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X-ray and radio emission in the nuclei of radio galaxies and the disk-jet connection

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Abstract. It appears that relativistic jets are produced by accreting black holes. We might therefore expect that events observed in jets, such as the appearance of bright radio knots moving at apparent superluminal speeds, originate as disturbances in the central engine. This is observed in a number of compact X-ray binary systems in our Galaxy, manifested as changes in the X-ray emission state followed by superluminal ejections. The author and collaborators have detected somewhat similar events in the radio galaxies 3C 120 (type Fanaroff-Riley I) and 3C 111 (FR II). The data both confirm the disk-jet connection in accreting supermassive black holes and provide constraints on the structure of the jet between the central engine and the millimeter-wave core.

Key words: galaxies:active – galaxies: jets – galaxies: individual (3C 111, 3C 120) – X-rays – radio continuum

1. Introduction

Perhaps the greatest incentive to undertake research on active galactic nuclei (AGN) is to learn about how accretion onto supermassive black holes creates such a spectacular array of observed phenomena. These include jets of ultra-hot, nonthermal, magnetized plasma shooting away from the central engine at velocities extremely close to the speed of light (Lorentz factors sometimes exceeding 40; Jorstad et al. 2005), luminous, concentrated emission of X-rays, huge fountains of radio emission, and very broad emission lines, often corresponding to states of high ionization. The currently prevailing wisdom holds that the black hole and its surrounding accretion disk generate this splendid assortment of exotic effects.

We need to be clever to explore the immediate environs of the black hole, since our instruments have angular resolutions too coarse to do so with imaging. Fortunately, we have at our avail interferometers that can, at millimeter wavelengths, produce images with linear resolution down to parsec or, for relatively nearby AGN, subparsec scales. In addition, along with the small sizes of the emitting regions come short timescales of variability, so we can use multiwaveband light curves as well. Progress is often slow, since we must amass vast quantities of data in order to draw conclusions about these capricious, enigmatic objects. Nevertheless, progress is definitely being made.

This paper describes some seemingly promising work on radio galaxies that the authors and collaborators have been carrying out on how the jet relates to the central engine. The observational signatures of the disk-jet connection appear to be considerably more subtle in AGN than is the case for microquasars, in which obvious changes in X-ray states are associated with very bright features subsequently moving down the radio jet (e.g., Mirabel & Rodríguez 1994, 1998; Fender & Belloni 2004). Nevertheless, the same general trend is seen in two radio galaxies, with drops in X-ray flux from the central engine signaling the production of a knot that propagates down the jet at a superluminal apparent speed and an actual velocity of $\sim 0.98c$. We purposely selected the two most blazar-like radio galaxies known, 3C 120 and 3C 111. Their cm- and mm-wave radio emission is dominated by a relativistic jet pointing within about 20° of the line of sight, but their optical and X-ray emission is more Seyfert-like. The observation of an iron emission line at a rest energy of about 6.4 keV (e.g., Eracleous, Sambruna & Mushotzky 2000) strongly suggests that the X-rays arise from the central engine, as is the case in microquasars.

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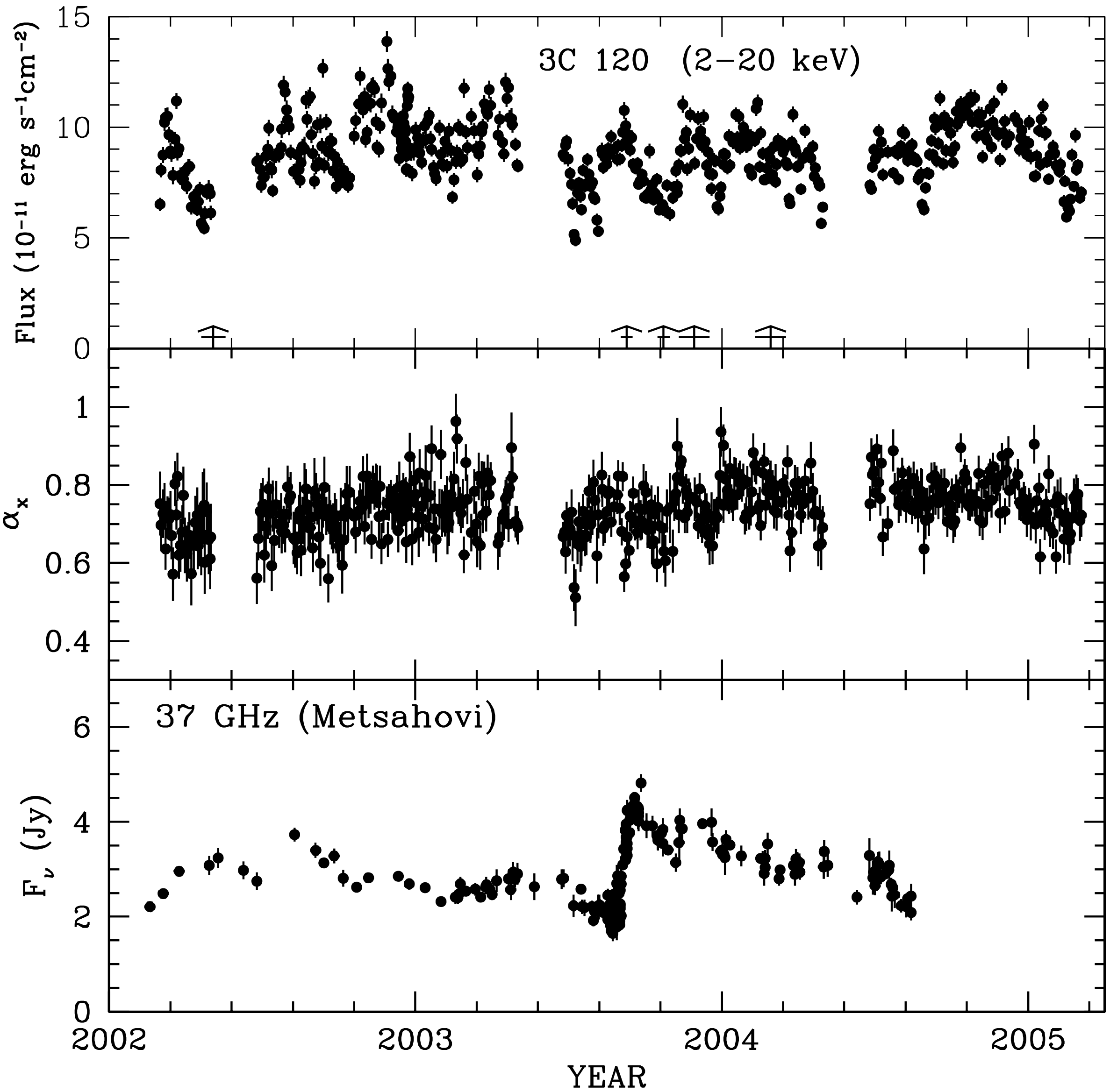

Fig. 1. X-ray light curve and energy spectral index vs. time of 3C 120 since early 2002. Note the tendency for the spectrum to be flatter during periods of lower flux. The extrapolated times when the positions of superluminal radio knots coincided with the core are marked by vertical arrows, with horizontal bars giving the uncertainty in the time of coincidence. The X-ray measurements are from the Rossi X-ray Timing Explorer (RXTE) PCA detector. Data are from Marscher et al. (in preparation), except radio data from 2003.1 to 2004.4 are from Ogle et al. (2005) and X-ray data prior to 2004.7 are from Marscher et al. (2004) and Marscher (2005b).

2. The FR I radio galaxy 3C 120

As reported previously (Marscher et al. 2002), the X-ray light curve of 3C 120 ($z = 0.0334$; Burbidge & Hewitt 1979) is punctuated by occasional dips in flux. While not nearly as pronounced as in the microquasar GRS 1915+105 (see Fender et al. 2004), they are statistically significant. They do, however, seem to be random events, meaning that there is no discernable pattern to the times of occurrence. Each significant X-ray dip observed between 1997 and 2000 was followed by the appearance of a bright, relatively highly polarized superluminal radio knot on Very Long Baseline Array (VLBA) images (Marscher et al. 2002). This one-to-one correspondence between dips and superluminal “ejections” demonstrates that there is indeed a direct connection between the jet and the hot regions near supermassive black holes. The fact that the X-ray signature is much more subtle than in microquasars might be the result of the larger size scales associated with larger masses in AGN. Perhaps the coherence of disturbances in the accretion disk or corona weakens as they propagate across the X-ray emission region. Alternatively, we may be seeing minor fluctuations in the AGN that would occur over extremely short time scales in microquasars. Another possibility is that competing sources of X-ray emission are more prominent in AGN, so a major decline in the flux of one component has less effect on the total flux.

Figure 1 consists of the X-ray light curve between March 2002 and March 2005. It therefore represents the data we have accumulated after obtaining the results reported in Marscher et al. (2002). Upward arrows mark the epoch 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. Figure 2 displays one of the VLBA images that contains three of the superluminal knots. 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, as is characteristic of the *bona fide* dips and reminiscent of the low-hard state of X-ray binaries. The onset of the first dip preceded the appearance of a bright superluminal radio knot by 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. 2005) to herald the ejection of the first knot after the double dip. The high mm-wave flux state persisted 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 time required for the knot to accelerate to its asymptotic Lorentz factor of about 5 (Jorstad et al. 2005). For any of these, the time interval measured in the observer's frame must be corrected for the Doppler effect.

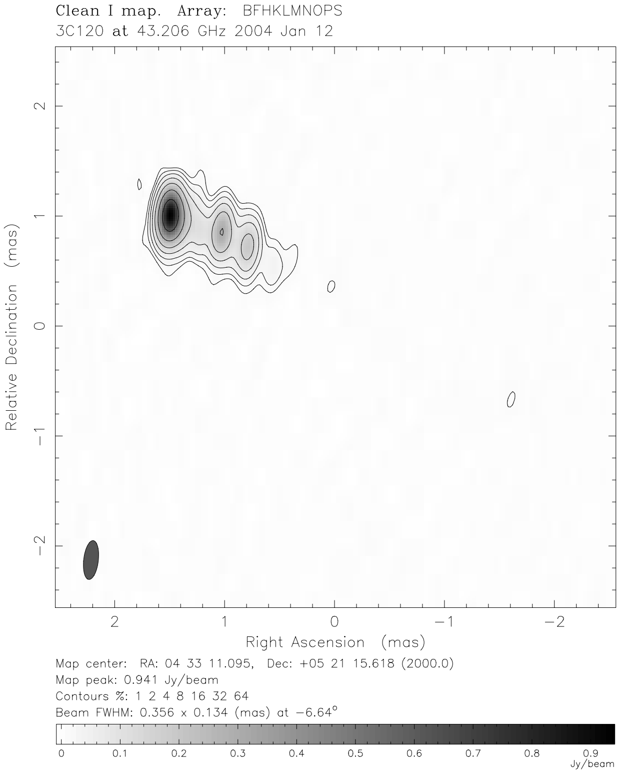

Fig. 2. Image of the compact jet of 3C 120 at 43 GHz, obtained from the Very Long Baseline Array (VLBA). The two bright features 0.5 and 0.75 milliarcseconds (mas) from the core were coincident with the core at 2003.81±0.02 and 2003.69±0.02, respectively, and a third knot corresponding to the bridge of emission about 0.3 mas from the core was coincident with the core at 2003.91±0.05. The scale is $1\,\mathrm{mas} = 0.64$ pc in projection on the sky.

It seems reasonable to 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 (2002) from the minima rather than the start 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. (2005) 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 $\sim$1 at the frequency of observation – is probably closer to the black hole. We can quantify this by noting that the observation frequency of 43 GHz is about a factor of two lower than the self-absorption turnover in the spectrum, as reported by Bloom et al. (1999) [1]. Since flat spectra generally correspond to the situation where the size of the region is inversely proportional to frequency, we can expect that the core at 90 GHz is twice as close to the black hole as the core seen in 43 GHz images. The jet geometry is approximated here as a straight cone with the black hole at the apex. We therefore arrive at the distance of the "true" core from the black hole: 0.3 pc, or 2×10^5 Schwarzschild radii if the mass of the black hole $\sim 3 \times 10^7\ \mathrm{M}_\odot$, the value derived by Wandel, Peterson & Malkan (1999) from emission-line reverberation mapping and by Marshall et al. (2004) from analysis of the power density spectrum of variations in the X-ray flux.

Of course, AGN are well known to be capricious. After nine consecutive observations of X-ray dips followed by ejections of major superluminal knots, with the last pair of events occurring in early 2004, at least two pronounced X-ray dips can be seen later in 2004 (see Fig. 1) with no counterpart in the radio images. We speculate that the cause of this might be an extended region of rarefaction waves induced by the prolonged enhanced outflow that caused the major radio out-

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[1] A check of unpublished millimeter-wave data during our monitoring indicates that the spectrum is roughly the same as at these earlier epochs.

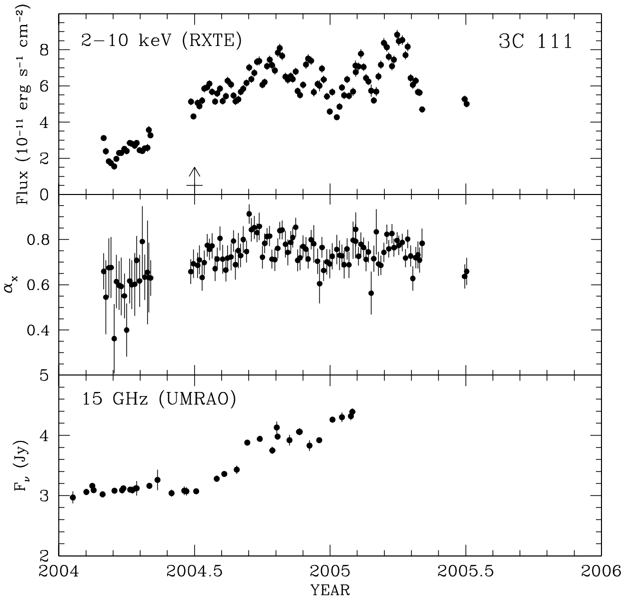

Fig. 3. X-ray light curve, X-ray energy spectral index, and 14.5 GHz flux density vs. time for 3C 111. The extrapolated time when the position of a bright superluminal radio knot coincided with the core is marked by a vertical arrow, with the horizontal bar giving the uncertainty in the time of coincidence. The X-ray measurements are from the RXTE PCA detector, while the radio observations in the bottom panel were taken at the University of Michigan Radio Astronomy Observatory by M.F. Aller and H.D. Aller. Data are from Marscher et al. (in preparation), except X-ray data prior to 2004.75 are from Marscher (2005b).

burst from 1993.7 to 2004.5. Perhaps the polarized intensity images, which we are in the process of constructing, will reveal some highly polarized features with weak flux following the X-ray dips.

3. The FR II radio galaxy 3C 111

Figure 3 presents the X-ray light curve we have obtained thus far for 3C 111 ($z = 0.0485$; Burbidge & Hewitt 1979). After an initial decline by $\sim 50\%$, the flux rose almost linearly by a factor ~ 4 over a six-month period before fluctuating about a value of $\sim 6 \times 10^{-11}$ erg s^{-1} cm^{-2}. In addition, the X-ray spectral index is clearly flatter at lower flux levels, as in 3C 120 and black-hole X-ray binaries. A bright superluminal knot with flux density at 43 GHz comparable to that of the core emerged in July 2004 (see Fig. 4). Extrapolation of its motion indicates that the knot was coincident with the 43 GHz core 0.3 yr after the minimum in the X-ray light curve. This X-ray dip/superluminal ejection episode appears similar to those in 3C 120 but on a somewhat larger size scale, as expected if the black hole in an FR II radio galaxy is more massive than in an FR I galaxy. We hope to be able to estimate the mass of the black hole in 3C 111 by measuring the break in the power density spectrum of the X-ray flux variations (see McHardy et al. 2004) once we have accumulated a sufficiently long data train.

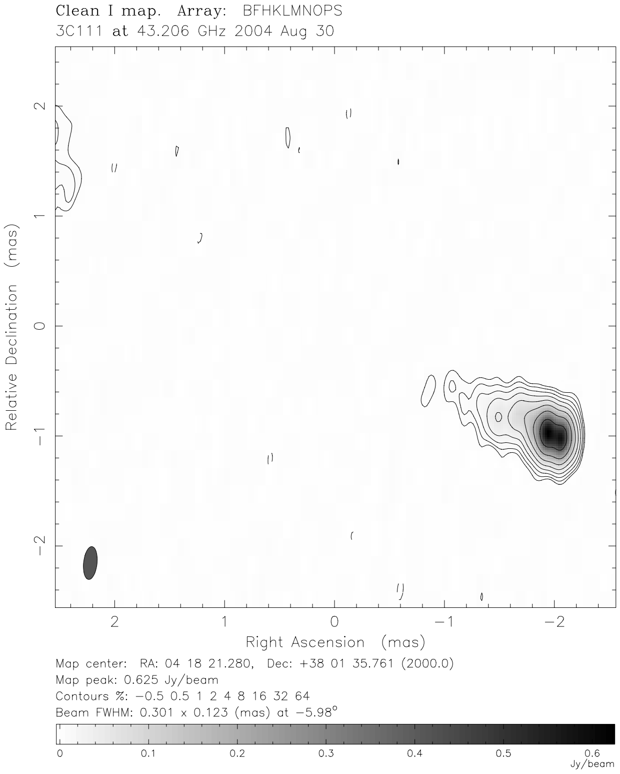

Fig. 4. Image of the compact jet of 3C 111 at 43 GHz, obtained from the VLBA. The feature very close to, and slightly brighter than, the core is the one ejected at 2004.5±0.03. The scale is $1\,\mathrm{mas} = 0.93$ pc in projection on the sky.

4. The quasar 3C 273

If we look around for other objects that similarly might be blazars at radio wavelengths and non-blazar AGN in the optical and X-ray bands, the quasar 3C 273 is an obvious candidate. It is very blazar-like at radio to infrared wavelengths, but its optical-ultraviolet spectral energy distribution is dominated by the big blue bump, which is thought to be from the accretion disk (Malkan & Sargent 1982). The X-ray emission has at least two components, the central engine and the jet (Grandi & Palumbo 2004). It would be extremely informative to separate the two in the hopes that dips in the central engine's X-ray emission might cause disturbances in the jet that could be followed from X-ray to radio wavelengths. It might be possible to do this, at least approximately, by using the 20–200 keV light curve measured by the HEXTE instrument of RXTE to define the variability of the jet emission, which has a flatter spectral index than that from near the accretion disk. The flux of the jet at 2–20 keV could then be estimated and subtracted to reveal the light curve of the central engine's X-rays. The author is in the process of carrying out this exercise.

5. The disk-jet connection

Most theorists think now that relativistic jets are driven from either the inner accretion disk or the ergosphere of a rotating black hole, with much of the collimation and acceleration caused by a twisted, mostly poloidal magnetic field (e.g, Meier, Koide, & Uchida 2000). Both processes might occur, leading to an extremely relativistic spine surrounded by a slower, funnel-shaped sheath (see, e.g., Punsly 1996; Meier 2003; McKinney 2005). For the two radio galaxies studied here, the bulk Lorentz factor of the jet ~ 5 (Jorstad et al. 2005), which would probably correspond to the faster flow in the spine. (Sources with higher Lorentz factor are very rare per unit volume despite their prevalence in flux-limited centimeter-wave radio surveys; see Lister & Marscher 1997.)

The acceleration and focusing of the jet might be a slow process, occurring over many thousands of Schwarzschild radii (Vlahakis & Königl 2004), or closer to the black hole (Meier et al. 2000 and references therein). In either case, the most obvious process by which the system can generate disturbances in the jet is to perturb the magnetic field. The observations described above, as well as the data from microquasars, imply that the change in magnetic field is associated with a variation in the accretion disk/corona system. In particular, extra injection of energy into the jet coincides with a drop in the X-ray emission. The latter is thought to come from nonrelativistic Compton scattering in a corona above the disk containing hot electrons, since the temperature of the inner disk of a supermassive black hole is thought to be too low for emission of photons above the ultraviolet range (e.g., Malkan & Sargent 1982). The nature of the corona, however, is uncertain. It could be an atmosphere above the accretion disk, the low-altitude portion of a wind flowing from the disk, or even the base of the jet below the point where the flow is highly relativistic.

A decrease in the X-ray emission could be the result of (1) a change in the flux or spectrum of the seed photons that are scattered in the corona, perhaps from the disappearance of the innermost section of the accretion disk, or (2) a decrease in the number of electrons in the corona. The first of these might correspond to a transition of the magnetic field from turbulent to predominately poloidal, in which case viscosity-driven accretion inside the transition radius would be inhibited (Livio, Pringle & King 2003). The second possibility is perhaps more generic: if the Compton-scattering "corona" is actually the base of a wind or even the jet, faster flow of material into the jet could decrease the number of scattering electrons, since the quantity nvA is conserved, where n is the number density, v is the velocity (assumed not highly relativistic at this location), and A is the cross-sectional area. In either scenario, the "equivalent width" of the X-ray dip should be proportional to the amount of extra energy injected into the jet, which should be related to the emitted flux of the corresponding superluminal knot. Once we have a sufficiently long data train, we will determine whether this is actually the case.

6. The inner Jet of a radio-loud AGN

One of the primary insights that we have obtained from our observations of 3C 120 and 3C 111 is that the observed core of the jet is a substantial distance from the black hole in objects that behave as blazars at low frequencies. Between the injection point near the black hole and the most upstream feature in the radio jet – the core – the disturbance passes through a mysterious "inner jet" region that channels energy from the origin of the jet to the core. It is not clear whether emission from this section of the jet is important at any waveband. That is, the entire observed spectral energy distribution might be formed by radiation from the immediate environs of the central engine plus the jet from the core to the extended lobes. If this is the case, it supports the model of gradual acceleration of the jet flow out to parsec scales (Vlahakis & Königl 2004). As discussed by the author 25 years ago (Marscher 1980), synchrotron emission from the core will be brighter than the inner jet if the jet cross-section increases slowly (i.e., the opening angle narrows) as the relativistic jet accelerates (see Figure 5). This only works for jets making small angles to the line of sight, as in blazars, since the dominance of the compact core at short millimeter wavelengths occurs only if the relativistic beaming (i.e., the Doppler factor) increases with distance from the base of the jet. Emission from the innermost region should dominate in objects where the jet is viewed side-on. Indeed, in the radio galaxy Cygnus A, there is no gap detected between the cores of the jet and counterjet, and the proper motion of knots is faster farther from the base of the jet (Bach et al. 2005). If this is found still to be true at higher resolution, it will support the accelerating jet model.

7. Conclusions

Although it is easy to become confused by all the noisy randomness of the light curves of AGN, it seems that if we keep close enough watch on them, they eventually reward us with a striking event whose analysis reveals some of the secrets of these enigmatic objects. The X-ray dips, ejections of bright, polarized superluminal knots, and the sharp radio flare in 2003 seen in 3C 120 are excellent examples, as are the long, deep minimum and bright superluminal knot in 3C 111. The author hopes that his collaboration's detailed analysis of the multiwaveband behavior of these objects, as well as that of the quasar 3C 273, will reveal further information leading to a clearer picture of the accretion disk-inner jet region that we cannot image directly.

Further understanding of the disk-jet connection and of the inner jet region might come from non-blazar radio galaxies such as Cyg A (Bach et al. 2004) and NGC1052 (Kadler et al. 2005), whose jets lie closer to the plane of the sky. The medium-energy X-ray emission should still be as highly variable as in 3C 120 and 3C 111, although the jet should evolve more slowly since the Doppler effect will be small or even reversed (transverse Doppler redshift). It will therefore require more patience to follow the evolution of such objects over many years. Furthermore, the jets are fainter, which makes high-frequency VLBI imaging quite difficult. Nevertheless, the rewards for those who persevere could be rich.

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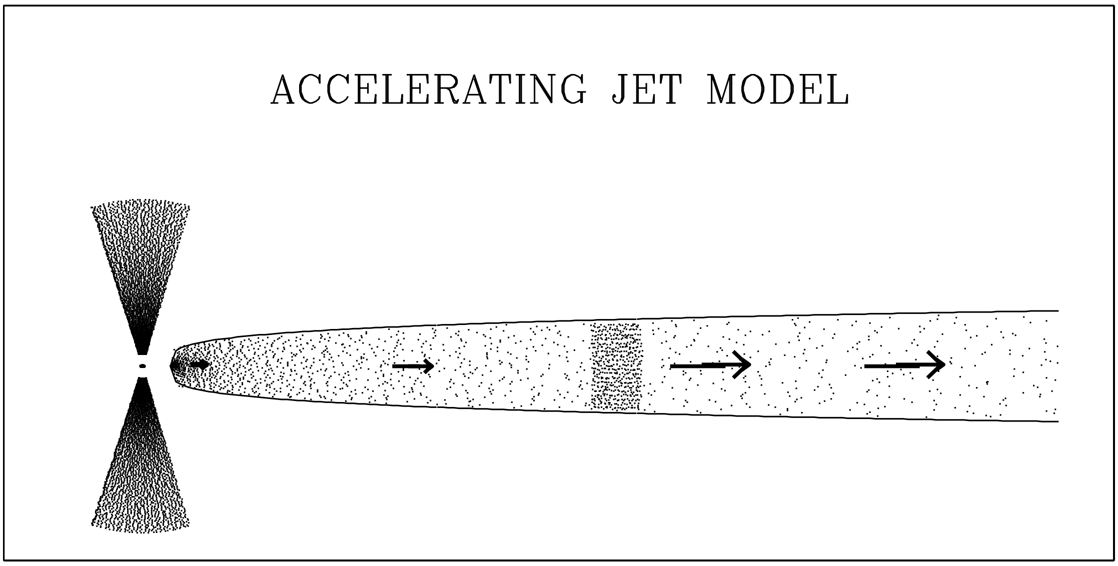

Fig. 5. Cartoon model of an accelerating relativistic jet emanating from a black hole and surrounding accretion disk. The dot at the center of the disk denotes the position of the black hole. The arrows represent the Lorentz factor of the flow in the jet. The shaded feature in the jet is the core, located at the site where the Lorentz factor reaches its asymptotic value.

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