

The High-energy emission of jetted AGN

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Abstract. Quasars with flat radio spectra and one-sided, arc-second scale, ≈ 100 mJy GHz radio jets are found to have similar scale X-ray jets in about 60% of such objects, even in short 5 to 10 ks *Chandra* observations. Jets emit in the GHz band via synchrotron radiation, as known from polarization measurements. The X-ray emission is explained most simply, i.e. with the fewest additional parameters, as inverse Compton (iC) scattering of cosmic microwave background (cmb) photons by the relativistic electrons in the jet. With physics based assumptions, one can estimate enthalpy fluxes upwards of 10^{46} erg s^{-1} , sufficient to reverse cooling flows in clusters of galaxies, and play a significant role in the feedback process which correlates the masses of black holes and their host galaxy bulges. On a quasar-by-quasar basis, we can show that the total energy to power these jets can be supplied by the rotational energy of black holes with spin parameters as low as $a = 0.3$. For a few bright jets at redshifts less than 1, the *Fermi* gamma ray observatory shows upper limits at 10 GeV which fall below the fluxes predicted by the iC/cmb mechanism, proving the existence of multiple relativistic particle populations. At large redshifts, the cmb energy density is enhanced by a factor $(1+z)^4$, so that iC/cmb must be the dominant mechanism for relativistic jets unless their rest frame magnetic field strength is hundreds of micro-Gauss.

Keywords. (galaxies:) quasars: general, galaxies: jets, X-rays: galaxies, radio continuum: galaxies, black hole physics,(cosmology:) cosmic microwave background

1. Introduction

Radio astronomy is intimately related to high energy astronomy. Estimates of magnetic fields in the lobes of radio sources led to the recognition that TeV electrons must be present to radiate via the synchrotron mechanism. This motivated early suggestions ([Morrison \(1958\)](#), [Savedoff \(1959\)](#)) that direct detection of celestial gamma rays might be feasible. Estimates of the energy contents of these radio lobes were extremely large, posing difficulties for explaining the origin and possible relation to the associated galaxy or quasar. The dilemma was solved by theoretical explanations of how collimated beams of particles and fields, i.e. jets, could carry energy to the lobes ([Rees \(1971\)](#), [Longair et al. \(1973\)](#), [Scheuer \(1974\)](#), [Blandford & Rees \(1974\)](#), [Begelman, Blandford, & Rees](#)), and by direct imaging of these radio jets ([Turland \(1975\)](#), [Waggett et al. \(1977\)](#), [Readhead et al. \(1978\)](#), [Perley et al. \(1979\)](#), [Bridle & Perley \(1984\)](#)). The existence of X-ray emission from the nearest, brightest jets in Cen A ([Feigelson et al. \(1981\)](#)), 3C273 ([Willingale \(1981\)](#)), and M87 ([Schreier et al. \(1982\)](#)) resulted from observations by the *Rosat* and *Einstein* X-ray telescopes, each with about $5''$ angular resolution. The *Chandra* X-ray observatory ([Weisskopf et al. \(2002\)](#), [Weisskopf et al. \(2003\)](#), [Schwartz \(2014\)](#)) with its $0''.5$ resolution telescope gives a 100-fold increase in 2-dimensional imaging capability. This has led to the discovery of X-ray jets in a wide variety of astronomical systems ([Schwartz \(2010\)](#)), and in particular has exploded the study of X-ray emission from extra-galactic radio jets.

1.1. Importance of jets

In their 1984 review, Begelman, Blandford, & Rees wrote “...the concept of a jet is crucial to understanding all active nuclei, ...” Jets can carry significant amounts of energy, and since that power is not subject to the Eddington radiation limit jets may allow super-Eddington accretion rates. Such accretion may be relevant to the growth of super-massive black holes in the early universe. High energy observations using the *Chandra* Observatory revealed the effects of jets on the gas filling clusters of galaxies (Fabian *et al.* (2000)). This solved a long standing problem that the cooling time of gas in clusters of galaxies was much less than the Hubble time, implying that the cluster gas should collapse catastrophically. Jets on parsec scales in the nuclei of galaxies explain the blazar phenomena of rapid variability and apparent superluminal expansion. It is now known from direct imaging that regions within X-ray jets may be variable even 10’s of kpc from the black hole (Marshall *et al.* (2010), Hardcastle *et al.* (2016)). From gravitational lensing observations (Barnacka (2018)) of γ -ray blazars it was found that variability could originate from regions many kpc from the black hole (Barnacka *et al.* (2015)) and that γ -ray flares occur at locations distinct from the radio core (Barnacka *et al.* (2016)). These X-ray and γ -ray variability cases constrain the mechanisms of particle acceleration.

1.2. Outline of this review

This review considers non-thermal jets from extra-galactic sources, and will emphasize X-ray observations of powerful quasars. In the case of FR-I radio sources, the X-ray jet emission can generally be interpreted as an extension of the radio synchrotron spectrum (Worrall (2005), Harris & Krawczynski (2006), Harris & Krawczynski (2007), Worrall (2009)). The subject of this review will be FR-II quasars, in which case an optical flux or upper limit generally shows that the X-rays can not be an extension of the radio synchrotron emission. In section 3 we will see how this gives information on the relativistic parameters of the jet, and/or on multiple distinct populations of relativistic electrons.

2. Application of the minimum energy assumption

The intensity of synchrotron radiation from a power law distribution of relativistic electrons, $dN/d\gamma = \kappa\gamma^{-(2\alpha+1)}$ is proportional to the product of κ and the magnetic field strength B . Here, α is the energy index of the observed radiation, γmc^2 is the electron energy, and the spectrum is usually assumed to extend from a minimum γ_1 to a maximum γ_2 . From the radio synchrotron flux density alone, one cannot determine either the magnetic field strength or the relativistic particle density. Another relation between B and κ can be obtained by assuming minimum total energy in particles and fields, which is nearly equivalent to assuming equipartition of energy between those two channels (Burbidge (1956)). This assumption is now widely used for the interpretation of sources emitting synchrotron radiation.

Miley (1980) has previously discussed the assumptions necessary to apply the minimum energy condition. We update that discussion by considering the relativistic particle spectrum to extend from γ_1 to γ_2 instead of fine tuning the γ to extend from the limits of observed radio frequencies, and by considering the application to X-ray jet measurements. This picture allows the equation for the minimum energy magnetic field strength to be written in the form given by Worrall (2009):

$$B_{min} = f_{min} [G(\alpha)(1+k)L_\nu \nu^\alpha (\gamma_1^{1-2\alpha} - \gamma_2^{1-2\alpha}) / (\phi l r t)]^{1/(\alpha+3)},$$

where $G(\alpha)$ is a combination of physical constants and functions of α .

In the on-line version we have color-coded the symbols as follows: green symbols for quantities which can be measured directly, namely the spectral index α , the luminosity

density L_ν at frequency ν , and the length of the jet element l . In turn, the luminosity is determined from the flux density and the length is determined from the angular extent by using the measured redshift and a cosmological model. Here we use $H_0=67.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m=0.315$ from the [Planck Collaboration et al. \(2017\)](#) results, in a flat universe. Blue symbols are not directly measured, but have some observational limits. These include the extremes of the power law electron spectrum, γ_1 and γ_2 , and the width of the jet r . We note that γ_2 has a negligible effect on the calculation, since it is typically orders of magnitude larger than γ_1 . Red symbols are based on intuitive or simplifying assumptions, such as the ratio, k , of energy in relativistic protons to the energy in electrons (including positrons), the filling factor, ϕ , of particles and fields in the jet, the line of sight thickness, t , through the jet, and the assumption, f_{min} that the magnetic field strength corresponds exactly to the minimum energy condition. Here we will take the values $k = \phi = f_{min} = 1$ and $t=r$. In addition to assuming minimum energy, we must transform observed quantities to the jet rest frame using the Doppler factor $\delta = 1/(\Gamma(1 - \beta \cos(\theta)))$ where θ is the angle of the jet to our line of sight and Γ is the Lorentz factor of the jet relative to the cmb frame. The above discussion shows that we must consider possible magnetic field strength uncertainty of a factor of 2 or 3 in any modeling.

The *Lynx* X-ray observatory ([Gaskin et al. \(2017\)](#), [Gaskin et al. \(2018\)](#), [Özel \(2018\)](#), [Vikhlinin \(2018\)](#)), which is being studied for submission to the 2020 Decadal Committee for Astronomy and Astrophysics, would have $0''.5$ angular resolution and 2 m^2 effective area. The *Lynx* capabilities will allow significant improvements in the determination of some of the quantities needed to calculate B_{min} for X-ray jets. Currently, the modest photon statistics from *Chandra* observations allow only an upper limit of $\approx 0''.5$ for the width, r , and assumed thickness, t , of X-ray jets. With the 30-fold increase in collecting area, *Lynx* should allow measurements of widths down to $0''.1$, or of order 700 pc even for the most distant jets. At 200–300 eV, the *Lynx* throughput will be 100 times that of *Chandra*. This should allow direct determination of γ_1 via measurement of the soft X-ray turn-over at those energies. With *Chandra* this measurement could only be applied to PKS 0637-752 ([Mueller & Schwartz \(2009\)](#)) due to the build-up of contamination on the filter of the ACIS camera. The improved statistics will also allow precise measurement of the jet X-ray spectral index α . The iC/cmb mechanism assumes this is the same index as the GHz spectrum, although it could be flatter if the radiative lifetime of the GHz emitting electrons is comparable to or less than the age of the jet.

3. The iC/cmb interpretation

The X-ray emission of the luminous jet in PKS 0637-752 could not be explained by reasonable models of synchrotron, inverse Compton, or thermal mechanisms ([Schwartz et al. \(2000\)](#), [Chartas et al. \(2000\)](#)). [Tavecchio et al. \(2000\)](#) and [Celotti et al. \(2001\)](#) provided the insight of invoking relativistic bulk motion of the jet with Lorentz factor Γ , and using the result from [Dermer and Schlickeiser \(1994\)](#) that this increased the energy density of the cosmic microwave background in the rest frame of the jet by the factor Γ^2 . Subsequently the iC/cmb model has been widely used to interpret the X-ray emission from the jets of powerful quasars ([Siemiginowska et al. \(2002\)](#), [Sambruna et al. \(2002\)](#), [Sambruna et al. \(2004\)](#), [Sambruna et al. \(2006\)](#), [Marshall et al. \(2005\)](#), [Schwartz \(2005\)](#), [Marshall et al. \(2011\)](#), [Marshall et al. \(2018\)](#), [Schwartz et al. \(2006\)](#), [Schwartz et al. \(2006b\)](#), [Worrall \(2009\)](#), [Perlman et al. \(2011\)](#), [Massaro et al. \(2011\)](#)).

Arguments supporting the iC/cmb model were originally based on the similarity of the X-ray and the radio jet profiles over extended angular distances, with the interpretation that they therefore originated from a single, broad relativistic electron population.

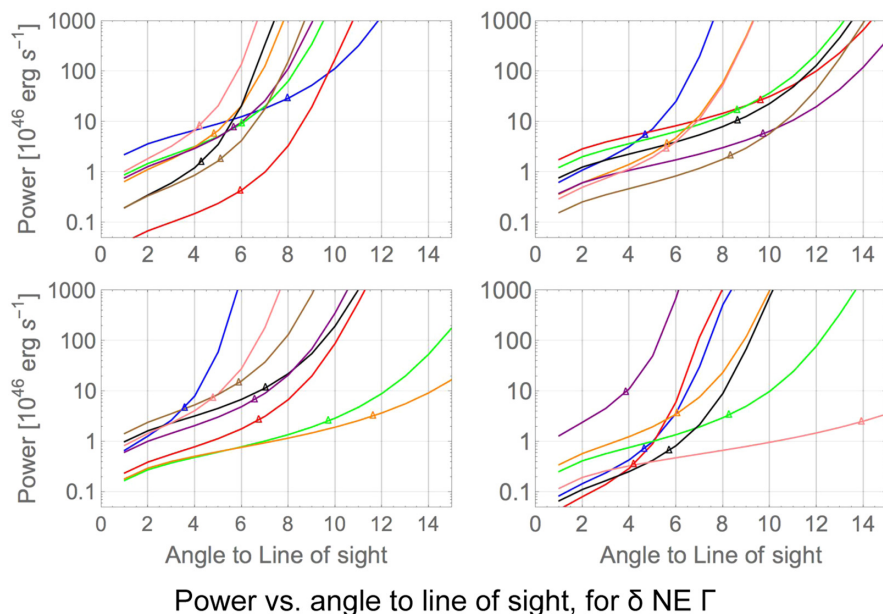


Figure 1. Each curve in one of the panels gives what would be the enthalpy flow in one of the 31 detected jets, calculated as a function of the unknown angle of that jet to our line of sight, and using the iC/cmb model. The triangle on each curve marks the point for which $\Gamma = \delta$, and gives reasonable values for the distribution of parameters of the jet sample.

(Schwartz *et al.* (2000), Schwartz (2005b), Harris *et al.* (2017)), Further evidence is suggested by the termination of X-ray emission just where the radio jet goes through a large change of direction (Schwartz *et al.* (2003), Schwartz (2010)). This is naturally explained by the X-ray to radio ratio of $\delta^{1+\alpha}$ discussed by Dermer (1995). However, powerful evidence against the iC/cmb mechanism in the case of PKS 0637-752 was presented by Meyer *et al.* (2015), and Meyer *et al.* (2017), while Breiding *et al.* (2017) presented similar evidence for 3 jets for which the iC/cmb model had not been indicated. They showed *Fermi* upper limits to GeV γ -ray emission was below the level expected *if* the electron spectrum producing the GHz radio emission also produced the jet emission observed in the *ALMA* and IR/optical regions. In any event, there must be two distinct populations of relativistic electrons, and the X-rays could possibly arise from iC/cmb if the second population produced the *ALMA* and optical emission. The existence of two populations immediately shows that the assumption on the filling factor, $\phi = 1$, is not correct.

In this review we will continue to interpret the X-ray emission as iC/cmb, which we note involves no new parameters for these relativistic jets. In particular, we discuss the results from the systematic survey of Marshall *et al.* (2005), Marshall *et al.* (2011), Marshall *et al.* (2018) and previously presented by Schwartz *et al.* (2015). Figure 1 shows the deduced enthalpy power (Bicknell (1994)) carried by the 31 detected jets, parameterized as a function of the unknown angle to our line of sight. Qualitatively it is apparent that very small angles imply a very large population of unrecognized sources which lie at larger angles. Large angles, greater than 6° to 12° for most of the objects, imply unrealistically large powers; namely, greater than 10^{49} ergs s^{-1} . An assumption is often made that $\Gamma = \delta$. This corresponds to the jet being at the largest possible angle to our line of sight for the given value of δ . Those points are indicated by the triangles on each curve, and we expect they give a reasonable estimate of the distribution of results from the sample.

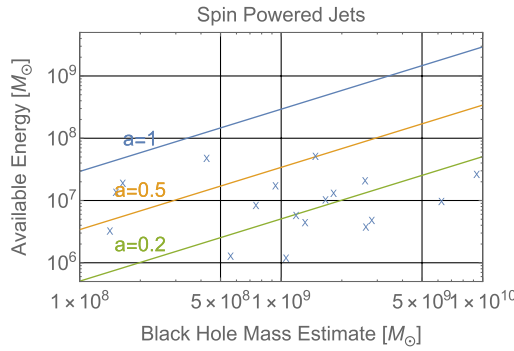


Figure 2. The solid lines show the available rotational energy, in terms of rest mass, which can be recovered by optimal spin-down of a black hole as a function of initial mass. The different spin parameters $a=1,0.3,0.2$, respectively allow 29%, 1%, and 0.5% of the mass-energy of the black hole to be recovered in principle. The x 's plot the amount of energy required to sustain the power of the jets for 10^7 years. The black hole mass estimate here is taken as a median value of estimates in the literature tabulated by Shen *et al.* (2011), and by Xiong & Zhang (2014) and references therein. Even black holes with only 0.2 to 0.3 of the maximum possible angular momentum, can power the jets we measured for millions of years.

4. Connection to the super-massive black hole

The rotational energy, E_r of a Kerr black hole manifests as a contribution $E_r/c^2=M_r$ to the total mass of the black hole. The relation is non-linear, with the fraction

$$M_r/M = 1 - \sqrt{0.5(1 + \sqrt{(1 - a^2/M^2)})}$$

being available in principle to be expelled. Here, a is the spin parameter in units of the total black hole mass M . The solid lines in Figure 2 show the available mass that can, in principle, be released as a function of the total black hole mass. The x 's plot the mass-energy equivalent required to energy to power the jets for 10^7 years, as determined from the $\Gamma = \delta$ point in Figure 1. We plot those masses against the estimated mass of the given black hole. That black hole mass is taken from the median of values given in the literature for 18 objects where it is available. We see that maximally spinning black holes, $a \approx 1$ can provide more than the required energy, and super-massive black holes with spin parameters even as low as 0.3 could in principle power the observed jets for millions of years. Of course, this consideration does not address the dynamics of actually extracting such energy in a collimated flow.

Numerical calculations of the magnetically arrested disk (MAD) model (Narayan *et al.* (2003), Igumenshchev (2008), Sądowski *et al.* (2014), Tchekhovskoy *et al.* (2011), Zamaninasab *et al.* (2014)) for a rapidly spinning black hole have had some success showing that jets can be formed, and can extract more than the potential energy of the accreting matter. A magnetic field is advected in with the accreting matter, and is compressed and amplified until its pressure balances the gravitation pull (Narayan *et al.* (2003)). This results in chaotic variability of the accretion, and the rapidly spinning black hole wraps the magnetic field lines into a tight spiral about the spin axis. Observations of rotation measure gradients across pc-scale radio jets provides evidence for such field geometry (Gabuzda (2014), Gabuzda *et al.* (2015), Gabuzda *et al.* (2017)). The magnetic pressure then causes ejection along the spin axis. If we assume that the initial ejection right at the gravitational radius of an extreme Kerr black hole is a pure Poynting flux, then we can obtain a lower limit to that initial magnetic field by assuming 100% efficiency

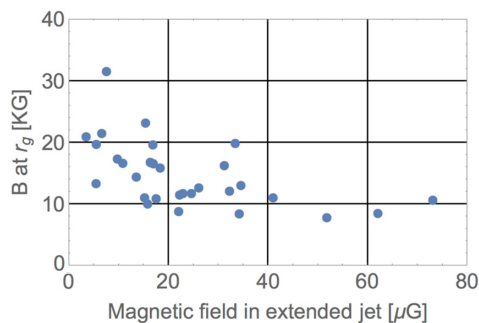


Figure 3. Ordinate: Magnetic field strength at the gravitational radius such that the Poynting vector equals the power deduced for the kpc-scale jet. Abscissa: Mean magnetic field strength in the rest frame of the kpc scale jet, according to the iC/cmb model. Points are the 31 jets detected in the survey discussed in section 3. (In view of numerous uncertainties, we do not consider the possible anti-correlation to be significant.)

for converting that Poynting flux into the energy flux deduced for the kpc-scale jet. Such initial field strengths are shown in Figure 3. We have taken the mass from fundamental plane relation of Gültekin *et al.* (2009) to deduce the gravitational radius r_g of each quasar.

5. Summary

We use Chandra X-ray observations to estimate the power of quasar jets, by observing the jet itself. We tie this to the central black hole mass on an individual object basis. The rotational energy of super-massive black holes can power these quasar jets, even with spin parameters as low as $a=0.2$, for lifetimes longer than millions of years. If the power we observe originates as a pure Poynting flux, we derive initial magnetic field strengths of a few 10's of kilo-Gauss. For models of magnetically arrested disks this inferred magnetic flux is of the order of magnitude of predictions, for Eddington limited accretion onto maximally spinning super-massive black holes.

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