Beam Induced Line Emission in the Broad Line Region of AGN

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ABSTRACT. Models of the Broad Line Region (BLR) of Active Galactic Nuclei (AGN) require dense, photoionized clouds in orbit around a central, compact object to generate the observed optical and UV line radiation. In this paper, we calculate the effects associated with the passing of a relativistic jet through the BLR clouds. We show that plasma processes can slow the jet, transfering significant momentum and energy to the ambient medium. One of the consequences of this transfer of energy to the ambient medium is the formation of high-energy tails on the Maxwell-Boltzmann distribution of the electrons in the gas. For a gas temperature of 1 eV ($10^4 K$), the tails can have an effective temperature of 100 eV. Therefore, these non-Maxwellian, high-energy tails must readily ionize the gas in the ambient medium, and will significantly change the ionization rates predicted by any thermal model. We present a preliminary calculation of changes in line emission obtained with and without the presence of a relativistic jet for parameters appropriate to the BLR. We also present a calculation which shows that the total line luminosity generated by a relativistic jet can be of the same order as that obtained from observations of the BLR.

1. Introduction

We have discussed the details of observations of the Broad Line Region (BLR) of Active Galactic Nuclei (AGN) in a previous proceedings of this series of conferences (Beall and Guillory 1994). In that paper, we have also made arguments for the presence of relativistic jets in some (and perhaps all) AGN. Here, we provide a synopsis of those arguments, which show that relativistic jets in the cores of AGN have important observational consequences.

The emitting region in active galactic nuclei (AGN) remains an important area of study. The cores of AGN appear to contain a central, massive black hole which indirectly produces the observed radiation via accretion disks. The disks are likely to produce IR, optical, UV, and X-ray radiation. Some models for very high temperature disks around massive black holes use Comptonization of disk photons in a hot disk corona to produce the γ-ray emission observed by the Compton Gamma Ray Observatory's OSSE instrument. To produce the very high energy γ-ray emission observed by the CGRO's EGRET instrument, a number of authors have proposed that jets of material moving at relativistic velocities interact with the ambient medium in the AGN's central region.

Bulk relativistic motion is also suggested by VLBI radio data which show super-luminal expansion on scales of parsecs in some sources.

In at least 10% of AGN, the accelerating region produces collimated jets of material that extend for distances of 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 "jets," but a brighter central source. The 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.

Most of the sources discussed above have Broad Line Regions (BLRs) and Narrow Line Regions (NLRs) in their cores. Type II Seyferts are thought to have a BLR obscured by a torus of material which probably feeds the accretion disk, while BL Lac objects are believed to be the consequence of our looking "down the barrel" of the jet. The consequent Doppler boosting of the beamed emission from the jet obscures our observations of the BLR and NLR of those sources. Thus, it is possible that all AGN have a BLR and NLR.

The hypothesis that all AGN contain a BLR and NLR is likely to be critical to any "unified" model of AGN phenomena. Likewise, a unified model must either explain why some AGN accretion disks produce relativistic jets while others do not, or we must posit that the jets emerge from the accelerating region in all AGN, but are stopped (in 90% of the cases) within a few parsecs, while in 10% of the objects they are capable ultimately of producing the kiloparsec scale supersonic flows.

Plasma processes may explain the different propagation lengths between the two classes of sources (Radio Bright and Radio Quiet). Collisionless plasma processes are the dominant energy loss mechanism for a relativistic jet interacting with an ambient medium for parameter ranges appropriate to the BLR of AGN (Beall 1990). As we show in this paper, plasma processes provide efficient mechanisms both for decelerating the relativistic charged-particle beam and for producing high energy tails on the Maxwell-Boltzmann distribution of the plasma electrons.

We show in this paper that such beams can produce line emission luminosities of the same order as that observed, and that the ionization produced by the jets can significantly alter the line emission ratios from that expected via photoionization only. Therefore, beam-induced processes must be taken into account when modeling the BLR source parameters.

Shocks which are generated by the interaction of relativistic jets with the ambient medium do not preclude the processes we propose to study (see Kilkenny 1976 and Beall and Guillory 1994). Additionally, the presence of magnetic fields (both ambient fields and beam-generated self-fields) have very minor effects on the processes discussed herein.

We now turn to a discussion of the beam-induced processes in AGN.

2. Propagation Lengths of Jets in the Cores of AGN

From our previous large-scale computation of the energy deposition due to the nonlinear stage of the instabilities in the beam-plasma system (Rose et al. 1984, 1987, Beall 1990, Beall and Guillory, 1992, 1994), we have calculated the energy deposition lengths, Ł$_D$ of the relativistic beams in 1 eV ($T = 10^4 K$) plasmas of various densities. These beam propagation ranges are shown for e^+e^- jets in Figure 1 as solid lines for various values of n_b and γ. For purposes of comparison, we have also plotted range-density relations for the beam for inverse-Compton losses via thermal bremsstrahlung radiation in a 10^4 K plasma and relativistic bremsstrahlung.

Fig. 1. Beam Propagation Lengths for Plasma (Collisionless) vs. Other Loss Processes: The solid lines represent plasma losses through the two-stream instability for the indicated beam densities and γs, while the dashed and dash-dotted lines show losses for relativistic bremsstrahlung and inverse Compton losses off of thermal bramsstrahlung, respectively. Note that the dotted horizontal line is the propagation distance of 1 parsec

An examination of Figure 1 will show that plasma losses dominate over losses by inverse Compton scattering on a $10^4 K$ thermal bremsstrahlung, or relativistic bremsstrahlung for cloud densities $\leq 10^{10}$. For these parameter ranges and for jets with the kinetic energy capable of generating the kinetic luminosity of the BLR, plasma processes will slow e^+e^- beams significantly within the central parsec of the source. Therefore, the beams can contribute significantly to the energetics of the BLR (see, also, Rose et al. 1984, 1987, and Beall 1990).

3. Beam-Generated Line Luminosity in the BLR

For parameter ranges appropriate to the BLR, plasma effects represent the dominant energy loss mechanism for such beams. Initial calculations and laboratory plasma experiments demonstrate that relativistic beams can transfer momentum to the ambient medium and generate high-energy tails to the Maxwell- Boltzmann distribution of the electrons of the gas. These non-Maxwellian, high-energy tails further ionize the minority species (e.g. elements other than hydrogen and helium) in the ambient medium, and may prove to be the dominant source of line emission for at least some spectral regions. However, earlier estimates of these effects (Rose et al. 1984, 1987; Morales and Lee 1990) have not been made self-consistently, since the distribution function of the gas becomes non-Maxwellian with the generation of the high energy tails, and it is the distribution function which determines the growth rates and saturation levels of the operant plasma instabilities.

As we show in this paper, the relativistic beam's effect on the ionization and excitation rates of the ambient medium will produce line emission signatures in the optical, UV, and EUV observations of AGN.

As the beam of relativistic particles deposits energy into 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 periodic acceleration as the two-stream instability generates regions of high electric field intensity which then further "sweep out" electrons from the region of the caviton. These "cavitons" are microscopic, pancake-shaped structures that have a net motion with respect to the ambient medium. During the time when they form, evolve, and then collapse, they transfer energy to electrons of the medium and transfer momentum to the ambient medium in the direction of the beam motion.

The high-frequency component of the caviton electric field interacts with electrons in the ambient medium in a manner that changes the electron velocity distribution of the gas, producing a high-energy tail. **It is this high-energy tail on the Maxwell-Boltzmann distribution of the ambient gas that is the remarkably efficient new mechanism we propose for enhancing ionization in the Broad Line Regions of AGN**. In addition, the high-energy tail on the distribution can decrease the growth rate of the parametric (oscillating two-stream) instability that generates the cavitons (Freund, Smith, Papadopoulos, and Palmadesso 1981) and thus affects the heating rate of the beam upon the plasma, and the resulting cooling rate via inelastic processes and radiation transport.

4. Enhancement of the Tail of the Electron Velocity Distribution, $\mathbf{f}_e(v)$

The steady-state energy spectrum of electrons in an optically thin photoionized plasma depends on its optical depth, on the ionizing photon spectrum, on the abundance of different elements in the plasma, and on the steady-state degree of ionization (including multiple ionization) and excitation of the plasma elements. In astrophysical plasmas where recombination rates are low and UV photon fluxes high, H and He are often fully stripped while heavier elements are multiply but not completely ionized. When ionized hydrogen predominates strongly enough that all other elements contribute a negligible fraction of the electrons, the electron energy spectrum in steady state is determined by (a) the photoelectron spectrum generated by the photons, (b) electron heating, thermalization, and cooling processes, including inelastic collisions with minority-species ions, and (c) electron loss processes, e.g. boundary and gradient effects (neglected here) and recombination.

If for example we use the values associated with the Kwan and Krolik two-phase model of the BLR, the local environment through which the beam propagates could have a range of densities, from that of low density interstellar matter to clouds of much higher density. In the densest regions, the electron density is governed by a balance between ionization (by photons and electrons) and radiative recombination (Elwert 1952, Kallman et al., 1992). The generation of this ionization is assisted by the development of high-energy tails via the interaction of the relativistic jet with the ambient medium. Therefore, the detailed results of the usual coronal equilibrium calculations do not apply for a low density plasma. It is necessary to compare the contributions of photoionization, shock heating, time-dependent cooling, and the interaction of the beam with the ambient medium over a wide range of parameters in order to determine which processes become dominant in a particular regime.

To demonstrate the necessity of such a complete calculation, we estimate the rate of energy deposition into the high-energy tail of the electron distribution, and thus the integrated line luminosity that the jet is able to produce. To do this, we note that the average power generated by the electric fields within each microscopic caviton is $de/dt = \int \mathbf{J} \cdot \mathbf{E} dV$, where the integral is over the volume of a single caviton, E is the time averaged electric field within the caviton, and J is the electron current density, which for our purposes is determined by the high-velocity portion of the distribution function of the gas as these electrons enter the caviton. For the lowest velocity electrons of the gas, the potential barrier produced by the parametric instability (the Oscillating Two-Stream instability) is likely to exclude them from being pumped into the high-energy tail of the distribution function (this assertion obviously needs to be confirmed by a fully self-consistent calculation). We may estimate the current density within the cavity as $J = 2q \int v f_e(v) dv$, where q is the electron charge and v is velocity with limits from v_{th} (the thermal velocity) to infinity, and we are interested in electrons that enter the caviton from either direction. This becomes a definite integral of the form $\int x e^{-x^2} dx = 1/2e$ from 1 to ∞, where we have ignored the effect of the potential of the caviton on the distribution function because we are considering in this estimate only the high-velocity portion of that function (i.e, a lower limit of integration of $x = 1$, roughly the thermal velocity). The volume of a caviton is parameterized in terms of Debye lengths as $V = (\alpha \lambda_D)^3$, and the caviton density is equal to the normalized wave energy density, W_1 (Rose et al. 1987). Thus, the rate at which energy is pumped into the high-energy tail of the distribution function of the gas, in regions where the beam propagates, is

$$de/dt = 2.7 \times 10^{-7} \alpha^3 T^4 W_1 n_e^{-3/2} ergs\ cm^{-3} s^{-1}.$$

For $T = 10^4 K$, $W_1 = 10^{-4}$ (Beall 1990), $\alpha^3 = 10^3$ in terms of Debye lengths^3, and $n_e = 10^8 cm^{-3}$, the deposited (and radiated) power density $de/dt = 2.5 \times 10^{-7}$ $ergs\ cm^{-3} s^{-1}$. For a jet with a diameter of order $10^{15} cm$ and a propagation length, L_p, of roughly a parsec (Rose et al.1987 and Beall 1990), the total volume is of order $2.7 \times 10^{49} cm^3$. Therefore, this order-of-magnitude estimate shows that relativistic jets can supply a luminosity of up to $5.9 \times 10^{42} ergs\ s^{-1}$ to the BLR. This is of the same order as the integrated line luminosity of some brighter BLRs (Krolik 1991). Relativistic jets can thus provide the power required to drive the BLR of AGN. We seek to determine whether they can reproduce the line spectra and detailed line emission fluxes (The reader should note that the above apparent scaling of density and temperature in the above equation is possibily misleading, since the wave energy, W_1, also is a non-linear function of these parameters). In addition to providing enough power to generate the integrated line luminosity for BLRs, momentum transfer from the energetic beam via plasma processes will accelerate the ambient medium (Beall 1990). It is possible that the velocity of the line emitting region thus produced can contribute to the effective Doppler broadening of the BLR.

5. Line Emission Generated from Beams in the BLR

It is possible to calculate the rate of growth and decay of cavitons in a plasma of known electron density traversed by an energetic charged-particle beam (Robinson, Newman, and Goldman 1988; and Zakharov 1972), and from that to infer a distribution of non-identical cavitons in a quasisteady state. The typical shape of the cavitons has also been computed (Robinson, Newman, and Goldman 1988; and Newman, Robinson, and Goldman 1989). The growth rate formulae for the plasma instabilities used to determine the quasisteady state wave energy levels can be modified to include the nonthermal electrons, but in the presence of the beam-generated instability, the nonthermal tail is a small perturbation on the whole distribution. We expect, therefore, that the current results we present are correct to within reasonable precision.

It is also relatively straightforward to generalize the calculations of excitation, ionization and recombination rates for an electron energy distribution which is not Maxwellian, provided the distribution is known (Lotz 1968), and also possible to calculate the depletion of the energetic region of a known electron distribution by these inelastic processes (although some cross-sections are not accurately known).

Typically for a thermal, optically-thin plasma with solar coronal abundances and electron temperatures well below 1 keV, the power in UV line radiation from incompletely-stripped trace elements exceeds Bremsstrahlung levels by more than an order of magnitude and is much more sensitive to temperature than is the Bremsstrahlung. As we will show later in this paper, **a 1% nonthermal hot 'tail' on the electron energy spectrum can lead to a very significant ($\leq 10^6$) increase in individual line intensities and more than factor of three increase in total radiated UV power. Plasma densities and thermal energy content inferred from observations by using a thermal model for the production of line emission and luminosity can thus be in error by orders of magnitude**.

We can calculate the average energy gain per ambient electron that enters a caviton as follows: The rate of change in electron energy with charge q in the electric field, E, of the caviton is $de/dt = qvE$, where v is the electron velocity. If we assume the velocity is of order v_{th} and the time within the cavity is dt=l/v, where l is the scale size of the caviton, which can be parameterized in terms of Debye lengths so that $l = \alpha\lambda_D$. Thus, $\delta E/kT = 2.83\alpha$. Typical sizes for the cavitons are of order $30 \times \lambda_D$, based on computer simulations. Thus $\delta e \sim 100$ eV.

We would thus expect enhancements of the line emission in the BLR of AGN from the presence of the jet, especially in the Extreme Ultraviolet (EUV).

To estimate the effect of such a hot, non-thermal tail on the emission from a photoionized cloud with parameters consistent with those of the BLR, we have modified the Kallman photoionization code, XSTAR, to include the effects of collisional ionization and excitation by by a small fraction (nominally 1%) of hot electrons at roughly 100 eV. The 1% figure is taken from our estimate of the fraction of thermal electrons capable of penetrating the initial potential distribution of the caviton. These conditions are probably typical of the nonlinear stage of the hot electron tail formed from the instabilities discussed herein. Superimposed on these collisional processes is photionization by the power-law spectrum from the central object (which we suppose to be a $10^{42} ergs\ s^{-1}$ central source with an E^{-1} powerlaw above 10 eV. Standard cosmic abundances are used. We compare in Table 1 the radiated power in selected lines for cases with and without the 100 eV electron tail to the 1 eV Maxwell-Boltzmann distribution of the gas. The results are shown for ambient plasma densities of $10^4 cm^{-3}$ and $10^{10} cm^{-3}$, a range

BLR Cloud with $T = 10^4$, and:

		Photo-ionization Only	Photoionization plus 1% hot electron tail
Cloud Density, $n_H = 10^4$			
	$\lambda\dot{A}$	Flux	Flux
Si_{vi}	83.83	$1.74\mathrm{x}10^{-5}$	$2.05\mathrm{x}10^{-5}$
	99.50	$4.40\mathrm{x}10^{-6}$	$1.54\mathrm{x}10^{-2}$
Fe_{viii}	98.52	$4.33\mathrm{x}10^{-7}$	$2.07\mathrm{x}10^{-3}$
O_{ii}	3729.9	$1.08\mathrm{x}10^{-7}$	$2.14\mathrm{x}10^{-8}$
Si_{ii}	4130.0	$1.67\mathrm{x}10^{-9}$	$3.76\mathrm{x}10^{-7}$
I(3800-6600$\dot{A}$)		$1.00\mathrm{x}10^{-3}$	$0.91\mathrm{x}10^{-3}$
Cloud Density, $n_H = 10^{10}$			
Si_{vi}	99.50	$5.26\mathrm{x}10^{-13}$	$2.66\mathrm{x}10^{-2}$
Fe_{viii}	98.52	$2.51\mathrm{x}10^{-8}$	$2.51\mathrm{x}10^{0}$
O_{ii}	3730.00	$2.55\mathrm{x}10^{-4}$	$6.48\mathrm{x}10^{-4}$
Si_{ii}	4130.00	$3.75\mathrm{x}10^{-4}$	$5.44\mathrm{x}10^{+3}$
I(3800-6600$\dot{A}$)		$1.36\mathrm{x}10^{+2}$	$5.00\mathrm{x}10^{+3}$

TABLE I

Comparison of Photoionization-Only and Photoionization with Beam Models for a Relativistic Beam Interacting with a Cloud in the BLR. The line fluxes shown are representative of the changes that occur in the optical vs. EUV portions of the spectrum when a relativistic beam is present in the cloud. The table shows that with a beam-generated 100 eV high-energy tail on the 1 eV (10^4K) gas of the BLR cloud, the principal changes in the output flux are in the EUV, although for a high-density cloud, the integrated optical line luminosity can change significantly. This shows that where jets are present, models must take these effects into account to properly determine source parameters.

that may span the densities associated with the BLR and NLR. For the 10^4 case, the overall luminosity is nearly unchanged, but certain UV and soft x-ray lines, e.g., the Si_{vi} at $99.5\dot{A}$ and the Fe_{viii} at $98.52\dot{A}$ are increased by orders of magnitude. For the 10^{10}, these lines are also strongly enhanced, and the overall luminosity increases by an order of magnitude, but the energetic beam range is reduced.

The case for intense photon fluxes has been treated by a series of papers as part of the "two-phase medium" model. The work presented here shows, however, that the density and temperature estimates of the BLR are model dependent. The presence of non-thermal electrons generated by the beam-cloud interaction significantly changes the line emission signatures upon which the density and temperature estimates of the BLR and NLR depend.

It is obviously necessary to model a range of parameters to assess the implications of the models for the physical conditions in the emitting region. Parameters of importance include temperature and density of the ambient medium, the γ-factor of the beam and its density, the opening angle of the beam, the constitution of the beam, and the species abundances of the absorbing material. We also note that X-ray fluxes cause ionization in non- trivial ways by exciting or ionizing inner-shell electrons.

6. Conclusions

The following comments seem relevant:

1. The cores of at least some AGN contain a significant source of kinetic energy in the form of relativistic jets which are likely to propagate through the broad line regions (BLR) and perhaps the narrow line regions (NLR) of AGN. However, current models of the BLR and NLR ignore the contribution of these phenomena to the overall kinematics and radiation dynamics of the region.

2. The dominant energy loss mechanism for such jets is due to collective (plasma) effects. These plasma effects produce regions of microscopic, oscillating electric fields (so-called "cavitons") which both accelerate the ambient medium and produce non-thermal, high energy tails to the Maxwell-Boltzmann distribution of the plasma electrons. These high energy tails readily ionize and excite the ions of the ambient medium, thus producing additional line emission. We have made estimates of these effects which demonstrate that the beams can supply the integrated line luminosity of the BLR and alter the spectrum of emission lines from the medium. However, no self-consistent calculation of the consequences of these relativistic jets is available. If beams are pesent in the BLR, the picture we have of the source region temperatures and densities will change radically.

3. Calculation of the consequences of beams in the cores of AGN may yield estimates of beam parameters when compared to observed line fluxes. These beam parameters will be important elements in a consideration of any self-consistent model of the central regions of AGN.

References

Acosta-Pulido, J.A., Perez-Fournon, I., Calvani, M., and Wilson, A.S. 1990,*Astrophys. J.* ., 365,119.

Beall, J.H., and Guillory, J. 1994, "Jets in the Broad Line Region of AGN," pub. in Proc. of the Vulcano Workshop on Frontier Objects in Astrophysics and Particle Physics, F. Giovannelli and G. Mannocchi, eds., CNR/IAS, Frascati, Italy.

Beall, J.H., W. Bednarek, S. Karakula, W. Tkaczyk 1987, Proc. 20th Intnational Cosmic Ray Conference (Moscow: NAUKA).

Beall, J.H. 1990, "Energy Loss Mechanisms for Fast Particles in an Ambient Medium," in Proc. of 1989 NATO Workshop on Physical Processes in Hot Cosmic Plasmas, p. 341ff, W. Brinkmann, A.C. Fabian, and F. Giovannelli, eds. (Kluwer Publishers: Dordrecht).

Beall, J.H. and Rose, W.K. 1981, Ap.J. 238, 539.

Bednarek, W. and Calvani, M. 1991, Astron. and Ap., 245, 41.

Bednarek, W., Giovannelli, F., Karakula, S., and Tkaczyk, W. 1990, Astron. and Ap., 236, 268.

Begelman, M.C., Blandford, R.D., and Rees, M.J. 1984, Rev. Mod. Phys., 56, 283.

Bloom, S.D. and Marscher, A.P. 1991, Proceedings of the Compton Observatory Science Workshop, Annapolis, MD. (NASA Pub. 3137), Chris R. Shrader, Neil Gehrels, and Brian Dennis, eds.

Bochkarev, N.G., Shapovalova, A.I., Zhekov, S.A. 1991, Astr. J., 102, 1278.

Boryshev, Y.V., Babadzanyautz, M.K., and Belokon, Y. 1991, pub. in "Variability of BLAZARS," (Cambridge Univ. Press: London).

Bridle, A.H. 1984, in Physics of Energy Transport in Extragalactic Radio Sources, Proceedings of NRAO Workshop 9, A.H. Bridle and J.A. Eilek, editors.

Cawthorne, T.V. 1991, in "Beams and Jets in Astrophysics," (Cambridge University Press: New York), P.A. Hughes, ed.

Clavel, J. 1991 in "Variability of Active Galactic Nuclei," (Cambridge University Press: New York), H. Richard Millar and Paul J. Wiita, eds.

Crenshaw, D.M. and Blackwell, J.H. 1991in "Variability of Active Galactic Nuclei," (Cambridge University Press: New York), H. Richard Millar and Paul J. Wiita, eds.

David, L.P. and Durisen, R.H. 1989, Ap. J., 346, 618.

Davidson, K. and Netzer, H. 1978, Rev. Modern Physics.

Davis, R.J., Muxlow, T.W.B., and Conway, R.G. 1985, Nature, 318, 343.

Elwert, G. 1952, Z. Naturforsch.,7A,432.

Fabian, A. et al. 1986, MNRAS, 223, 29P.

Gaskell, C.M. 1988, Ap.J., 325, 114.

Gehrels, N. 1989, Proc. of IAU Symposium No. 34, Active Galactic Nuclei, Santa Cruz, CA., D. Osterbrock, ed. (Kluwer Publishers: Dordrecht).

Galvez, M. and Barnes, C. 1988, Phys. of Fluids, 31, 863.

Galvez, M. and Gisler, G.R. , "Electromagnetic computer simulations of collective ion acceleration by a relativistic electron beam", J. Appl. Phys. 69, 129 (1991).

Guillory, J. 1976, Parallel Injection of Intense Ion beam Pulses..., ERDA Panel on High Energy Ion Pulses for CTR Applications, May 1976.

Kafatos, M. 1973, Ap.J., 182, 433.

Kallman, T.R., Wilkes, B.J., Krolik, J.H., and Green, R. 1992, "Consistency of Spherical, Gravity Dominated Dynamics with quasar High Ionization Emission Line Profiles," NASA GSFC preprint.

Kallman, T.R. and Krolik, J.H. 1986, Ap.J., 308, 805.

Kallman, T.R. and Krolik, J.H. 1993, preprint.

Kilkenny, J.D. 1976, Plasma Physics, 18, 905.

Krolik, J.H., McKee, C.F., and Tarter, C.B. 1981, Ap.J., 249, 422.

Krolik, J.H. 1991, in "Variability of Active Galactic Nuclei," (Cambridge University Press: New York), H. Richard Millar and Paul J. Wiita, eds.

Lahav, O., Rowna-Robinson, M., and Lynden-Bell, D. 1988, MNRAS, 234, 677.

Leahy, J.P. 1991, in "Beams and Jets in Astrophysics," (Cambridge University Press: New York), P.A. Hughes, ed.

Newman, D.L., Robinson, P.A., and Goldman, M.V. 1989, Phys. Rev. Letters, 62, 2132.

Malkan, M.A. 1991, in "Variability of Active Galactic Nuclei," (Cambridge University Press: New York), H. Richard Millar and Paul J. Wiita, eds.

Morales, G.J. and Lee, Y.C. 1977, Phys. Fluids, 20, 1135.

Morales, G.J. and Maggs, J.E. 1990, "Kinetic Nonlinearities in Nonuniform Plasmas," published in Topical Conference of Research Trends in Nonlinear and Relativistic Effects in Plasmas, La Jolla, CA.

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

Muxlow, T.W.B. and Garrington, S.T. 1991, in "Beams and Jets in Astrophysics," (Cambridge University Press: New York), P.A. Hughes, ed.

Osterbrock, D.E. and Mathews, W.G. 1986, Ann. Rev. of Astr. and Ap., 24, 171.

Ottinger, P.F. and Guillory, J. 1979, Physics of Fluids, 22, 466 and 476.

Peterson, B.M. 1991, in "Variability of Active Galactic Nuclei," (Cambridge University Press: New York), H. Richard Millar and Paul J. Wiita, eds.

Piro, L., Massaro, E., Perola, G.C., and Molteni, D. 1988, Ap.J. Lett., 325, L25.

Rose, W.K., Guillory, J., Beall, J.H., and Kainer, S. 1984, Ap. J., 280, 550.

Rose, W.K., Beall, J.H., Guillory, J.H., and Kainer, S. 1987, Ap. J., 314, 95.

Roberts, Dana 1984, Ap.J., 285, 64.

Rosen, A. and Wiita, P.J. 1988, Ap.J., 330, 16.

Urry, C.M. 1989, proc. of BL Lac Objects: 10 Years After, L. Maraschi, ed.

Walker, R.C. 1984, in Physics of Energy Transport in Extragalactic Radio Sources, Proceedings of NRAO Workshop 9, A.H. Bridle and J.A. Eilek, editors.

Wardle, J.F.C. and Potash, R.I. 1984, in Physics of Energy Transport in Extragalactic Radio Sources, Proceedings of NRAO Workshop 9, A.H. Bridle and J.A. Eilek, editors.

Wiita, P.J. 1991, in "Beams and Jets in Astrophysics," (Cambridge University Press: New York), P.A. Hughes, ed.

Wilkes, B.J., and Elvis, M., 1987 Proc. of the Conf. on "Supermassive Black Holes," held at George Mason Univ., Fairfax, VA, Oct. 1986.

Willingale, R. 1981, MNRAS, 194, 359.

Wills, B., Netzer, H., and wills, D. 1985, Ap.J., 288, 94.

Zheng, W., Binette, L., and Sulentic, J.W. 1990, Ap.J., 365, 115.