Jets in Astrophysics

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ABSTRACT.

Jets are ubiquitous in astrophysical settings, from bipolar flows in star-forming regions to the highly relativistic propagation of beams of particles in Active Galactic Nuclei (AGNs). In this paper, we discuss some elements of the propagation of jets in microquasars and AGN.

1. The Family Tree of Astrophysical Jets

Jets appear to be commonplace in astrophysics. From the highly energetic, bipolar flows in star-froming regions (see, e.g., Panagia, 1999, Vittone, 1999, and Lovelace, Romanova, & Contopoulos, 1997), through the Crab Pulsar (a conical 'jet' of relativistic electrons and positrons), to galactic microquasars (relativistic galactic jets), SS433, and other systems (see, e.g., Mirabel et al.'s 1992 discussion of 1E1740.7-2942; Cui, 1999; Parades, 1999). It appears that even the cores of normal galaxies contain baby quasars. This is of course a thesis that Jeff Burbidge posed when the study of AGN was in its infancy.

Active galaxies also contain jet-like structures. Even Seyferts hold linear radio structures confined their cores, while giant ellipticals and BL Lacs objects show evidence for large-scale, linear structures that extend for many thousands of parsecs or emit radiation that must clearly come form bulk, relativistic motion (see, e.g. Rees, Begelman, and Blanford, 1981, for a review.

In a real sense, my task in giving my opinions on the nature of jets in astrophysics (and especially AGN) has been made much more practicable by the fine discussions of Catanese (1999) and Sambruna (1999) presented in these proceedings. And of course, W. Kundt's (1999) discussion of $e^{+/-}$ jets has made it unnecessary (and even redundant) to comment in great detail on those models.

I confine myself, therefore, to some elements of the problem of jets in astrophysics that have fascinated and puzzled me for some time.

It is intriguing to note the relationships between the various classes of sources that show jet-like phenomena. In a prior workshop (Beall, Guillory, and Rose, 1999) have shown the AGN family tree, which on the surface shows a kindredness between the galactic jets and those in AGN (see, also, Blundell et al. 1999).

In at least 10 % of AGN, the accelerating region produces collimated jets of material that extend for distances of kiloparsecs . These large scale jets o extend for distances of

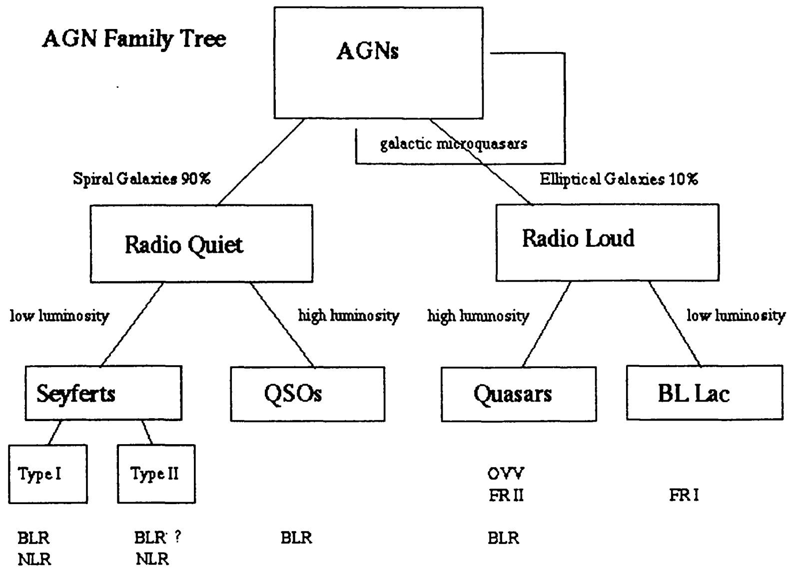

Fig. 1. The AGN Family Tree: broadly divided between two classes, Radio Quiet and Radio Loud. FR I = Fanaroff-Riley Type I radio sources, with strong cnetral radio emission, but weak lobes. FR II = Fanaroff-Riley Type II radio sources, with strong lobes and weaker central sources. BLR = the Broad Line Region (Doppler line broadening with $v = 500 - 7000kms^{-1}$) and NLR = the Narrow Line Region (Doppler line broadening with $v = 300 - 1000kms^{-1}$). Normal galaxies have velocities $\sim 100 - 100kms^{-1}$. Note that the galactic microquasars may form an equivalent tree structure, and thus may be distinguished from AGN phenomena only by luminosity (taken from Beall, Guillory, and Rose, 1999)

kiloparsecs. These large scale jets appear to be typically associated with giant elliptical galaxies, and are denoted "radio loud." Radio Loud AGN are further subdivided into Quasars (with high luminosity) and BL Lac type objects, which are less luminous and have strong central emission. The BL Lac type objects are therefore classed as Fanaroff-Riley I (FR I) sources, which have extended ets," but a brighter central source. Quasars may have bright radio lobes extending to distances of kiloparsecs. Because the lobes are brighter at radio frequencies than the central sources, these objects fall into the FR II source classification.

The remaining 90% of the AGN are divided into Seyfert (spiral) galaxies and QSO's, both having no kiloparsec scale radio structures. However, some Seyferts and at least one spiral galaxy, the Milky Way, have jet like structures which remain within the central cores (< 10 parsecs) of the galaxies (see e.g., Beall, Guillory, and Rose, 1999, Figure 1).

The constitution of these jets and the physical conditions within them have received considerable study. Burbidge (1956) and Felten (1968) showed strong arguments for the presence of hadronic jets, given the great distances through which the jets propagate from the cores of AGN such as M87.

The association of radio, IR, optical, UV, and x-ray structures in AGN has provided further diagnostics for the source parameters in the jets which help to constrain theoretical models of these sources (see, e.g. Beall et al. 1978, Beall and Rose 1981; Feigelson et al. 1981; Begelman, Blanford, and Rees, 1984). These jets appear ultimately to be responsible for the formation of the giant radio lobes which typically contain energies of order 10^{60} ergs.

Sambruna et al. (1999), Catanese et al. (1999), and Kundt (1999) have presented a synopsis of arguments for the presence of relativistic $e^{+/-}$ jets as a source for the radio-to-γ-ray emission and short-time-scale variability of such sources. As something of an aside, it is interesting to note that the recent models for Blue Blazars bear some similarity to the blackbody-Compton model proposed by Beall and Rose (1981) for the x-ray emission from Centaurus A. Beall, Bednarek, and Karakula (1987), Bednarek et al. 1990, Beall (1990), Dar and Laor (1997), and Beall and Bednarek (1999) have considered the consequences of hadronic jets for γ-ray emission from such sources.

2. Energy Transport Issues

But how can jets of material moving at very high speeds (and even relativistically) maintain this condition as they propagate through the enormous interstellar distances manifest from observations? Or put another way, what is the source of energy that powers the giant radio structures in some AGN and the γ-ray light in others?

Burbidge (1956) was perhaps the first to bring such an issue to the fore when he commented that the extended jet in M87 requires that the jet be composed at least in part of hadronic matter in order to sustain itself against energy losses and allow it to form the giant radio structures in that source. Felten also (1968) showed in a direct extension of Burbidge's work that an hadronic component was necessary in order for the jets to propagate a significant distance. Felten used the then-known plasma processes to calculate the limits to propagation lengths of a jet composed of hadrons and leptons.

In considering energy transport issues associated with AGN, Beall and Rose (1981) showed that the non-thermal activity in core of Centaurus A can, when integrated over time provide the necessary energy to supply the 10^{60} ergs of energy estimated to be in the radio lobes. That is, $\int dE/dt * dt$ (in the core) $= E_{tot}$ in radio lobes.

Melia and Konigl (1989) have discussed the radiative deceleration of relativistic jets, showing that relativistic flows are tightly constrained in parameter space if they are to emerge from the intense radiation field of the accretion disk in which the jets are supposed to originate. Of course, this thesis holds only if the jet particles are not in some manner re-accelerated. Finally, Hardee (1987) has discussed the spatial stability of relativistic jets against a number of loss processes.

3. Observations of Active Galaxies

Active galaxies show a considerable variety of emission patterns, but some striking similarities.

Seyfert galaxies show short radio jets that are double-sided on scales of 10's of parsecs, but one-sided on scales of parsecs (see, e.g. Ulvesstadt et al., 1999, and Bower,

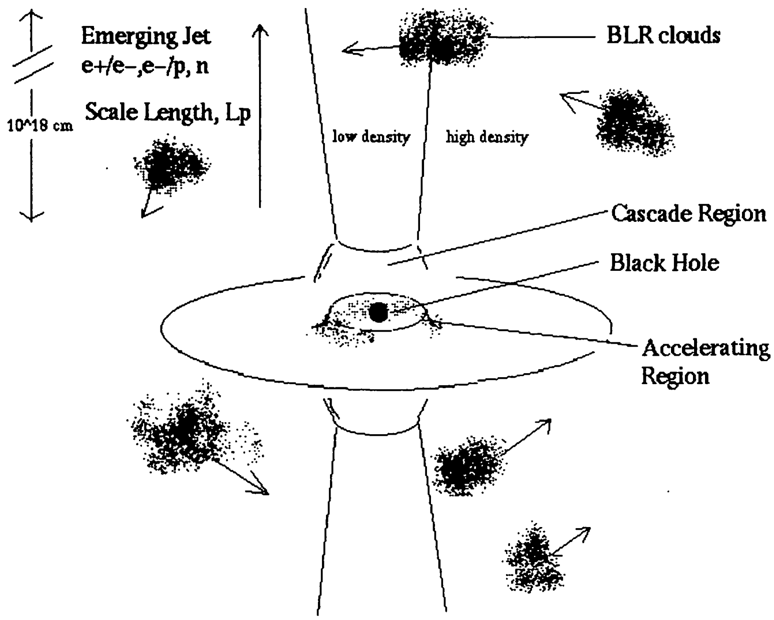

Fig. 2. Schematic of Model: This figure shows a sketch of the likely arrangement of the inner few parsecs of the AGN core. Note that the black hole is surrounded by an accelerating region that produces the initial accelerated particles. These interact with the radiation field or material of the accretion disk or funnel and process the initial beam constituents. What is likely to emerge is a highly relativistic, electron-positron or electron-proton jet. This jet interacts with the dense, interstellar clouds in the broad line region (BLR). The jet slows and eventually becomes supersonic via the processes discussed in Beall, Guillory, and Rose (1999), from whence this diagram is taken.

G. et al. 1995). In fact, if one doubts the ubiquitousness of jets in these sources, a search of the http://adsabs.harvard.edu/ will show 1200 + entries under jets + Seyferts! Hardt et al (1998) comment on the hidden X-ray Seyfert nucleus in 3C273, using Beppo SaX data. On-average, of course, Seyferts are luminous but (relatively) radio-quiet.

Elliptical galaxies can, on the other hand, contain jets that extend from parsec to kiloparsec scales. These sources are radio-loud (i.e., the sources have radio luminosities that are on a par with the luminosity of the source at other decades), and are highly variable.

Perhaps the classic example of a radio galaxy is NGC 5128 (Centaurus A at 5 Mpc distant), which has giant radio lobes with a 5 degree separation on the sky, and smaller, inner radio lobes with 5 arc minutes separation. The connection between radio lobe and core was inferred by Beall et al. (1978), and Beall and Rose, (1981), and firmly established by Feigelson et al. (1981) in a paper using the ROSAT data to map the x-ray jet as it propagates from the core, outward, toward the inner radio lobe.

Another 'nearby' source, M87 (an Active galaxy in Leo) bears a similiarity to BL Lac objects (see Tsvetanov et al, 1998). Along with Cen A, M87, 3C273, and perhaps

3C390.3, it shows evidence in radio, IR, optical, and x-rays for a significant jet.

Finally, a remarkable set of observations of 3C120 using radio maps at various scales shows a one-sided relativistic jet (on a scale of milli-arcseconds) propagating outword to form giant, double radio lobes that extend for kiloparsecs.

Many of these observations suggest a mechanism that transports energy from the core through milli-arcsecond jets to parsec scale jets and in some cased to kiloparsec scale lobes.

4. Origin and Constitution of Jets

I am indebted to Prof. Kundt (1999), and to Drs. Catanese (1999) and Sambruna (1999) for their discussions of likely emission mechanisms for the radiation from the AGNs.

These allow me to confine my speculations to some of the processes that can accelerate jets to highly relativistic energies in the cores of AGN.

Perhaps foremost in terms of likely candidates are the so-called 'membrane-related processes' around black holes. These processes can generate electric fields of order 10^{10} Volts (see MacDonald, et al. 1986).

In addition, it is possible that accretion disk threaded B-fields can reconbine (see, e.g. Romanova and Lovelace, 1992) in a manner kindred to processes associated with solar flares. Blanford and Znajek (1977) have discussed acceleration mechanisms associated with plasma processes, as have Subramanian, Becker, & Kazanas, (1999). Finally, relativistic shocks, and Fermi processes in the boundary between the jet and the ambient medium have been used as possible models of the acceleration processes (see e.g. Begelman & Kirk 1990, and Ostrowski 1999).

Given the fecundity of physical models, it might not be possible to decide definitively which acceleration processes are operant. But perhaps we can divide the problem, and consider the processes in an accelerating region and an interacting region as distinct.

The jet schematic shown in Figure 2 and in Beall, Guillory, and Rose (1999) tries to delineate the problem in this way.

But such a schematic assumes that jets in Seyferts might have the same nature same as those in ellipticals. If so, why do they not propagate for extended distances In other words, do we believe:

1. The fizzled jet model - the engine is different, somehow, or
2. The frazzled jet model - the environment if different, somehow.

A principle question toward deciding this will be a determination of the constitution of the early jet (i.e., do electrons and positrons get accelerated first, or are protons part of the picture?

This is beginning to be answered by studies of spectra produced by jet interaction with ambient medium.

Studies of the behavior of electron-positron jets are relatively well developed, and show that such jets can account for the observed emission from AGN. Henri, Pelletier, and Roland (1993) have shown that the γ-ray emission from active galactic nuclei is consistent with the signature of electron-positron beams, while Xie, Liu, and Wang, (1995) have suggested that the observed radiation in BL Lac objects is consistent with radiation from electron-positron beams. And as mentioned earlier, Kundt (1999) has argued for the presence of $e^{+/-}$ jets.

On the other hand, hadronic jets, as noted earlier, are suggested by considerations of energy transport, and have been studied reasonably well.

Rose et al. (1984, 1987) and Beall (1990) have discussed the energy loss mechanisms and radiation associated with $e^{+/-}$ and e^-/p jets interacting with interstellar clouds. Morrison, Roberts, and Sadun 1984, has also considered hadronic jet interactions with interstellar clouds, and Dar and Laor(1997) consider hadronic production of TEV gamma-ray flares from blazars. Bednarek and Protheroe (1999) have considered γ-ray and neutrino flares produced by protons accelerated on an accretion disc surface in active galactic nuclei, and Beall and Bednarek, (1999) have calculated the effects of plasma turbulence on the hadronic beam model for γ-ray production in blazars.

While models for the $e^{+/-}$ jets seem to be more highly evolved than those for e^-p jets, it is apparent that signatures associated with electromagnetic processes might never determine the constitution of the jets at genesis in AGN. Neutrino detectors might actually solve this dilemma, since the detection of neutrinos from jet sources would imply hadronic component at relativistic (i.e. early) stages of jet formation.

David Eichler (1979) was perhaps the first to suggest that neutrino detectors could be probes of the very cores of AGN. The successful construction of the next generations of sensitive neutrino detectors can show both the energies and time signatures of hadronic processes. For example, γ-ray and neutrino flares produced by protons accelerated on an accretion disc surface in active galactic nuclei could be detected with coordinated observations by γ-ray and neutrino telescopes. Waxman and Bahcall (1998) have calculated the neutrino flux from AGN sources based on the assumption of isotropy, although the more physical assumption of anisotropic production is likely to be of the most interest in determining detectable fluxes.

At all events, neutrino instruments coming of age (see, e.g. Gaisser, Halzen, & Stanev, 1995; Frichter, Ralston, & McKay, 1996; Halzen, 1998; and Palanque-Delabrouille (1999) for discussions of the new neutrino detector designs.

5. Modeling jet interaction with ambient medium

Rose et al. (1984, 1987) and Beall (1990) have shown that beyond the cascade region, the dominant energy loss mechanism for a jet of relativistic particles is associated with processes that derive form plasma turbulence

Such processes can significantly modify line emission ratios from the ambient medium through which the jet propagates (Beall 1999), and in fact changes in line emission ratios could serve as a diagnostic for the presence of relativistic jets in some sources.

Even with this in mind, it appears that large-scale jets ($>$ 1 kpc) interact with the ambient medium through essentially hydrodynamic and MHD processes. On medium-scales with jet lengths of 10 pc $- >$ 1 kpc, relativistic hydrodynamics models may be plausible. However, for small-scale jets ($<$ 10 pc), which are one-sided, superluminal, and highly relativistic, it is plausible that only some future PIC (Particle-In-Cell) code simulation can truly model such interactions. It is with PIC codes that the detailed relations of particles and electric and magnetic fields within the ambient medium can be properly modelled.

On the other hand, such PIC codes calculations are beyond the capabilities of any computer for the forseeable future (which for the admixture of computational science and astrophysics is probably about ten years!).

We are thus left with the option to benchmark the plasma wave model code using the PIC codes in regimes where the PIC code can provide guidance (i.e. rather far from the parameter range of astrophysical jets).

With this method, we have obtained good agreement between the plasma wave model code and the PIC code (see, e.g., Beall, Guillory, and Rose 1999).

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DISCUSSION

A. IYUDIN: What one could expect as observational consequence of plasma turbulence development in a jet?

J.H. BEALL: First, in the γ-ray region, there would be a shift to higher energies of the peak in the spectrum as the spectrum of π^o-decays was attenuated for lower jet γ's (due to plasma-jet energy losses). Additionally, there will be time-dependent EUV lines correlated with γ-ray fluence and (perhaps) anti-correlated with γ-ray fluxes.