wind indicator. This distance is relative to the best-fit curve tracing the locus of points in the C IV EW–blueshift plane, where quasars with large EW and small blueshift have small distance, while quasars with small EW and large blueshift have large distance.

The Rivera et al. (2020) analysis was based on independent component analysis (ICA) reconstructions of the SDSS-RM spectra using the spectral components determined from Rankine et al. (2020). As a result of those spectral reconstructions, these 133 quasars have high-S/N composite spectra and accurately determined continua, including in the region of the broad emission line. These data are conducive to measuring both broad and narrow absorption features in the quasar spectra. Because the ICA reconstruction process both requires and enables accurate determination of the systemic redshift (uncertainty $\approx$230 km s^{-1} as compared to the $\approx$1000 km s^{-1} from SDSS-I/II single-epoch spectra), it is possible to recognize absorption systems that are *redward* of the emission-line peaks despite being at/near the systemic redshift (Bowler et al. 2014). We illustrate the C IV region of 15 spectra with ICA-based C IV blueshift greater than 1500 km s^{-1} in Figure 1.

We find that 20–27 of the 133 quasars analyzed by Rivera et al. (2020) have AAL0s, depending on the criteria chosen for equivalent width of the absorption feature and resolution/ionization (which may distinguish narrow, but deep broad absorption line troughs (mini-BALs), at relatively small distances from the black hole, from AALs, potentially at large distances). We require the C IV doublet to be visually resolved and within $\approx \pm$ 500 km s^{-1} of the systemic redshift. More work is needed to formally distinguish AAL0 systems from mini-BALs, so we adopt an AAL0 fraction of 10%–20% and include only the 20 most likely sources in our analysis herein.

In addition to a sample where AAL0s can be recognized, our proposed test of the orientation hypothesis requires sensitive X-ray data. The SDSS-RM field has 6.13 deg^2 of X-ray coverage from XMM-Newton to an effective depth of $\approx$15 ks (Liu et al. 2020), with detection of 584 of the 849 quasars in the full SDSS-RM sample and 96 of the 133 quasars from Rivera et al. (2020). In addition, Liu et al. (2020) performed forced photometry at the location of the full SDSS-RM sample, which provides 2σ upper limits for another 19 sources from Rivera et al. (2020).

There is also archival multiwavelength coverage of the field. We include Chandra detections of RMIDs 452, 573, and 611 from the Chandra Source Catalog Release (CSC) 2.0 (Evans et al. 2020), in addition to four upper limits from the CSC and four matches in the AEGIS field (Nandra et al. 2015; including another three that also have XMM-RM observations). Chandra limits are taken as the sensitivity limits provided by the CSC for a "marginal" detection at the location of the source.

Thus we have X-ray detections or upper limits for $96 + 19 + 3 + 4 + 4 = 126$ of the sources analyzed in Rivera et al. (2020), including 18 of the 20 AAL0s.

4. The Test

Using these data, Figure 2 presents evidence that is consistent with the second prediction from Section 2, namely, that quasars with evidence of accretion disk winds are more likely to be X-ray weak if they host AAL0s. We plot $\alpha_{\rm ox}$ versus $L_{\rm UV}$ for the full SDSS-RM sample detected in the X-ray as open blue circles. We highlight the subsample analyzed by Rivera et al. (2020) using filled light green circles for X-ray detections and dark green inverted triangles for (2σ) upper limits. Sources with AAL0s are filled with red. To indicate likelihood of having a strong accretion disk wind, the size of the points is scaled by the C IV distance, with the 14 largest blueshift objects indicated by their SDSS-RM IDs in gray next to the data point. A dashed line indicates a luminosity-corrected X-ray weakness ($\Delta\alpha_{\rm ox}$ of -0.2; Just et al. 2007).

Below log $L_{2500\text{Å}} = 31.2$, we find only a single X-ray weak AAL0 source (of seven total) and that lone object corresponds to RMID 738 where the absorption is more suggestive of a mini-BAL than an AAL0. Contrarily, at higher luminosity, we find that four of the five AAL0 objects with large C IV blueshift (RMIDs 10, 363, 454, and 611) are well below the best-fit $L_{\rm UV}$–$\alpha_{\rm ox}$ line and might be described as X-ray weak, thus confirming the second prediction of our hypothesis. The fifth source (RMID 562) has $\Delta\alpha_{\rm ox} \approx 0$, but is an X-ray upper limit, so could be X-ray weaker than indicated.

However, our current analysis is degenerate in a way that keeps us from confirming the first prediction of the orientation hypothesis from Section 2. Specifically, the data do not reveal a difference between the X-ray properties of luminous quasars with large blueshifts that do and do not host AAL0s. It could be that the apparent confirmation of the second prediction is simply the result of blueshift being correlated with orientation or the known decrease in X-ray strength with increasing C IV blueshift (e.g., Richards et al. 2011). This result may not be

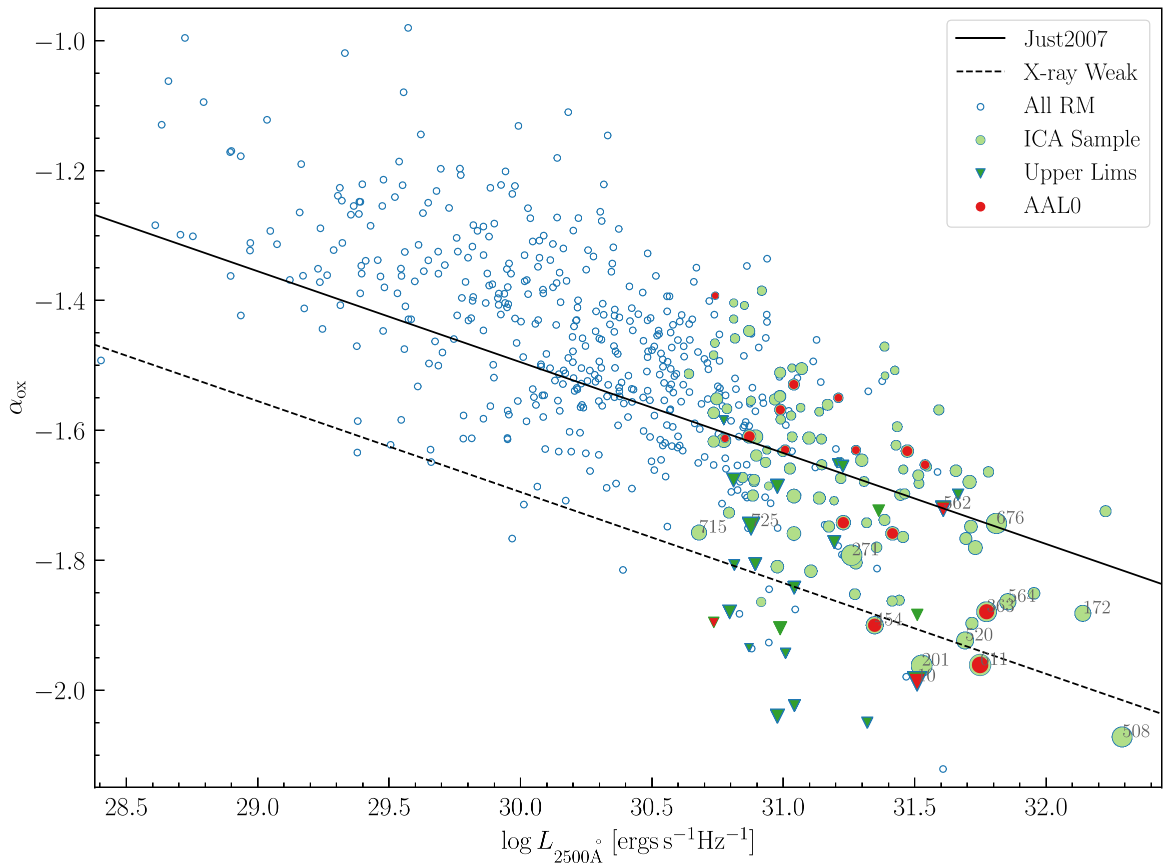

Figure 2. Optical–X-ray flux ratio, α_{ox} vs. UV luminosity, $\log L_{2500\,\text{Å}}$ [ergs s^{-1}Hz^{-1}] for the SDSS-RM sample. Open blue points are all the SDSS-RM sources detected in the XMM-RM catalog and are plotted with uniform marker size. The remaining marker types are all scaled by the "distance" along the C IV parameter space: larger points have larger C IV distance (14 sources with the largest blueshifts also being labeled in gray by their SDSS-RM ID numbers). Filled points are the sources investigated by Rivera et al. (2020): light green indicates X-ray detections, and dark green inverted triangles are nondetections in the X-ray (2σ upper limits). Points include both data from XMM-RM and from archival observations. Sources with AAL0 systems (18 of the 20 identified by Rivera et al. 2020 having X-ray data) are filled in red. Our hypothesis predicts that larger points filled with red are more likely to be X-ray weak (as indicated by the dashed line relative to the best fit from Just et al. 2007).

unexpected given that Ni et al. (2018) find that there is a strong transition to X-ray weakness as the C IV emission-line EW goes from 20 to 10 Å and our sources have a minimum C IV EW of ≈10 Å. Thus our sample, lacking formal WLQs, may not be a good test of the orientation hypothesis.

Nevertheless, we note the well-known rise of median C IV blueshift with UV luminosity (e.g., Richards et al. 2011) and the suggestion that winds may require $L_{bol} > 3 \times 10^{45}$ erg s^{-1} (e.g., Veilleux et al. 2013; Zakamska & Greene 2014), which corresponds to $\log L_{2500\text{Å}} \approx 30$—that is, lower than the proposed slim-disk systems herein. Moreover, there is no evidence for a sharp phase transition in the distribution of C IV emission-line blueshifts, so it seems likely that the development of a slim disk would be a smooth transition (e.g., in terms of scale height for X-ray absorption) rather than an abrupt one. Thus, high-luminosity, high-blueshift SDSS-RM sources still are likely to host a strong accretion disk wind, which may indicate a similar, if less extreme, accretion disk geometry. Indeed, the WLQ sample of Luo et al. (2015) is predominantly sources with C IV blueshifts in excess of 2000 km s^{-1} (where we adopt a positive, rather than a negative sign convention to represent an outflow). Fifteen of the quasars in our SDSS-RM subsample of 133 with the most extreme C IV distances have blueshifts in excess of 1500 km s^{-1} and are shown in Figure 1; 14 of these have X-ray information.

A logical next step would be to examine the Luo et al. (2015) and Ni et al. (2018) WLQs for AAL0s to determine if X-ray weakness correlates with the presence of AAL0s. However, that experiment is impossible with the current data as both samples excluded "objects with narrow absorption features around C IV" in addition to BALs and mini-BALs. Thus the Luo et al. (2015) and Ni et al. (2018) data do not enable a test of this hypothesis—despite otherwise being ideal samples. Further analysis of AAL0 systems in WLQs is needed.

5. Discussion and Conclusions

While our test does not provide definitive proof that AAL0s have an edge-on orientation, our results suggest that there is merit to following up this hypothesis further. It is important to note that our test relying on X-ray weakness as a potential indicator of edge-on orientation applies only to objects with slim-disk geometries, but the AAL0 orientation hypothesis posed is generic. That is, we would predict that all of the AAL0 systems in Figure 2 are observed edge-on, but do not expect the AAL0 objects with small C IV distances to be X-ray weak, as the standard disk geometry is not expected to hide the X-rays in such sources. Indeed such objects (with large C IV EW) are consistent with relatively "hard" SEDs and a "failed" wind as discussed by Giustini & Proga (2019). The crucial point is that our test of a very small sample could potentially be leveraged into an orientation indicator for a far larger number of quasars (those with moderately high resolution and high-S/N coverage of the C IV emission line) than currently have orientation estimates (which currently requires sensitive radio or X-ray observations), particularly those that are radio quiet.

Additional work is needed to explore the narrow absorption-line properties of an unbiased sample of WLQs in order to determine if both results predicted by the orientation hypothesis presented herein are confirmed. Further tests would also benefit from X-ray spectral analyses, as X-ray weak edge-on systems accreting from a slim disk should display harder X-ray spectra (Ni et al. 2018). A larger sample and/or time-resolved X-ray data would also be beneficial, as Ni et al. (2020) find that X-ray weak WLQs can transform to X-ray normal; thus we should not necessarily expect that all potential slim-disk AAL0 systems be X-ray weak at any given time.

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