Black Holes from Stars to Galaxies – Across the Range of Masses
Proceedings IAU Symposium No. 238, 2006
V. Karas & G. Matt, eds.

doi:10.1017/S1743921307004863

Constraining jet physics in weakly accreting black holes

Sera Markoff

Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098SJ Amsterdam, The Netherlands

email: sera@science.uva.nl

Abstract. Outflowing jets are observed in a variety of astronomical objects such as accreting compact objects from X-ray binaries (XRBs) to active galactic nuclei (AGN), as well as at stellar birth and death. Yet we still do not know exactly what they are comprised of, why and how they form, or their exact relationship with the accretion flow. In this talk I focus on jets in black hole systems, which provide the ideal test population for studying the relationship between inflow and outflow over an extreme range in mass and accretion rate.

I present several recent results from coordinated multi-wavelength studies of low-luminosity sources. These results not only support similar trends in weakly accreting black hole behavior across the mass scale, but also suggest that the same underlying physical model can explain their broadband spectra. I discuss how comparisons between small- and large-scale systems are revealing new information about the regions nearest the black hole, providing clues about the creation of these weakest of jets. Furthermore, comparisons between our Galactic center nucleus Sgr A* and other sources at slightly higher accretion rates can elucidate the processes which drive central activity, and pave the way for new tests with upcoming instruments.

Keywords. Black hole physics – accretion, accretion disks – radiation mechanisms: nonthermal – X-rays: binaries – galaxies: active – galaxies: jets

---

1. Introduction

One of the most basic predictions of general relativity is that black hole physics should be the same regardless of black hole mass. However, black holes at different ends of the stellar-to-galactic mass range are accreting from different environments; i.e., from one star versus an entire stellar cluster. This difference, together with the huge range in dynamical timescales which go roughly linearly with the mass, has made it challenging to discover if the observed physical processes are indeed similar between accreting systems such as X-ray binaries (XRBs) and Active Galactic Nuclei (AGN).

Recent advances in simultaneous broadband observing techniques have resulted in the first confirmation of scaling physics across the black hole masses, in particular for the case of weakly accreting black holes. For XRBs this means the Low/Hard state (for definitions see, e.g. McClintock & Remillard 2006), and for AGN this includes the general class of low-luminosity AGN (LLAGN; Ho 1999), and likely FR Is and BL Lacs. All of these classes are believed to be accreting at rates significantly below the Eddington limit, and thus in similar state to each other. This state is of particular interest for studying jet physics because it is the only XRB state associated with steady jet production, and jets are observed to increasingly dominate the power output of the accreting system as $\dot{M}$ decreases (Fender *et al.* 2003).

In brief summary, simultaneous observations in the radio and X-ray bands of the XRB GX 339-4 in its Low/Hard state established a tight correlation between the respective

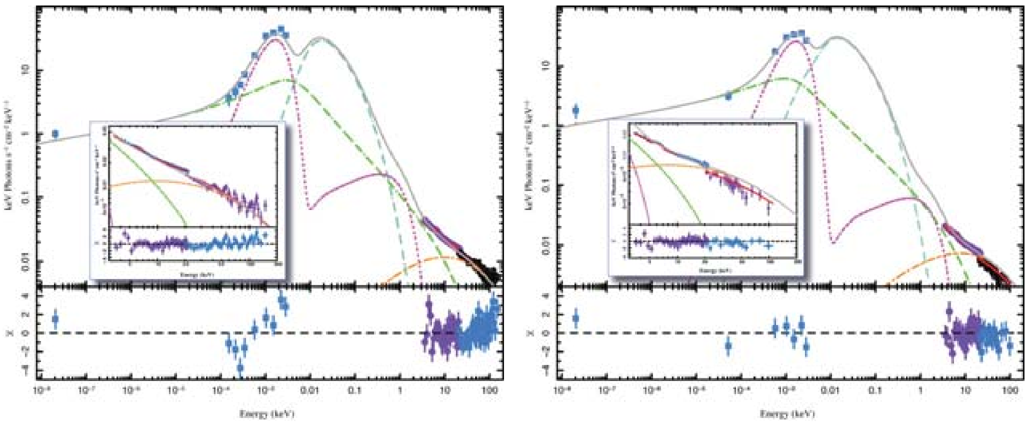


Figure 1. Model fits with residuals to broadband simultaneous observations of X-ray binary GRO J1655-40 in the Low/Hard state on 24 Sep (left) and 29 Sep (right), 2005. The data are from the VLA, Spitzer, SMARTS and RXTE, see Migliari *et al.* (2007) for details. Inset shows the X-ray band only. Emission components indicated are jet base/corona synchrotron (blue-green), post-acceleration outer jet synchrotron (green), jet base/corona Comptonization (external and SSC; red), and the single blackbody for the star plus the multicolor blackbody thermal accretion disk (magenta). The reduced χ^2 for these two fits are 1.7 and 0.9, respectively.

luminosities holding over orders of magnitude in power (Corbel *et al.* 2000, 2003). Gallo *et al.* (2003) then found that this correlation appears in most Low/Hard state XRBs for which we have good simultaneous data. Markoff *et al.* (2003) and Heinz & Sunyaev (2003) explored the physical mechanisms responsible for the correlation, and two independent groups then showed that the same correlation is present in samples of weakly accreting AGN (Merloni *et al.* 2003; Falcke *et al.* 2004). The theoretically predicted and empirically confirmed relationship between radio luminosity, X-ray luminosity and mass has been named the "fundamental plane of black hole accretion". Some recent papers have further explored and improved upon the original statistics (Merloni *et al.* 2006; Körding *et al.* 2006).

These results support the picture that similar processes are at work in these classes of sources. In order to further test this idea, as well as to learn more about the physics near the black holes and especially jet formation, my colleagues and I have been exploring how well the same model can apply to objects at extreme ends of the mass scale. Not only would this provide independent checks on the "fundamental plane", but also by comparing stellar and supermassive black hole accretion we can better understand which physical mechanisms act exactly the same across the mass scale.

2. Scaling physics across the mass scale

The model used in the fits presented here is described in detail in Markoff *et al.* (2005). It is an outflow-dominated model in the sense that we include the corona as a compact, weakly beamed region comprising the base of the jets. Beyond arguments why such outflowing, magnetized coronae are useful for reducing the amount of reflected emission (e.g. Beloborodov 1999), we also wanted to explore the relationship between the corona and jets for this most extreme case. A cooler, thermal accretion disk is also included both as a weak spectral component, as well as a source of photons for Compton upscattering within the jets/coronae. In Markoff *et al.* (2005), we showed that statistical fits of this model to the X-ray region alone (including a Gaussian iron line, and convolved with a

https://doi.org/10.1017/S1743921307004863 Published online by Cambridge University Press

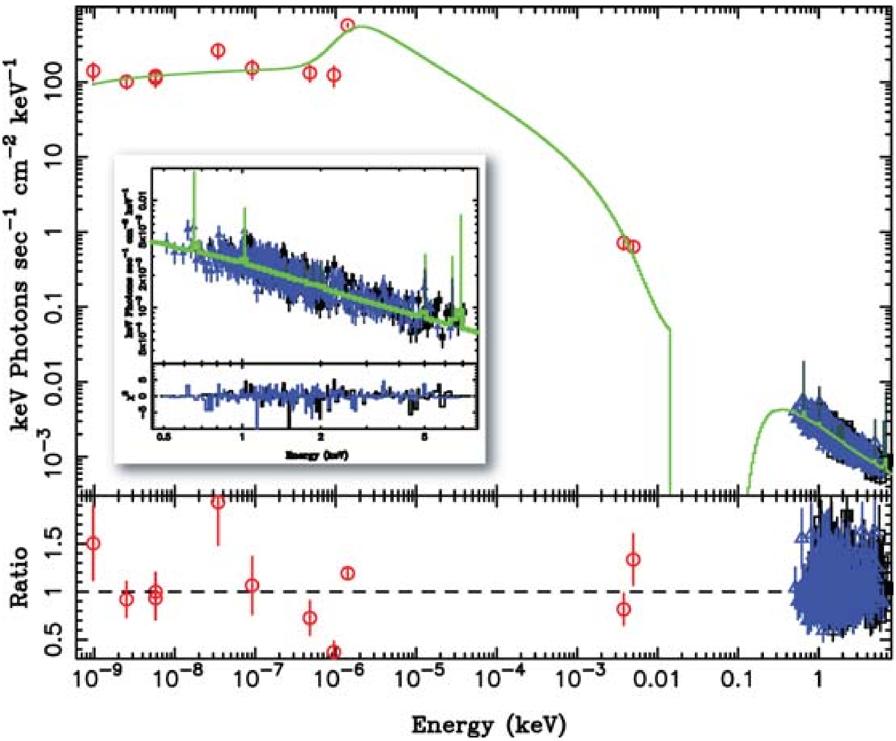


Figure 2. The same exact model used for GRO J1655-40 shown here applied to data from a simultaneous broadband campaign of the low-luminosity AGN M81*, with mass $\sim 10^7$ times greater. The data are from the GMRT, VLA, IRAM, SMA, HST (not simultaneous) and Chandra with the grating spectrometer (see Markoff *et al.*, in prep. for details). The reduced χ^2 of this fit is 1.37. Several lines were detected in the X-ray band as well, see Young *et al.* (2007).

reflection model) could describe data from two Galactic XRBs, GX 339-4 and Cyg X-1, as well as thermal corona models. Furthermore this model also naturally addresses the simultaneous radio emission and thus the correlations. Based on the fitting of several epochs of Low/Hard state data for both sources, we concluded that several physical parameters which we had previously left free to vary could be frozen for future fits. These parameters included the ratio between the height and width of the jet base/corona, which always remained quite compact ($\sim 1 \div 1.5$), and the fraction of particles accelerated in the jets, which we found to be consistently high ($\sim 75\%$).

More recently we have obtained new broadband spectra for other sources which also include the infrared/optical (IRO) frequencies, providing even further constraints on this outflow-dominated model. In Fig. 1 we show the result of two examples of such fits for the Low/Hard state of XRB GRO J1655-40, with an inset detailing the X-ray fit (from Migliari *et al.* 2007). The IRO range is mostly dominated by the stellar companion, but a NIR excess indicates a significant contribution from jet synchrotron, consistent with the conclusions of Russell *et al.* (2006), who found $\sim 90\%$ of the NIR is contributed by the jets in bright Low/Hard state sources.

The exact same model has also been successfully applied to several weakly-accreting supermassive black holes. In Fig. 2 we show the results for the nearby galaxy M81.

https://doi.org/10.1017/S1743921307004863 Published online by Cambridge University Press

3. Discussion

Both Low/Hard state XRBs and LLAGN are accreting significantly below the Eddington rate, exhibit a correlation in their radio/X-ray luminosities, and we have shown here that their emission can be explained in the context of the same physical scenario. As further support of the increased domination of outflows at low-luminosities, both of these classes are well described by a model in which the radio through X-ray band is predominantly due to outflowing plasma, where the compact jet base successfully "subsumes" the canonical role of the compact corona.

The results presented here, as well as those from several other sources, suggest that basic similarities hold in the physical parameters and emission processes over at least seven orders of magnitude in black hole mass. In particular, we have found that all such sources can be modeled with a weak accretion disk component plus weakly accelerated ($\Gamma \sim 1$ in the bases to $\Gamma \sim 2 \div 3$ in the outer regions) outflows with compact (a few-10 r_g) bases, with significant particle acceleration in their outer jets beginning around $10 \div 100 r_g$, and which are weakly magnetically dominated (by factors $\sim 1.5 \div 10$). The fact that the ranges in fit parameters are so small despite the enormous range in masses is an indication of both the success of the description as well as the power of simultaneous broadband fitting.

Only one low-luminosity source so far does not fit the pattern of the others: Sgr A*, our own Galactic center supermassive black hole. With a bolometric luminosity of $\sim 10^{-9} L_{\rm Edd}$, it is the dimmest black hole we can observe with any statistics. Sgr A* first of all does not appear to follow the radio/X-ray correlation, falling short of its expected X-ray luminosity by several orders of magnitude except during the brightest of flares (see, e.g. Markoff 2005). Interestingly, we can use the results of the above spectral modeling in combination with morphological constraints from VLBI (Bower *et al.* 2004; Shen *et al.* 2005; Bower *et al.* 2006) to probe the reasons behind such differences. Spectrally, Sgr A* can be explained with the same context of other weakly accreting black holes *only* if particle acceleration is very weak in its jets, either with a very low fraction or a very steep ($p > 4$) electron distribution spectrum. The lack of a strong optically thin power component in its spectrum makes Sgr A* quite different from other LLAGN, and can also account for the difficulty in resolving its jets through the intervening electron scattering screen. We demonstrate this explicitly in Markoff *et al.* (2007). Our results suggest that particle acceleration in the outflows may break down at extremely low accretion rates, hinting at at least one of the many mechanisms that must build up in order to create signs of black hole "activity". This also suggests that classes/states of active objects which do not show resolved jets may still have outflow structures which lack the mechanism to accelerate.

References

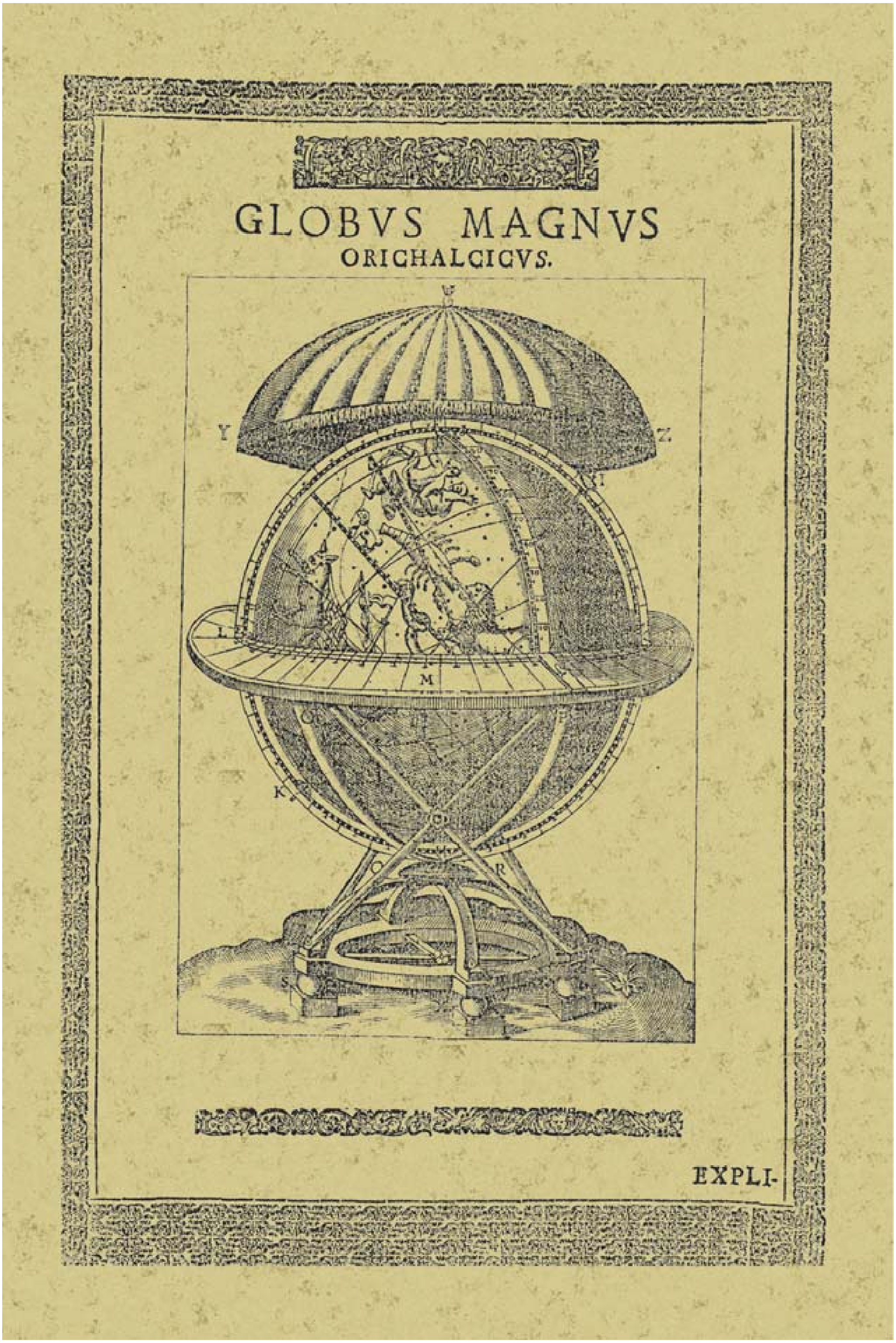
Beloborodov, A. M. 1999, ApJL, 510, L123
Bower, G. C., Falcke, H., Herrnstein, R. M., *et al.* 2004, Science, 304, 704
Bower, G. C., Goss, W. M., Falcke, H., *et al.* 2006, ApJL, 648, L127
Corbel, S., Fender, R. P., Tzioumis, A. K., *et al.* 2000, A&A, 359, 251
Corbel, S., Nowak, M., Fender, R. P., *et al.* 2003, A&A, 400, 1007
Falcke, H., Körding, E. & Markoff, S. 2004, A&A, 414, 895
Fender, R. P., Gallo, E. & Jonker, P. G. 2003, MNRAS, 343, L99
Gallo, E., Fender, R. P. & Pooley, G. G. 2003, MNRAS, 344, 60
Heinz, S., Sunyaev, R. A. 2003, MNRAS, 343, L59
Ho, L. C. 1999, ApJ, 516, 672

Körding, E., Falcke, H. & Corbel, S. 2006, A&A, 456, 439
Markoff, S. 2005, ApJL, 618, L103
Markoff, S., Bower, G. C. & Falcke, H. 2007, MNRAS, submitted
Markoff, S., Nowak, M., Corbel, S., Fender, R. & Falcke, H. 2003, A&A, 397, 645
Markoff, S., Nowak, M. A. & Wilms, J. 2005, ApJ, submitted
McClintock, J. E., Remillard, R. A. 2006, in: W. H. G. Lewin & M. van der Klis (eds.), Compact Stellar X-ray Sources (Cambridge University Press: Cambridge), p. 157
Merloni, A., Heinz, S. & di Matteo, T. 2003, MNRAS, 345, 1057
Merloni, A., Körding, E., Heinz, S., Markoff, S., *et al.* 2006, New Astronomy, 11, 567
Migliari, S., Tomsick, J. A., Markoff, S., *et al.* 2007, ApJ, submitted
Russell, D. M., Fender, R. P., Hynes, R. I., *et al.* 2006, MNRAS, 371, 1334
Shen, Z.-Q., Lo, K. Y., Liang, M.-C., Ho, P. T. P. & Zhao, J.-H. 2005, Nature, 438, 62
Young, A. J., Nowak, M. A., Markoff, S., Marshall, H. L., *et al.* 2007, ApJ, submitted

Gregory Beskin: Some years ago we detected several very short optical flashes of duration around one millisecond and brightness temperature above 10^{10} K in A0620–00. In some sense this is a proof of magnetized corona.

Sera Markoff: Yes, this is a very interesting and lively topic which I could not cover in detail. There is a lot of variability that cannot be coming from the star.

https://doi.org/10.1017/S1743921307004863 Published online by Cambridge University Press



https://doi.org/10.1017/S1743921307004863 Published online by Cambridge University Press