Mem. S.A.It. Vol. 83, 283

Memorie della

The interaction of astrophysical jets with the ambient medium: a review

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Abstract. This paper reviews some data from observations associated with the interaction of astrophysical jets with the ambient medium through which they propagate. 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 (Beall et al., 1978) on Centaurus A (NGC 5128), 3C120 (Marscher (2005), and 3C454.3 as reported in the recent paper by Bonning et al. (2009), 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. I also comment on some details of the results of the MOJAVE Collaboration radio data at mas (i.e., parsec) scales. These data all show the remarkable richness of patterns of variability for astrophysical jets across the entire electromagnetic spectrum. I hypothesize that these patterns of variability arise from the complex structures through which the jets propagate. Consistent with this hypothesis, I conclude that the observed concurrent radio and x-ray variability of Centaurus A (Beall et al. 1978) was caused by the launch of a jet element from Cen A's central source.

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

1. Introduction

Space experiments (see, e.g., Giovannelli and Sabau-Graziati, 2004 for a review), in concert with ground-based measurements via both electromagnetic and (apparently) nuclear channels, have greatly increased our knowledge of the nature and structure of astrophysical jets over the last four decades of 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 that can be associated with jets are found in star-forming regions, in compact binaries, and of course in AGN.

The confirmed 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

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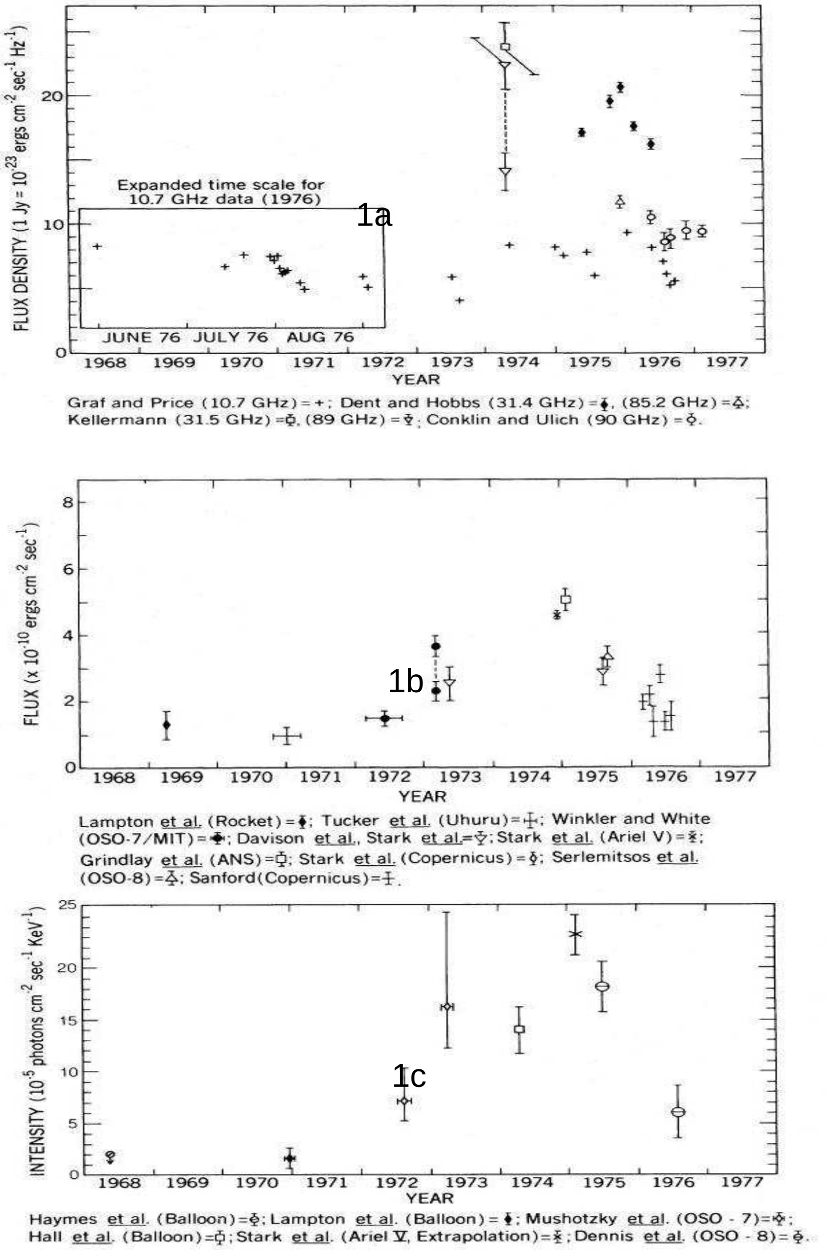

Fig. 1. Radio and x-ray variability of Centaurus A (NGC 5128) These data were gathered from various, independent radio and x-ray observing campaigns, as well as a concurrent radio and x-ray observing program from June through July 1976. The entire history runs from early 1968 through mid 1977. Figure 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 as cited in Beall et al., 1978.

of microquasars, and Paredes (2007) has considered the role of microquasars and AGNs as sources of high energy γ-ray emission. One of the still-unanswered questions regarding the nature of these astrophysical jets is whether or not some jets (for example, those with shorter propagation lengths), are essentially different from those that have much longer ranges. In this paper, I consider the complexities of the jet-ambient medium interaction, and suggest that the medium in which the jet propagates has a great deal to do not only with its propagation length, but also its actual constitution.

It is also worthy of note 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. Here, I note the similarities of those data with observations of galactic microquasars and AGNs, including the recently reported observations from the Fermi Space Telescope of concurrent γ-ray, IR, Optical, and UV variability of 3C454.3 (Bonning et al., 2009).

2. Jet launch associated with the 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). 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 Interferometer 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 ($\sim$ 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 1975, 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 triangles 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 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, $\sim$ 30 GHz, and $\sim$ 90 GHz) clearly track one another throughout the interval whenever concurrent data are available.

A 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. In other words, the observations are consistent with the interaction of the astrophysical jet with the ambient medium in the core of Cen A.

One might think that a distinction needs to be made here about which observational signatures are associated with the jet 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., Marscher 2005). This behavior is also evident in the observations of Sco X-1 by Fomalant, Geldzahler, and Bradshaw (2001), as discussed below, but on much shorter physical and temporal scales.

We can perhaps distinguish these elements at least nominally by calling the material that originates directly from the accretion disk processes a "beam" and considering the material that results from the "beam" and its entrainment of the ambient medium, an astrophysical jet.

3. A comment on van der Laan expansion

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 (2007) 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).

The most likely explanation for the Cen A data is that the emitting region suffered an injection of energetic electrons, that is, a jet-ambient-medium interaction, or, equivalently, that there was a re-acceleration of the emitting electrons on a timescale short compared to the expansion time of the source.

4. Galactic microquasars and AGN jets

Recently, Bonning et al. (2009) performed an analysis of the multi-wavelength data from 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

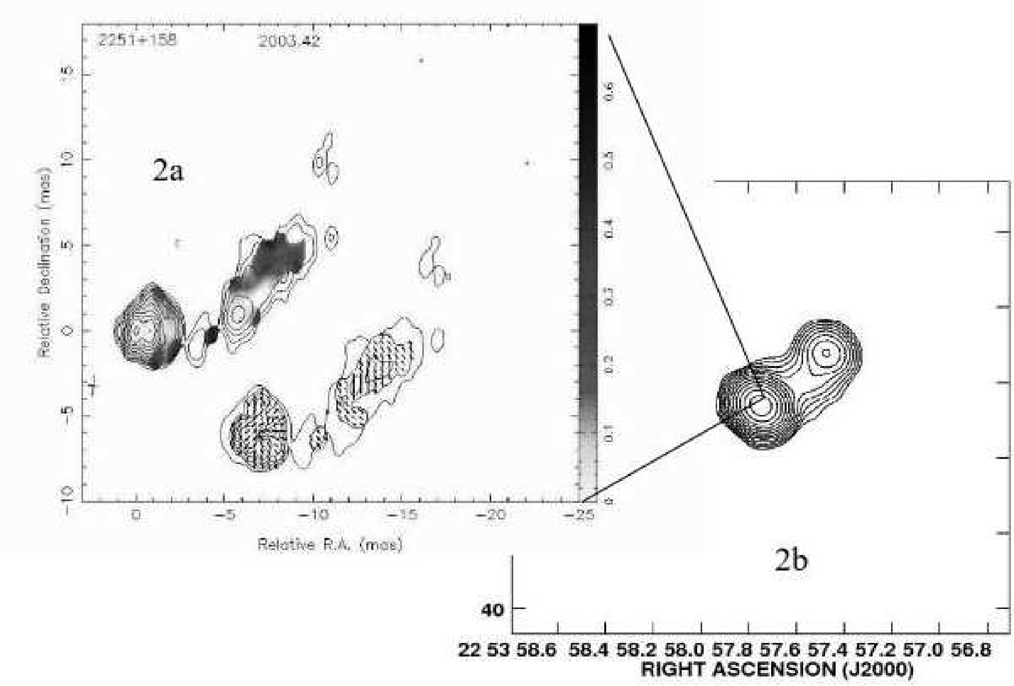

Fig. 2. Data for 3C454.4 at milliarcsecond scales (Figure 2a (top left), have been obtained from the MOJAVE database (Lister et al, 2009) maintained by the MOJAVE Team (see, also, acknowledgements at the end of this paper), and arcsecond scales (Figure 2b (bottom right), taken from the VLA and presented by Cooper et al., 2007). The data show the remarkable complexity of the jet the first few parsecs of its evolution, including a significant change in direction as it evolves. On the other hand, the jet on the scale of hundreds to thousands of parsecs is stable and has a constant direction.

the observations of spatially and temporally resolved galactic microquasars and AGN 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.

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.

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.

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.

To my mind, 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 (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).

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, as is suggested by the complex structures in, for example, 3C120.

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

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 2a). 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 Figure 2b), 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 et al. (2002), and Romanova and Lovelace (2009) that might help explain the complexity present in the data. Clearly, however, a lot more work is needed.

5. The complex interactions of jets with the ambient medium

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. Dar (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 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.

6. Discussion

PETER MEINTJES The moving magnetic fields you showed look like reconnection which should be associated with particle acceleration. Is there evidence of reacceleration and spectral hardening in radio and x-ray data when these "reconnection" events occur?

JIM BEALL We have clear evidence in Centaurus A in the ha x-ray (i.e., 100 keV) for hardening in the x-ray spectral index. This is consistent either with either injection of jet particles into the radiating environment or with reacceleration due recombination of magnetic fields in the jet structure.

MANEL PERUCHO You have made an important point about the entrainment that seems to be building up the jet. Jets propagate in a clumpy ambient medium interacting with winds from stars and clouds. In addition, they develop instabilities that favor the incorporation of matter into the jet. Thus, I think that jets are indeed modified and that what we see at kiloparsec scales is the result of all those processes.

JIM BEALL Thank you. I think it is really important to underscore this point. The animations that I showed for 3C120 and 3C454.3, and even the one for the Sco X-1 data show the complexity of the jet structures as they evolve from the central source. It is likely that many physical processes, including shocks, ram pressure, magnetic recombination, and plasma processes (as discussed in my next talk) all contribute to the entrainment of the ambient medium into the jet.

Acknowledgements. The author gratefully acknowledges the support of the Office of Naval Research for this research. This research has made use of data from the MOJAVE database that is maintained by the MOJAVE team (Lister et al., 2009, AJ, 137, 3718). The author gratefully acknowledges the data provided by the MOJAVE Team.

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