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The Relationship between Radio and Higher-Frequency Emission in Active Galactic Nuclei

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Abstract. Active galactic nuclei emit radiation across the entire electromagnetic spectrum. This involves different regions with distinct physical characteristics and therefore a variety of emission mechanisms, each with a dominant frequency range. Here I review the observational tools we use to probe the various components of AGNs and the implications of some of the results. I discuss how the combination of radio imaging and multiwaveband monitoring in both total and polarized flux is a particularly powerful method for studying both the relativistic jets and their connection to the central engine.

Key words. active galactic nuclei; relativistic jets; radio emission; X-ray emission; multi-frequency observations

1. Introduction

Active galactic nuclei (AGNs) are very complex physical systems. Many investigations of AGNs involve a single technique at a single waveband (or even a single frequency), which is usually inadequate to gain an understanding of even one physical component of the object observed. The situation has improved with the availability of substantial amounts of time on astronomical instruments at different wavebands. Radio interferometry is particularly important since it produces images on parsec to kiloparsec scales. On parsec scales, repeated obsrevations with very long baseline interferometry (VLBI) even provide movies of the evolution of relativistic jets.

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The jets emit nonthermal radiation at higher frequencies as well, hence a multiwaveband approach is essential for exploring the physics of jets. Furthermore, since jets are launched from the central engine—which is a source of variable X-ray, ultraviolet, and optical emission—multifrequency monitoring can probe the connection between accreting black holes and jets. The cartoon sketch shown in the top panel of Figure 1 indicates likely locations of the emission regions at different wavebands, while the bottom panel presents a possible physical interpretation. As the drawings suggest, there is competition for the observer's attention from the accretion disk/corona, emission-line clouds, and jet. The jet has the advantage if the observer lies close to the direction of its axis, in which case its radiation is strongly beamed. We call such objects "blazars," observations of which can inform us of the nature of the relativistic, directed outflows in the more extreme AGNs.

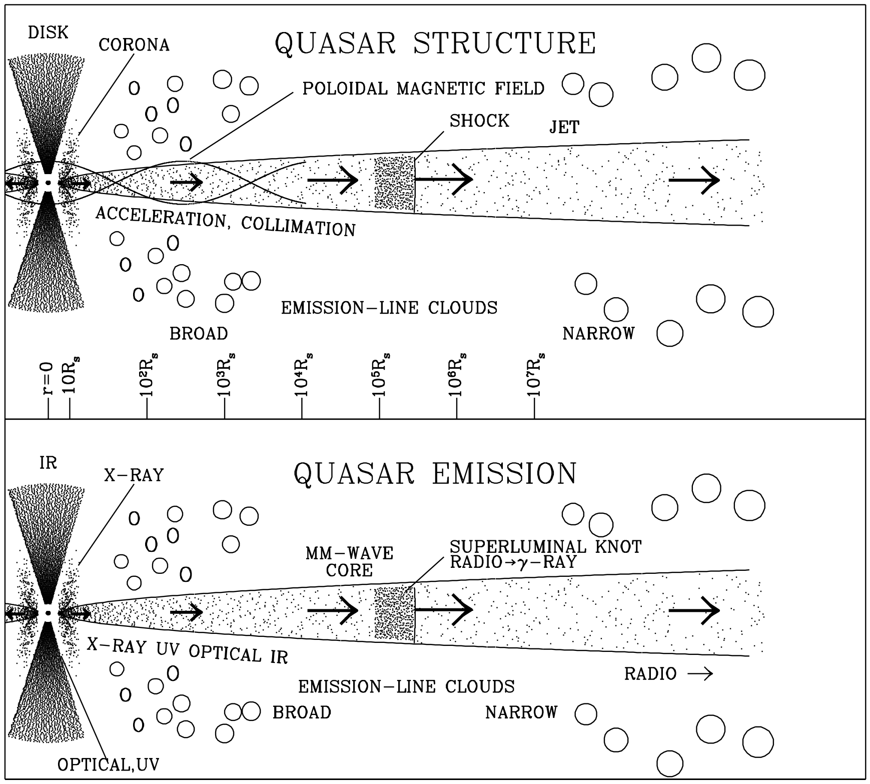

Fig. 1. Cartoon of the physical structure and emission regions of a radio-loud AGN. Not shown are the extended radio lobes. The density of the dots in the disk, corona, and jet very roughly indicates the density of plasma (top panel) or intensity of emission (bottom panel) in a reference frame in which there is no beaming. Note the logarithmic length scale beyond $10R_s$, where R_s is the Schwarzschild radius. Only a single superluminal knot is shown; usually there are several.

If we wish instead to observe the unbeamed emission regions, we need to select AGNs with weak jets, because of either intrinsically low luminosity or wide angles to our line of sight. The intermediate case can be interesting as well, but we then need to deal with multiple important radiation mechanisms at optical and X-ray frequencies.

2. Outstanding questions and tools for answering them

The cartoon model can provide a convenient mental picture of the paradigm under which most AGN researchers operate. It cannot, however, hide the fact that we still do not have definitive answers to a number of basic questions. Those related to jets include:

1. How are jets made by accreting black holes?
2. How does thr jet kinetic luminosity compare with the total luminsoity of an AGN?
3. Where and how are jets accelerated to high bulk Lorentz factors?
4. Out to what distance does a relativistic jet retain high Lorentz factor?
5. How and where are jets focused into narrow cones?

6. How and where are relativistic electrons accelerated?
7. What causes the radio loud/quiet dichotomy (if there is one rather than a continuous distribution)?
8. What is the physics of the jet flow (shocks, turbulence, interaction with gas, matter content, instabilities, magnetic field pattern, bending, precession,...)?
9. Are high-frequency events related to the "ejection" of superluminal radio knots?

Detailed studies of individual objects appear to resolve some of these issues, but different conclusions are often drawn from one source to another. This may be a case of "whatever can happen, does happen," such that some AGNs behave in one manner, while alternative processes are at work in others. In order to sort out this complex array of behavioral patterns, we need techniques capable of providing deep insights into the physical nature of AGNs. The multi-component physical structure and both physically distinct and co-spatial or overlapping emission regions at different frequencies dictate that the best approach involves observations across the electromagnetic spectrum. Our multiwaveband tools include:

1. formation of spectral energy distributions (SEDs) from measurements of flux density at many frequencies. This allows the identification of separate components of emission through humps, valleys, and breaks in spectral slope.
2. spectroscopy. For example, the Fe Kα X-ray emission line is thought to arise from X-rays from a corona (or perhaps the innermost section of the jets) shining on the optically thick accretion flow. The broad optical emission lines require a strong ultraviolet continuum from the disk and its neighborhood, and both the broad and narrow lines indicate the pressure of the medium surrounding the jets at different radii.
3. variability in all wavebands that we can observe. The minimum timescale of flux changes is related to the size of the emission region, while cross-frequency time lags help to locate the sites of emission.
4. radio/mm-wave imaging, which provides pictures of jets as well as their polarization at resolution as fine as 0.1 milliarcsec or less. Multi-epoch images allow us to watch as the jets perform a variety of tricks such as superluminal apparent motion, sudden appearance or disappearance of strong features, and rapid changes in polarization.
5. multiwaveband polarization. This not only informs us on the changes in the magnetic field geometry, but also points to the cross-frequency identification of emission regions revealed by variability and VLBI images (see below).

The historical ability of AGNs to surprise and confuse us highlights the limitations of these observational tools. For example, SEDs do not by themselves indicate the locations of the different emission regions, only their existence. And, as recently driven home by the study of 3C 273 by Grandi & Palumbo (2004), more than one emission mechanism might contribute substantially to the flux within a given waveband. Spectral lines represent reprocessed emission and we can measure only the radial component of the velocity, hence they are not straightforward to interpret. While variability provides information on the maximum size of the emission region, knowledge of the Doppler beaming factor is needed as well. In addition, small size does not necessarily inform us as to the location of the emitting plasma, i.e., whether it is situated near to or far from the central engine. Infrared and higher-frequency observations have spatial resolution much too coarse to image an AGN on parsec-scales and smaller, and even mm-wave VLBI images are subject to opacity that restricts how close to central engine we can explore directly. Can we overcome these limitations? I think that the answer is "yes" if we can combine some of the tools listed above in our effort to construct a comprehensive description of AGNs. These combinations currently include:

1. variability of optical emission lines and optical-ultraviolet continuum (reverberation mapping). Peterson et al. (2004) have used this technique to determine the distance of broad emission-line clouds from

the central engine and to estimate the masses of the central black holes in a number of AGNs.

2. variability of the SED. If done with enough data and careful analysis, this allows separation of emission components (e.g., Grandi & Palumbo 2004).
3. multiwaveband variability and multiepoch VLBI. Armed with sequences of images and well-sampled light curves, we can place the emission regions at different wavebands relative to each other. This can be especially effective if the monitoring and imaging includes linear polarization, which allows us to identify a parcel of plasma as it emits at different frequencies through its particular polarization angle or distinctly high degree of polarization. Furthermore, since we can monitor the apparent speed and projected direction of the jet with VLBI, we can explore how the jet kinematics influences the SED and separate the effects of relativistic beaming from intrinsic changes in the physical parameters of the jet.

3. Application of the multiwaveband tools

Of course, it is easy to claim that a thorough set of multiwaveband, multiepoch observations will reveal the secrets of AGNs, and not so easy to demonstrate. Even for a single object, the combined techniques require a very large amount of observing time on a number of world-class instruments, as well as laborious reduction and analysis of the data. Even then unambiguous results rely on the cooperation of notoriously capricious objects. Do we have any examples of success? While we cannot claim complete victory over even a single AGN, I think that the answer is a robust "We've learned a few things."

I have already mentioned the important results of reverberation mapping and multiepoch analysis of X-ray data on 3C 273 spanning a factor of $\sim$ 1000 in energy by Grandi & Palumbo (2004). Here I concentrate specifically on what we have learned from combining radio with higher frequency observations. Space only allows a subset of these modest victories, hence I will select those of which I am most familiar.

3.1. Combining radio with γ-ray and X-ray data

VLBI monitoring of γ-ray blazars revealed that the distribution of their apparent speeds peaks at considerable higher values than does that of the general class of bright compact radio sources (Jorstad et al. 2001a; Kellermann et al. 2004). Furthermore, Jorstad et al. (2001b) found that high γ-ray states are statistically associated with ejections of superluminal radio knots, with the γ-ray event occurring a bit *later*. Lähteenmäki & Valtaoja (2003) similarly determined that a flare at 37 GHz starts before the γ-ray flux increases.

Along with a group of collaborators, I have been monitoring a few blazars 1-3 times per week with the *Rossi* X-ray Timing Explorer (RXTE), $\sim$ monthly with the Very Long Baseline Array (VLBA), and with irregular time coverage at a number of optical telescopes. The results—see Figure 2 for two examples—have been quite revealing. In the quasar 3C 279, we find a general correspondence in the activity from radio to optical to X-ray. The optical/X-ray correlation is particularly strong, with the optical leading by 15 ± 15 days. The 37 GHz and X-ray fluxes are correlated as well, although not as strongly, with the X-ray leading by 140±40 days. But note that the peaks of the 37 GHz flares also lag the ejection times of new superluminal knots (Jorstad & Marscher 2005). We define the "ejection time" as the epoch when the *centroid* of the knot was coincident with the core based on back-extrapolation of the core-knot separation vs. time curve. In fact, the peak of an X-ray flare tends to occur slightly *after* the ejection. (We are in the process of quantifying this.)

We see a similar situation in the quasar PKS 1510−089. In this case, the X-ray and high-frequency radio (15 and 37 GHz) variations usually correlate very well, with an average of 6 days (*radio* leading). The lag varies, however, with the X-ray sometimes leading (e.g., in 2004), and the correlation was in-

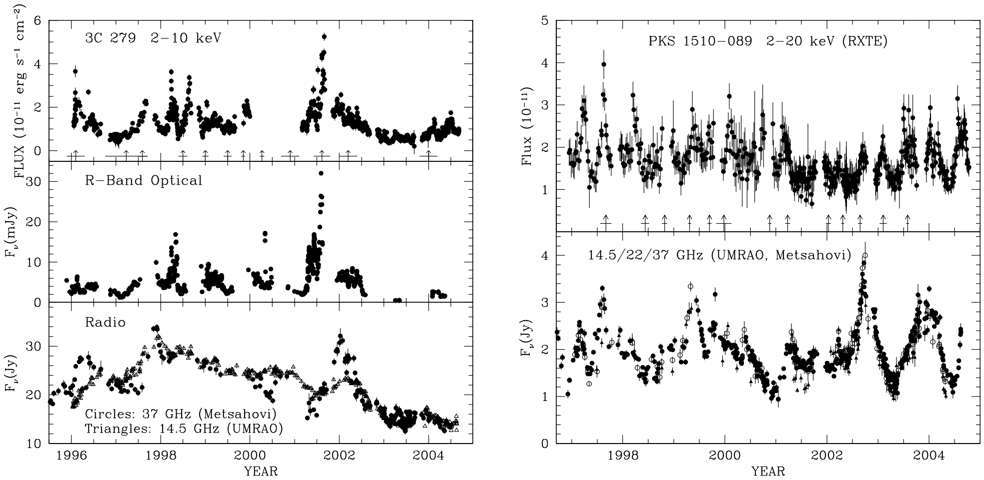

Fig. 2. X-ray and lower frequency light curves of 3C 279 and PKS 1510−089 from the long-term monitoring programs of the author and collaborators (Marscher et al. 2004,and in preparation). Arrows show times (horizontal lines: uncertainties) of known ejections (prior to mid-2004) of superluminal radio knots.

significant in 2000 and 2001. In BL Lac, the long-term X-ray and optical light curves are strongly correlated, with ∼ zero lag (Marscher et al. 2004), although if the data train is shorter than several weeks, the correlation is considerably weaker (Böttcher et al. 2003). A superluminal ejection occurred 0.1 ± 0.1 yr after the start of a major X-ray/optical outburst in late 2000 (Marscher et al. 2004). The obvious implication is that blazar X-ray emission comes predominantly from the mm-wave core region of the relativistic jet (Sokolov et al. 2004). As emphasized by Lähteenmäki & Valtaoja (2003), this contradicts the external Compton models for γ-ray emission that require seed photons from the broad emission-line region (Sikora, Begelman, & Rees 1994) and perhaps from the dust torus (Błażejowski et al. 2000).

Changes in the mean flux, amplitudes of flares, and radio/X-ray time lag appear related to shifts in the direction of the jet in PKS 1510−089 (Marscher et al. 2004). Jorstad & Marscher (2005) find that the direction of the jet in 3C 279 also affects the X-ray light curve. Although this is not surprising, it does demonstrate that the combined analysis of multifrequency lights curves and sequences of VLBI images provides powerful diagnostics for exploring the physical conditions in jets. For example, changes in the bulk Lorentz factor and the angle to the line of sight can be derived independently. This will eventually determine whether jets precess or swing erratically, as well as the extent to which the bulk Lorentz factors and physical parameters of the emitting plasma vary.

It seems that TeV blazars were not invited to the radio party. Their radio jets are comparatively slow and not highly variable on parsec scales (Marscher 1999; Piner & Edwards 2004). Even this rather negative result has very important implications, since it implies that the jets—which must be highly relativistic where the X-ray and TeV emission occurs (Georganopoulos & Kazanas 2003)—decelerate considerably by the time they get out to parsec scales. Maybe the jets are composed of pair plasma with a flat energy spectrum such that the jet loses momentum when the electrons cool from emission of nonthermal radiation, with a consequent drop in the

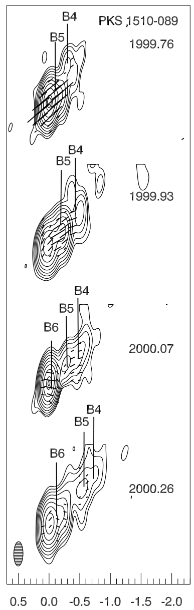

Fig. 3. Sequence of 43 GHz VLBA images of PKS 1510−089 showing an example of a superluminal knot (B5) whose polarization direction is stable as it moves down the jet.

bulk Lorentz factor. In support of this, Wardle et al. (1998) infer from circular polarization that positrons outnumber protons in the non-TeV blazar 3C 279 by a ratio of 5:1, although Ruszkowski & Begelman (2002) find that this conclusion does not necessarily follow from the observations. Alternative interpretations include fast spine/slower sheath structure (e.g., Ghisellini, Tavecchio, & Chiaberge 2004) and a much lower "pattern" Lorentz factor of the disturbance creating the knot (e.g., standing or reverse shocks) than that of the plasma flow.

Marriage of radio, optical, and X-ray imaging of extended jets has demonstrated that, at least in quasars, highly relativistic jets do not decelerate appreciably until they propagate most of the way to the giant radio lobes (e.g., Jorstad & Marscher 2004; Tavecchio et al. 2004). Diana Worrall's paper in these proceedings expounds further on what we have learned from multiwaveband studies of large-scale jets.

3.2. Polarization across wavebands and panchromatic emission maps

Studies over the past decade have established that the polarization properties of blazars are similar from radio to optical wavelengths (Gabuzda & Sitko 1994; Gabuzda, Sitko, & Smith 1994; Lister & Smith 2000; Jorstad et al. 2005). Marscher & Jorstad (2005) find that this includes variability as well, i.e., the changes in polarization at different wavebands track each other. This implies that one can use polarization "signatures"—peculiar position angles or degrees of polarization—of features on VLBI images to specify the location in the jet of a particular emission region (identified through variability of flux and polarization) with similar polarization properties at different wavebands. In addition, Jorstad et al. (2001a) found that high γ-ray fluxes tend to occur after ejections of superluminal radio knots, with accompanying increases in polarized radio flux. This provides evidence for a link between γ-ray light curves and the moving, polarized features we see on VLBI images. We should therefore be able to combine VLBI polarimetry with multiwaveband light curves to create maps of the emission in the jet at all wavebands. Difficult cases will include those objects where the high-frequency radiation is emitted from the section of the jet that is opaque and unresolved at millimeter wavelength, i.e., between the core and the central engine. Even then we should be able to identify the parcel of plasma responsible for the high-energy emission—if it remains intact (see Fig. 3 for an example of a knot with persistent polarization)—when it appears in the mm-wave jet, and the time delay will allow us to infer how far upstream of the core it flared at the higher frequencies.

4. Connecting the jet with the central engine

Some radio galaxies act as blazars at radio wavelengths and as radio-quiet AGNs at higher frequencies. In this case, we can study the jet and the central engine in the same object. This provides an opportunity to explore how the jet relates to the black hole and accretion disk system. We can also compare the results with observations of black-hole binaries in our Galaxy—"microquasars" (Mirabel & Rodríguez 1994)—in the hopes of improving our chances of figuring out the physics of jet production.

My group (Marscher et al. 2002) found that the X-ray flux of the radio galaxy 3C 120 drops for days or weeks ~ 0.1 yr prior to the appearance of bright, highly polarized superluminal knots in the radio jet. This is reminiscent of the behavior of the microquasar GRS 1915+105 (e.g., Mirabel & Rodríguez 1998), although the details are rather 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, and high-soft states. 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 from Peterson et al. 2004). In 3C 120, the recovery from X-ray dips occurs over 10^5-10^6 s, while in GRS 1915+105 the transitions between states occur over about 10 s to several minutes. Given the ratio of black-hole masses, the duration of a long dip in 3C 120, 3×10^6 s, would correspond to a drop in flux lasting only $\sim$ 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 FR 1 source like 3C 120 and even longer in higher-luminosity AGNs.

We therefore should proceed with caution in our comparison of AGNs with microquasars. Our observations of 3C 120 can, however, inform us on the distance of the 43 GHz core from the black hole: > 0.6 pc is the latest value based on the delay between the onset of an X-ray dip in July 2003 and the start of a sharp flare at 37 GHz in September 2003 (Marscher 2005). The connection between a drop in X-ray flux and the injection of energy into the jet supports models in which the jet is launched by twisting poloidal magnetic fields with footpoints in the accretion disk (e.g., Meier, Koide, & Uchida 2000; Livio, Pringle, & King 2003).

An intriguing new development in this area is the discovery by Kadler et al. (2004) of a change in the "relativistic" low-energy wing of the X-ray Fe Kα line in the LINER galaxy NGC1052. The ejection of a bright radio knot followed the change. If we assume that the events are related (the time coverage is insufficient to establish this), then we are led to the conclusion that an accretion event coincided with the injection of extra energy into the jet. It is curious, though, that there is no "red" wing to the Fe Kα line in 3C 120 (e.g., Ogle et al. 2005).

5. Conclusions

Combining multi-waveband techniques is a powerful way to explore the most interesting physics of AGNs. The methods proposed here require a lot of observing time and patience from the observer, observatory directors, and time-allocation committees. Hence, the proliferation of comprehensive multi-waveband studies is limited mainly by the amount of telescope—and astronomers'—time available. Although we will lose capable when RXTE dies (it is old in satellite years but still great), we should look forward to GLAST, AGILE, the various new Cherenkov telescopes, Swift (after its main phase of observing γ-ray bursts is completed), VLBI at 2 and 1 mm, and high-frequency VLBI in space. These, together with progress in theoretical models, will be powerful tools in our quest to understand active galactic nuclei.

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