Relativistic Jets in Astroparticle Physics

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Abstract

Astrophysical jets are a remarkable laboratory for a number of important physical processes. 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. In this paper, we use recent observational campaigns to consider the connection of galactic jets to jets in AGN and quasars over an enormous temporal, physical, and dynamic range. We then discuss some aspects of the jet-ambient medium interaction in order to show that an analysis of data from several frequency bands can help determine the constitution and dynamics of these jets.

1 Introduction

Over the course of two decades of astrophysical research, 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, galactic binaries, microquasars, active galaxies and quasars, clusters of galaxies, and γ-ray bursts. The presence and evolution of these jet-like structures is of course a testament to the principle of conservation of angular momentum.

The association 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. 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.

Sylvain Chaty (Chaty, 2007) discusses the role of microquasars in astroparticle physics, and Josep Paredes (Paredes, 2007) considers microquasars and AGNs as sources of high energy γ-ray emission. In this paper, we will focus on the similarities between one galactic microquasar and an AGN.

2 A Comparison of a Galactic Jet and an AGN Jet

In the spirit of these ideas of the common origins of jets, from star-forming regions to microquasars, AGNs, and γ-ray bursts, we investigate some elements of the jets in a galactic binary source (Sco X-1) and an AGN (3c120). The authors 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.

In this way, the role of jets (and especially relativistic jets) in astroparticle physics becomes clearer. The comments in this paper are directed toward the connection between microquasars, AGN jets, and their possible common physical processes.

2.1 Sco X-1 as a Galactic Microquasar

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.

The data from those observations form a time-lapsed "movie" over the period of 0400 UT, 11 June 1999 through 0900 UT, 13 June 1999, that is, roughly two days. Some snapshots of the movie are shown in Figure 1. While the snapshots do not do justice to the actual "movie," a number of observations of these episodes are in order. A detailed discussion of these remarkable data can be found in Fomalont, Geldzahler, and Bradshaw (2001). Our own brief commentary follows.

First, the movie begins after an initial flare of the central binary system has already occurred, an event most likely seated in the accretion disk around the compact object. Material has apparently been ejected along an axis inclined from the plane of the sky so that material is flowing at some angle both toward and away from the observer (i.e., like a classic radio jet from an AGN). The relativistic beaming effects are manifest in the intensity ratios of the two lobes, which have apparently been ejected earlier from the source. The first panel shown in Figure 1 (Figure 1a) is at the time when these first two lobes have faded from sight at frame 63 on 11 June 1999 at 17:39 UT.

The second panel (Figure 1b, frame 124, taken on 12 June 1999 at 08:18 UT) shows the system after the ejection of an "overburden" of material from the disk (in both directions). These also show relativistic beaming effects. The small blobs intermediate between the central source are moving with an apparent velocity at or slightly above the speed of light. These small blobs appear asymmetric with respect to the central source because of relativistic effects. When the blobs strike the larger, leading lobes, these lobes flare, indicating that a significant amount of energy has been deposited into the beam "head."

The third panel, Figure 1c, shows a later time (frame 202 taken on 13 June 1999 at 03:01 UT) when the furthermost lobe is again a target for another fast-moving blob of material. At this moment, the pair of relativistic

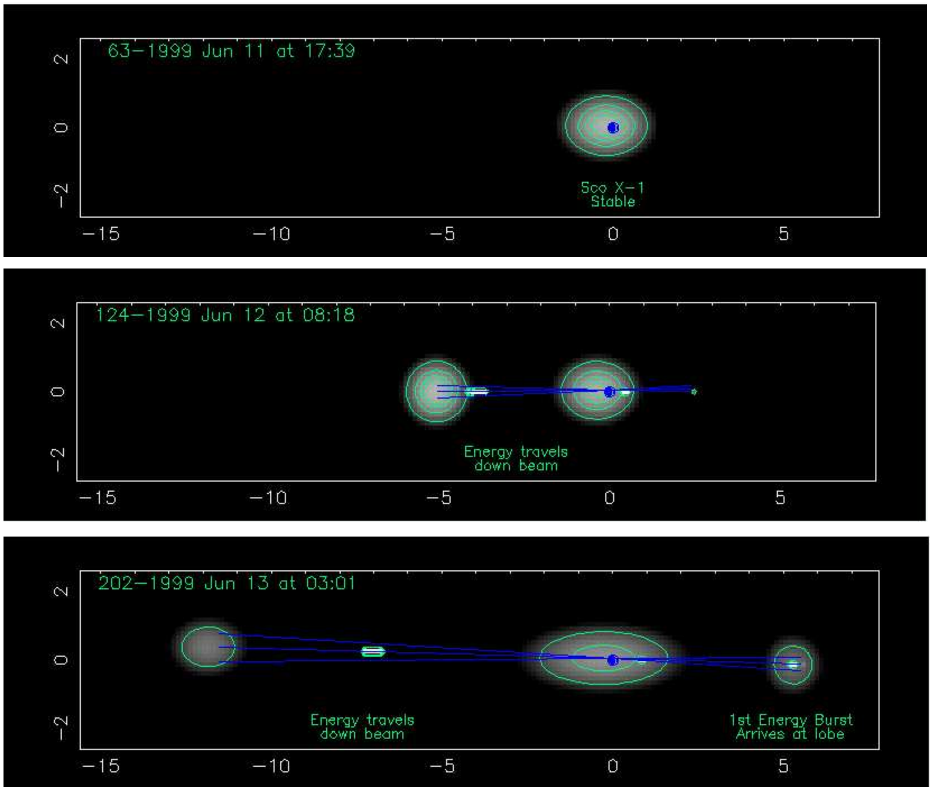

Figure 1: Snapshots taken from the "movie" of the flaring, jet production, and jet evolution the galactic x-ray binary, Sco X-1 (Fomalont et al 2001). The text refers to the panels as Figure 1a (topmost), Figure 1b (middle), and Figure 1c (bottom).

blobs moving along the jet axis toward the lobes shows the time delays. The blob moving toward the observer appears to be halfway to the lobe, while its counterpart is shown dimmer and to the immediate right of the central source. The blob which is striking the right lobe is the receding component of an earlier ejected pair.

These remarkable pictures of Sco X-1 at radio frequencies, together with the movie of the jet in the Crab Nebula taken by the Hubble telescope at optical and the Chandra telescope x-ray wavelengths (Hester et al. 2002), show the importance of detailed studies of the temporal evolution of these sources using concurrent observations.

2.2 The Radio and X-ray Variability of 3c120

We now consider the radio and x-ray variability of 3C120, as illuminated by the work of Alan Marscher, Svetlana Jorstadt, and colleagues (see, e.g., Jorstadt, 2005, and Gomez et al., 2000), taken as part of their survey of a number of AGN. The extent of the observations of radio bright sources in this survey is remarkable.

The radio data represent the contours of the 43 GHz intensity in radio light (contours) overlayed with the polarization intensity (shaded) and with polarization angles shown as hash marks. The inset shows the X-ray light curve taken from the Rossi XTE (see Marscher, 2003 for a discussion). The source is at a distance, D = 120 Mpc (for H = 65 km/s-Mpc), which means that an angular separation of 1 mas = 0.70 pc. These data are courtesy of Alan Marscher and Jose-Luiz Gomez. For a detailed discussion, see Gomez et al. 2000 Science, 289, 2317, and Marscher, A.P., et al., 2002, vol. 417, pp. 625-627, 6 June 2002. The intervals of the timing marks on the inset are roughly 0.2 years.

In the data for 3C120, shown in the Figure 2, the red ellipse represents an inference of the state of the inner accretion disk based on the soft x-ray emission from the source. When the soft x-ray emission (shown in the upper right insert) dips, this x-ray activity is thought to be associated with a process in the inner accretion disk that "dumps" material into a region where the jet-acceleration occurs. This depletes the material responsible for the soft x-ray emission, and the x-ray light drops in relative intensity. Such a picture is consistent with our understanding of the thermal emission of a Shakhura-Sunyaev disk (see e.g., Beall, 1987, 2003), where the inner edge of the disk can emit in the low-energy x-ray portion of the spectrum. Therefore, at the same time that the x-ray light dips, the jet is formed and begins to propagate outward (albeit without detectable emission) along the jet axis as defined by the linear radio emission produced from previous acceleration events. The reader should note that in Figure 2, the *bottom-most red mark is an arrow to guide the eye* to the time when the x-ray and radio frames were taken.

The individual frames in Figure 2 were extracted from the 3c120.avi movie using the *Xnview* (Gougelet, 2006), Gougelet, P. E., 2006, http://perso.orange.fr/pierre.g/xnview/enhome.html). Figure 2a shows the state of the jet at the time of the first observed drop in the x-ray data (represented by an increase in the center (black) region of the ellipse. This is 20 frames past the beginning of the data set, or roughly 7 weeks. In

Figure 2b, 40 frames (14 weeks) after this, the 43 GHz polarized and total fluxes reach a peak in brightness in the innermost (fartherest left, i.e. 0 mas on the bottom horizontal scale). It is interesting to note that the slightly curved structure extending from the bright peak toward the disk develops from the lobe and appears to move *toward* the central source in a few frames. This phenomena of apparent motion toward the central source can be seen in a perusal of several other frames also, and is likely to be an activation of the emitting medium rather than a counter flow in the jet environment. However, this effect bears further investigation, since the mechanism of charge-neutralization in a jet is still an open question.

In figure 2c, 110 frames ($\sim$ 40 weeks or 9 months) later, there is again a minimum in the x-ray brightness, suggesting that another acceleration event is occurring. At the same time, both the polarized and total flux emitting regions have moved farther from the central source. This is especially interesting when compared to figure 2d, 76 frames or $\sim$ 28 weeks after 2c, where the maximum in the polarized light is much farther along the jet structure (at 0.8 to 1.0 mas) than the interaction from the previous flare shown in the frame in Figure 2b. *There is no equivalent flaring in the polarized radio emission nearer to the central source in the intervening frames*, even though the total flux in that region remains bright. This suggests that the jet has a coaxial structure. The central, cylindrical region suffers the direct interaction of the jet and the ambient medium through which it propagates. This region is sheathed in material whose emission is activated by the direct, jet/ambient-medium interactions. The observations are consistent with a jet that first propagates through the ambient medium, then entrains and accelerates it to produce the the observed emitting structures.

As with Sco X-1, it is possible to estimate the velocity of the (undetected) jet by noticing the time from the dip in the x-ray light curve until the time when the ambient medium (as delineated by the 43 GHz radio contours) is fluoresced by the energy deposition of the jet into that medium. The central component of the jet is highly relativistic and moves with a velocity of $\sim 0.98c$, while the emission of the coaxial (possible) structure is $\sim 0.5c$ (see, e.g., Jorstadt, 2003, Marscher 2003)

If the hypothesis of the coaxial structure of these jets is correct, the jet-ambient medium interaction is likely to have a number of physical processes in operation. We will briefly discuss some plausible mechanisms for the jet/ambient-medium interaction later in this paper.

The authors note that this analysis is informed by a perusal of the Sco X-1 radio data. The principal points of comparison are as follows: the velocities of the jet material inferred by the time-delay method and the velocities observed by the motions of the radio contours is remarkably different ($v \sim .98c$ as opposed to $v \sim .45c$) in Sco X-1, also. Thus, the jet structure is remarkably complex and it is our interpretation of these data that the presence of the jet is made manifest for the most part when it interacts with material that preceded it from previous eruptions, that is, from material that was blown off the disk initially, or that has been entrained and accelerated by processes discussed later in this paper (see, also, Rose et al., 1984, Beall, 1990).

This analysis is a considerable simplification of the jet/ambient-medium interaction in the "movie" for 3c120, and we recommend to the reader a perusal of the actual movie and the individual frames to get some idea of the complexity of the phenomena involved. Our interpretation has the virtue of presenting a theory that organizes the experience of the phenomena into an at least somewhat coherent picture.

2.3 A comparison of the temporal evolution of Sco X-1 and 3C120

The data from Sco X-1 and 3c120 show remarkable similarities and reveal a consistent pattern of behavior, albeit on remarkabley different temporal and physical scales. The radio structures appear to originate from the central source and propagate along an axis that maintains itself over timescales long compared to the variability timescales of the respective sources. The emission from the lobes fades 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). We will outline the physical processes that can accelerate and entrain the ambient medium through which the jet propagates later in this paper. We have discussed these in detail in several venues (see, e.g., Rose et al., 1984, 1987, Beall, 1990, Beall et al., 2003).

For the purposes of distinguishing between the different relativistic components of these sources, it might be helpful to call the faster component a "beam," and the slower component(s) with which it interacts, the "jet." Both components show special-relativistic effects, including relativistic Doppler boosting, and different apparent velocities with regard to the approaching versus the receeding lobes of the beams and jets.

3 Modeling the Jet Interaction with the Ambient Medium

The question of how a relativistic jet of material propagating through an ambient medium interacts with that medium can acquire more specificity via the following questions: First, what mechanisms work to deposit energy in the ambient medium as the jet propagates through it, and second, how does the jet maintain its coherence as it propagates such remarkable distances? One ought also to ask what the jet is made of and whether or not there are different modes of interaction for jets with different constitutions.

Analysis based on hydrodynamic simulations has demonstrated a number of interesting effects originating from ram pressure and the consequent, turbulent acceleration of the ambient medium (see, e.g., Basson and Alexander, 2002; Zanni et al. 2005; and Krause and Camenzind 2003). However, these hydrodynamic approaches neglect an important species of physics: the microscopic interactions that occur because of the effects of particles on one another and of particles with the collective effects that accompany a fully or partially ionized ambient medium (i.e. plasmas). For a detailed discussion of these effects, see, e.g., Scott et al. 1980, Rose et al. 1984; Rose et al. 1987; Beall 1990, and Beall et al., 2003. The principal processes are outlined here.

For the purposes of specificity, we posit a relativistic jet of either $e^{\pm}$, $p - e^{-}$, or more generally, a charge-neutral, hadron-e^{-} jet, with a significantly lower density than the ambient medium. The primary energy loss mechanism for the electron-positron jet is via plasma processes, as Beall (1990) notes.

The physical processes in the plasma, including wave-wave and wave particle interactions, can be modeled by PIC (Particle-in-Cell) codes for some parameter ranges, but for astrophysical applications, a PIC code analysis is not possible with current or foreseeable computer systems. Fortunately, the plasma wave interactions can also be represented by a system of coupled differential equations (see, e.g. Scott et al., 1980, and Rose et al., 1984) which model the principal elements of the plasma processes that draw energy out of the jet. To confirm the wave population model, we therefore "benchmark" (see Oreskes et al. 1994) the wave population code by using the PIC code in regions of the parameter space where running the PIC code simulation is practicable, and use the wave population code for regions of direct astrophysical interest. A more detailed discussion, showing excellent agreement between the two methods of the PIC-code simulations and the wave-population model, can be found in Rose, Guillory, and Beall (2002, 2005).

A PIC code simulation of an electron-positron jet propagating through an ambient medium of an electron-proton plasma shows good agreement with the wave population model in terms of a characteristic scale length for the jet interaction with the ambient medium. The wave population model can be used to derive this scale length, $L_p = ((1/2)\gamma c n_b m c^2)/(d\alpha\epsilon_1/dt)$. L_p is the distance over which the plasma instabilities reduce the beam γ by a factor of two (see, e.g., Rose et al. 1984), where γ is the Lorentz factor, c is the velocity of light, n_b is the beam number density, mc^2 is the rest-mass energy of the beam particles, and $d\alpha\epsilon_1/dt$) is the energy deposition rate into the ambient plasma, as determined by the wave population code.

The wave population code represents the coupling of these instability mechanisms, which are expressed through a set of rate equations (Rose et al. 1984, 1987; Beall 1990). Initially, and for a significant fraction of its propagation length, the principal energy loss mechanisms for such a jet interacting with the ambient medium is via plasma processes.

At the same time, the ambient medium is heated and entrained into the jet. We believe that this configuration is a reasonable end point for the initial interaction of the relativistic jet with the interstellar medium, given the pressure exerted on the ambient medium even in the presence of an oblique or transverse magnetic field. These simulations show that a relativistic, low-density jet can interpenetrate an ambient gas or plasma.

Plasma effects can also have observational consequences. Beall (1990) has noted that plasma processes can slow the jets rapidly, thus truncating the low-energy portion of the γ-ray spectrum. This calculation was carried out in some detail by Beall and Bednarek (1999). A similar effect will occur for neutrinos and can also reduce the expected neutrino flux from AGN (Beall and Bednarek, 1999).

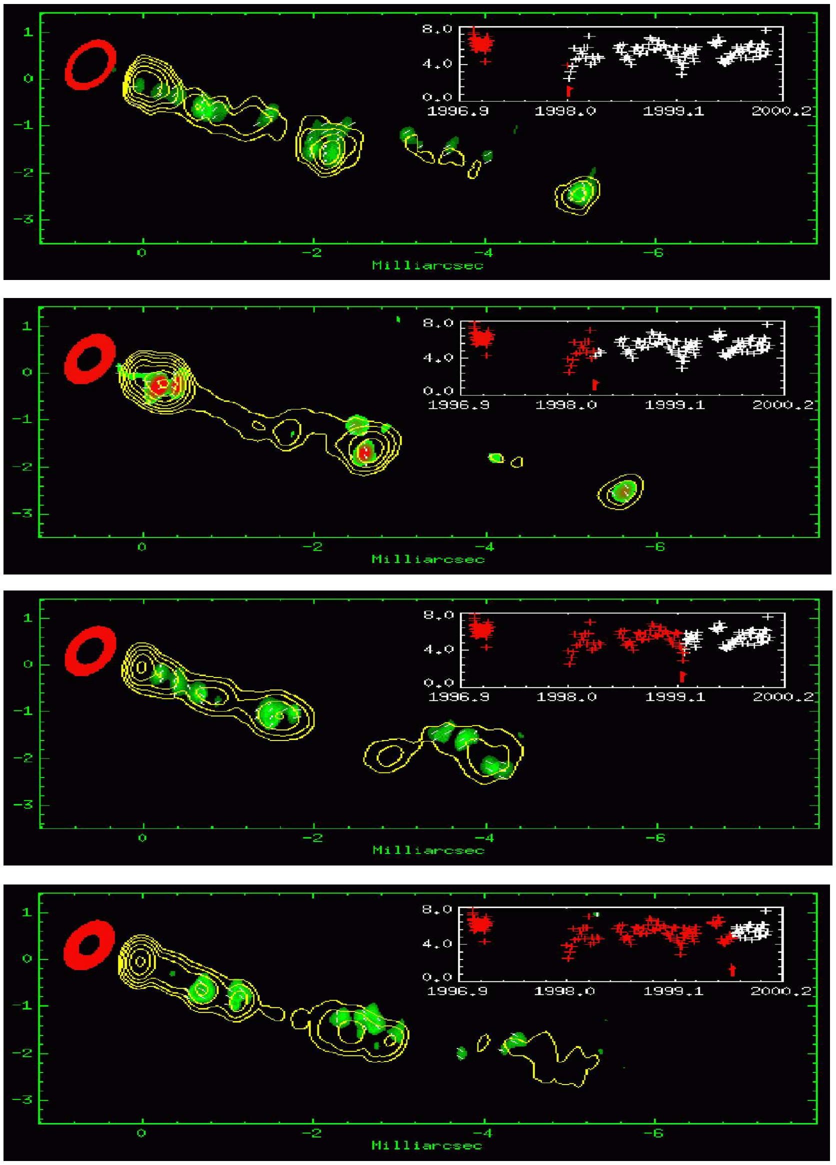

Figure 2: Snapshots taken from the "movie" of 3c120, showing the radio and x-ray flaring associated with the jet production and propagation of the jet (see Gomez et al. 2000 Science, 289, 2317, and Marscher, A.P., et al., 2002, vol. 417, pp. 625-627, 6 June 2002 for discussions). The data are courtesy of Alan Marscher and Jose-Luiz Gomez.

4 Conclusions

We have thus outlined a comparison of the data on the temporal and spatial evolution of the radio variability; on the one hand, of an active galaxy, and on the other, of a galactic microquasar. In doing so, we can establish an outline of source evolution that shows remarkable similarities between these two different sources over widely varying time scales (i.e. hours in the microquasar and years for 3c120). Of course, as has been noted that it is much more likely to see the evolution of microquasars, but this has only recently become true because of the availability of the remarkable instruments of the present epoch.

5 Acknowledgements

The authors express their appreciation to Alan Marscher, Svetlana Jorstadt, and Jose-Luiz Gomez for permission to use the data for 3c120.

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DISCUSSION

G. SHAVIV: How does the jet calculation behavee when there is an inhomogeneity in the ambient medium?

J. BEALL: The principal growth rate of the two-stream instability is determined by the ratio, n_b/n_p, of the beam density to the plasma density (.i.e., the ambient medium), the inverse of the beam γ, and the plasma frequency, ω_p. The growth rate is very fast compared to most other timescales. Therefore, if the density of the ambient medium changes, the plasma wave energy levels adjust quickly and continue to draw energy from the jet.

J. PAREDES: Comment: In the microquasar, GRS 1915+105, there were observed similar phenomena as those observed in 3c120, but occurring on timescales of hours (S. Chaty, Ph.D., 1998; Mirabel et al, 1998, A&A, 330, L9). The radio/x-ray activity observed in 3c120 over years timescales, strengthens the analogy between quasars and microquasars.

J. BEALL: I thank you for pointing this out and I agree with the importance of these observations. My point in using Sco X-1 as a comparison was to highlight those results and bring up the point that the compact object in that system is a neutron star. By implication, therefore, it is the disk-jet connection is what determines the microquasar's status and not the compact object, except in terms of the energy it provides through accretion.