Are 3C 120 and Other Active Galactic Nuclei Overweight Microquasars?

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Abstract. The appearance of superluminal radio knots follows drops in the X-ray flux in the FR1 radio galaxy 3C 120 and possibly the FR2 source 3C 111. This corresponds in a very general way to the behavior of the X-ray binary GRS 1915+105, but the light curves of the microquasar are much richer in detail. Starting in 2003.7, the character of the radio and X-ray light curves of 3C 120 changed, perhaps signaling a new stage of activity. I discuss what one might expect when a microquasar is scaled up to AGN dimensions, and compare this with what we see in 3C 120. There is a mismatch between expectations and observations.

Keywords: Active galactic nuclei, jets, accretion disks, black holes

1. Introduction

The discovery that some black-hole binary systems have relativistic jets has led to their nickname "microquasars" as well as to the hope that we might test our models for radio-loud active galactic nuclei (AGNs) by observing these nearby cousins (Mirabel & Rodríguez, 1994). Comparisons are hampered, though, by the utter dominance of the jet emission in blazars and the wimpiness of the jets in Seyfert galaxies, the AGNs that most resemble black-hole binaries at X-ray energies. Fortunately, there are a few broad-line radio galaxies whose jets lie at somewhat wider angles to our line of sight than is the case for blazars. These have optical and X-ray properties similar to Seyfert galaxies and microquasars, as well as prominent radio jets that display strong variability and superluminal apparent motions.

Along with a team of collaborators, I have been studying the FR1 radio galaxy 3C 120 extensively since 1997 in order to determine whether its behavior bears any resemblance to that of microquasars. Since March 2004 we have been observing the FR2 radio galaxy 3C 111 as well. The availability of two superb instruments—the *Rossi* X-ray Timing Explorer (RXTE) and the Very Long Baseline Array (VLBA)—makes it possible to engage in long-term monitoring programs with outstanding time coverage. The resulting X-ray light curves are exquisitely detailed, as are the ever-changing images at high radio frequencies.

As I describe below, there is an association of short-term low-hard X-ray states with injections of energy into the jet in 3C 120—and possibly in 3C 111 as well—that is reminiscent of the X-ray binary GRS 1915+105. The scaling of time scales with black-hole mass is not linear, however, and the rich detail of the X-ray light curves of the microquasar is either masked or absent in the radio galaxies. In other words, we still have a lot to learn before we can relate the phenomena at opposite ends of the luminosity, mass, and size scale.

2. The Long-Term Behavior of 3C 120

Early results (Marscher et al., 2002) demonstrated that each appearance of a superluminal knot in the radio jet of 3C 120 is preceded by a significant dip in the 2-20 keV X-ray flux. Under the premise that the X-rays are predominantly from the accretion disk or its immediate environs (e.g., a corona, a hot wind, or the base of the jet), some disturbance in the central engine seems literally to send a shock wave down the jet. This is the same scenario as that imagined to explain similar connections between transitions to low-hard X-ray states and energization of the jet in the microquasar GRS 1915+105 (Mirabel & Rodríguez, 1998, and papers by Fender and others in these proceedings).

Figure 1 displays the X-ray light curve we have accumulated since resuming our monitoring program in 2002. The date of each superluminal "ejection"—the time of coincidence of the centroid of a moving knot with the position of the core as determined from a linear fit to a plot of core-knot separation vs. time—is marked. There were two periods of low X-ray flux between 2002.15 and 2003.7: a long dip in early 2002 and a double-dip in summer 2003. The X-ray spectrum was flatter during the dips than during most high-flux states. The onset of the first dip preceded the appearance of a bright superluminal radio knot with a delay of 0.1 ± 0.03 yr. The pair of dips in 2003 were followed by the ejection in rapid succession (1.5-month interval) of two bright superluminal knots. The apparent velocities of the knots are $4.7c$ (for a Hubble constant of 70 km s^{-1} Mpc^{-1}), similar to those measured during the period 1997-1999 (Gómez et al., 2001; Marscher et al., 2002). The 37 GHz flux rose dramatically from 2003.65 to 2003.7 (Ogle et al., 2004) to herald the ejection of the first knot after the double dip, and then maintained a high level well into 2004. The delay of 0.04 yr between the start of the 37 GHz flare and the coincidence of the knot with the core probably corresponds to either (1) half the light-travel time across the knot, (2) the time it takes for the knot to become energized (or optically thin) as it enters the core region, or (3) the bulk acceleration

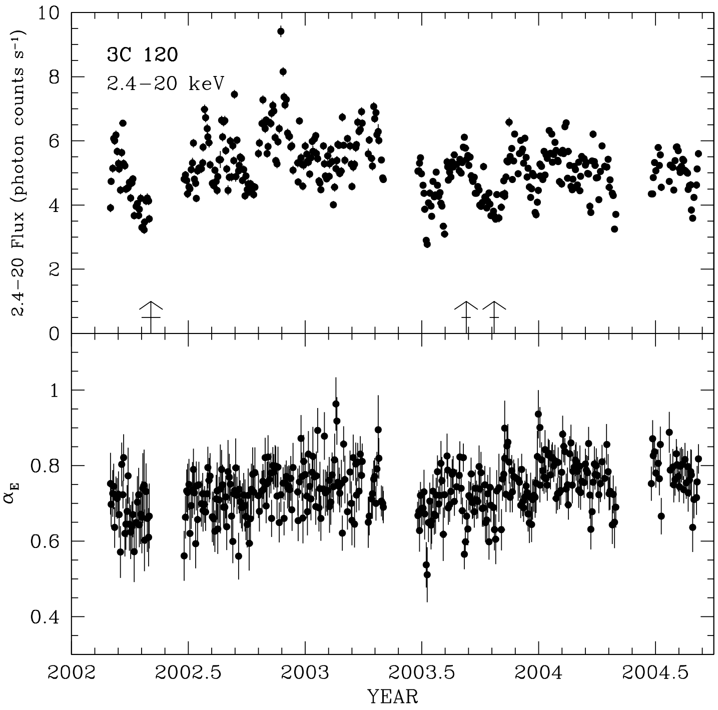

Figure 1. X-ray light curve and energy spectral index vs. time of 3C 120. Note the tendency for the spectrum to be flatter during periods of lower flux. The extrapolated times when the positions of superluminal radio knots coincided with the core are marked by vertical arrows, with horizontal bars giving the uncertainty in the time of coincidence.

time of the knot. For any of these, the time interval measured in the observer's frame must be corrected for the Doppler effect.

I associate the start of the 37 GHz flare at 2003.65 with the edge of the highly energized jet flow created by an event in or near the accretion disk that caused the X-ray dip starting at 2003.50. We can then infer a travel time of 0.15 yr between the disk and the position of the 43 GHz compact radio core as measured in our frame. This is 1.5 times longer than the value derived in Marscher et al. (2002) from the minima of the X-ray dips. The new determination should be more appropriate. We therefore raise the estimate of the displacement between the central engine and the ~ 40 GHz core to > 0.6 pc. This corresponds to the distance traveled down the jet in 0.15 yr: $4.7 \times 0.15 \times (\sin\theta)^{-1}$ lt-yr, where the angle between the velocity vector and the line of sight $\theta \leq 20°$ (Gómez et al., 2001; Jorstad et al., 2005). If the jet accelerates or if the viewing angle $< 20°$, the core must be farther downstream from the black hole. (Ogle et al., 2004) report that the flux density at 250 GHz was very high before the onset of the 37 GHz flare, hence the "true" core—where the jet plasma is energetically excited or where it reaches its asymptotic flow velocity (Marscher, 1995), as opposed to the boundary where the optical depth ~ 1 at the frequency of observation—is probably closer to the black hole.

¿From the appearance of the first superluminal knot in 2003.7 until 2004.3, the X-ray flux varied more smoothly than seen previously. This conclusion is supported by a change in the break in the structure function, which occurs at 13 days during most of the observations but lengthens to 37 days during the above interval. Furthermore, the X-ray flux is moderately correlated (with a coefficient ~ 0.5) with the 37 GHz radio flux (Ogle et al., 2004) over the same time range, with zero lag. This implies that a substantial fraction of the X-rays observed during this period may have been emitted by the jet near the radio core region, perhaps via inverse Compton scattering. In this case, the iron line equivalent width should have been lower, a possibility that we are currently checking by re-examining our RXTE database. The X-ray continuum has been flatter since early 2002 (α mostly in the range 0.6-0.8) than in 1997 and 1999 (energy spectral index $\alpha_{\rm E}$ from 0.8 to 1.0; Marscher et al. 2002) despite similar flux levels. This could be a sign of either a stronger jet-to-disk emission ratio or a physical change in the primary X-ray emission region.

3. The FR2 Radio Galaxy 3C 111

Figure 2 presents the X-ray light curve we have obtained thus far for 3C 111. After an initial decline by a factor ~ 2, the flux has risen almost linearly by a factor ~ 4 over 6 months up to the time of writing. A bright superluminal knot with flux density at 43 GHz comparable to that of the core emerged in July 2004, with a "birth" date 0.3 yr after the minimum in the X-ray light curve. The continuation of our monitoring program will determine whether this is an X-ray dip/superluminal ejection episode similar to those in 3C 120 but on a larger size scale, or an outburst of X-rays associated with the new knot. In support of the dip interpretation is the essentially linear relation between X-ray spectral index and flux. This is similar to, but even more pronounced than, the spectral flattening observed during the X-ray dips in 3C 120 (see above).

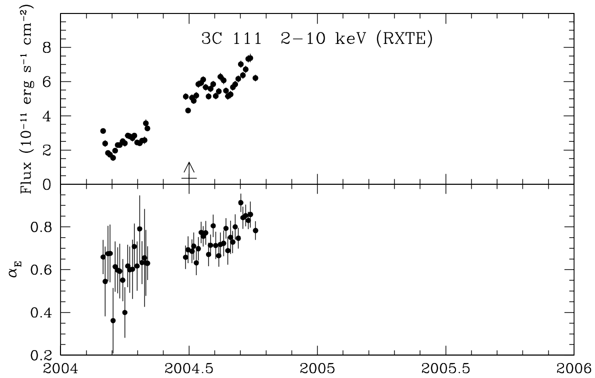

Figure 2. X-ray light curve and energy spectral index vs. time of 3C 111. The extrapolated time when the positions of a superluminal radio knot coincided with the core is marked by a vertical arrow, with horizontal bars giving the uncertainty in the time of coincidence.

4. Discussion and Conclusions

Our observations have established an association between low X-ray states and enhanced flow of energy into the relativistic jet in at least one radio galaxy, 3C 120. Although this is to zeroth order what is seen in the microquasar GRS 1915+105 (e.g., Mirabel & Rodríguez, 1998), the details are quite different. The intensity of the jet in 3C 120 fluctuates with position but never drops to zero, while the microquasar jet flows seem to be more episodic. The X-ray light curves of microquasars involve more pronounced, distinct phases than seen in 3C 120: prolonged low-hard states rather than ragged dips, quasi-periodic oscillations, high-soft states, etc. It therefore appears that the systems do not scale completely as one goes from a 10-20 $M_\odot$ to a $(5.5 \pm 3) \times 10^7$ $M_\odot$ black hole (mass estimates by Peterson et al., 2004, and Marshall et al., 2004).

Although the Marscher et al. (2002) paper appeals to chunks of disk material plunging into the black hole as a possible mechanism for the X-ray dips, there is little evidence in the X-ray spectrum for this interpretation. No low-energy wing has ever been observed in the spectrum of 3C 120, a point emphasized by A. Fabian (these proceedings). Another scenario that seems more appealing is a change in the magnetic field structure in and above the disk. As discussed by Livio, Pringle, & King (2003 and these proceedings), a turbulent magnetic field, which presumably provides the main source of viscosity in the disk, can spontaneously align in the poloidal direction. This would reduce the viscosity at the same time as it directs flow of energy into the jet. The lower viscosity would decrease the dissipation of energy and therefore suppress the optical, ultraviolet, and X-ray flux. We hope to obtain more optical observations in the future to test this.

Since our original goal was to apply what we can learn from microquasars to AGNs, we need to consider how one might expect black-hole accretion systems to scale as the mass is increased from $M_{\rm BH} = 10 - 20 M_\odot$ to $M_{\rm BH} \geq 10^7\, M_\odot$. Unfortunately, this involves too much guesswork to be accurate, but we can at least do some crude approximations. The size of the inner accretion disk should scale directly as $M_{\rm BH}$, and we imagine that the dimensions of other structures near the black hole (e.g., the base of the jet) should scale in the same manner. The cooling time of electrons owing to thermal bremsstrahlung, on the other hand, is approximately proportional to the square-root of the temperature divided by the square of the density. If we imagine the latter to be roughly independent of $M_{\rm BH}$, then the ratio of the cooling to the dynamical time scale decreases with mass, leading to cooler disks around more massive black holes, a well-known result. If the magnetic field plays an important role in controlling outflow from the disk, then we should note that the Alfvén speed varies as the field strength divided by the square-root of the density, and probably does not depend strongly on black-hole mass. This means that the system should be slower to respond to re-configurations of the magnetic field in the AGNs. One might then expect transition times to be roughly proportional to $M_{\rm BH}$.

In 3C 120, the recovery from X-ray dips occurs over 10^5-10^6 s, while in GRS 1915+105 the duration of transitions between states ranges from about 10 s to several minutes. The ratio of black-hole masses, on the other hand, is $2 - 4 \times 10^6$. This means that 3C 120 actually varies faster than one would anticipate by scaling up a microquasar. So, the duration of a long dip in 3C 120, 3×10^6 s, would correspond to a drop in flux lasting only ~ 1 s in GRS 1915+105. That is, the dip/ejection events observed in 3C 120 might be seen as some relatively unimportant, rapid "blip" in a microquasar, while the counterparts to the 5-10 minute low-hard states of X-ray binaries would last for decades in an FR1 source like 3C 120 and even longer in higher luminosity AGNs.

However, at this point we should admit to ourselves that our knowledge of accretion-disk/jet systems is not yet sophisticated enough to bridge the gap between systems containing stellar-mass and supermassive black holes. Rather, we need to continue to develop our understanding of both microquasars and AGNs separately while keeping in mind the observed similarities and differences between the two classes.

Acknowledgements

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