Mem. S.A.It. Vol. 81, 395

Memorie della

Jets in astrophysics: a review

J.H. Beall[1,2,3]

[1] Space Sciences Division, Naval Research Laboratory, Washington, DC
[2] College of Science, George Mason University, Fairfax, VA
[3] St. Johns College, Annapolis, MD, e-mail: beall@sjca.edu

Abstract. This paper briefly reviews some historical data on the broad-band variability of active galaxies, including Centaurus A (NGC 5128), and shows that these data bear some remarkable similarities and significant differences to data from some epochs of galactic microquasars, including GRS 1915+105. The paper then considers the details of some of the results of the MOJAVE Collaboration radio data at mas (i.e., parsec) scales for the complex structures of AGN jets. I also comment on the recent paper by Bonning et al. (2009) which shows the first results from the Fermi Space Telescope for the concurrent variability at optical, UV, IR, and γ-ray variability of 3C343.3.

Key words. astrophysical jets, active galactic nuclei, UHE cosmic rays, quasars, microquasars

1. Introduction

We have increased our knowledge of astrophysical jets greatly over the last four decades of research, due in large measure to observations over a broad range of frequencies and time scales, both from space experiments (see, Giovannelli and Sabau-Graziati, 2004, for an especially thorough review) and ground-based measurements via both electromagnetic and nuclear channels. We have become aware that jets are ubiquitous phenomena in astrophysics. Extended linear structures that can be associated with jets are found in star-forming regions, in compact binaries, and of course in AGN.

The apparent connection of jets with accretion disks strengthens the case for similar physical processes in all these phenomena (see, e.g., Beall, 2003, and Marscher, 2005), and it has become plausible that essentially the same physics is working over a broad range of temporal, spatial, and luminosity scales. Hannikainen (2008) 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, the similarities of those data with both galactic microquasars and an AGN, and the recently reported observations from the Fermi Space Telescope of concurrent γ-ray, IR, Optical, and UV variability of 3C454.3 reported by Bonning et al. (2009).

Send offprint requests to: J.H. Beall

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 Figure 1, taken from Beall et al., 1978). J.H. Beall et al. conducted the observing campaign 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. Beall et al. (1978) also used data from other epochs to construct a decade-long radio and x-ray light curve of the source.

Figure 1a shows the radio data for the interval of the OSO-8 x-ray observations, as well as the much longer timescale flaring behavior evident in the three different radio frequencies and at both low-energy (2-6 keV, see Figure 1b) and in high-energy (~ 100 keV, see Figure 1c) x-rays.

A perusal of Figure 1a shows 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 minimum 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 ~ 30 GHz data (shown as open diamonds and triangles, and the ~ 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) and Mushotzky 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 time scales, 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), can be used to set interesting limits on the parameters of the emitting region. In addition, the observations at the three radio frequencies (10.7 GHz, ~ 30 GHz, and ~ 90 GHz) clearly track one another throughout the interval whenever concurrent data are available.

Van der Laan (1976) discussed the theoretical interpretation of cosmic 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 of Beall (2007). 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. Van der Laan's calculations show a marked difference between the peaks at various frequencies.

The data from Cen A (as discussed more fully in Beall (2007, 2009) are, therefore, **not** consistent with van der Laan expansion. For van der Laan expansion, we would expect the different frequencies to achieve their maxima at different times. Also, the peak intensities should decline with increasing frequencies at least in the power-law portion of the spectrum. Chaty (2006) and Hannikainen (2007) have pointed out that for galactic microquasars, there are some episodes which are consistent with van der Laan expansion, and some that are not.

An episode that seems nominally consistent with van der Laan expansion of an isotropic source has been presented by Mirabel et al. (1998) for a galactic microquasar. Mirabel shows a series of observations of GRS 1915+105 at radio, infrared, and x-ray frequencies. These data associate the genesis of the first galactic microquasar with instabilities in the accretion disk that are inferred from the x-ray flaring (see, e.g., Beall 2009).

To reiterate, the behavior of the radio light at the three frequencies of the detection of con-

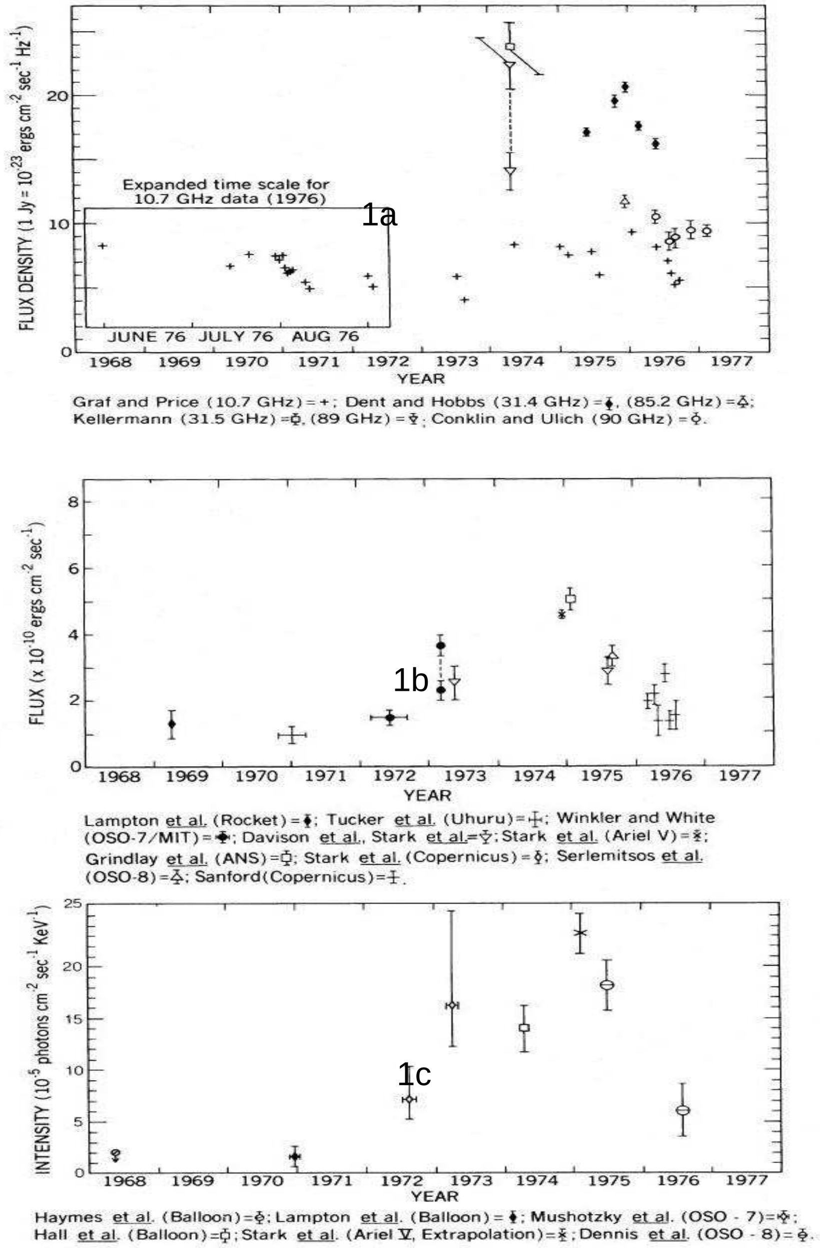

Fig. 1. Radio and x-ray variability of Centaurus A (NGC 5128) These data were gathered from various, independent radio and x-ray observing campaigns, as well as a concurrent radio and x-ray observing program from June through July 1976. The entire history runs from early 1968 through mid 1977. Figure 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. n the lowest intensity rangs and in the three-month inset to the bottom left of the panel. Plotted in Figure 1b are the data from various alow-energy x-ray experiments, and in Figure 1c at 100 keV. These data are taken variously from rocket flights, balloon, and satellite experiments. (Beall et al., 1978)

current radio and x-ray variability of Cen A is inconsistent with van der Laan (1976) expansion, while the data from GRS1915+105 can be plausibly interpreted by that model. The most likely explanation for the Cen A data is that the emitting region suffered an injection of energetic electrons, or, equivalently, that there was a re-acceleration of the emitting electrons on a timescale short compared to the expansion time of the source.

3. Concurrent γ-ray, UV, optical, and IR variability of 3C454.3

Recently, Bonning et al. (2009) performed a multi-wavelength monitoring campaign on the blazar, 3C454.3, using IR and optical observations from the SMARTS telescopes, optical, UV and X-ray data from the Swift satellite, and public-release γ-ray data from the Fermi Space Telescope. They find an excellent correlation between the IR, optical, UV and gamma-ray light curves, with a time lag of less than one day.

While a more precise analysis of the data will be required to determine the characteristics of the emitting regions for the observed concurrent flaring at the different frequencies, the pattern of a correlation between low-energy and higher-energy variability is consistent with that observed for Cen A, albeit with the proviso that the energetics of the radiating particles in 3C454.3 is considerably greater. That is, the pattern of variability is consistent with the injection of relativistic particles into a region with relatively high particle and radiation densities (i.e., an interstellar cloud). The picture that emerges, therefore, is consistent with the observations of spatially and temporally resolved galactic microquasars and AGN jets.

4. Comments on temporally and spatially resolved multi-frequency observations of jets

For the Cen A data, and now for the data from 3C454.3, it is the concurrent variability that suggests that the radio to x-ray (in Cen A's case) and the IR, Optical, and UV to γ-ray fluxes (in 3C454.3's case) are created in the same region. This leads to the possibility of estimates of the source parameters that are obtained from models of these sources.

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 (1974) 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.

Modern observing campaigns have gone a long way toward complicating the efforts of theorists in modeling these sources. 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 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 historical Cen A data, 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. Even the Stanford Interferometer was subject to this limitation. For the x-ray telescopes, the resolutions amounted to *degrees* on the sky. Thus, the variability became a critical element in assigning the radio and x-ray flux to the same region in order to use those data to model the source.

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 tempo-

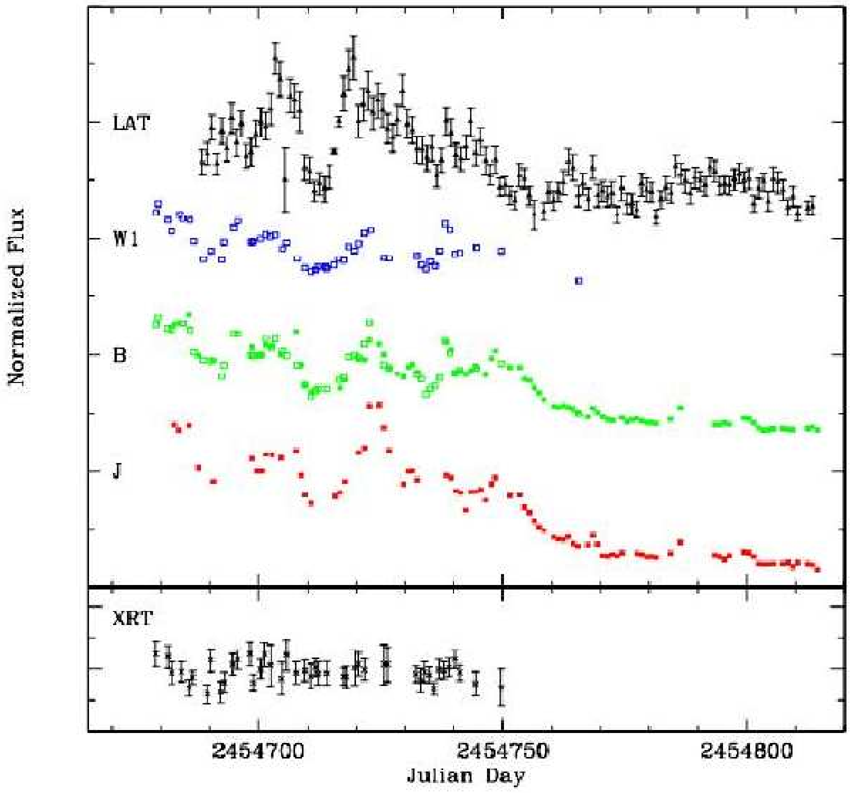

Fig. 2. Variability of 3C 454.3 Fermi 0.1 300 GeV gamma-ray, UV (W1), optical (B),and IR (J) , and x-ray (XRT), taken from Figure 1, Bonning et al. 2008, submitted to Ap.J.(arXive:0812.4582v1). The data show concurrent variability similar to that previously noted for Centaurus A, as discussed in the text.

ral and spatial scales. 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.

Concurrent must still mean 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.

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. For a detailed discussion of the effect of differing temporal and spatial resolutions, see the discussion of one AGN jet (3C120 in VLBI radio and x-ray) and the microquasar Sco X-1 in radio light (see Beall et al., 2006).

An analysis of the 3C120 results compared 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 believe 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 re-acceleration 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.

5. Galactic microquasars and AGN jets

In the spirit of these ideas of the common origins of jets from star-forming regions, microquasars, AGNs, and γ-ray bursts, we have investigated some elements of the jets in a galactic binary source (Sco X-1) and an AGN (3c120) (see, e.g., Beall, 2009). I believe that we are now at a point in our collective studies where the observational record is sufficiently detailed that we can gain some perspective on the processes that operate when the jet interacts with the ambient medium through which it propagates. In this regard, a comparison of Sco X-1 and 3c120 can be a kind of 'Rosetta" stone that allows a detailed explication of jet energy loss processes. The broad association of astrophysical jets with accretion disks can also give some specificity for models of the acceleration process of the jets.

Perhaps the most remarkable saga regarding the discovery of quasar-like activity in galactic sources comes from the decades long investigation of Sco X-1 by Ed Fomalont, Barry Geldzahler, and Charlie Bradshaw (Fomalant, Geldzahler, and Bradshaw, et al. 2001). During their observations, an extended source changed relative position with respect to the primary object, disappeared, and then reappeared many times. We now know that they were observing a highly variable jet from a binary, neutron star system. The determinant observation was conducted using the Very Large Array (VLA) in Socorro, New Mexico and the VLBA interferometer (see, e.g., Beall, 2007) for a more complete discussion).

Put briefly, the data from Sco X-1 and 3c120 show remarkable similarities and reveal a consistent pattern of behavior, albeit on remarkably different temporal and physical scales. The radio structures appear to originate from the central source and propagate along an axis that maintains itself over time scales long compared to the variability time scales of the respective sources. The emission from the lobes fade over time, as one would expect from a source radiating via synchrotron and perhaps inverse Compton processes.

The subsequent brightening of the lobes is apparently from a re-energizing or re-acceleration via the interaction of the highly relativistic "bullets" of material, which propagate outward from the source and interact with the radio-emitting jets. The radio jets apparently come from prior eruptions in the central source, or from the ambient material through which the jet moves. It is unclear whether all of the material in Sco X-1 comes from the central source, but it is likely that in 3c120, some part of the ambient medium through which the very fast beam propagates (i.e. the Broad Line Region), contributes to the material in the jet. As Marscher et al. (2002) note, this radiating material is intermediate between the Broad Line Region (BLR) and the Narrow-Line Region (NLR).

There are a number of physical processes that can accelerate and entrain the ambient medium through which the jet propagates. These have discussed these in detail in several venues (see, e.g., Rose et al., 1984, 1987, Beall, 1990, Beall et al., 2003, and Beall, 2009).

The data outlined here suggest a model for the jet structures in which beams or blobs of energetic plasmas propagates outward from the central engine to interact with the ambient medium in the source region. This ambient medium in many cases comes from prior ejecta from the central source. The jet can apparently also excavate large regions that are suggested by the complex structures in, for example, 3C120.

On the scale of the galactic microquasars, a concurrent observation might be separated by weeks, given the arcsecond resolution of the older instruments. For milliarcsecond resolution, a concurrent observation would require an observational campaign of much finer time res-

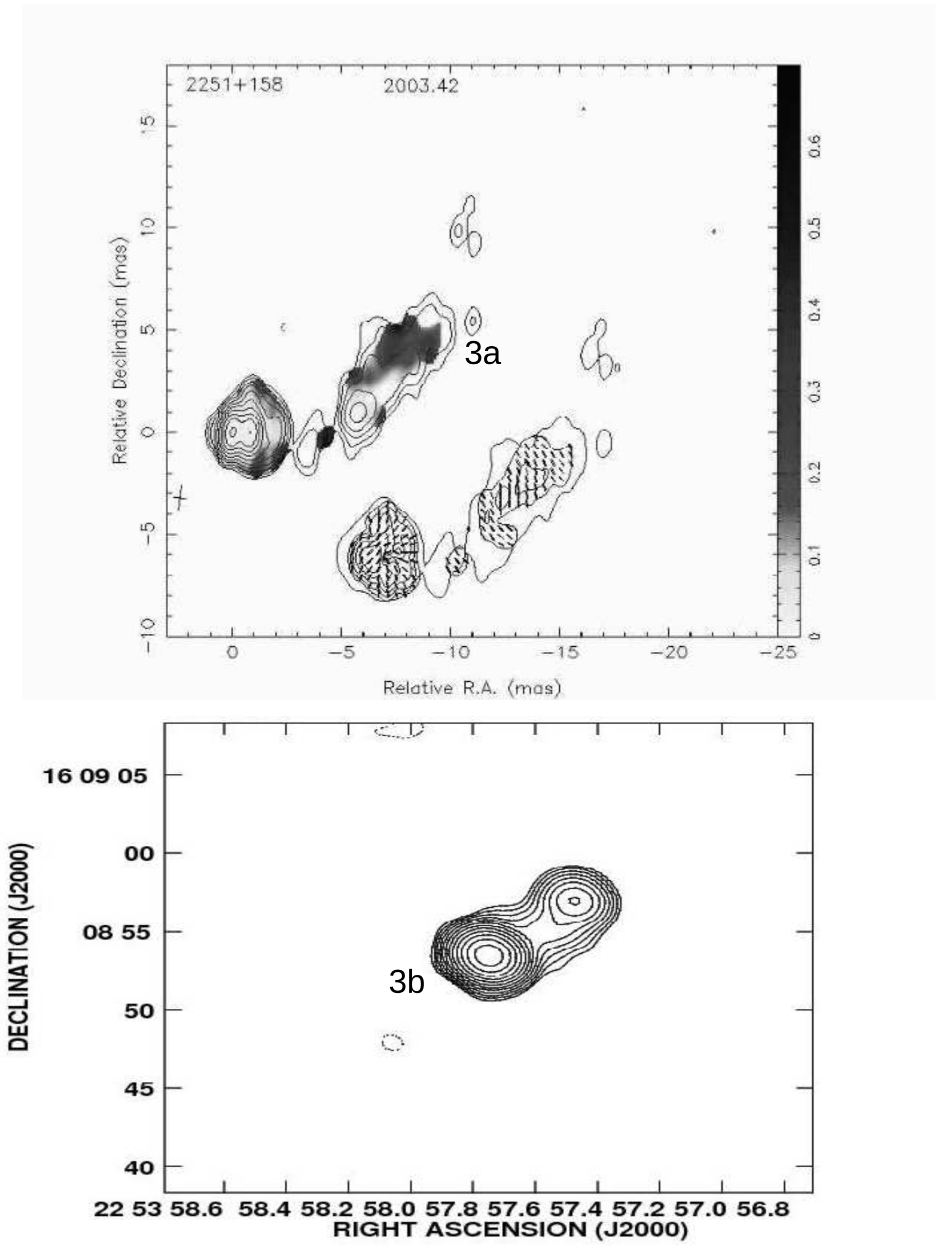

Fig. 3. 3C454.4 shown at milliarcsecond scales (Figure 1a (top), taken from the MOJAVE VLBA campaign) and arcsecond scales (Figure 1b (bottom), taken from the VLA). The data show the remarkable complexity of the jet the first few parsecs of its evolution, including a remarkable change in direction as it evolves. On the other hand, the jet on the scale of hundreds to thousands of parsecs shows a remarkable stability and constancy of direction.

olution, as well as the realization of interferometric techniques at all observed frequencies (i.e., including optical and x-ray frequencies).

The recent observations of the concurrent IR, Optical, UV, and γ-ray variabiltiy of 3C454.3 can lead us to a reinvestigation of the VLBA data for this source using the MOJAVE observations. The milliarcsecond observations show a complex evolution of structure at parsec scales, including an apparently sharp change of directions associated with changes in the polarization of the radio light at that point in the jet's evolution (see Figure 3a). This can be compared with VLA data from the same source, which shows the jet on scales of hundreds to thousands of parsecs. The parsec scale jet seems to eventually order itself in the direction of the large-scale jet, but it shows quite a dynamic evolution in its early stages. These data are even more complex than the data from Sco X-1 or 3C120, since they add (to the time-dependent evolution of the linear structure of the objects) an apparent change in direction of the jet on a scale of a few parsecs.

Regarding the acceleration region and the possible mechanisms for the collimation of the jets, a number of models have been proposed (see, e.g., Kundt and Gopal-Krishna (2004), Bisnovaty-Kogan (2009), and Romanova and Lovelace (2009) that might help explain the complexity present in the data. Clearly, however, a lot more work is needed.

6. Jets reconsidered

The detail available from observatories in the current epoch provides considerable guidance to those interested in modeling these sources. It is understandable that jets have been considered as remarkable for their stability and persistence, given the data we have seen in the past, even in spite of the variability observed from AGN and microquasar jets. However, as A. Darr (2009) has pointed out, what we are now seeing suggests a more complex and dynamic structure to the source regions.

This, coupled with the recent detections of very high energy cosmic rays (by the Auger Collaboration, 2007, and Letessier-Selvon, 2008, and the Fermi Telescope (M. Lovellette, private communication, 2009), and the apparent association of these cosmic rays with the nearby AGN, has caused considerable speculation about the role of AGN jets as a mechanism for particle acceleration. Benford and Protheroe (2008) have speculated that large-scale structures in the "fossilized" jet which produced the intermediate and giant radio lobes in Cen A were instrumental in the acceleration of such high-energy particles. Of course, the first person to suggest that nearby AGN could be the source of these UHE cosmic rays was M. Shapiro in a talk he gave at one of the early Vulcano Workshops.

7. DISCUSSION

GIULIO AURIEMMA What is the present understanding of the Jets' collimation mechanism?

JIM BEALL I think our understanding is rather rudimentary at present, especially in light of the complex connection between the jet at milliarcsecond versus the jet at arcsecond scales. Bisnovatyi-Kogan, Romanova and Lovelace and Kundt and Gopal-Krishna have outlined models that might provide collimation mechanisms, but I think it's too early to decide what can account for the remarkable observations we are seeing at this time.

Acknowledgements. The author gratefully acknowledges the support of the Office of Naval Research for this work.

References

Basson, J.F., Alexander, P., 2002, MNRAS 339, 353.
Beall, J.H. et al., 1978, ApJ 219, 836.
Beall, J.H., Rose, W.K., 1980, ApJ 238, 579.
Beall, J.H., 1987, Ap. J. 316, 227.
Beall, J.H., 1990, *Physical Processes in Hot Cosmic Plasmas* (Kluwer: Dordrecht), W. Brinkman, A. C. Fabian, & F. Giovannelli, eds., pp. 341-355.
Beall, J.H., 2009, in *Frontier Objects in Astrophysics and Particle Physics*, F.

Giovannelli & G. Mannocchi (eds.), Italian Physical Society, Editrice Compositori, Bologna, Italy, 98, 283

Beall, J.H., Bednarek, W., 2002 ApJ 569, 343.

Beall, J.H., 2002, in *Multifrequency Behaviour of High Energy Cosmic Sources*, F. Giovannelli & L. Sabau-Graziati (eds.), Mem. S.A.It. **73**, 379.

Beall, J.H., 2003, in *Multifrequency Behavior of High Energy Cosmic Sources*, Chin. J. Astron. Astrophys. 3, Suppl., 373.

Bisnovatyi-Kogan, Genaddi, 2009, in *Proceedings fo the Vulcano Workshop on High-Energy Cosmic Sources, in press*

Chaty, S., 2007, in *Frontier Objects in Astrophysics and Particle Physics*, F. Giovannelli & G. Mannocchi (eds.), Italian Physical Society, Editrice Compositori, Bologna, Italy, 93, 329.

Dar, Arnon, 2009, in *Proceedings fo the Vulcano Workshop on High-Energy Cosmic Sources, in press*

Fomalont, E., Geldzahler, B., Bradshaw, C., 2001, Ap.J. **558**, 283-301.

Giovannelli, F., Sabau-Graziati, L., 2004, Space Science Reviews, 112, 1-443 (Kluwer Academic Publishers: Netherlands).

Gómez et al. 2000, Science 289, 2317

Gougelet, P.E., 2006, `http://perso.orange.fr.pierre.g/xnview/enhome.html`

Hester, J.J., Mori, K., Burrows, J., Gallagher, J.S., Graham, J.R. et al. 2002, Ap. J. Letters 577, pp L49-L52.

Hiribayashi et al., 2000 PASJ 52, 997.

Hannikainen, D.C., Rodriguez, J., 2008, in *Multifrequency Behavior of High Energy Cosmic Sources*, Chin. J. Astron. Astrophys. 8, Suppl., 341.

Jorstad, S.G., Marscher, A.P., Lister, M.L., Stirling, A.M., Cawthorne, T.V. et al., 2005, Astron. J. 130, 1418-1465.

Jorstadt, S., Marscher, A., Stevens, J., Smith, P., Forster, J. et al., 2006, in *Multifrequency Behavior of High Energy Cosmic Sources*, Chin. J. Astron. Astrophys. 6, Suppl. 1, 247.

Kundt, W. and Gopal-Krishna, 2004, Journal of Astrophysics and Astronomy, 25, 115-127.

Krause, M., Camenzind, M., 2003, in *The Physics of Relativistic Jets in the CHANDRA and XMM Era*, New Astron. Rev. 47, 573.

Lightman, A. P., Eardley, D. N., 1974, Ap. J. Letters 187, L1.

Marscher, A.P., et al., 2002, Nature, 417, 625-627.

Marscher, A.P., 2006, in *Multifrequency Behavior of High Energy Cosmic Sources*, Chin. J. Astron. Astrophys. 6, Suppl. 1, 262.

Mushotzky, R.F., Serlemitsos, P.J., Becker, R.H., Boldt, E.A., and Holt, S.S., ApJ 220, 790-797.

Paredes, J., 2007, in *Frontier Objects in Astrophysics and Particle Physics*, F. Giovannelli & G. Mannocchi (eds.), Italian Physical Society, Editrice Compositori, Bologna, Italy, 93, 341.

Romanova, M. and Lovelace, R., 2005, 2009, *Triggering Triggering of Relativistic Jets"*, (Instituto de Astronomia, Universidad Nacional Autonoma de Mexico, William H. Lee and Enrico Ramirez-Ruiz, eds.); also at arXiv:0901.4753v1, astro-ph.HE, 29 Jan 2009.

Rose, W.K., et al., 1984, ApJ. 280, 550.

Rose, W.K., et al., 1987, ApJ 314, 95.

The Pierre Auger Collaboration, et al., 2007, Science 318, 938.

van der Laan, H., 1966, Nature 211, 1131.

Zanni, C., Murante, G., Bodo, G., Massaglia, S., Rossi, P., Ferrari, A., 2005 Astron. Astrophys. 429, 399.