Chin. J. Astron. Astrophys. Vol. 8 (2008), **Supplement**, 311–318
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

The Importance of Multifrequency Emission from Jets in Astrophysics

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Abstract In this paper, I discuss some historical data on the radio and X-ray variability of the active galaxy, Centaurus A (NGC 5128). The Cen A data reviewed herein were the first detection of concurrent radio and X-ray variability of an active galaxy. Such concurrent variability demands that the radio and X-ray light originate from the same region in the source, a result that allows us to further constrain the physical parameters in the emitting region. The radio and X-ray data from Cen A during this epoch bear a remarkable resemblence to both the radio data from 3C120 (and other AGN) and the radio data from galactic microquasars. The radio data for Cen A are *not* consistent with van der Laan expansion, a circumstance reminiscent of some of the time variability of the galactic microquasars. This suggests that concurrent, spatially resolved data from multifrequency campaigns will be critical to a refinement of source models for these objects, a result that motivates some comments on what we mean by concurrent, spatially resolved, multifrequency observations. Astrophysical jets are thus a remarkable laboratory: They provide a confirmation of special relativity in terms of relativistic Doppler boosting, superluminal motion, and time dilation effects. When coupled with their black hole neutron star origins, jets have implications for testing general relativity. As our understanding of the ubiquity of the jet phonomena has grown, we have been required to abandon the assumption of anisotropy in the emitting region in most but not all cases.

Key words: astrophysical jets – active galactic nuclei – quasars – microquasars

1 INTRODUCTION

Our knowledge of the emission characteristics of astrophysical jets has increased greatly over the course of more than four decades of astrophysical research, due in large measure to observations over a broad range of frequencies and time scales. We have become aware that jets are ubiquitous phenomena in astrophysics. Extended linear structures now associated with jets can be found in star-forming regions.

The association of jets with accretion disks strengthens the case for similar physical processes in all these phenomena (see, e.g., Beall 2003; Marscher 2006), and it has become plausible that essentially the same physics is working over a broad range of temporal, spatial, and luminosity scales. Jets have, therefore, become a "laboratory", or pehaps an anvil, that we can use to help us forge our understanding of the physical processes in the sky.

Hannikainen (2007) and Chaty (2007) have discussed some of the emission characteristics of microquasars, and Paredes (2007) has considered the role of microquasars and AGNs as sources of high energy γ-ray emission. In this paper, I will consider some historical data on Centaurus A at radio and X-ray frequencies, and the similarities of those data with both galactic microquasars and an AGN. In the process, I hope to show that we still face the same problems with respect to issues of spatial and temporal resolution even with a much more robust observing infrastructure. I will then comment on possible directions which may help this.

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2 CONCURRENT RADIO AND X-RAY VARIABILITY OF CENTAURUS A (NGC 5128)

The first detection of concurrent, multifrequency variability of an AGN occurred in 1976, and came from Centaurus A (see Fig. 1, and Beall et al. 1978). As reported in that paper, J. H. Beall and W. K. Rose arranged concurrent radio observations of Cen A at three different radio frequencies in conjunction with observations from two different instruments on the OSO-8 spacecraft in the 2–6 keV and 100 keV X-ray ranges. These data were obtained over a period of a few weeks, with the Stanford Interforemeter at 10.7 GHz obtaining the most data.

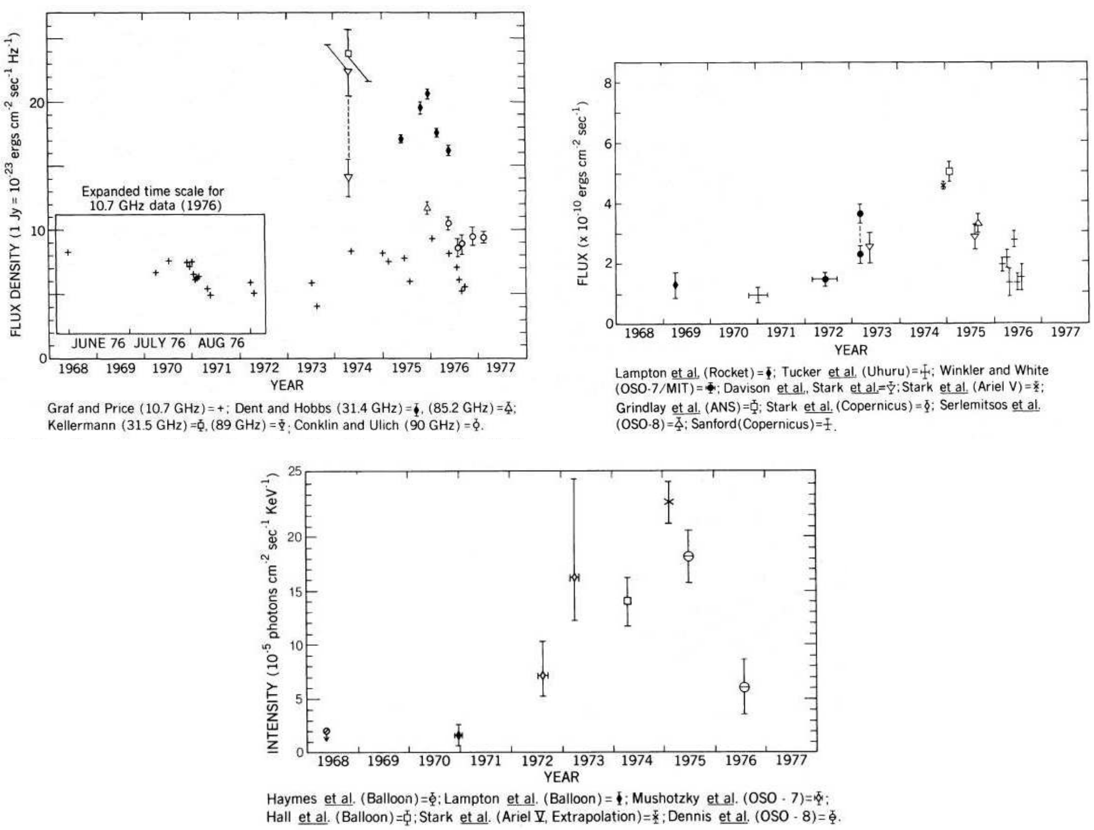

Fig. 1 Radio and X-ray variability of Centaurus A (NGC 5128) These data were gathered from various, independent radio and X-ray observing campaigns, as well as a concurrent radio and X-ray observing program from June through July 1976. The entire history runs from early 1968 through mid 1977. Fig. 1a (the top panel) shows the radio light curve in three frequency ranges, from ∼30 GHz for the topmost data in the panel, at ∼ 90 GHz in the middle, and at the lowest intensity level, the synchrotron self-absorbed data at 10.7 GHz. in the lowest intensity rangs and in the three-month inset to the bottom left of the panel. Plotted in Fig. 1b are the data from various low-energy X-ray experiments, and in Fig. 1c at 100 keV. These data are taken variously from rocket flights, balloon, and satellite experiments (Beall et al. 1978).

Because of the intrinsic interest in the source, it was possible to use data from other epochs to construct the radio and X-ray light curve of the source. As noted, the radio data are shown in Figure 1 (see the inset for the two-week interval), as well as the much longer timescale flaring behavior that is evident in the three different radio frequencies in Figure 1a, and at both low-energy (2–6 keV, see Fig. 1b) and in high-energy (∼ 100 keV, see Fig. 1c) X-rays.

A perusal of Figure 1a will show the data at 10.7 GHz (represented as a "+" in the figure) generally rise during 1973 to reach a peak in mid-1974, then decline to a relative minium in mid-1975, only to go through a second peak toward the end of 1974, and a subsequent decline toward the end of 1976.

This pattern of behavior is also shown in the $\sim$ 30 GHz data (shown as open diamonds and triangles, and the $\sim$ 90 GHz data, with the greatest intensity and shown as circles or open circles), albeit with less coverage at the higher two radio frequencies.

A number of interesting observations can be made concerning these data. First, as Beall et al. (1978) note, the radio and X-ray light curves track one another. This result is the first report of concurrent radio and X-ray variability of an active galaxy. Mushotzky et al. (1978) using the same 10.7 GHz data as shown in the inset along with the 2–6 keV X-ray data, show that the radio and X-ray data track one another on weekly timescales, also.

The concurrent variability at radio and X-ray frequencies suggests that the emitting region is the same for both the radio and X-ray light. This, as has was noted by Beall and Rose (1980), as well as numerous other authors, can be used to set interesting limits on the parameters of the emitting region.

In addition, I note that the observations at the three radio frequencies (10.7 GHz, $\sim$ 30 GHz, and $\sim$ 90 GHz) clearly track one another throughout the interval whenever concurrent data are available.

I will shortly remind us of the time evolution of radio light from a process consistent with van der Laan expansion. But at the outset it is worthy of note that the behavior of the radio light at these three frequencies of the detection of concurrent radio and X-ray variability of Cen A is inconsistent with van der Laan (1976) expansion. For van der Laan expansion, as I will show, we would expect the different frequencies to achieve their maximum emission at different times. The most likely interpretation of these data is that the emitting region suffered an injection of energetic electrons, or, equivalently, that there was a reacceleration of the emitting electrons.

As Chaty (2006) and Hannikainen (2007) have pointed out for galactic microquasars, there are some episodes which are consistent with van der Laan expansion, and some that are not. I intend to speculate on how I think these two poles arise by looking at the data from 3C120 and the galactic microquasar SCO X-1.

But first, I remind us of the early and extremely influential work on radio emission from astrophysical sources due to van der Laan (1976).

3 COMMENTS ON VAN DER LAAN EXPANSION

Van der Laan (1976) discussed the theoretical interpretation of cosmis radio data by assuming a source which contained uniform magnetic field, suffused with an isotropic distribution of relativistic electrons. The source, as it expanded, caused an evolution of the radio light curve at different frequencies as shown in Figure 2. Each of the curves represents a factor of 2 difference in frequency, the vertical axis representing intensity of the radio flux and the horizontal axis representing an expansion timescale for the emitting region. As can be seen, these calculations show a marked difference between the peaks at various frequencies.

The data from Cen A reprised above are, therefore, **not** consistent with van der Laan expansion. Before we come to an intepretation of these data, however, I should make a few timely comments on observing campaigns.

4 COMMENTS ON TEMPORALLY AND SPATIALLY RESOLVED, MULTI-FREQUENCY OBSERVATIONS OF JETS

Modern observing campaigns have gone a long way toward improving and complicating the apparently straightforward issue of concurrent variability established in the Cen A observations of Beall et al. (1978).

The claim of concurrent variability at radio and X-ray frequencies (i.e., concurrent, multifrequency observations) is complicated by several issues. The first equivocation is what is meant by the definition of a multi-frequency observation. The ideal elements of such a campaign would be a spread of observations that can constrain the spectrum of the source in order to facilitate the construction of models of it. In the case of Cen A, where the central engine is obscured by dust, it is only the X-ray and radio light that lends itself to such observations. This is clearly not the case in all sources.

The question of the definition of concurrent observations also has in it an element of what one expects from the source. Observations to detect concurrent variability at different frequencies are most helpful

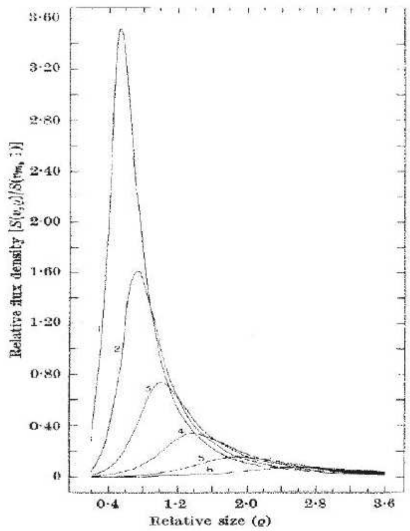

Fig. 2 Radio variability of an isotropic, expanding, synchrotron source with a uniform, randomly oriented magnetic field. The different curves represent differences in frequency by $\sim$ a factor of 2 (from van der Laan 1967).

when the observing interval is "finer" than the expected time scale for variability of the source. The well-known sampling theorems for electronic communications (i.e., the Nyquist frequency) can inform such a discussion.

For the Cen A data, it was the concurrent variability that suggested that the radio and X-ray fluxes were created in the same region. This led to estimates of the source parameters that were obtained from the observations, conbined with the source models.

Grindlay (1975) first suggested that synchrotron radiation be used to model the radio light at the core of Cen A, with optical and infrared from thermal sources, with the X-rays and high-energy X-rays produced by the SSC (synchrotron self-Compton) emission. Beall et al. (1978), and Beall and Rose (1978) suggested an external or BBC (blackbody-Compton model to produce the hard X-ray and γ-ray light. At around the same time, Lightman and Eardly suggested that some of the hard-xray flux was produced from multiple self-Compton scattering. Hadronic processes were considered much later as possible sources for the then-undetected γ-rays from other sources.

Again, these models only work to constrain source parameters if the various emitted frequencies of the radiation are produced in the same region.

For the Cen A data, it was the *concurrent* variability that allow us to determine that the radio and X-ray fluxes arose within the same source region. The radio telescopes used for the observations could separate the inner and outer radio lobes of Cen A from the radio source at the core, but the X-ray telescopes had resolutions of *degrees* on the sky. Thus, the variability became a critical element for the modeling of the source.

To give us some idea of the issue, consider the data from Feigelson et al. (1981) and the Burns and Price 6 cm VLA image taken in 1983 and showing the inner radio lobes separated by 3.5 arcmin, and shown in Figure 3.

The data shown in Figure 3 have the virtue of having roughly the same resolution, albeit being separated by two years. On the scale shown here, the early X-ray data showing the concurretn radio and X-ray variability have a resolution well off the page.

The recent VLBI observations of BL Lac (Bach et al. 2006) show the structure of the core vs. jet as they change in frequency and time. It has thus become possible to separate and study the time variability of the jet vs. the core of AGN at remarkably fine temporal and spatial scales.

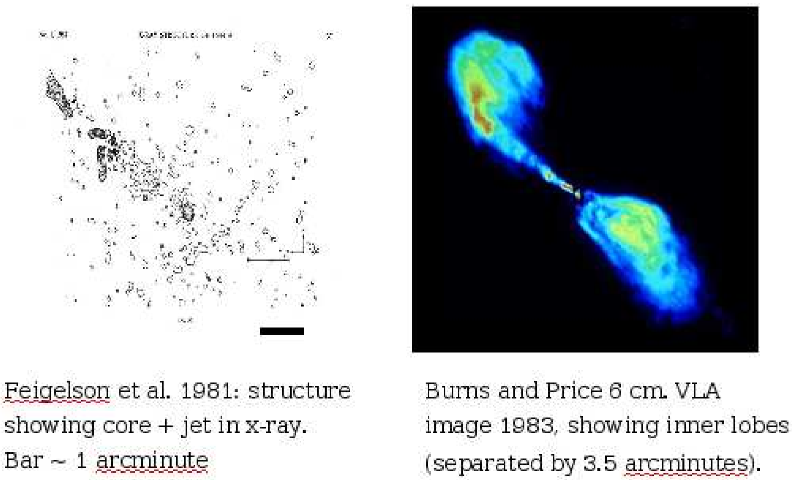

Fig. 3 Centaurus A (NGC 5128) core and inner radio lobe. The X-ray data in the left panel are taken Feigelson et al. (1981) and show the structure of the X-ray emitting region. Note that the horizontal, black bar is 1 arcmin in length. The right panel shows the 6 cm. VLA data where the inner radio lobes (outermost at this scale) are separated by 3.5 arcmin. The data are thus at the same scale, but separated in time by roughly two years.

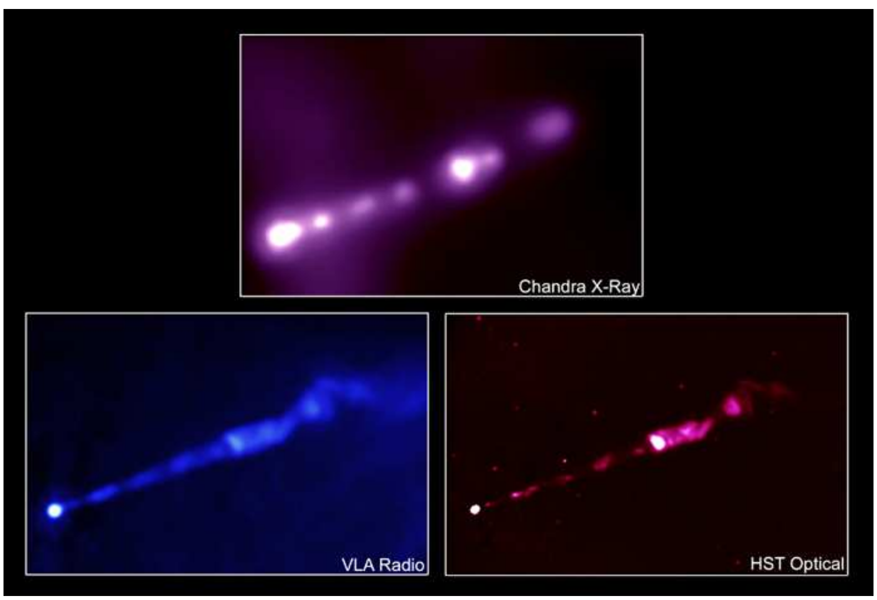

Fig. 4 Jet in M87: Multifrequency observations in X-ray (from Chandra, top panel), radio (VLA, bottom left), and optical (HST) of the active galaxy, M87. These data show the evolution of the jet emission as it propagates outward from the central engine to interact with the ambient medium and the prior ejecta and excavations from the central source. On this scale, a concurrent observation might be separated by weeks (given the scale that the arcsecond resolution of the instruments represents). For milliarcsecond resolution, a concurrent observation would require an observational campaign of much finer time resolution.

Unfortunately, the differing resolution of the observing instruments and their lack of availability for interesting sources mean that even today, the definition of concurrent is unlikely to mean at exactly the same time, and the definition of multifrequency never means at all possible frequencies.

As noted earlier, concurrent must mean, still, within a window of time that is short compared to the expected time scales for variability of the object, and multifrequency means some representation of the frequencies over which one expects the emission to occur.

In general, resolutions depend on the frequency of the observatory. To illustrate the typical resolutions of the various observing systems, I note that:
- radio data from VLBI is milliarcsec,
- radio data from VLA in arcsec,
- Hubble space telescope 0.1 arcsec,
- ground based optical telescopes in arcsec or tenths of arcsec,
- optical and IR interferometers claim milliarcsec resolution,
- Chandra X-ray detector has a resolution of 0.5 arcsec,
- SWIFT X-ray telescope has a resolution of 18 arcsec,
- γ-ray detectors (AGILE, INTEGRAL, SWIFT, and GLAST) have resolutions of degrees to a few minutes, and
- HESS, Magic, Whipple, and others have resolutions of order a few arcmin.

We often rely on assumptions about relative intensities and variability of core versus jet luminosities in our estimations of source fluxes without confirming this independently.

We can further illustrate the effect of differing resolutions by recalling the differing spatial and temporal variability as we observe the evolution of one AGN jet (3C120 in VLBI radio and X-ray) and the microquasar Sco X-1 in radio ligh (see Beall 2006; Marscher 2006; Jorstad et al. 2005, 2006).

These data, from the campaign organized by Marscher and colleagues, show a number of remarkable phenomena. First, the resolved radio brightness of 3C120 is shown as colored contours. Second, the measured, strongly polarized radio flux suggests a well-ordered magnetic field (the sticks are in the direction of the magnetic field). The bright “knots” appear and move down the jet, with their polarization changing. The red disk with the black center represents the accretion disk, and the lLight curve shows X-ray brightness varying with time. When the X-ray brightness decreases, the dark part of the accretion disk is illustrated as becoming larger. About 4 weeks later, the starting point of the jet gets bright and a new superluminal knot moves down the jet.

A comparison of the 3C120 results with the data from the galactic microquasar, Sco X-1, undertaken by Beall (2006) shows a similar radio evolution, with rapidly moving “bullets” interacting with slower moving, expanding blobs. It is highly likely that the elements of these sources that are consistent with van der Laan expansion are the slower-moving, expanding blobs. I suspect that the relativistically moving bullets, when they interact with these slower-moving blobs, are the genesis of the flaring that we see that seems like a reacceleration of the emitting, relativistic particles.

The true test of this hypothesis will require concurrent, multifrequency observations with resolutions sufficient to distinguish jet components from core emissions in galactic microquasars as well as for AGN jets.

The principle can be demonstrated by the X-ray, radio, and optical observations of the jet in M87, as shown in Figure 4.

These data show the evolution of the jet emission as it propagates outward from the central engine to interact with the ambient medium and the prior ejecta and excavations from the central source. On this scale, a concurrent observation might be separated by weeks (given the scale that the arcsec resolution of the instruments shown. For milliarcsec resolution, a concurrent observation would require an observational campaign of much finer time resolution, as well as the realization of interferometric techniques at all observed frequencies (i.e., including optical and X-ray frequencies).

5 CONCLUDING REMARKS

A perusal of the data represented in these pictures can help constrain source models for both the jet and the central engine, as perhaps most importantly, the critical region that connects the jet with the core.

To obtain such resolutions for optical frequencies has been a long-awaited dream. Of course, the Rayleigh Criterion implies modest sizes for optical and infrared interferometers. For a single telescope, the angular resolution for diffraction-limited optics is, sin$\theta = 1.22\lambda/D$, where λ is the wavelength, and D is the size of the telescope aperture. For an interferometer, sin$\theta = \lambda/D$, where D is the maximum spacing between elements.

The Very Large Telescope array (VLT) in Chile, consisting of four Unit Telescopes with main mirrors of 8.2 m diameter and four movable 1.8 m diameter Auxiliary Telescopes is beginning to show promising results for milliarcsecond resolutions at optical and IR frequencies. The telescopes can work together, in groups of two or three, to form a giant interferometer, the ESO Very Large Telescope Interferometer.

At radio frequencies, the VLBA is currently providing milliarcsecond resolution at radio frequencies. These are located at:

- Mauna Kea, Hawaii (194804.97N, 1552719.81W)
- Owens Valley, California (371353.95N, 1181637.37W)
- Kitt Peak, Arizona (315722.70N, 1113644.72W)
- Pie Town, New Mexico (341803.61N, 1080709.06W)
- Los Alamos, New Mexico (354630.45N, 1061444.15W)
- Fort Davis, Texas (303806.11N, 1035641.34W)
- Brewster, Washington (480752.42N, 1194059.80W)
- North Liberty, Iowa (414617.13N, 913426.88W)
- Hancock, New Hampshire (425600.99N, 715911.69W), and
- St. Croix, United States Virgin Islands (174523.68N, 643501.07W).

For acrsecond resolution, the VLA near Socorro, NM, can provide radio observations consistent with current X-ray and optical telescopes.

Ground-Space-Based VLBI gives a factor of 1000 better resolution. The VSOP mission is a Japanese-led project to image radio sources with sub-milliarcsec resolution by correlating the signal from the orbiting 8-m telescope, HALCA, with a global array of telescopes. Twenty-five percent of the scientific time of this mission is devoted to a survey of 402 bright, small-diameter extra-galactic radio sources at 5 GHz (see Hirabayashi et al. 2000).

What is the ultimate resolution we can expect from X-ray and γ-ray telescopes? G. Bignami, Director of ASI, the Italian Space Agency, said in an interview in *Physics Today* (Physics Today, May 2007, p.28), that it might be possible to fly two satellites in formation, one with the instruments, and one with the X-ray mirrors in order to obtain focal lengths of 40 meters, and access to much higher energies for an imaging instrument. If interferometic techniques were possible at such frequencies, formation flying would perhaps not be necessary. Recent work has demonstrated interference fringes at X-ray frequencies. This is a similar situation to the state of optical interferometers at the beginning of their development nearly 30 years ago.

Yet we will always have daunting technical problems at higher energies. Ground based TeV instruments such as the HESS, MAGIC, and Whipple Observatory are also important (see, e.g., Bartko 2008; Santangelo 2007; Monoploid 2005; Monoploid et al. 2005), and there is no clear path to extremely high resolutions for these techniques.

Finally, neutrino observatories, if they are able to detect jet sources at all, will have a resolution of the whole sky (see, e.g. Beall 2005).

Astrophysical jets are, then, remarkable fields of study, and in some cases, anvils upon which we temper our theories and for which we prepare our observational campaigns. They have required concurrent, multifrequency observations in order to interpret them since they emit over the entire electromagnetic spectrum. They have provided a nice confirmation of special relativity, both in terms of Doppler boosting and superluminal expansion.

When coupled with black hole/neutron star origins, jets have implications for testing general relativity. But the highly variable and anisotropic nature of both galactic microquasars and AGN jets suggests that we apply anisotropic emission models to these sources.

Nearly all source models use the assumption of isotropy to make the calculations of source spectra tractable. Some anisotropic calculations (see, e.g., Bednarek, Karakula, Tkaczyk, and Giovannelli) have been done and could be used as a model for future theoretical work.

Acknowledgements The author expresses his appreciation to Alan Marscher, Svetlana Jorstad, and Jose-Luiz Gomez for permission to use the data for 3c120. JHB gratefully acknowledges the support of the Office of Naval Research for this research.

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DISCUSSION

K. Ebisawa A comment: The Second Japanese Space VLBI program "VSOP2" has been approved, and the planned launch date is 2011. It has a short wavelength detector, and will reach the best angular resolution ever less than 0.1milliarcseconds.

J. Beall I was aware of the proposal, albeit in outline, but not aware that it had been approved. I certainly consider this very good news for the Astronomical Community. Thanks for pointing this out.

Th. Boller If you increase the VLBI resolution by a factor of 10, do you still have enough signal strength, as the visibility function goes with $((\sin x)/x)^2$?

J. Beall It's my impression that a factor of 10 increase in resolution will not be problematic for detection of most jets.