Line Emission from Relativistic Jets

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ABSTRACT.
Line emission originating within the Broad Line Region (BLR) in AGNs (Active Galactic Nuclei) is usually modelled by the heating of dense clouds of interstellar gas with ultraviolet and x-ray light from the accretion disk of the massive black hole at the core of the AGN. Line emission in such a model can be modified significantly by the presence of relativistic jets interacting with BLR clouds, this because the jet-cloud interaction generates a high-energy tail to the thermal distribution of the gas. This high-energy tail is produced by plasma turbulence generated as the jet transfers momentum and energy to the ambient medium.

1. Introduction

Jets originating in the centers of active galaxies propagate outward to significant distances. It appears that such jets are ubiquitous. Furthermore, given observations of γ-ray fluxes from some sources (i.e., Blazars), it is plausible to assume that these jets are relativistic as they propagate through the Broad (BLR) and Narrow (NLR) Line Regions of Active Galactic Nuclei. Even Seyfert galaxies show attenuated jet-like structures in the radio-frequency band.

Line emission originating within the Broad Line Region (BLR) clouds in AGN can be modified significantly by the presence of relativistic jets propagating through those clouds. The presence of such jets militates against the assumption of the "thermal equilibrium" model (see, e.g., Osterbrock and Matthews, 1986, for a review). In this model, the observed line emission is produced by illumination of the BLR clouds by ultraviolet and x-ray radiation arising from the inner region of an accretion disk around a massive black hole. Because of the presence of jets, line intensity estimates obtained from thermal equilibrium models will be significantly modified. Therefore, estimates of BLR cloud temperatures and densities which are derived from comparing the thermal equilibrium models with observed line intensities, must also be emended. In this paper, we show the modifications of the BLR line emission that jets can produce.

2. The Cores of AGN

The cores of AGN appear to contain a central, massive black hole which indirectly produces some of the observed radiation via processes in the accretion disk surrounding the black hole. 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.

Sambruna et al. (1999), Catanese et al. (1999), and Kundt (1999) have presented (in these proceedings) 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 Krakula (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.

For parameter ranges appropriate to the BLR of AGN (i.e. low-density jets interacting with a high-density cloud, Beall (1990) has shown that "collisionless" processes represent the dominant energy loss mechanism for such jets. If jets are present in all AGN, plasma effects considered herein could provide a natural explanation for different features, including propagation lengths, in the various classes of sources.

3. Propagation of Relativistic Electron-Proton Beams Through Interstellar Clouds

Beall and Rose (1981), and Rose et al. (1984, 1987) first suggested 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 come to the fore. The material in the jet cone or cylinder suffers local 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. It is plausible that these 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 addition to the transfer of momentum to the ambient medium by the bulk motion of the cavitons and the electric fields contained within, a high-frequency component of the caviton electric field interacts with electrons in the ambient medium in a manner that changes the Maxwell-Boltzmann distribution of the gas electrons, producing a high-energy tail. This high-energy tail is a remarkably efficient mechanism for ionizing the gas in the jet-illuminated Broad and Narrow Line Regions of AGN (Beall and Guillory, 1996). In addition, the high-energy tail on the Maxwell-Boltzmann distribution can decrease the growth rate of the parameteric (Oscillating two-stream) instability (Freund, et al. 1980) and thus affects the heating rate of the beam upon the plasma, and the cooling rate via inelastic processes and radiation transport.

Propagation lengths of the $e^{+/-}$ and $e^{-}p$ jets have been discussed by Rose et al. (1984, 1987) and Beall (1990) using a model of the interaction of the relativistic jet with the ambient medium through which it propagates. This model consists of a set of coupled, differential equations which describe the growth, saturation, and decay of the three wave modes likely to be produced by the jet-medium interaction.

As the jet excites waves in traversing a background plasma, it loses energy and γ decreases. For an electron-proton beam the principal collisionless interaction is between the beam electrons and background plasma. Consequently, the beam electrons will tend to slow down with respect to the beam protons, and consequently, the beam protons will also lose momentum to the plasma interactions.

The propagation length Lp (i.e., the distance over which $\gamma = (1 - v^2/c^2)^{-1/2}$ decreases by a factor of $\sim 2) = (\gamma/2) v_b n_b m^{'} c^2 / < d\alpha e_1/dt >$, where $< d\alpha e_1/dt >$, the time average rate of excitation of the wave energy density, γ is the Lorentz factor of the jets, $m^{'}$ is the mass of the jet particles, and c is the speed of light (Rose et al. 1984). This estimate of jet propagation distances has been substantially confirmed by Particle-in-Cell (PIC) simulations (Beall, Guillory, and Rose, 1999).

In addition, the jet-cloud interaction heats the ambient medium of the cloud and produces a high-energy tail on the Maxwell-Boltzmann distribution of BLR cloud.

4. Formation of the High-Energy Tail in the BLR Cloud Gas

We have performed a bench-mark using a PIC code to confirm the propagation lengths given by the plasma wave model code. The sample PIC simulations we have carried out (Beall, Guillory, and Rose 1999) represent an upper limit to the current computational capabilities of PIC codes on an ORIGIN 2000 computer. This makes evident the utility of the plasma wave model for the calculation of jet-cloud iteractions for parameter ranges of astrophysical interest.

For the purposes of our benchmark, we chose an $e^{-/+}$ jet with $\gamma = 2$ interacting with an ambient medium of density $n_p = 10^1 \# cm^{-3}$. The beam density for this simulation is $n_b = 5x10^{-2}$, and the ambient plasma has an axial magnetic field, $B_o \sim 2.4x10^{-3} G$. This B-field serves to suppress a filamentation process in the beam, but does not otherwise affect the propagation length. We have chosen the plasma temperature to be equal to $T = 10^7 K$ to help minimize the compute-time for the PIC code simulations.

An examination of Figure 1a obtained from the PIC code simulations clearly shows the beginning development of the two-stream instability in the electron components

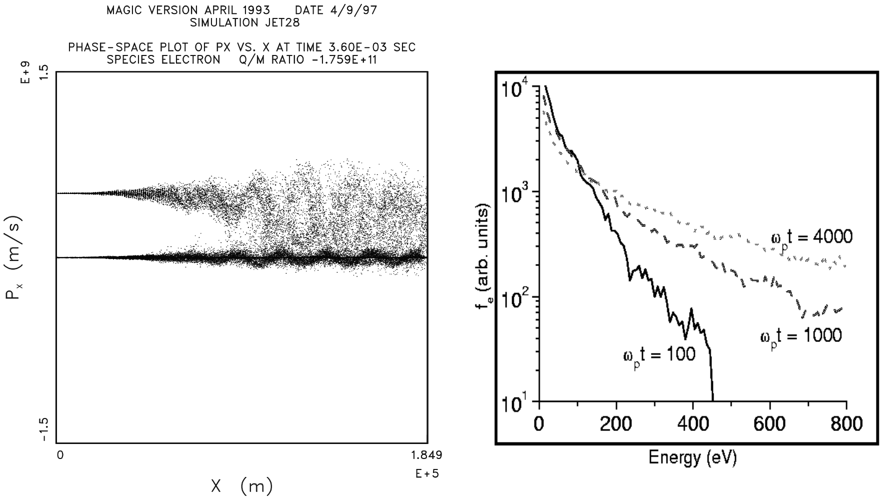

Fig. 1. Figure 1a shows the heating of the gas in the ambient medium as a jet of material propagates through it. The parameters for this bench-mark test are given in the text and in Beall, Guillory, and Rose (1999). For a similar parameter range, Figure 1b shows the development of the high-energy tail to the Maxwell-Boltzmann distribution of the gas in the ambient medium. It is this high-energy tail that produces the remarkable changes in the ionization rates that are responsible for the changes in the line emission from the gas.

of the relativistic beam and the heating and entrainment of the gas in the ambient medium. The length scale at which the jet begins to develop these significant effects is of order $L_p \sim 0.9x10^7 cm$. Note that the plot in the figure has units of meters. This is in agreement with the propagation length, $L_p \sim 0.5x10^7 cm$, for such a beam as determined from the plasma wave model.

It is also interesting to note that the PIC code simulations do not show the formation of a shock front (except perhaps a radial one at late times) in these simulations. Furthermore, while the beam reduces the density of the ambient medium by some small fraction during the PIC code simulations, the beam **does not** form an evacuated channel through the ambient medium. The collisional excitation of the ambient medium therefore can produce line species significantly different from those associated with a thermal distribution for the interstellar cloud (Beall, Guillory, and Rose, 1999).

We may calculate the average energy gain per ambient electron that enters a caviton as follows: The pressure exerted by the electric field in the caviton, $P_E = (1/3)E^2/8\pi$ for a randomly oriented electric field. This is in equilibrium with the gas pressure, $P_g = nkT$. Equating these, we solve for E to find that $E = ((8/3)\pi nkT)^{1/2}$. 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 $l = \alpha\lambda_D$, then $\delta E_{electron}/kT = 2.83\alpha$. Typical sizes for the cavitons are of order $30 \times \lambda_D$, based on computer simulations. Thus $\delta E_{electron} \sim 100$ eV.

Figure 1b shows PIC code results consistent with this analytical calculation. The evolution of the Maxwell-Boltzmann distribution of the gas electrons in the ambient medium, from 100 to 4000 plasma periods, is clearly demonstrated.

These data clearly show the heating of the ambient medium by the jet, and the development of the high-energy tail on the thermal distribution of the BLR cloud gas.

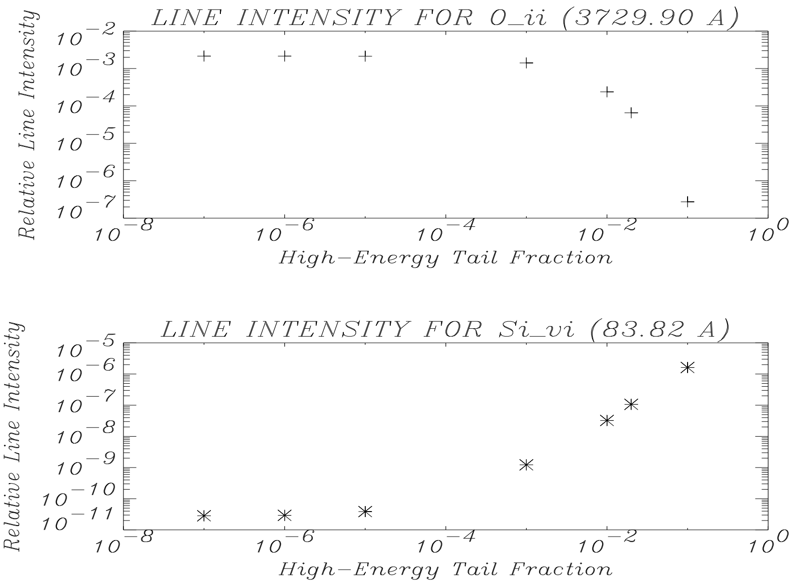

Fig. 2. Figures 2 a and b the evolution of the momentum space distribution along the propagation axis of the beam at somewhat later times than shown in Figure 5 as the jet propagates through the ambient medium. These data show clearly the energy loss of the beam to the ambient medium and the heating of the ambient medium by the relativistic jet.

A 1% non-thermal tail on the Maxwell-Boltzmann distribution of gas in the ambient medium can yield remarkably different line intensities. For example, with a cloud density, $n_H = 10^{10}$ and a temperature, $T = 10^4 K$, the line intensity for O_{ii} (3730.00) is $2.55x10^{-4}$ **without** a non-thermal tail, and $6.48x10^{-4}$ with a 100 eV non-thermal tail. With a thermal distribution, the silicon line Si_{ii} (4130.00) has a line intensity of $3.75x10^{-4}$, while with the 100 eV non-thermal tail, the silicon line has an intensity of $5.44x10^{+3}$. These calculations are obtained from our modification of the XSTAR code (Kallman and Krolik 1993) and are more fully discussed in Beall and Guillory (1996). To show the parameterization of the line intensity changes vs. the fraction of the ambient electrons in the high-energy tail, we note Figure 2, a and b, which shows the characteristic of a logistic supply curve for the lines indicated. This pattern is consonant with the changes in the occupation states of the electrons whose transitions produce the line radiation.

5. Comments

It is apparent from the PIC code simulations and analytical calculations that a jet of relativistic particles propagating through an ambient medium heats the electrons in that medium, and that a non-thermal, high-energy tail develops on the Maxwell-Boltzmann distribution of the electrons therein.

It is also of interest to note that the PIC code simulations do not show the formation of a shock front (except perhaps a radial one at late times) in these simulations. Furthermore, while the beam reduces the density of the ambient medium by some small fraction during the PIC code simulations, the beam **does not** form an evacuated channel through the ambient medium. The jet-driven collisional excitation of the ambient medium can therefore produce line intensities significantly different from those associated with an interstellar BLR cloud in the canonical model.

Since these jet-induced, non-thermal tails readily excite distinctly different line emission profiles from the gas, such signatures can provide an important indication of the presence of relativistic jets in some sources.

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