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Low-Frequency Constraints on Weakly Accreting Black Hole Jets

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All accreting black holes produce associated jets at least some of the time. In stellar black holes accreting in X-ray binaries (XRBs), compact and steady jets are predominantly associated with the weakly (sub-Eddington) accreting hard state. These jets are apparently quenched at transition to the high luminosity state, thus jet production can be a cyclic phenomenon during outbursts. XRBs are therefore an ideal source population to study the physics of jet formation where many fundamental questions remain, such as the physics driving jet formation in the first place, or what jets comprise in terms of matter and electromagnetic fields. Using multiwavelength observations over the broadband spectrum, we have already made significant progress addressing some of these open questions. In the context of these results I will discuss how instruments probing the lowest end yet of the spectrum will specifically help us develop a better understanding of jet dynamics and energetics. I will also emphasize the importance of simultaneous observations at higher frequencies to allow stricter constraints.

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1. Introduction

Despite extensive study, we are still mostly in the dark about how the jets observed in accreting black hole systems are formed and collimated, let alone their overall particle content and energy distribution. Jets are common in other accreting systems, so we would also like to know how far we can extend our theories to encompass a broader range of classes. At the moment the two types of sources which seem to share the most similarities in terms of jet formation, behavior and correlations with accretion rates are accreting black holes and neutron stars. It remains to be proven exactly how analogous these systems really are, and a clear understanding of their relative jet properties would cast significant light on at least one major question regarding jet formation.

At the moment there are two general groupings of theories, that trace back to two classic papers in the field. In one case, jets are formed via the extraction of spin energy from a black hole ergosphere, resulting in at least initially pair-dominated, Poynting flux-dominated flows (Blandford & Znajek, 1977). This scenario obviously cannot contribute for objects with a hard surface, in which case the jets are predicted to form when plasma is accelerated out along field lines anchored in the accretion disk, as originally suggested by, e.g., Blandford & Payne (1982). Recently, one group has claimed that the jets in a neutron star system, Cir X-1, seem to be as powerful as those routinely observed in black hole XRBs (Fender et al., 2004a; Heinz et al., 2007). If confirmed, this would be strong support for the direct accretion disk "feeding" scenario dominating in black holes as well as neutron stars. However, most state of the art magnetohydrodynamical (MHD) codes are favoring the alternate scenario of tapping spin energy for the origin of black hole jets (e.g. McKinney, 2006; Hawley & Krolik, 2006). Observations clearly can play a major role discerning between the two pictures, by constraining the jet power, bulk velocities and internal content.

A new window is opening up in the coming years, which we hope will greatly increase our prospects for understanding jets themselves, as well as the differences in jets between all sources. So far I can only speak qualitatively about what we think the low-frequency radio bands will add to the current picture, because the three major up-and-coming instruments (LOFAR, in which I am involved, as well as the MWA and LWA) are not yet fully operational. But beyond just the addition of many new transients which will be discovered via, e.g., LOFAR's radio all-sky monitoring (RSM) program, the low frequencies bring an extension of jet spectra into a predominantly unexplored band, which at the very least can extend the lever arm for theoretical models. The low-frequency band in combination with the broadband spectrum even up to the highest frequency bands provided by HESS, MAGIC and now *GLAST* and eventually the Cherenkov Telescope Array (CTA) should enable more powerful constraints on the internal workings of jets. For this proceedings, I will quickly summarize the status quo of our knowledge of black hole jets, and then describe where low-frequency radio observations can be expected to contribute significantly.

2. Black hole jets: where we stand

Black holes are especially important for theoretical studies of accretion and jets, because of their existence over at least eight orders of magnitude in mass and accretion power. Because one of the basic tenets of general relativity is the self-similarity of black holes, it is not so far-fetched to consider whether the accretion process around black holes could also scale predictably with mass, at a given accretion power (in mass-dependent Eddington units). The main difference between accretion in XRBs compared to Active Galactic Nuclei (AGN) would then be in the dynamical timescales, which depend roughly linearly on the central mass following the linear dependence of characteristic size scales with mass. Such a scaling has been the focus of much research in the last several years (e.g. Merloni et al., 2003; Falcke et al., 2004; McHardy et al., 2006; Körding et al., 2006), and the main conclusion seems to be that there is strong evidence for some kind of XRB/AGN mapping, but that we are a long way away from having a complete picture.

The fundamental line of inquiry can be summarized as whether or not there is a direct analog for each XRB accretion state in a longer-lived AGN "state" that we likely interpret as a distinct AGN class. Such a unification then needs to be absorbed into what we already understand about orientation effects (e.g. Urry & Padovani, 1995). The search for such mappings must be necessarily focused on trends in XRBs, whose dynamical timescales can be probed directly and repeatedly over human timescales.

Based entirely on X-ray monitoring programs mostly carried out by *RXTE*, we have identified two types of XRB accretion states that have jets: the stable hard state and a transient state that occurs as the system increases in accretion rate and eventually settles into the stable soft state. Alternate names suggested for the two stable states are the nonthermally dominated and thermally dominated; for a full description of some of this phenomenology, see other talks in this volume or, e.g., McClintock & Remillard (2006). The transient state is referred to alternately as the soft intermediate hard state or the "zone" between soft/hard intermediate states (cf. J. Homan), and is associated with discrete ejecta (or distinct regions within a continuous flow) that are accelerated to relatively high Lorentz factors (Fender, 2006). In contrast, the hard state jets are compact, self-absorbed (as evidenced by the flat spectrum), and seemingly less relativistic. One idea put forward for the difference is that the accretion disk is recessed in the hard state but moves inwards towards the innermost stable circular orbit (ISCO) as the accretion rate approaches the Eddington limit (Esin et al., 1997). The resulting smaller radius would result in a faster characteristic initial velocity for the jets (assuming they are rooted in the accretion disk), and internal shocks where fast flow meets slow could account for the discrete and more relativistic zones (Fender et al., 2004b). While this is a promising idea, again it relies more on the Blandford & Payne type solution, which may be problematic until this can be reconciled with many MHD simulations. Another factor complicating this scheme is the recent claims that the accretion disk may not in fact be recessed during the hard state (e.g. Rykoff et al., 2007).

Resolving this question is critical for our understanding these sources, and jet formation within them. However for the stable hard state, we seem to be on slightly less shaky ground. For instance there is already a strong case for a mapping onto the class of Low-Luminosity AGN (LLAGN; e.g., Ho 1999), which is sensible because they are both comparatively weakly accreting and thus perhaps in a simpler "ground state" for the system. This association has provided a framework to constrain both the accretion physics via correlations (for the most recent discussion see, e.g., Körding et al., 2006), as well as physical parameters via spectral modeling.

One of the most compelling pieces of evidence for such a scaling is the fact that the exact same model can explain both XRB hard state as well as LLAGN broadband spectra with similar model parameters. Fig. 1 illustrates the radio/X-ray correlation and two exemplary fits. The model used here is outflow-dominated, where the corona is envisioned as a region of mildly accelerated,

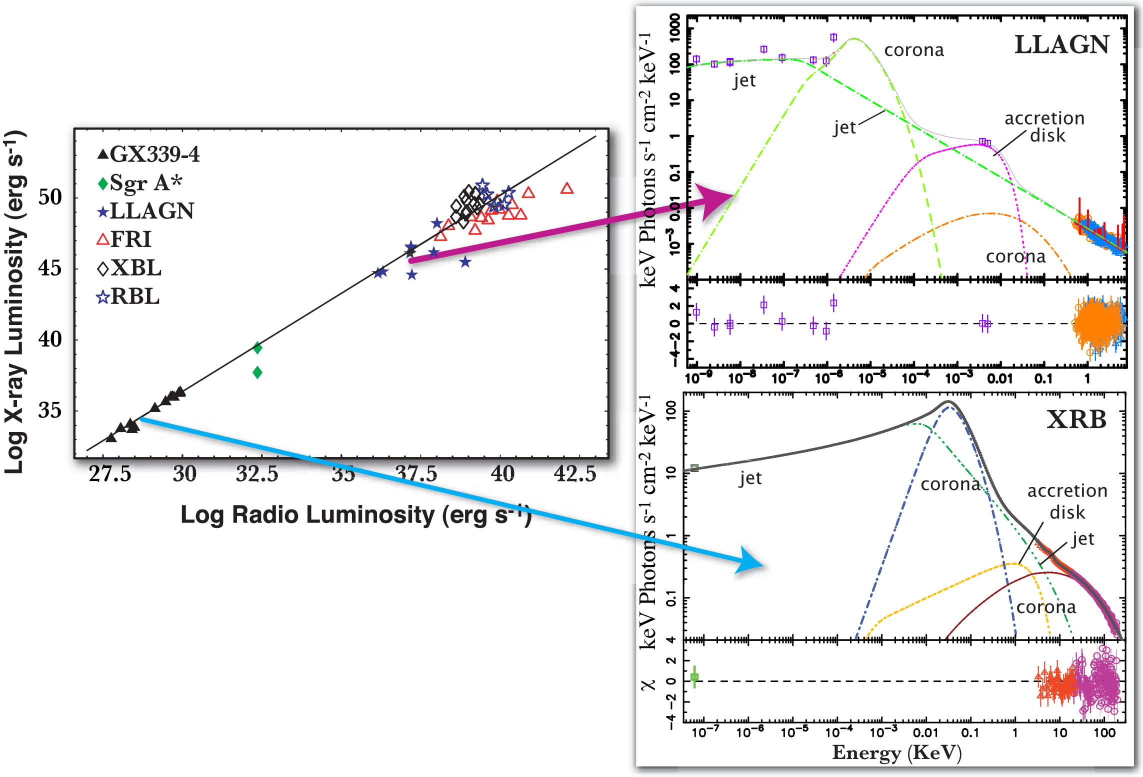

Figure 1: *Left:* mass-scaled radio/X-ray luminosity correlation showing the same behavior between the XRB GX 339−4 (bottom left) and AGN (top right). The X-ray luminosities of the AGN have been renormalized to what they would be if they had the same mass as GX 339−4, using scaling jet theory (e.g. Falcke et al., 2004). *Right:* The correlation indicates that the same physics is likely at work in both hard state X-ray binaries, and low-luminosity AGN. The top and bottom panels, show that exactly the same model can fit broadband, simultaneous data from both populations (Markoff et al., 2005; Migliari et al., 2007; Gallo et al., 2007; Markoff et al., 2008). The upper spectrum is from a simultaneous broadband campaign on the nearby LLAGN, M81*, while the bottom source is from ongoing simultaneous radio/X-ray monitoring of the Galactic XRB Cyg X-1.

magnetized plasma that directly feeds the jets. Thus all model parameters are "initialized" in that base region, which is seen in the hard X-rays via inverse Compton emission (dominated for the most part by synchrotron self-Compton). For a description of the model, see Markoff et al. (2005).

3. Extending our knowledge with the low-frequency radio band

The case of weakly accreting black holes exemplifies how simultaneous multiwavelength observations have contributed to many new discoveries within a short period of time. It is clear that with dedicated low-frequency radio monitoring, conducted whenever possible simultaneously with other wavebands, we will be much better equipped to unravel the various components of XRB states, and extend the mapping of XRB states to AGN classes. For instance, we may yet be missing radio-dominated, X-ray weak accretion states in our current paradigm. Filling in this gap (if there is one, or more) will be one of the most significant contributions of the RSM programs to the understanding of inflow/outflow connections in XRBs. The low frequencies will also allow us to continue studying ejected plasma as it ages and evolves, interacting with the surrounding material.

In addition to the outstanding questions I have mentioned so far, there is still significant debate about the matter content of jets, because the radio through X-ray emission we detect stems entirely from leptons that could either be the dominant plasma component, or coexist with heavier particles as the secondary results of hadronic (ion-ion) collisions. Unfortunately there is no reason why both directly accelerated and secondary electrons cannot both be present, so picking apart these two populations will be tricky. The power requirements for these two scenarios are quite different, though, since the work required to accelerate ions-lepton plasma up to high bulk Lorentz factors will obviously be much higher than for a leptonic-only plasma. Detecting more cavities carved out by XRB jets in the interstellar medium, as has been done so far only for Cyg X-1 (Gallo et al., 2007), will help in determining the average energy budget for the jets, and such aged electron populations will be more visible in the lower frequency radio bands. To really constrain the internal physical parameters, realistic models must be constructed that can reproduce the multiwavelength data at the same time that energy constraints derived from the environment are met.

The newest low-frequency bands can provides additional constraints for such models, at least in sources where there is not significant free-free absorption. While we do not yet know how much the average transient will be affected, the results so far from the Westerbork Low-Frequency Front-Ends and GMRT on a few known sources (see talk by J. Miller-Jones, this volume) are encouraging that many will in fact reveal their intrinsic spectral shapes. Incorporating this turnover, when observed, into the current picture will constrain the minimum energy for the internal particle distributions in the jets, and thus the total power budget, as well as the outer jet geometry. With the recent successful launch of *GLAST*, it will soon be possible to compile quasi-simultaneous spectra even up to the TeV range when HESS and MAGIC are included. The addition of these new "lever arms" (see Fig. 2) may well be what it takes to break the current deadlock in theoretical scenarios.

Once we have a better handle on jet powers and content, as well as the partition of energy within the jets, we are well on the way to understanding the conditions of their formation. Our studies of the hard state have provided a reasonable foundation where a steady treatment seems valid. For the transitional jets, we clearly need time-dependent physical models, and likely some supporting framework from accretion disk theory and simulations. I predict that the hard-to-soft transition is where we will see the most progress in the coming few years, as theory starts to finally catch up with the data.

4. Radio/X-ray monitoring

At the moment our understanding of the variability in XRB jets is limited both by their relatively faint emission on very compact scales in the hard state, and the transient nature of the brighter jet states. This situation will definitely change with the onset of RSM in combination with the IR/O bands and the X-rays. From longterm monitoring campaigns we have been able to study "waves" of higher amplitude emission seemingly moving out along the compact jets of LLAGN such as M81* (see Fig. 3) and Sgr A* (Yusef-Zadeh et al., 2006), providing us with important constraints on the size, bulk plasma velocity and collimation. Because the relevant timescale for these motions in AGN is on the order of weeks to months, for direct mass scaling it would be predicted to be on the

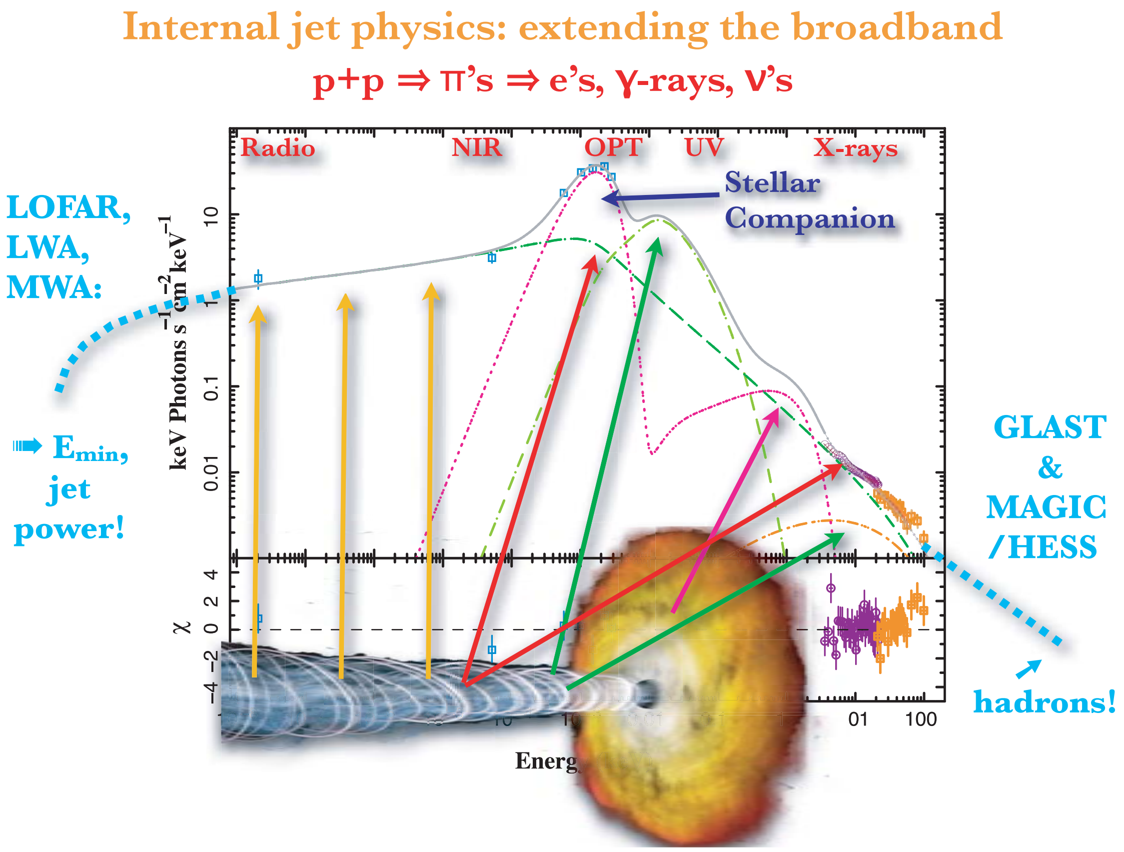

Figure 2: Accreting black holes in the hard state are by definition multiwavelength beasts. Superimposed upon a recent fit to GRO J1655-40 in a 2005 hard state (Migliari et al., 2007) is a representation of a disk/jet system and its contributions. In this scenario, the base of the jets comprises the corona. The addition of low-frequency on the lowest end will provide new constraints on the minimum lepton energy and thus jet power. At the highest end, new GeV γ-ray spectra from *GLAST* in combination with existing TeV facilities, will clarify if hadronic jets are viable, or possibly even required.

order of minutes or less for XRBs. Thus catching an interesting flare and monitoring it will become much more likely with the onset of RSM programs like that of LOFAR, where a flare originating in the highest frequencies can be detected during simultaneous monitoring and the lags/correlations studied. In Fig. 4 we show a rare near-simultaneous radio/X-ray flare caught in Cyg X-1. A further detection of such a flare in the low-frequency bands would be very constraining for models of the jet flow, geometry and collimation.

The ability to detect such flares from XRBs is also very important now that the first γ-ray flare from a microquasar has been claimed with the MAGIC detector, and in fact from the same source as the radio/X-ray flare shown in Fig. 4, Cyg X-1 (Albert et al., 2007). Unfortunately the detected γ-ray flare was serendipitous and thus no corresponding low-frequency observations were obtained. However, by coordinating RSM with GeV/TeV instruments such as HESS, MAGIC, *GLAST* and eventually the CTA, we can expect more flares to be discovered, and the time lags will help us understand the most likely origin of the highest energy emission. Modeling the spectra of these flares will also help us to determine the extent of a hadronic presence in these jets. These results

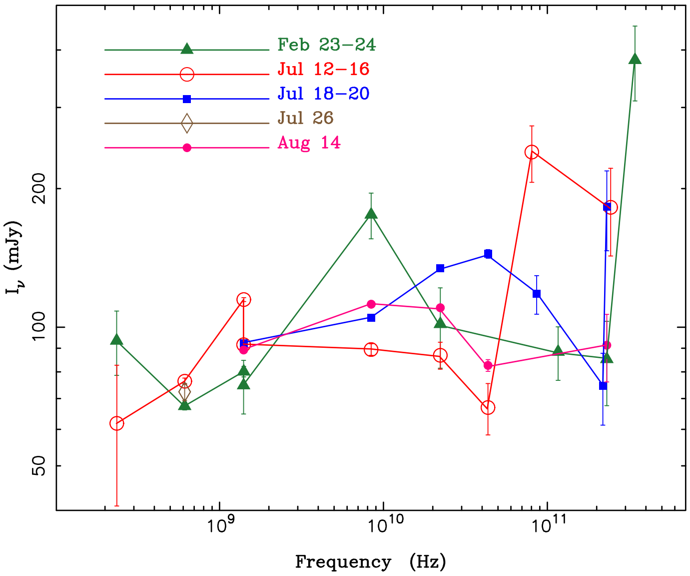

Figure 3: Spectral energy distribution of the centimeter through submm observations of a 2005 campaign on M81* (Markoff et al., 2008). We detect flaring regions moving lower in frequency and amplitude, consistent with the expectations of adiabatic expansion.

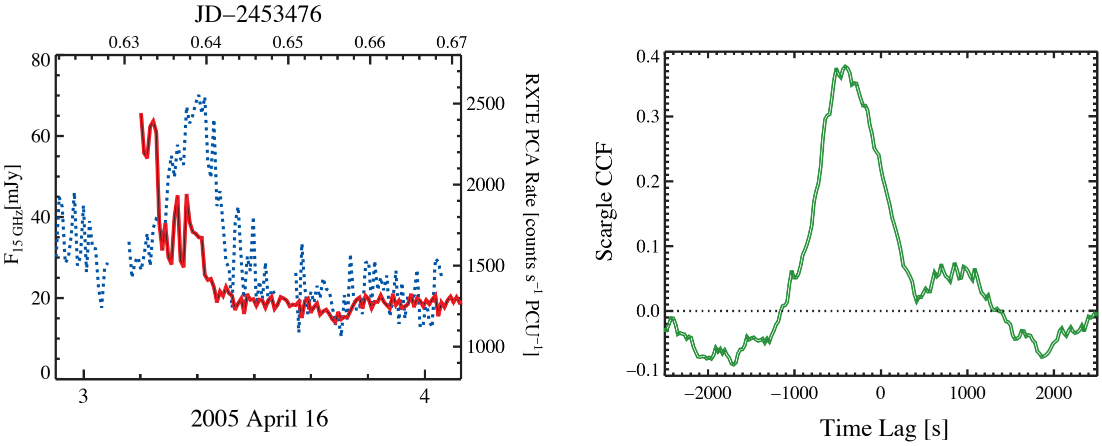

Figure 4: *Left:* Radio (15 GHz from the Ryle Telescope) and *RXTE* PCA X-ray light curves of Cyg X-1 during a rare simultaneously detected flare event. *Right:* The cross-correlation function of the event reveals that the radio lags the X-rays by about 400 seconds (see Wilms et al. 2007

are not too far afield. For the first year of operation of LOFAR, we already have agreements with MAGIC and *GLAST* for joint monitoring of a few test sources, and are currently discussing similar agreements with several other facilities. We anticipate that these programs will yield significant progress, especially because we are probing such unexplored territory.

5. Discussion

In summary, the addition of the low-frequency regime to astronomy will have many important consequences for our understanding of jets and jet formation in black hole systems at the very least, likely many others as well. By simply monitoring the radio sky continually, we will inevitably discover new classes of sources or even new states in sources we are already familiar with. But it is critical to combine such radio monitoring with observations across the entire broadband, which so far has produced significant progress in a relatively short number of years. The challenge will be in handling such large data rates, the likely high number of new transients, and in the development and "training" of automated pipelines for the identification and archiving of new sources, as well the triggering of other instruments. It is of concern that we will likely be without *RXTE* by the end of this year, and while other instruments are on the horizon (e.g., *ASTROSAT*) as well as *SWIFT*, the loss of a dedicated X-ray monitoring mission may hinder us at least in the earliest years. On the other hand, advances in optical and infrared monitoring may compensate to some extent, especially given that we are starting to understand the behavior of these bands for a given X-ray state (Homan et al., 2005; Russell et al., 2006).

Beyond this we are still in a realm of speculation, but I hope within 6 months of my writing we will begin to have concrete results that can back up some of these hopes. Given the fruitful results for the shorter periods of monitoring conducted by the Parkes Observatory (e.g. Lyne et al., 2004; McLaughlin et al., 2006), it does not seem overly optimistic to hope for a revolution in our understanding of radio synchrotron sources, and thus the drivers of jet emission. With the full electromagnetic spectrum available to us in combination with non-photon messengers such as neutrinos and ultra-high energy cosmic rays, we should finally have the tools we need to lay to rest several long-standing debates about jet physics.

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