Chin. J. Astron. Astrophys. Vol. 3 (2003), **Suppl.**, 137–146
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

AGN Jet Interactions with the Intracluster Medium

J.H. Beall[1, 2, 3 ⋆], John Guillory[2], D. V. Rose[4], Sabine Schindler[5] and
S. Colafrancesco[6]

[1] E.O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC
[2] Center for Earth Observing and Space Research, School for Computational Sciences, George Mason University, Fairfax, VA
[3] St. John's College, Annapolis, MD
[4] Mission Research Corporation, Albuquerque, NM
[5] Institut für Astrophysik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria
[6] INAF - Osservatorio Astronomico di Roma, Monteporzio (Roma), I-00040, Italy

Abstract Clusters of galaxies contain large ellipticals near their cores. Elliptical galaxies in the centers of these clusters are often found to be the source of large-scale jets that propagate outward into the intracluster medium. These jets are thought to be produced by accretion-powered processes in the active galactic nuclei (AGN) at the centers of some giant ellipticals. In this paper, we discuss the origin of these jets and the likely consequences of their interactions with the intracluster medium in clusters of galaxies.

Key words: jets: active galaxies: intracluster medium

1 INTRODUCTION

Clusters of galaxies typically contain giant ellipticals near their centers. These giant ellipticals can be active galaxies, wherein processes in the elliptical's core produce extended jets.

Accretion onto a compact object represents the most plausible source for the power in many astrophysical settings, including AGN, because of the efficiency of the accretion process relative to the rest mass energy of the object. This is so, somewhat surprisingly, even though the nuclear force is the strongest force and gravity is the weakest. The kinetic luminosity released by accretion is

$$dE/dt \sim (GM(dm/dt))/r\,, \tag{1}$$

where M is the mass of the compact object, G is the gravitational constant, dm/dt is the accretion rate, and r is the radius at which the energy is released.

The escape velocity, v, is related to the mass of the attracting body by

$$(1/2)mv^2 \sim GMm/r, \tag{2}$$

⋆ E-mail: `beall@sjca.edu`

and for a compact object, $v \sim c$, i.e., the speed of light. Therefore,

$$dE/dt \sim \eta(1/2)(dm/dt)c^2\,, \tag{3}$$

where η is an efficiency factor usually taken to be $\sim 10\%$, and c is the speed of light. The efficiency for nuclear reactions is $\sim 1\%$. Of course, accretion-powered sources include astrophysical jets.

2 ASTROPHYSICAL JETS

The more detailed the observations of astrophysical sources, the more that jets seem to appear, to the point where they have become commonplace in astrophysics (see, e.g., Beall 2003 for a review). Jets appear to occur in the highly energetic, bipolar flows in star-forming regions (see, e.g., Panagia 2001, Vittone 2001, and Lovelace, Romanova, and Contopoulos 1997), in the Crab Pulsar (which appears to be a conical "jet" of relativistic electrons and positrons - see, e.g. Massaro 2001), and in galactic microquasars, (i.e., relativistic galactic jets, including SS433 and other systems - see, e.g., Mirabel et al.'s 1992 discussion of 1E1740.7–2942; Cui 2002; Parades 2002). It appears that even the cores of normal galaxies contain baby quasars. This is of course a thesis that Geoff Burbidge (1956) posed when the study of AGN was in its infancy.

Good reviews of these issues have been presented in a number of talks in the prior Vulcano workshops, including Catanese (2002) and Sambruna (2002), as well as the talks by Wei Cui (2002) and Steve Eikenberry (2001). Wolfgang Kundt (1987, 2002) has presented an informative discussion of $e^{+/-}$ flows of leptonic jets.

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

It is intriguing to note the relationships between the various classes of sources that show jet-like phenomena. In a prior workshop in 1999, 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).

3 ENERGY TRANSPORT ISSUES

Jets of material moving at relativistic speeds maintain this state as they propagate through enormous interstellar distances. This fact is manifest from observations.

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 extended radio structures in that source. Felten (1968) also 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. Rose et al. (1984, 1987) and Beall (1990) have confirmed these propagation distances even in the face of our current understanding of two-stream plasma processes.

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

in radio lobes. The total energy for relativistic electrons producing the synchrotron radiation in the giant radio lobes of Centaurus A is $\sim 10^{60}$ erg.

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.

Eichler (1979) first suggested that neutrino detectors could be probes of the very cores of AGN. The successful construction of the next generations of sensitive neutrino detectors could 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, based on the assumption of isotropy. In the presence of jets, however, the more realistic assumption may be an anisotropic production of neutrinos, and such a calculation is, therefore, likely to be quite informative.

Beall (1990) has noted that plasma processes can slow the jets rapidly, thus truncating the low-energy portion of the γ-rays 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.

4 ACTIVE GALAXIES

The family tree or zoo of active galaxies includes many varieties, including Seyferts and ellipticals. There is considerable evidence for jets in many of these sources.

Short radio jets have been detected in many Seyfert galaxies. Such jets appear double-sided on scales of tens of parsecs, but are one-sided on parsec scales. Any number of papers in the literature note the details of these (see, e.g., Ulvestad et al. 1999, Bower, G. et al. 1995, Hardt et al. 1998, Roy et al. 2001, and Falcke, Markoff, and Biermann 2001). A search of the ADS abstracts (http://adsabs.harvard.edu) yielded 1200 + entries under jets + Seyferts! On average, central luminosity of these sources is the same, but Seyferts are (relatively) radio-quiet compared to their output at other frequencies.

One-sided jets are believed to be caused by bulk relativistic flows, while two-sided jets are usually considered sub-relativistic. The transition from one-sided to two-sided jets within $\sim$ 10s of parsecs suggests a rather efficient mechanism for decelerating the jets (see, e.g., Beall 1990).

Elliptical galaxies 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.

The nearest active galaxy, the radio galaxy NGC 5128 (Centaurus A at 5 Mpc distance), 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. (1991) 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 the constellation of Leo) bears a similarity to BL Lac objects (see Tsvetanov et al, 1998). Along with Cen A, M87, 3C273, and perhaps 3C390.3, it shows evidence of jets in radio, IR, optical, and x-rays. Of course, the recent work from Sambruna (2001) has increased the number of detected x-ray jets substantially.

The 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 outward to form giant, double radio lobes that extend for kiloparsecs.

Kameno et al. (2001) show a dense plasma torus around the nucleus of NGC 1052. The torus is compact and absorbs (free-free?) VLBI radio blobs. Kleijn et al. 2001 shows 21 FR I galaxies with 19 dust lane detections (HST/WFPC2) and radio jets roughly perpendicular to dust lanes. These observations all suggest that jets can transport outward the energy acquired by accretion in the core of the galaxy. The plausible transport mechanism is via milli-arcsecond jets to parsec-scale jets and in some cases to kiloparsec-scale lobes. Since giant ellipticals are present at the bottom of the potential well of clusters of galaxies, the presence of the jet can significantly effect the energetics of the intracluster medium.

Scott et al. (1980) first suggested that plasma turbulence from jets propagating through an intracluster medium could produce significant heating of the gas therein. The work of Rose et al. (1984, 87) uses a time-dependent calculation of the wave energy levels produced by such a scenario. Benchmarking of the wave population code using a PIC code (Rose et al. 2001) has confirmed the original Scott et al. hypothesis and has helped to define the precise heating rates that may obtain. At all events, a significant, non-thermal effect from jets from AGN, operating in the gas of the intracluster medium, must be considered as a possible energy source in any modeling of gas temperature and density. Shock heating is also a possible mechanism for heating of the intracluster gas (see, e.g., Inoue and Sasaki 2001).

5 THE ORIGIN AND CONSTITUTION OF THE JETS

As noted earlier, the energy that drives the jets in AGN and quasars must come from an accretion process. Yet the details of the acceleration mechanism (or mechanisms) are remarkably difficult to ascertain. For a review of possible acceleration processes, (see, e.g., MacDonald, Thorne, Price, and Zhang, 1986), accretion-disk-threaded B-fields (see, e.g., Lovelace et al. 2002, and Blanford and Znajek 1977); plasma processes (Subramanian, Becker, & Kazanas, 1998); and relativistic shocks (see e.g. Begelman & Kirk 1990, Ostrowski 2002).

The constitution of the jets is equally controversial. Henri, Pelletier, and Roland 1993 have argued that the γ-ray emission of active galactic nuclei can be interpreted as a signature of electron-positron beams. Xie, Liu, and Wang (1995) suggest that relativistic e^+/e^- jets can produce the observed spectra and variability in BL Lacertae objects. Hartman et al. 2001, in a multi-epoch, multiwavelength study of the spectral variability of the Blazar, 3C279, also sites electron-positron jets as a possible origin of the observed radiation.

On the other hand, a number of authors have considered the implications of hadronic jet models. For example, Rose et al. (1984, 1987) have discussed the effects of e^+/e^- and p/e^- jets interacting with interstellar clouds. Morrison, Sadun, and Roberts (1984) have also considered the observational signatures of hadronic jets interacting with interstellar clouds, while Dar and Laor (1997) calculated the possible hadronic jet production of TEV gamma-ray flares from blazars.

Bednarek and Protheroe (1999) have discussed γ–ray and neutrino flares produced by protons accelerated on an accretion disc surface in active galactic nuclei. Beall and Bednarek (1999) have also considered the observational effects of the hadronic jet model for gamma-ray production in blazars. Given the radically different propagation lengths that seem to obtain in Seyfert vs. elliptical galaxies, it is natural to ask whether or not the jets in Seyferts are the same as those in ellipticals.

From the point of view of energy transport, a natural hypothesis to explain the differences between jets in ellipticals and Seyferts would be that the jets in ellipticals have a mixed composition of hadrons and leptons, while jets in Seyferts have only leptons. A principle step 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?).

Multi-wavelength studies such as those undertaken by Hartman et al. (2001), for the Blazar, 3C279, and the studies reported by Sambruna (2001) and Catanese(2001), and by Sikora and Madejski (2001) can help to answer these questions. But the definitive determination of the early acceleration of hadrons may come only with the detection of neutrino radiation from these sources.

6 ENERGY LOSS PROCESSES

There are a number of well-known loss mechanisms that extract energy from moving particles. Here, we discuss both collisional and collisionless processes.

6.1 Particle Energy Loss Mechanisms

Estimates of particle-particle and particle-photon energy losses can be obtained from a perusal of Jackson (1962).

For a particle traversing a gas of density N with Z electrons/atom, the energy loss is given by

$$dE_{\rm coll}/dx = -4\pi NZ(z^2e^4/mv^2)\ln B,\ \ {\rm erg/cm}\,, \tag{4}$$

where $B = \gamma^2 mv^3/ze^2\omega$, $\gamma = E/mc^2$, ω is a characteristic atomic frequency, m is the mass of the electron, N is the number of atoms per unit volume with charge Z, e is the electron charge, and ze is the charge of the incident particle.

Non-relativistic Bremsstrahlung losses can be estimated by

$$dE_{\rm non-rel-rad}/dx = -(16/3)NZ^2(e^2/\hbar c)(z^4e^4/Mc^2)\,, \tag{5}$$

where $e^2/\hbar c$ is the fine-structure constant, M is the mass of the incident particle, and ze is the charge of the incident particle..

By way of comparison, we note that for relativistic bremsstrahlung, the loss in erg/cm is

$$dE_{\rm rel-rad}/dx = -(16/3)NZ^2(Z^2e^2/\hbar c)(z^2e^2/Mc^2)^2\ \ \ln(b)\ \gamma Mc^2, \tag{6}$$

where $b = 192\lambda M/mz^{1/3}$, M is the mass of the incident particle, ze is the charge of the incident particle, m is the mass of the electron, Ze is the total charge of the scattering nucleus, N is the number density of the scattering centers, and λ is a quantum-mechanical factor of order unity.

It is interesting to note that the equation above has the form

$$dE/dx = -E/Xo. \tag{7}$$

There are two more collisional energy loss mechanisms relevant to our discussion: synchrotron and inverse Compton losses. Schott (1912) shows the energy loss of a particle due to the synchrotron mechanism as

$$dE_{\rm sync}/dx = -(2e^4/3m^2c^4)\gamma^2H^2\,, \tag{8}$$

where H is the magnetic field intensity. This equation can be rewritten as

$$dE_{\rm sync}/dx = -(8\pi/3)\sigma_T\gamma^2u_H\,, \tag{9}$$

with u_H expressing the energy density of the magnetic field. Written in this form, the expression for the energy loss associated with synchrotron emission is similar the the energy loss formula for inverse Compton scattering, which is (Felten and Morrison 1986)

$$dE_{ic}/dx = -\sigma_T \gamma^2 u_{\rm ph}, \tag{10}$$

where σ_T is the Thompson cross-section and $u_{\rm ph}$ is the photon energy density of the radiation field.

It is helpful to note that the output frequency of the scattered photon in the inverse Compton process is

$$\nu_f \sim \gamma^2 \nu_i \,, \tag{11}$$

and depends on the scattering angle of the photon-electron interaction. Blue and Red Blazars are thought to arise from the differing input frequency, ν_i, in this process. In addition to radiative and collisional processes for electrons, hadronic interactions can play a significant role for some observations. The propagation lengths associated with hadronic interactions is typically much longer than the scale lengths shown above. For nuclear cross-sections, the scale length can be written as

$$L_{\rm nuclear} = 1/\sigma_{pp} * n_p h \,, \tag{12}$$

where the nuclear collisional cross-sections are small compared to the electromagnetic cross-sections. In addition to the interaction of fast particles with other particles and radiation fields in the source, significant losses can occur by collective or plasma processes.

6.2 Collisionless (Plasma) Losses

Rose et al. (1984, 1987) suggest that the interaction of relativistic particles with dense interstellar clouds could account for the variability and flux of the hard x-ray and γ-ray sources in active galaxies, and discussed in detail the mechanisms of energy loss for a relativistic, low-density beam of electrons, electrons and positrons, or electrons and protons as it interacts with clouds in the BLR and NLR of AGN.

As the beam of relativistic particles deposits energy in the ambient medium via the generation of electrostatic plasma waves, a number of important physical processes are operant. The material in the jet cone or cylinder suffers intermittent acceleration as the two-stream instability generates regions of high electric field intensity which then further "sweep out" electrons (and eventually background atoms) from the region where the high electric fields are generated. These "cavitons" are low-density, microscopic structures that have a net motion with respect to the ambient medium. During the time when they form, evolve, and then collapse (much like a wave breaking on a shore), they transfer momentum to the ambient medium in the direction of the jet's motion.

In order to calculate the propagation length of the electron-proton jet described above, we model the interaction of the relativistic jet with the ambient medium through which it propagates by means of a set of coupled, partial differential equations which describe the growth, saturation, and decay of the three wave modes likely to be produced by the jet-medium interaction. First, two-stream instability produces a plasma wave, W_1, called the resonant wave, which grows initially at a rate $\Gamma_1 = (\sqrt{3}/2\gamma)(n_b/2n_p)^{1/3}\omega_p$, where γ is the Lorentz factor of the beam, n_b and n_p are the beam and cloud number densities, respectively, and ω_p is the plasma frequency, as described more fully in Rose et al. (1984).

$$dE_{\rm plasma}/dx = -(1/n_b v_b)(d\alpha\epsilon_1/dt), \tag{13}$$

can be obtained by determining the change in γ of a factor of 2 with the integration

$$\int d\gamma = -\int [d(\alpha\epsilon_1)/dt]/(v_b n_b m^{'} c^2)\,, \tag{14}$$

as shown in Rose et al., 1978 and Beall 1990, where $m^{'}$ is the mass of the beam particle. Thus,

$$L_p = ((1/2)\gamma c n_b m c^2)/(d\alpha\epsilon_1/dt)\,, \tag{15}$$

is the characteristic propagation length for collisionless losses for an electron or electron-positron jet, where $d\alpha\epsilon_1/dt$ is the normalized energy deposition rate (in units of thermal energy) from the plasma waves into the ambient plasma. In many astrophysical cases, this is the dominant energy loss mechanism.

Plasma effects can also have observational consequences. For example, Beall and Bednarek (1999) note that collisionless processes can change the output spectrum of hadronic and inverse Compton interactions.

7 JET INTERACTION WITH THE INTRACLUSTER MEDIUM

The hypothesis of jets from AGN interacting with the intracluster medium via collisionless (plasma) processes requires that the jets overcome collisional and collisionless losses and propagate to significant distances into the intracluster medium. This in turn allows us to constrain the jet parameters as the jet emerges from the elliptical AGN. In general, the jets must have values of γ, the ratio of the total particle energy over the particle rest mass, that are at least rather relativistic over a significant fraction of their propagation length.

An analysis of the energy loss due to plasma processes, taken from Equation 15, and the computer simulations that determine $(d\alpha\epsilon_1/dt)$, the average wave energy deposition into the ambient medium per unit time, yields some useful bounds for possible energy deposition rates due to plasma processes.

We can further constrain the jet parameters by expressing the kinetic luminosity of the jet as

$$P_b = dE/dt = \gamma m c^2 n_b v_b \pi r_b^2, \tag{16}$$

where γ is the ratio of total energy to rest mass energy, mc^2 is the rest mass energy of the beam particles, v_b is the beam velocity, and r_b^2 is the beam radius.

If the beam is significantly heated by the jet-cloud interaction, the beam will expand transversely as it propagates, and will therefore have a finite opening angle. These "warm beams" result in different growth rates for the plasma instabilities, and therefor produce somewhat different propagation lengths. A "cold beam" is assumed to have little spread in momentum. The likely scenario is that the beam starts out as a cold beam and evolves into a warm beam as it propagates through the ambient medium. This scenario is clearly illustrated by the Particle-In-Cell (PIC) simulations we have used to benchmark the wave population codes appropriate for the astrophysical parameter range (see, e.g., Beall, Guillory, and Rose 1999).

Assuming that the ambient medium is also significantly heated by the jet (at some late times in the history of the interaction), the ambient medium will have in effect a two temperature distribution (see, e.g., Beall, Guillory, and Rose 1999). The effect of the jet-cloud interaction is to produce a high-energy tail on the thermal distribution of the cloud. This high-energy tail critically enhances the Landau damping rate of waves in the plasma.

Some examples may prove helpful. For a cold beam with a beam radius, $r_b = 3 \times 10^{19}\,\mathrm{cm}$, the temperature of the ambient medium, $T_c = 1 \times 10^4\,\mathrm{K}$, a high-energy tail temperature, $T_h = 1 \times 10^5\,\mathrm{K}$, a hot tail fraction, $f_h = 0.10$, $\gamma = 100$, $n_b = 0.001$, and $n_p = 0.01$, the propagation length for an electron-proton jet, $L_{pe-} = 9 \times 10^{20}$ cm (i.e., $\sim$ 300 pc), and an energy deposition rate, $dE/dt = 3.6 \times 10^{-15}$ erg cm^{-3} s^{-1}. For the same parameters, but with $n_p = 0.1$, $L_{pe-} = 7 \times 10^{19}$ cm (i.e., $\sim$ 20 pc), and $dE/dt = 2.4 \times 10^{-15}$ erg cm^{-3} s^{-1}.

For a warm beam with a beam radius, $r_b = 3 \times 10^{19}$ cm, the temperature of the ambient medium, $T_c = 1 \times 10^4$ K, a high energy tail temperature, $T_h = 1 \times 10^5$ K, a hot tail fraction, $f_h = 0.10$, $\gamma = 100$, $n_b = 0.001$, and $n_p = 0.01$, the propagation length for an electron-proton jet, $L_{pe-} = 9 \times 10^{20}$ cm (i.e., $\sim$ 300 pc), and an energy deposition rate, $dE/dt = 3.4 \times 10^{-15}$ erg cm^{-3} s^{-1}.

For the same parameters, but with $n_p = 0.1$, $L_{pe-} = 1 \times 10^{20}$ cm (i.e., $\sim$ 30 pc), and $dE/dt = 2.4 \times 10^{-15}$ erg cm^{-3} s^{-1}. With these parameters, the energy deposited in the volume through which the jet propagates can be of order 10^{44} erg s^{-1}.

8 CONCLUDING REMARKS

If jets are hadronic (a scenario that would help with the energy transport problem), then they probably also have a significant e^+/e^- component that will "fill in" to account some of the observed radiation. Furthermore, the detection of neutrinos from jet sources would directly suggest an hadronic component at relativistic (i.e. early) stages of jet formation. Such an hypothesis is consistent with Eichler's (1979) suggestion of using neutrinos as a probe of AGN.

Bednarek and Protheroe (1999) have calculated the likelihood of γ-ray and neutrino flares produced by protons accelerated on an accretion disc surface in active galactic nuclei, while Waxman and Bahcall (1998) have estimated the neutrino flux from AGN based on the assumption of isotropy of neutrino emission. A fully anisotropic calculation of the neutrino flux from a jet-cloud scenario will be of considerable interest. In this regard, neutrino instruments are coming online (see, e.g., Gaisser, Halzen, & Stanev 1995, and Frichter, Ralston, & McKay, 1996, and Halzen 1998.

Jets from active elliptical galaxies in the cores of clusters can provide a significant source of energy that may contribute to the dynamics of the intracluster medium. This source of energetics bears further study in our efforts to understand the dynamics of clusters.

References

Beall et al., 1978, ApJ, 219, 836

Beall J. H., Rose W. K., 1981, ApJ, 238, 539

Beall J. H. *On the Physical Environment in Galactic Nuclei*, NASA Technical Memorandum 80569, NASA Goddard Space Flight Center, Greenbelt, MD

Beall J. H. and Bednarek W., 1999, ApJ, 510, 188

Beall J.H., Guillory, J., & Rose, D.V., 1999, *Journal of the Italian Astronomical Society*, 70, 1235

Beall J.H., 2003, these proceedings

Bednarek, W. and Protheroe, R. 1999, MNRAS, 302, 373

Begelman, M.C. and Kirk, J.G. 1990, ApJ, 353, 66

Begelman, M.C., Blandford, R.D., and Rees, M.J. 1984, MNRAS, 56, 283

Bower, G. et. al 1995, ApJ, 454, 106.

Blanford, R.D. and Znajek, R. 1977, MNRAS, 179, 433

Blundell, K., et al. 1999, ApJ, 468, L91

Burbidge, G. 1956, ApJ, 124, 416

Catanese, M., et al. 2002, *Journal of the Italian Astronomical Society* 72, 116

Cui, W. 2002, *Journal of the Italian Astronomical Society*, 72, 272

Dar and Laor, 1997, ApJ, 478, L5

Eichler, D. 1979, ApJ, 232, 106

Eikenberry, S., 1999, *Journal of the Italian Astronomical Society*, 70, 1223

Falcke, H., Markoff, S., and Biermann, P. 2001, PASP, 227, 56

Feigelson E. et al 1991, ApJ, 251, 31

Felten, J. 1968, ApJ, 151, 861

Frichter, Ralston, and McKay, 1996, *Phys Rev D*

Gaisser, Halzen, and Stanev, 1995, *Phys. Rev* **258**, 173

Halzen, F. 1999, *Nucl. Phys. Proc. Suppl.* **77**, 474-485

Hardee, P. 1987, ApJ, 318, 78

Hardt et al 1998, A&A, 340, 35

Hartman, et al. 2001, ApJ, 558, 583

Henri, Pelletier, and Roland 1993, ApJ, 404, L41

Inoue, S. and Sasaki, S. 2001, ApJ, 562, 618

Jackson, J.D. 1962, *Classical Electrodynamics*, (John Wiley & Sons, Inc., New York)

Kameno, S. 2001, PASJ, 53, 169

Kundt, W. 2002, *Journal of the Italian Astronomical Society: Proceedings of the Vulcano Workshop*, in press

Kundt, W., 1987, In *Astrophysical Jets & Their Engines: Erice Lectures*, ed. W. Kundt (Reidel: Dordrecht. Netherlands), 1

Lovelace, R., Li, H., Koldoba, A. V., Ustyugova, G. V., and Romanova, M. 2002, ApJ, 572, 445

MacDonald, Thorne, Price, and Zhang 1986, *The Membrane Paradigm* (Yale: Thorn, Price, and MacDonald, eds), 121

Melia and Konigl, 1989, ApJ, 340, 162

Mirabel et al. 1992, Nature, 358, 215

Morrison, P., Sadun, A., and Roberts, D. 1984, ApJ, 280, 483

Ostrowski, M. 2002, *Journal of the Italian Astronomical Society*, 72, 387

Panagia, N. 2002, *Journal of the Italian Astronomical Society*, 72, 88

Parades, J. 2002, *Journal of the Italian Astronomical Society*, 72, 330

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

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

Sambruna, R., et al. 2002, *Journal of the Italian Astronomical Society*, 72, 181

Subramanian. P., Becker, P., & Kazanas, D. 1999, ApJ, 552, 209

Tsvetanov, et al, 1998, ApJ, 293, L83

Ulvestad et al 1999, ApJ, 516

Vittone, A., et al. 2002, *Journal of the Italian Astronomical Society*, 72, 232

Waxman, E. and Bahcall, J. 1998, *Phys. Rev. D.*, 59, 023002

Xie, Liu, and Wang, 1995, ApJ, 454, 50

FRED LAMB: Are there situations in which the magnetic field in the jet is strong enough to affect its interaction with the surrounding medium, perhaps even changing it from a beam-target interaction to a hydromagnetic interaction?

JIM BEALL: In some circumstances, this is clearly a possible evolution for the jet-cloud interaction. The model I have presented here assumes that the magnetic field is co-linear with the jet axis. The PIC simulations we have done for this scenario show that this configuration suppresses some of the beam filamentation instabilities. Even without this, the propagation length shown in the PIC simulations is in good agreement with the L_p calculation from the plasma wave model, albeit in rather different parameter ranges. A transverse magnetic field tends to produce a hydromagnetic interaction, at least initially.