Constraints on supermassive black hole spins from observations of active galaxy jets

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We discuss the origin of the low-energy cutoff, or LEC, seen in the radio spectra of many extragalactic jets and relate this to the spin of the supermassive black holes that presumably power them. Pion decay via proton-proton collisions is a possible mechanism to supply a secondary positron population with a low energy limit. We expect that pion production would occur in advection dominated accretion flows or ADAFs. In radiatively inefficient ADAFs the heat energy of the accreting gas is unable to radiate in less than the accretion time and the particle temperature could be high enough so that thermal protons can yield such pion production. Strong starbursts are another option for the injection of a truncated particle population into the jet. The role of both mechanisms is discussed with respect to the black hole spin estimate. The energy demanded to produce the pion decay process involves a minimum threshold for kinetic energy of the interacting protons. Therefore the mean proton speed in the flow can determine whether a LEC is generated. In ADAFs the random velocity of the protons can exceed the minimum speed limit of pion production around the jet launching region in the innermost part of the flow. Finally we summarize the additional work needed to put the model assumptions on a more rigorous basis.

1 Introduction

It has been long argued that a high spin might be a necessary requirement for some of the extremely powerful relativistic jets in AGN (e.g., Blandford & Znajek 1977; Donea & Biermann 1996). Although the specific formulae differ substantially depending upon the jet launching model, the jet power in all of them depends very sensitively on the BH spin (Meier 2003; McKinney & Narayan 2007; Tchekhovskoy, Narayan & McKinney 2010). The converse does not hold: an observed high jet power does not necessarily imply a high spin. For such a conclusion it would be essential to know the mass of the central BH and its associated magnetic field at the base of the jet, which may or may not be maximal.

This begs the question: what other evidence is available for a high spin, apart from modeling jets? There are a number of radio galaxies for which the radio spectra suggest a low-energy cutoff or LEC in their energetic electron spectra (Leahy, Muxlow & Stephens 1989; Carilli et al. 1991; Celotti & Fabian 1993; Duschl & Lesch 1994). An attractive physical mechanism for this is pion decay resulting from proton-proton collisions (Biermann, Strom & Falcke 1995; Gopal-Krishna, Biermann & Wiita 2004), although alternative suggestions have been made (Lesch, Schlickeiser & Crusius 1988). Using hadronic interactions and pion production in a hot disk (Mahadevan 1998) to provide positrons from pion decay does require a relativistic temperature in the accretion disk near the foot of the jet. Such a high temperature is possible only in a low density disk, which is typical for an “advection dominated accretion flow” or ADAF. These ADAFs are commonly believed to describe the low accretion rate regime (Narayan & Yi 1994). The extremely high temperature, in turn, seems to require a BH angular momentum parameter above 0.95 (Falcke & Biermann 1995; Gopal-Krishna et al. 2004; Falcke, Malkan & Biermann 1995).

The mass of the pion created in proton hadronic interactions gives the minimum Lorentz factor of a final decay product, an electron or positron (Gaisser 1991; Stanev 2010). Thus the leptons emitting in radio galaxies might be predominantly secondary, having this low energy limit (Gopal-Krishna et al. 2004). As the 511 keV emission in the Galactic Center indicates, there can also be large positron production as a consequence of prodigious star formation and the ensuing supernova explosions (e.g., Biermann et al. 2010). The difference in radio spectra is in the temporal variability...
of a core; however, supernova explosions also show temporal variability in their non-thermal radio emission, but no relativistic motion except in the rare cases of a GRB.

A strong starburst may provide a possible alternative to explain the low energy cutoff in the cosmic ray lepton spectrum, although it obviously will never produce the brightness temperature of a compact relativistic jet. In the observed cosmic rays, the positron fraction is known to rise towards lower energies (Protheroe 1982; Adriani et al. 2009), which can be explained as interactions in the environment of massive stars (Biermann et al. 1991; Biermann 1998; Biermann et al. 2009; Biermann et al. 2010; Biermann et al. 2012); the model prediction is that the positron fraction increases as $E^{-5/9}$ toward lower energies. It is important to realize that such a model can only be verified with isotope ratios, since the influence of the Solar modulation can then be minimized. Normal Solar modulation affects isotope ratios, since the influence of the Solar modulation increases as $E^{-5/9}$ toward lower energies. It is important to realize that such a model can only be verified with isotope ratios, since the influence of the Solar modulation can then be minimized. Normal Solar modulation affects isotope ratios, since the influence of the Solar modulation can then be minimized. Normal Solar modulation affects isotope ratios, since the influence of the Solar modulation can then be minimized. Normal Solar modulation affects isotope ratios, since the influence of the Solar modulation can then be minimized.

## 3 Pion production in the ADAF

### 3.1 Proton energy: a key parameter

In proton-proton collisions the partial cross-section rises to a high peak for pion production, far above the partial cross-section for electron-positron pair production, and therefore we focus on pion decay electrons and positrons, which have a relatively high energy. At relativistic particle energies the collision of two protons typically yields a proton, a neutron and a positively charged pion. Pions decay further according to the process $\pi^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ or $\pi^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$, where the secondary positron population shows the LEC. At lower energies some hydrogen fusion occurs and as a consequence a primary positron population is formed. We are interested in the first case. A threshold energy for pion production comes from the conservation of energy, assuming two protons moving with equal and opposite velocities (then the total momentum is zero):

$$E = 2\gamma m_0 p c^2 = m_{0,p} c^2 + m_{0,n} c^2 + m_{0,\pi^+} c^2.$$ (1)

Substituting the rest mass of particles the above equality yields $\gamma = 1.08$ and $v = 0.37c$ in the relativistic frame. Using the relativistic velocity addition formula, it corresponds to $v_{p,\min} = 0.65c$ and $\gamma_{p,\min} = 1.31$ in the rest frame of one proton. Then a required minimum kinetic energy for the protons: $E_{\text{kin}} = \gamma E_{m_0,p} - E_{m_0,n} \approx 290 MeV$. We expect that the presence of such high proton kinetic energies would be a good indicator of an environment adequate to produce substantial pion production.

### 3.2 Advection Dominated Accretion Flows

A unified description of black hole accretion disks supplies four equilibrium solutions for the differentially rotating viscous flows (Chen et al. 1995). In the ADAF the heat energy is stored as entropy of the accreting gas, which leads to radiative inefficiency $\eta \equiv L/Mc^2 < 0.1$ (Narayan & McClintock 2008).

The ADAF solutions are characterized by extremely low density, large pressure and sub-Keplerian rotation. The gas has positive Bernoulli constant, which means it is not bounded to the central BH. Therefore if the orbiting matter reverses its direction in the flow it would reach infinity with a positive energy. This suggests that an ADAF likely generates powerful winds and relativistic jets. The observed radio and X-ray radiations of some low-luminosity AGNs and Fanaroff-Riley I type radio galaxies are explainable by using of a coupled jet plus an underlying ADAF (e.g., Yuan, Markhoff & Fulcke 2002; Yuan et al. 2002), which again suggests a connection between the jets and the ADAFs.
The gas density \( \rho \), its radial and angular velocities \( v \) and \( \Omega \) and the isothermal sound speed \( c_s \) change in the flow according to the differential equations presented below (e.g., Narayan & Yi 1994). They describe a two-dimensional, steady state, axisymmetric flow. The equations are vertically averaged and all variables of the flow motion have dependence just on their \( R \) coordinate (\( \partial / \partial \phi = 0 \), \( \partial / \partial t = 0 \) in the \( R \phi \) plane; \( \phi \) is the azimuthal coordinate). The continuity equation, radial and azimuthal components of the momentum equation and the energy equation, respectively are:

\[
\frac{d}{dR}(\rho RHv) = 0, \tag{2}
\]

\[
v\frac{dv}{dR} - \Omega^2 R = -\Omega_K^2 R - \frac{1}{\rho} \frac{d}{dR}(\rho c_s^2), \tag{3}
\]

\[
v\frac{d(\Omega R^2)}{dR} = \frac{1}{\rho RH R} \frac{d}{dR} \left( \frac{\alpha \rho c_s^2 R^2 H d\Omega}{\Omega_K} \right), \tag{4}
\]

\[
\Sigma v T \frac{ds}{dR} = \frac{3+2 \epsilon}{2} \frac{\rho H}{v} \frac{d^2 v}{dR^2} - 2c_s^2 H v \frac{dp}{dR} = Q^+ - Q^-. \tag{5}
\]

Here \( Q^+ \) measures the energy input per unit area (due to viscous dissipation) and \( Q^- \) is the outward flowing energy per unit area (due to radiative cooling). The left hand side of the energy equation (5) is the advected entropy and the energy equation in a compact form is \( Q^{adv} = Q^+ - Q^- \). As shown by Narayan and Yi (1994) these equations have self similar solutions in the form of scaling laws:

\[
v = -(5 + 2 \epsilon') \frac{g(\alpha, \epsilon')}{3 \alpha} v_K, \tag{6}
\]

\[
\Omega = \left[ \frac{2 \epsilon'(5 + 2 \epsilon') g(\alpha, \epsilon')}{9 \alpha^2} \right]^{1/2} \Omega_K, \tag{7}
\]

\[
c_s^2 = \frac{2(5+2 \epsilon') g(\alpha, \epsilon')}{9 \epsilon'^2} \frac{v_K^2}{v}, \tag{8}
\]

\[
g(\alpha, \epsilon') \equiv \left[ 1 + \frac{18 \epsilon'^2}{(5 + 2 \epsilon')^2} \right]^{1/2} - 1, \tag{9}
\]

where \( \epsilon = (5/3 - \gamma)/((\gamma - 1) \) is a parameter of the flow (\( \gamma \) is the ratio of specific heats, \( \gamma = 5/3 \rightarrow \epsilon = 0 \), \( \gamma = 4/3 \rightarrow \epsilon = 1 \)). The Keplerian velocity and angular velocity are denoted as \( v_K = (GM/R)^{1/2} \) and \( \Omega_K = (GM/R^3)^{1/2} \), respectively, where \( G \) is the gravitational constant and \( m \) is the central mass. Let \( f \) measure the degree of advection so that if \( f = 1 \), the total amount of the viscous heat is stored in the particles and this limit yields an extreme ADAF (\( Q^- = 0 \)). Whereas with \( f = 0 \) the radiative cooling is very effective and this limit yields an extreme thin disk solution. \( \epsilon' \equiv \epsilon / f \). All of these quantities are now expressed solely in terms of \( R, \alpha \) and \( \epsilon' \); the last two of these parameters are suitable for a description of the nature of the flow.

### 3.3 Speed limit around the jet launching region

Since \( \alpha^2 \ll 1 \) in ADAFs we can expand \( g(\alpha, \epsilon') \) in powers of \( \alpha \) and this yields

\[
c_s^2 \approx \frac{2}{5 + 2 \epsilon'} v_K^2. \tag{10}
\]

As the protons in the plasma are not significantly relativistic, we first assume that protons can be treated as an ideal gas to a decent approximation and particle speed is characterized by the Maxwell-Boltzmann distribution. Then the adiabatic index should be quite close to 5/3. According to the equation of state of an ideal gas, the isothermal sound speed is expressible as a function of \( T \),

\[
c_s^2 = \frac{P}{\rho} \rightarrow c_s^2 = \frac{kT}{\overline{m} H (\equiv \overline{m})}, \tag{11}
\]

in a gas pressure dominated accretion flow and if we assume a pure hydrogen plasma \( \overline{m} = (m_p + m_n + m_e)/3 \). Eq. (10) and Eq. (11) yield a \( T(\epsilon', R, m) \) function:

\[
T \approx \frac{\overline{m}}{k} \left[ \left( \frac{2}{5 + 2 \epsilon'} \right) \frac{GM}{R} \right]. \tag{12}
\]

The radial velocity in an ADAF disk is usually high compared to that of a standard thin disk, since, while \( \alpha \) is low, \( v \sim \alpha c_s^2 / v_K \) and \( c_s \) is large. Therefore the random velocities of protons in the disk could be sufficiently high to reach the minimum speed requirement for pion production in the relativistic temperature regime of the ADAF, since random motions in the disk are related to its temperature. According to the Maxwell-Boltzmann (MB) distribution of the particle speeds we can calculate the probability (\( P \)) that the proton speed is between the required minimum value of the workable proton collisions \( v_{p,min} \approx 0.65 \text{c} \) (which provide a pion) and \( v_{p,max} \approx 1 \text{c} \) at a given temperature or radius.

In Fig. 1 all points arise from a numerical integration of the MB distribution between the required minimum speed and the maximum speed at a given temperature. In our oversimplified model strong pion production will only occur near to the black hole and as a consequence a LEC showing positron population can be injected into the jet. However, in this regime general relativity effects are strong and the scaling laws break down (Gammie & Popham 1998).

On the other hand, if the flow is not highly advection dominated then there is a significant contribution from radiation pressure and the local pressure in the disk is the sum
of the pressure of matter and radiation $P = P_r + P_m$, $P_r = \left(\gamma - 1\right)\epsilon_r$ and if the photons are in equilibrium then $\gamma = 4/3$ and $P_r = \frac{1}{2}aT^4$ where $a = 4\pi\gamma c \approx 7.56 \cdot 10^{-16} \text{J m}^{-3} \text{K}^{-4}$. Under these circumstances the simple scaling law relations for the quantities in the ADAF fail as the ratio of the thermal to the radiation pressure depends on $R$. Then the effective value of $\gamma$ will vary between $5/3$ when fully gas pressure dominated down toward $4/3$ when the radiation pressure is much greater. In that case the general expression $c_s^2 = \frac{dP}{dp}$ must be used and one must obtain the solution numerically. While we have assumed the protons have a thermal distribution, there is an indication that for all accretion rates the Coulomb collisions may be too inefficient to thermalize the protons (Mahadevan & Quataert 1997).

4 Concluding Remarks

The supermassive black holes at the centers of galaxies and their immediate environs can emit a pair of relativistic jets. The morphology and energetics of these relativistic jets are tightly coupled to the central engine and a careful analysis can provide interesting possibilities to understand the SMBH behaviour.

In this paper we established an explanation of the low-energy cutoff seen in the synchrotron spectra of many radio active galaxies and operating under the reasonable assumption that the LEC arises through pion decay processes via protonic collisions. Only a low density and very hot ADAF is able to maintain the relativistic temperature which is required to yield substantial pion production. Such a very hot disk requires the dimensionless spin parameter $a > 0.95$. Another possible hypothesis that could inject secondary positrons into the jet would be a strong starburst being present in the central region of the host galaxy. That situation would not require a high black hole spin, but in the absence of a starburst the existence of a LEC indicates a high spin of the central black hole. We have calculated the minimum kinetic energy such that colliding protons generate the desired decay products. The speed of the colliding protons must exceed $v_{p,\text{min}} \approx 0.65 c$ to allow for pion production.

Since an ADAF is the only type of accretion flow that seems capable of producing such high kinetic energies, we summarized those differential equations and their self similar solutions. We connected the ADAF temperature to the typical random velocities of protons trough the isothermal sound speed. In a simplified model, we treated protons as an ideal gas in thermal equilibrium and assumed that the flow is highly advection dominated. We have shown that below about 2 Schwarzschild radii the random speed of 10 percent of protons can exceed the “speed limit” and so around the innermost region the pion production via proton collisions should be an important process. Pions are unstable, they will decay further to positrons and neutrinos, and so that positron population will be imprinted with a LEC. Future work will include the analysis of the general case where the plasma is predominantly thermal but radiation pressure plays a significant role, as well as an analysis for the case where the protons do not come into thermal equilibrium. A general relativistic treatment and use of Maxwell-Juttner distribution to determine $P$ would be another key extensions.

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