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FROM GALACTIC TO EXTRAGALACTIC JETS: A REVIEW

J.H. Beall[a,b,c,*]

[a] *St. John's College, Annapolis, MD*
[b] *SSD, NRL, Washington, DC*
[c] *College of Science, George Mason University, Fairfax, VA*
[*] corresponding author: beall@sjca.edu

Abstract. An analysis of the data that have recently become available from observing campaigns, including VLA, VLBA, and satellite instruments, shows some remarkable similarities and significant differences in the data from some epochs of galactic microquasars, including GRS 1915+105, the concurrent radio and X-ray data [3] on Centaurus A (NGC 5128), 3C120 [35], and 3C454.3 as reported by Bonning et al. [16], which showed the first results from the Fermi Space Telescope for the concurrent variability at optical, UV, IR, and γ-ray variability of that source. In combination with observations from microquasars and quasars from the MOJAVE Collaboration [32], these data provide time-dependent evolutions of radio data at mas (i.e., parsec for AGNs, and Astronomical Unit scales for microquasars). These sources all show a remarkable richness of patterns of variability for astrophysical jets across the entire electromagnetic spectrum. It is likely that these patterns of variability arise from the complex structures through which the jets propagate, but it is also possible that the jets' constitution, initial energy, and collimation have significant observational consequences. On the other hand, Ulrich et al. [42] suggest that this picture is complicated for radio-quiet AGN by the presence of significant emission from accretion disks in those sources. Consistent with the jet-ambient-medium hypothesis, the observed concurrent radio and X-ray variability of Centaurus A [3] could have been caused by the launch of a jet element from Cen A's central source and that jet's interaction with the interstellar medium in the core region of that galaxy.

Keywords: astrophysical jets, active galactic nuclei, UHE cosmic rays, quasars, microquasars.

1. Introduction

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.

In so-called blazar sources (see, e.g., [35, 42]) there seems to be a confirmed connection of jets with accretion disks. In sources without large-scale linear structures (i.e., jets), as Ulrich et al. [42] note, the source variability could result from the complex interactions of the accretion disk with an X-ray emitting corona. But to the extent that "small" jets are present in these sources, the disk-jet interaction must still be of paramount importance, since it provides a mechanism for carrying away energy from the disk.

Current theories (see e.g., [15, 26] for a discussion of disk structure and jet-launch issues, respectively) suppose that the jet is formed and accelerated in the accretion disk. But even if this is true in all sources, it is still unclear whether or not astrophysical jets with shorter propagation lengths are essentially different in constitution from those that have much longer ranges, or whether the material through which the jet propagates determines the extent of the observational structures we call jets. At all events, the complexities of the jet–ambient-medium interaction must have a great deal to do with the ultimate size of the jets.

This sort of argument has applications to both quasars and microquasars, especially if essentially similar physical processes occurs in all these objects (see, e.g., [9, 35]). To some, it has become plausible that essentially the same physics is working over a broad range of temporal, spatial, and luminosity scales. Hannikainen [25] and Chaty [17] have discussed some of the emission characteristics of microquasars, and Paredes [38] has considered the role of microquasars and AGNs as sources of high energy γ-ray emission. In fact, the early reports of the concurrent radio and X-ray variability of Centaurus A can be plausibly interpreted as the launch of a jet from Cen A's central source into the complex structures in its core. Additionally, these observations are remarkably similar to the observations of galactic microquasars and AGNs, including the observations from the Fermi Space Telescope of concurrent γ-ray, IR, Optical, and UV variability of 3C454.3 [16], and observations [33] for BL Lac, among others.

2. Concurrent radio and X-ray variability of Centaurus A (NGC 5128) as an indication of jet launch or jet–cloud interactions?

The first detection of concurrent, multifrequency variability of an AGN comes from observations of Centaurus A (Fig. 1 of [3]). Beall et al. conducted the observing campaign of Cen A at three different radio frequencies in conjunction with observations from two different X-ray instruments on the OSO-8 spacecraft in the $2 \div 6$ keV and 100 keV X-ray ranges. These data were obtained over a period of a few weeks, with the Stanford Interferometer at 10.7 GHz obtaining the most data. Beall et al. also used data from other epochs to construct a decade-long radio and X-ray light curve of the source. Figure 1a of [12] shows the radio data during 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 ($2 \div 6$ keV, see Fig. 1b of [12]) and high-energy (~ 100 keV, see Fig. 1c of [12]) X-rays.

As noted by Beall [12], a perusal of Fig. 1a shows that the data at 10.7 GHz (represented as a "+" in that 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 1975, and a subsequent decline toward the end of 1976. This pattern of behavior is also shown in the ~ 30 GHz data and the ~ 90 GHz data albeit with less coverage at the higher two radio frequencies.

Several points are worthy of note. First, as Beall et al. [3] 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. [37], using the weekly 10.7 GHz data obtained by Beall et al. [3] demonstrate that the 10.7 GHz radio data track the $2 \div 6$ keV X-ray data 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 was noted by Beall and Rose [4], 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.

One plausible hypothesis for the observations is that we witnessed physical processes associated with the "launch" of an astrophysical jet into the complex structures in the core of Centaurus A. The 6-day X-ray flare early in 1973 is likely to be associated with an accretion disk acceleration event, while the longer timescale evolution from early 1973 through 1977 appears to be associated with the evolution of a larger structure over more extended regions. It is also possible, however, that observations are consistent with the interaction of the astrophysical jet with an interstellar cloud (i.e., the ambient medium) in the core of Cen A.

It is clear from this discussion that a distinction needs to be made here about which observational signatures are associated with the jet launch, the jet itself, and which are associated with the ambient medium's reaction to the jet. But this issue is greatly complicated by the fact that the ambient medium (through which the jet propagates) is accelerated and in fact becomes part of the jet. This occurs in AGNs on scales of parsecs. This issue will be discussed later in this paper when we consider the data from 3C120 (see, e.g., [35]). This behavior is also evident in the observations of Sco X-1 by Fomalont, Geldzahler, and Bradshaw [21], as discussed below, but on much shorter physical and temporal scales.

3. A comment on particle acceleration in the jet–ambient-medium interaction

Van der Laan [44] discussed the theoretical interpretation of cosmic radio data by assuming a source which contained a 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. Each of the curves in Van der Laan's paper 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 2008, [11] are, therefore, **not** consistent with van der Laan expansion, since 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 [17] and Hannikainen [25] have pointed out that for galactic microquasars, there are some episodes which are consistent with van der Laan expansion. Remarkably, some episodes that are not. Another 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., [11]).

The most likely explanation for the changes in the spectrum of the Cen A data at 100 keV [3] is that the emitting region suffered an injection of energetic electrons. That is, a jet–ambient-medium interaction dumped energetic particles into a putative "blob", or, equivalently, that there was a re-acceleration of the emitting electrons on a timescale short compared to the expansion time of the source.

Bonning et al. [16] performed an analysis of the multi-wavelength data from 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-LAT experiment and demonstrated an excellent correlation between the IR, optical, UV and γ-ray light curves, with a time lag of less than one day.

Urry [43] in her recent paper noted that 3C454.3 can be a laboratory for multifrequency variability in Blazars. 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.

Perhaps most importantly, 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. VLBI observations of cores vs. jets (see, e.g., the study of BL Lac by Bach et al. [2]) show the structures 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 and the core of AGN at remarkably fine temporal and spatial scales.

4. Galactic microquasars and AGN jets

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. I note that a similar scenario could be operating in Cen A.

This is not to say that the "slower-moving blobs" are not themselves moving relativistically, since the bi-polar lobes have significant enhancements in brightness due to relativistic Doppler boosting for the blobs moving toward us.

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.

One of the most remarkable sagas 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 [21]. 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, 2008) 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. [34] note, this radiating material is intermediate between the Broad Line Region (BLR) and the Narrow-Line Region (NLR).

The data outlined here suggest a model for the jet structures in which beams or blobs of energetic plasmas propagate 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, but can also come from clouds in the Broad Line Region. The jet can apparently also excavate large regions, as is suggested by the complex structures in, for example, 3C120. The physical processes which can accelerate and entrain the ambient medium through which the jet propagates, have been discussed in detail in several

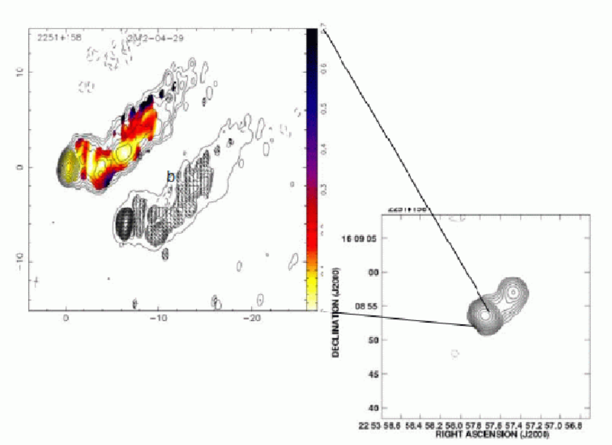

Figure 1. 3C454.3 shown at milliarcsecond scales (left side), taken from the MOJAVE VLBA campaign) and arcsecond scales (right side, taken from the VLA) (Lister et al. [32], Cooper et al. [18], respectively). The data show the remarkable complexity of the jet on the first few parsecs of its evolution, 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. The data at milliarcsecond scales are the most recent available and were taken in April of 2012.

venues (see, e.g., [6, 9, 11, 40, 41]).

The observations of the concurrent IR, Optical, UV, and γ-ray variability of 3C454.3 suggest a reinvestigation of the VLBA data for this source using the MOJAVE observations. It is worthy of note that 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 Fig. 1a). 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 (see Fig. 1), 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. Furthermore, the suggestion of such an enormous scale of the dynamo region in 3C454.3 argues that we need to model magnetic structures on parsec scales for AGN jet acceleration.

It is also of interest to note that in cases like Sco X-1 and 3C120, the complex jet structure consisting of slower moving "blobs" and very rapidly moving "bullets" is aligned on an apparently stable axis, while in the case of 3C454.3 and 1308+326.1, there is evidence of radical changes in direction over 10s to 100s of parsecs (see Fig. 2). This is also true of the galactic microquasar SS433 (see, e.g., Mioduszewski et al. [36], and Doolin and Blundell [20]), which shows a helical structure to the jet in both directions.

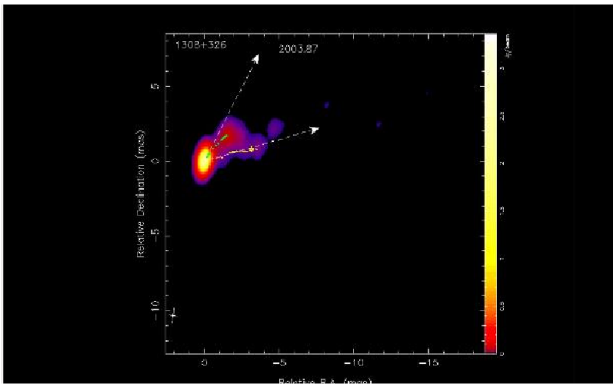

Figure 2. Observations of 1308+326.1 on a scale of milliarcseconds from the MOJAVE VLBA campaign [32] show an apparent precession of the jet in that source. These data thus apparently show a remarkable change in the propagation of the relativistic jet on the scale of parsecs. Such a change in propagation direction bears directly on the question of the strength and large-scale structure of the magnetic field in the jet-interacting region.

This behavior is indeed remarkable. Such a change in propagation direction bears directly on the question of the strength and large-scale structure of the magnetic field in the jet-interacting region.

Regarding the acceleration region and the possible mechanisms for the collimation of the jets, a number of models have been proposed (see, e.g., [14, 15, 29, 39] which might help explain the complexity present in these data.

5. Concluding remarks

Our realization of the dynamic nature of jets from microquasars to AGN has come from laudable persistence on the part of observing teams throughout the world. The detail available from observatories in the current epoch provides considerable guidance to those interested in modeling these sources. Prior to these efforts, it was understandable that jets could have been considered as remarkable for their stability and persistence, given the data we had seen in the past, even in spite of the variability observed from AGN and microquasar jets. However, what we are now seeing suggests a more complex and dynamic structure to the source regions.

Our condition is similar to that which occurred three decades ago when we broke from assumptions of spherical symmetry in our models of active galaxies. We did this to consider the linear structures we saw on the sky. We now find that the true nature of these sources is even more complex. We must face the challenge this poses for our modeling of these truly dynamic, complex, and asymmetric structures.

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References

[1] The Pierre Auger Collaboration, et al., 2007, *Science* **318**, 938

[2] Bach, U., Villata, M., Raiteri, C. M., et al. 2006, “Structure a variability in the VLBI jet of BL Lacertae during the WEBT campaigns (1995-2004),” *A&A*, 456, 105

[3] Beall, J.H. et al., 1978, *Ap. J.*, **219**, 836

[4] Beall, J.H., Rose, W.K., 1980, *Ap. J.*, **238**, 579

[5] Beall, J.H., 1987, *Ap. J.*, **316**, 227

[6] Beall, J.H., 1990, *Physical Processes in Hot Cosmic Plasmas* (Kluwer: Dordrecht), W. Brinkman, A. C. Fabian, & F. Giovannelli, eds., pp. 341–355

[7] Beall, J.H., Bednarek, W., 2002, *Ap. J.*, **569**, 343

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

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

[10] Beall, J.H., 2009, *Societa Italiana di Fisica*, 98, 283–294

[11] Beall, J.H., 2010, in *Multifrequency Behaviour of High Energy Cosmic Sources, Frascati Workship 2009*, F. Giovannelli & L. Sabau-Graziati (eds.), *Mem. S.A.It.* **81**, 395

[12] Beall, J.H., 2011, *Mem. S. A. It.*, 83, 283–290

[13] Benford, Gregory, and Protheroe, R.J., 2008, *M.N.R.A.S.*, 383, 417–816

[14] Bisnovatyi-Kogan, Genaddi, et al., 2002, *Mem. S.A.It.* **73**, 1134., in *Proceedings of the Vulcano Workshop on High-Energy Cosmic Sources, 2001*

[15] Bisnovatyi-Kogan, Genaddi, 2012, *Acta Polytechnica*, Vol. 53, Supplement

[16] Bonning, E. W., Bailyn, C., Urry, C. M., Buxton, M., Fossati, G., Maraschi, L., Coppi, P.,Scalzo, R., Isler, J., Kaptur, A. 2009, *Astrophys. J. Lett.*, 697, L81

[17] 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

[18] Cooper et al., 2007, *Ap.J. Supplement*, **171**, 376

[19] Dar, Arnon, 2009, private communication

[20] Doolin, S., and Blundell, K.M., 2009, *Ap. J.*, 698, L23

[21] Fomalont, E., Geldzahler, B., Bradshaw, C., 2001, *Ap. J.* **558**, 283–301

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

[23] Gómez et al. 2000, Science **289**, 2317

[24] Hiribayashi et al., 2000 PASJ **52**, 997

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

[26] Hawley, J.F., 2003, *Phys. Plasmas* 10, 1946

[27] Jorstad, S.G., Marscher, A.P., Lister, M.L., Stirling, A.M., Cawthorne, T.V. et al., 2005, Astron. J. **130**, 1418–1465

[28] 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

[29] Kundt, W. and Gopal-Krishna, 2004, *Journal of Astrophysics and Astronomy*, 25, 115–127

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

[31] Lightman, A. P., Eardley, D. N., 1974, *Ap. J.* Letters **187**, L1

[32] Lister et al., 2009, *A.J.*, **137**, 3718

[33] Madejski, Greg M., et al., 1999, *ApJ*, 521, 145–154

[34] Marscher, A.P., et al., 2002, Nature, **417**, 625–627

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

[36] Mioduszewski, A. J., Rupen, M. P., Walker, R. C., Schillemat, K. M., & Taylor, G. B. 2004, BAAS, 36, 967

[37] Mushotzky, R.F., Serlemitsos, P.J., Becker, R.H., Boldt, E.A., and Holt, S.S., *Ap. J.* **220**, 790–797

[38] 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

[39] Romanova, M. and Lovelace, R., 2005, 2009, *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

[40] Rose, W.K., et al., 1984, *Ap. J.* **280**, 550

[41] Rose, W.K., et al., 1987, *Ap. J.* **314**, 95

[42] Ulrich, Marie-Helene, Maraschi, Laura, and Urry, C. Megan, 1997, *Ann. Rev. Astron. Astrophys*, 35, 445–502

[43] Urry, C. Megan, 2011, *J. Astrophys. Astr.* 32, 139–145

[44] van der Laan, H., 1966, Nature **211**, 1131

[45] Zanni, C., Murante, G., Bodo, G., Massaglia, S., Rossi, P., Ferrari, A., 2005 Astron. Astrophys., **429**

Discussion

Giora Shaviv — If my colleague, Arnon Dar, were here, he would have asked you if you can say that the clouds you have described as moving in the jet are "Cannon Balls".

Jim Beall — Although I don't think our colleague, Arnon Dar, would like the equivocation, I believe that it is a matter of perspective whether or not you consider these clouds as "cannon balls". They seem to be associated with instabilities in the accretion disks of AGNs, galactic binary systems, and perhaps even star forming regions. And there appear to be at least two kinds of structures emitted: the slower moving blobs and the very fast bullets.

Matteo Guainazzi — Could you comment on the experimental evidence for "jets stacked in the ambient medium"? Do radio and X-ray measurements indicate that compact radio galaxies are young rather than "frustrated"?

Jim Beall — It does appear that the jets have a significant effect on the ambient medium through which they propagate. But my saying this suggests that the distinction between the jet and the ambient medium is somewhat arbitrary. The jets are enormously energetic. They therefore heat the ambient material, accelerate, and entrain it. However, the larger and more important question you are asking is whether the jets are somehow different in Seyferts (where the jets are confined within the AGN core) than the jets in giant radio galaxies, where they can extend hundreds of kiloparsecs. My guess is that the jets evolve as they propagate. They are likely to be electrons, positrons, and hadrons to begin with, and then an admixture of stellar-like material as they evolve. The difference in propagation lengths might be due to the energetics of the accretion disk, but that, too, is only a guess.