A DISTINCTIVE DISK–JET COUPLING IN THE LOWEST-MASS SEYFERT, NGC 4395

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ABSTRACT

Simultaneous observations of X-rays and radio luminosities have been well studied in accreting-stellar-mass black holes. These observations are performed in order to understand how mass accretion rates and jetted outflows are linked in these individual systems. Such contemporaneous studies in supermassive black holes (SMBH) are harder to perform, as viscous times scale linearly with mass. However, as NGC 4395 is the lowest known mass Seyfert galaxy, we have used it to examine the simultaneous X-ray (Swift) and radio (Very Large Array) correlation in a SMBH in a reasonably timed observing campaign. We find that the intrinsic X-ray variability is stronger than the radio variability, and that the fluxes are only weakly or tentatively coupled, similar to prior results obtained in NGC 4051. If the corona and the base of the jet are one and the same, this may suggest that the corona in radio-quiet active galactic nucleus filters disk variations, only transferring the strongest and/or most sustained variations into the jet. Further, when both NGC 4395 and NGC 4051 are placed on the stellar-mass L_X–L_R plane, they appear to reside on the steeper L_X–L_R track. This suggests that SMBHs also follow two distinct tracks just as stellar-mass black holes do, and supports the idea that the same physical disk–jet mechanisms are at play across the mass scale.

Key words: galaxies: active – galaxies: dwarf – galaxies: jets

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1. INTRODUCTION

Observations have revealed a plane connecting the X-ray and radio luminosity of black holes that spans the mass scale: the fundamental plane of black hole activity (Merloni et al. 2003; Falcke et al. 2004; Gültekin et al. 2009; Plotkin et al. 2012). This plane suggests there is an underlying physical mechanism driving the relation, which acts across the mass scale (a similar relation across the mass scale is also seen in black hole disk-winds and is consistent with disk–jet power relations; King et al. 2013). In the fundamental plane of black hole activity, the black hole mass is thought to set a limit to the amount of power that can be extracted from the system. The radio luminosity is taken to be a rough proxy for the jet power as the emission is thought to be synchrotron emission along the jet. Finally, the X-ray luminosity is either directly associated with accretion rate (e.g., Merloni et al. 2003) or with the base of the jet (e.g., Falcke et al. 2004; Plotkin et al. 2012).

In stellar-mass black holes, one can examine how individual sources move across this fundamental plane, as the timescales for variations are particularly short (e.g., Corbel et al. 2003, 2013; Gallo et al. 2003, 2012). However, the viscous times on which stellar-mass black holes have been probed scale with mass, resulting in relatively long observing campaigns for all but the smallest of supermassive black holes (SMBHs).

Fortunately, there are a select few low-mass SMBHs with short enough viscous timescales for a simultaneous observing campaign. In particular, the Seyfert NGC 4395 is the smallest mass SMBH whose mass has been measured with reliable reverberation mapping techniques. NGC 4395 has a mass of $M_{BH} = (3.6 \pm 1.1) \times 10^5 M_\odot$ (Peterson et al. 2005) and is accreting at $<0.1\%$ of its Eddington luminosity (e.g., Shih et al. 2003). It has a very variable X-ray flux (e.g., Nardini & Risaliti 2011) and harbors a compact, non-thermal radio source (Wrobel & Ho 2006), making it ideal for a simultaneous campaign aimed to examine the disk–jet connection in an SMBH.

We present the results of a nearly simultaneous Swift X-ray and Karl G. Jansky Very Large Array (VLA) radio observing campaign. We begin with a brief description of the observations taken, followed by a discussion of the correlation between the two bands. We end by discussing the relation of NGC 4395 with other Seyferts as well as its stellar-mass counterpart parts.

2. OBSERVATIONS

2.1. Radio

As part of our radio-X-ray monitoring campaign, 16 radio observations were taken with the VLA from 2011 June 11 to 2011 August 6 with an average spacing of 3.7 days. The data were taken at 8.4 GHz with 256 MHz bandwidth in the A configuration. This gave a beam size of $\sim 0.29 \times 0.26$. 3C 286 was used as the flux calibrator and J1242+3720 was used as the phase calibrator. We adopted the flux scale Perley-Butler 2010. Approximately 15 minutes were spent on source, NGC 4395, during each observation. The residuals reached an rms of approximately $2 \times 10^{-5}$ Jy beam$^{-1}$. We used CASA version 3.4.0 (McMullin et al. 2007) to perform standard flagging, and to create a primary beam corrected image. We utilized the clean routine with natural weighting of the visibilities. The images showed unresolved point sources and were fit with imfit. The errors reported include the observational errors and a 3% systematic error added in quadrature. Although this systematic error is relatively small, we note that the phase calibrator in Figure 1(a) shows a stable flux density, with an rms at $<3\%$($F_\nu$). In addition, the flux calibrator 3C 286 is known to be extremely stable (Perley & Butler 2013), which is a necessity for this study. The flux densities are shown in Figure 1(a), divided by the mean flux density, which for NGC 4395 is $F_\nu = 5.6 \times 10^{-3}$ Jy.

2.2. X-Rays

The 50 X-ray observations were taken with Swift in the photon counting mode on 2011 June 5 to 2011 August 9 with an average spacing of 1.3 days. The observations had approximately 1 ks exposures, and an average count rate of 0.13 counts s$^{-1}$, with a
The average cstat per degree of freedom is made with a bootstrapping analysis to determine the linear-fit correlation coefficient of $\tau = 0.51$, and a Kendall’s $\tau$ correlation coefficient of $\tau = 0.15$ with a null probability $p = 0.51$, and a Kendall’s $\tau$ correlation coefficient of $\tau = 0.15$ with a null probability $p = 0.42$. The correlation test indicates that the weak correlation is not statistically significant. The X-ray flux versus the radio flux-density variability, which could influence our correlation analysis. We used the z-transformed discrete correlation function with a minimum of 11 data points per bin to determine a time lag (Alexander 2013). See Figure 3. We find no evidence of a time lag, as there were no statistically significant correlation coefficients different from 0 at a 5$\sigma$ confidence level. This was determined by dividing each correlation coefficient by its minus side error.

### 3.2. X-Ray versus Radio Correlation

Because the data are consistent with no time lag, we used the nearly simultaneous X-ray and radio observations in our correlation analysis. The average temporal separation between the X-ray and radio observations was 0.55 days, with a maximum separation of 1.6 days. When correlating the data, we find a Spearman’s $\rho$ correlation coefficient of $\rho = 0.18$ with a null probability of $p = 0.51$, and a Kendall’s $\tau$ correlation coefficient of $\tau = 0.15$ with a null probability $p = 0.42$. The correlation test indicates that the weak correlation is not statistically significant.

The X-ray flux versus the radio flux density is plotted in Figure 4(a). As the ranking correlation suggested only a weak correlation, we fit the data with a linear relation. We found that the data are consistent with a flat relation but were also consistent with the fundamental plane given by the red dashed line. We used a bootstrapping analysis to determine the linear-fit coefficients. Figure 4(b) shows the normalized histogram of the $10^5$ bootstrap resamplings of the data, and the resulting slope, $m$, from these linear fits. There is a peak in the distribution at $m = 0.06$, a second broad peak at $m = 0.6$, and a small tail of the distribution at slopes less than 0. This shows that the data favor a flat slope, but are also consistent with the fundamental plane slope, $m = 0.67$ (Gültekin et al. 2009).
4. DISCUSSION

The goal of this study was to examine the disk–jet coupling in an accreting SMBH. We chose to probe the viscous timescale of the inner accretion disk, as jets are thought to be launched within this region (e.g., Doeleman et al. 2012). In SMBHs, this timescale is on the order of a few days to months, making a simultaneous X-ray and radio observing campaigns feasible. Conversely, in stellar-mass black holes, this timescale is only a few tens of seconds.

In particular, we chose NGC 4395 because it is a bright, nearby Seyfert with the lowest known mass, making the appropriate cadence of such a campaign only a few days. We used Swift and the VLA to monitor both the X-ray from 2–10 keV and radio at 8.4 GHz over a two month period.

In detail, we found that the X-ray variability was dominated by neutral absorption, but both the intrinsic X-ray continuum and compact radio emission did show variability. There was no statistically significant time delay between the X-ray and radio variability. We also correlated the nearly simultaneous X-ray and radio observations using a Spearman’s ranking correlation test and found a weak positive correlation, $\tau = 0.15$. Further, a linear correlation function for the X-ray fluxes vs. radio flux densities (Alexander 2013). We do not find any evidence of a statistically significant ($>5\sigma$) delay in the times series.
Figure 4. (a) This plot shows the X-ray flux vs. the radio flux density. The red dashed line has a slope of the fundamental plane of black hole activity (Gültekin et al. 2009). (b) This is a histogram of the slopes from a bootstrap of $N = 10^4$ resampling of the data shown in (a). The peak is at $m = 0.06$. The slope is driven by the lowest X-ray flux at $\log F_{X,\text{ray}} = -11.61$ and the highest X-ray flux at $\log F_{X,\text{ray}} \approx -10.84$ as shown in (a). This is evidenced by the two main peaks at $m = 0.06$ and $m = 0.60$ and the small tail at $m < 0$. The red dashed line is the slope 0.67 of the fundamental plane of black hole activity (Gültekin et al. 2009).

(A color version of this figure is available in the online journal.)

Figure 5. (a) The above plot shows both NGC 4395 and NGC 4051 as they lie on the fundamental plane of black hole activity measured by Gültekin et al. (2009). The solid line in both (a) and (b) shows the plane derived by Gültekin et al. (2009), $\log (L_{\nu, 5\text{GHz}}) = 3.8 + 0.78 \log (M_{\text{BH}}) + 0.67 \log L_X$. The radio observations were converted to 5 GHz assuming $F_{\nu} \propto \nu^{-1}$. The dashed line shows the best fit lines to each of the Seyferts. In general, NGC 4395 and NGC 4051 lie on the fundamental plane but move out of it when looking at simultaneous X-ray and radio observations on viscous timescales of the inner disk. (b) This plot shows NGC 4395 and NGC 4051 plotted against the stellar-mass black holes as described in Gallo et al. (2012). The plot shows the Eddington ratio vs. the radio luminosity corrected by the mass term, which is derived from the fundamental plane relation (black line; Gültekin et al. 2009). NGC 4395 and NGC 4051 appear to lie on the second, steeper track, which is suggestive that SMBH follow two distinct tracks just as stellar-mass black holes do.

(A color version of this figure is available in the online journal.)

Fit to the data gave the relation $\log (L_R) = 0.06 \log (L_X) + 32.6$, but the data were also consistent with the fundamental plane of black hole activity with a slope of $m = 0.67$. See Figures 4(a) and (b). This is consistent with the idea that the amplitude of the X-ray variability is greater than the radio variability, and the latter is responsible for driving NGC 4395 horizontally in the $L_X-L_R$ plane.

NGC 4395 is not the only Seyfert that shows this general behavior. In our previous work, we show that NGC 4051 has higher variability in the X-ray as compared to its simultaneous radio observations (King et al. 2011). NGC 4051 is slightly larger at $1.73^{+0.55}_{-0.52} \times 10^6 M_\odot$ (Denney et al. 2010), and the simultaneous X-ray and radio observing campaign of NGC 4051 probed the same viscous times as in NGC 4395 (King et al. 2011).

Shown in Figure 5(a) are both NGC 4395 and NGC 4051, as they move out of the fundamental plane as given for Seyferts by Gültekin et al. (2009). Both sources are fairly constant in
the radio, while the X-ray drives them out of the plane. Each of their respective best fit slopes are plotted as the dashed lines on Figure 5(a). As the two sources do lie on the plane, the X-ray variability may be partially responsible for the observed scatter of the fundamental plane.

In Figure 5(b), the two Seyferts are now plotted against the fundamental plane of stellar-mass black holes taken from work by Gallo et al. (2012). All the black holes have been corrected for mass using the fundamental plane derived from Gültekin et al. (2009), and a mass of 10 $M_\odot$ has been assumed for the stellar-mass black holes. As noted in Gallo et al. (2012), the stellar-mass black holes occupy two different tracks: (1) the typical “fundamental plane” track that scales as $L_R \propto L_X^{0.63\pm0.03}$, and (2) a second track that is steeper that scales as $L_R \propto L_X^{0.98\pm0.08}$. NGC 4395 and NGC 4051 do lie on and may follow this steeper $L_X-L_R$ relation. If some SMBHs also follow a second, steeper $L_X-L_R$ relation, it would imply that two distinct modes of accretion and jet production occur in both stellar-mass and SMBHs, and gives rise to a picture that the underlying physical mechanisms in disk–jet coupling scale across the black hole mass scale.

Further, the flat slope in the $L_X-L_R$ plane traced by NGC 4395 and NGC 4051 suggests they are tracing a branch between the two tracks. This would be similar to the behavior of H1743-322, which jumps between the two tracks (Coriat et al. 2011; Gallo et al. 2012). However, the slope of NGC 4395 is also consistent with a steeper slope. In addition, as the amplitude of the X-ray variability is more variable than the radio variability, it is possible that strong variations in the disk or corona may get washed out when transferred to the jet on larger scales (e.g., Maitra et al. 2009). In essence, the base of the jet might act as a low-pass filter for transferring only sufficiently large or sustained variations to the jet. This would imply that on short timescales and any Eddington ratio, a source would follow a flat relation and move out of the $L_X-L_R$ relation in Figure 5(b). On longer timescales variations, the SMBH may trace out the fundamental plane, $L_R \propto L_X^{0.7}$ or the steeper relation of $L_R \propto L_X^{1.1}$. This is interesting because jets are known to be launched within tens of gravitational radii (Doeleman et al. 2012), which would correspond to viscous times of the inner disk. Yet our study points to longer timescales for disk–jet couplings, indicating global effects that propagate from further out in the accretion disk are vital to the disk–jet coupling.

Additional tracks in the $L_X-L_R$ plane have also been seen in not only stellar-mass black holes, but also in a few samples of low excitation galaxies (LEG) and Fanaroff–Riley I (FR I) galaxies (e.g., Chiaberge et al. 2002; Hardcastle et al. 2006, 2009; Evans et al. 2006; de Gasperin et al. 2011). These sources generally fall above the conical “fundamental plane,” i.e., are radio bright or X-ray dim (Hardcastle et al. 2009; de Gasperin et al. 2011). It has been suggested that the discrepancy between these sources is due to the LEG and FR I jet-dominated X-ray emission, while sources on the fundamental plane from (e.g., Merloni et al. 2003) have accretion-dominated X-ray emission (Chiaberge et al. 2002; Evans et al. 2006; de Gasperin et al. 2011). Interestingly, NGC 4395, NGC 4051 and the second stellar-mass track do the opposite and lie below the “fundamental plane,” i.e., are X-ray bright and radio dim. This would argue that unlike the LEG and FR I sources whose X-ray emission is jet-dominated, that the X-ray emission is accretion-dominated like the fundamental plane sources but more efficiently radiating. This argument has also been suggested for active galactic nucleus (AGN) by Wu et al. (2013), who find low luminosity AGN form a second track as well, but in the $L_B-L_R$ plane where $L_B$ is the $B$ band luminosity, another accretion disk proxy.

5. CONCLUSION

In this study, we have observed NGC 4395 for approximately two months with nearly simultaneous 8.4 GHz radio observations with the VLA and 2–10 keV Swift X-ray observations. We find that the X-ray flux has large variability that is dominated by variable neutral absorption. When we correlate the unabsorbed continuum X-ray variability with the radio variability, we find that the data are consistent with no time delay between the two bands and that the X-ray variability dominates over the radio variability. In addition, the data are consistent with the slope of the fundamental plane but also with a flat slope in the $L_X-L_R$ plane.

The average X-ray and radio luminosity of NGC 4395 as well as NGC 4051 are consistent with lying on the fundamental plane of black hole activity, and the X-ray variability driving some of the observed scatter. Furthermore, both Seyferts appear to lie on the “second” $L_X-L_R$ stellar-mass black hole track discussed in Gallo et al. (2012). These sources may be probing a second, distinct disk–jet coupling, which is also seen in stellar-mass black holes. Our future work will be to probe higher accretion regimes in SMBHs to see if at higher Eddington ratios the SMBHs follow one of the two tracks or still move out of the plane like NGC 4395 and NGC 4051. In addition, longer timescales will be examined in order to assess global accretion affects.

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REFERENCES

Alexander, T. 2013, arXiv:1302.1508
Arnaud, K., Dorman, B., & Gordon, C. 1999, XSPEC: An X-ray Spectral Fitting Package, Astrophysics Source Code Library, 10.005
Blackburn, J. K. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 367
Cash, W. 1979, ApJ, 228, 939
Chiaberge, M., Capetti, A., & Celotti, A. 2002, A&A, 394, 791
Corbel, S., Coriat, M., Brocksopp, C., et al. 2013, MNRAS, 428, 2500
Corbel, S., Nowak, M. A., Fender, R. P., Tzioumis, A. K., & Markoff, S. 2003, A&A, 400, 1007
Coriat, M., Corbel, S., Pratt, L., et al. 2011, MNRAS, 414, 677
de Gasperin, F., Merloni, A., Sell, P., et al. 2011, MNRAS, 415, 2910
Denney, K. D., Peterson, B. M., Pogge, R. W., et al. 2010, ApJ, 712, 715
Doeleman, S. S., Fish, V. L., Schenck, D. E., et al. 2012, Sci, 338, 355
Evans, D. A., Worrall, D. M., Hardcastle, M. J., Kraft, R. P., & Birkinshaw, M. 2006, ApJ, 642, 96
Falcke, H., Körding, E., & Markoff, S. 2004, A&A, 414, 895
Gallo, E., Fender, R. P., & Pooley, G. G. 2003, MNRAS, 344, 60
Gallo, E., Miller, B. P., & Fender, R. 2012, MNRAS, 423, 590
Gültekin, K., Cackett, E. M., Miller, J. M., et al. 2009, ApJ, 706, 404
Hardcastle, M. J., Evans, D. A., & Croston, J. H. 2006, MNRAS, 370, 1893
Hardcastle, M. J., Evans, D. A., & Croston, J. H. 2009, MNRAS, 396, 1299
Iwasawa, K., Tanaka, Y., & Gallo, L. C. 2010, ApJ, 514, A58
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
King, A. L., Miller, J. M., Cackett, E. M., et al. 2011, ApJ, 729, 19
King, A. L., Miller, J. M., Raymond, J., et al. 2013, ApJ, 762, 103
Lira, P., Lawrence, A., O’Brien, P. et al. 1999, MNRAS, 305, 109

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Maitra, D., Markoff, S., & Falcke, H. 2009, A&A, 508, L13
McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
Merloni, A., Heinz, S., & di Matteo, T. 2003, MNRAS, 345, 1057
Moran, E. C., Eracleous, M., Leighly, K. M., et al. 2005, AJ, 129, 2108
Nardini, E., & Risaliti, G. 2011, MNRAS, 417, 2571
Perley, R. A., & Butler, B. J. 2013, ApJS, 204, 19
Peterson, B. M., Bentz, M. C., Desroches, L.-B., et al. 2005, ApJ, 632, 799
Plotkin, R. M., Markoff, S., Kelly, B. C., Kording, E., & Anderson, S. F. 2012, MNRAS, 419, 267
Shih, D. C., Iwasawa, K., & Fabian, A. C. 2003, MNRAS, 341, 973
Wrobel, J. M., & Ho, L. C. 2006, ApJL, 646, L95
Wu, Q., Cao, X., Ho, L. C., & Wang, D.-X. 2013, ApJ, 770, 31