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CONSTRAINTS ON THE NATURE OF JETS FROM KPC SCALE X-RAY DATA

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RESUMEN

En vista del gran número de chorros detectados por el observatorio Chandra y del modelo de emisión por dispersión Compton inversa de rayos X para chorros relativistas, consideramos de nuevo dos preguntas básicas: "Si el fluido que lleva la energía del chorro está formado por electrones calientes ¿se puede acotar su energía a través del tamaño del chorro?" y "¿Porqué los chorros tienen nudos?". Con base en los dos procesos no térmicos para emisión en rayos X, consideramos restricciones sobre el fluido a partir de estas dos preguntas. Creemos que el flujo de momento del chorro no puede provenir principalmente de pares calientes, y que algunos mecanismos que producen variaciones en brillo a lo largo de los chorros están excluidos basados en morfología.

ABSTRACT

Motivated by the large number of jets detected by the Chandra X-ray Observatory, and by the inverse Compton X-ray emission model (IC/CMB) for relativistic jets, we revisit two basic questions: "If the fluid that carries the jet's energy consists of hot electrons, can we constrain the electron energies by jet length?" and "Why do jets have knots?". Based on the two non-thermal emission processes for X-rays from jets, we consider constraints on jet fluid and other properties from these two simple questions. We argue that hot pairs cannot be the dominant constituent of the fluid responsible for the jet's momentum flux and that some mechanisims for producing fluctuating brightness along jets (rather than a monotonically decreasing intensity) are precluded by observed jet morphologies.

Key Words: **GALAXIES: JETS**

1. INTRODUCTION

This paper is based on a poster contribution to the meeting, "Triggering Relativistic Jets", held in Cozumel, MX at the end of March 2005. The motivation arises from the current uncertainty as to the X-ray emission process from kpc scale jets for powerful (FRII) radio galaxies and quasars. Although the current consensus is that FRI radio jet emission comes from the synchrotron process from the radio to X-ray frequencies, most papers dealing with quasar jets ascribe the X-ray emission to inverse Compton emission from the normal power law (or broken power law) distribution of relativistic electrons responsible for the radio and optical emissions, scattering off photons of the cosmic microwave background (IC/CMB). This model relies on the bulk velocity of the jet fluid having values close to c so that the effective energy density of the CMB is augmented by the square of the jet's Lorentz factor, Γ (Celotti et al. 2001; Tavecchio et al. 2000; Harris & Krawczynski 2002; Sambruna et al. 2004).

There are several notable problems for the IC/CMB model (Stawarz 2004; Dermer & Atoyan 200), so we also consider constraints derived from values of Γ expected for synchrotron models (i.e. Γ of order 3 instead of 10 or greater).

A separate, but related problem is the mechanism that produces brightness changes along the jet, i.e. the structures we nomrally call 'knots'.

2. IF THE FLUID THAT CARRIES THE ENERGY CONSISTS OF HOT ELECTRONS, CAN WE CONSTRAIN THE ELECTRON ENERGIES BY JET LENGTH?

Disregarding the energy of the electrons producing the observed emission, we consider what might the 'fluid' be that is responsible for transporting the energy of the jet:

- a normal proton/electron plasma
- Poynting Flux
- a pair dominated plasma

Regardless of the magnetic field strength, any 'hot' electrons will suffer inescapable inverse Comp-

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ton losses to the photons of the microwave background (extremely energetic electrons for which IC losses are supressed by the Klein-Nishina cross section are precluded by even extremely weak magnetic fields). Simply by observing emission at the end of jets, we can calculate the 'age of the fluid', i.e. how long the various E^2 energy losses have been operating. In this way, we can find the maximum permissible Lorentz factor, $max(\gamma)$, for the pair dominated case.

The 'Half-life' plot shown (Figure 1) is essentially 9 versions of eq. (B5) of Harris & Krawczynski (2002). A simplified version of this equation for the half-life of electrons in the jet frame is:

$$\tau' = \frac{10^{13}}{\gamma'[B'^2 + 40 \times \Gamma^2 \times (1+z)^4]} \text{ (years)}$$

where B' is in μG.

We take 3 values of the bulk Lorentz factor for the jet: Γ=1 (no beaming, just for reference), Γ=3.16 (a typical value for synchrotron models), and Γ=10 (the classic solution for the PKS0637 IC/CMB model). For each of these we show 3 characteristic values of the redshift. Since we were interested in the largest possible value of τ, we took only the known CMB energy density and set the magnetic field strength to 3 μG. In reality, B' will most likely be significantly larger than this value over at least parts of the jet, and IC losses will be more severe than indicated for the initial parts of the jet where starlight and/or quasar radiation probably exceeds the CMB in energy density.

To calculate how old the jet fluid is by the time it reaches the end of the jet. We take the projected length, divide that by the most likely value of sinθ (θ is the angle between the l.o.s. and the jet axis); convert to light years; and divide by Γ. With this age for the jet fluid (in the jet frame), we know that any surviving electrons must have γ less than the value corresponding to the halflife calculated for that particular jet (i.e. the appropriate values of z and Γ).

For synchrotron models we take characteristic values of Γ=3, θ=20 (typical parameters which can hide the counterjet; e.g. M87, see Harris et al. 2003) and for the IC/CMB model we take larger values of Γ and smaller θ. We show 3 examples: 3C273, PKS0637, and PKS1127.

For 3C273, we take the most likely values for IC/CMB of Γ=10 and $\theta = 5°$. These conditions yield a $max(\gamma)$ of 15,000. For synchrotron models with relaxed beaming conditions, $max(\gamma) \approx 2\times10^5$. These two values are shown in Figure 1.

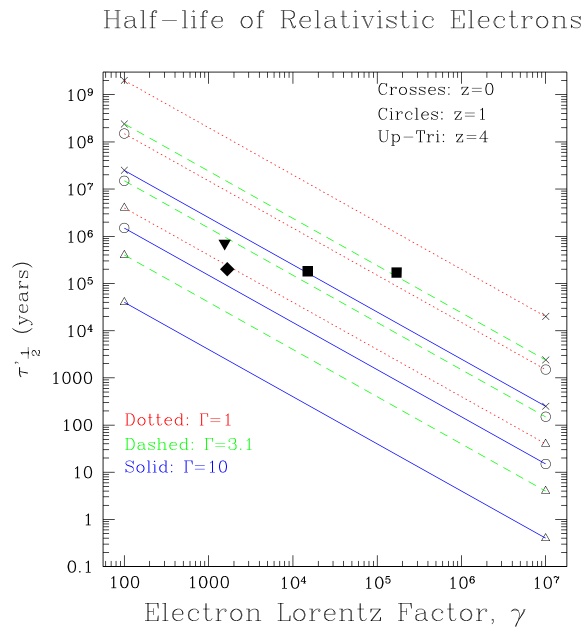

Fig. 1. The half-life for relativistic electrons. These plots show essentially the inverse Compton losses from the CMB, which are inescapable. Dotted lines are for jets which are not moving relativistically and are shown for reference. Dashed lines are for mildly relativistic bulk velocities (Γ=3.1) and solid lines are for Γ=10. The half life is given in the jet frame. Three characteristic values of the redshift are given for each Γ. The ages of the jet fluid at the ends of 3 jets are also plotted. For 3C273 (solid squares) we give two values: the one to the right corresponds to Γ=3, θ=20° while that to the left is for Γ=10, θ=5°. For PKS0637 (diamond) we assumed Γ=10, θ=5°. The down triangle indicates the age for the fluid at the end of the jet of PKS1127 with Γ=3, θ=20°.

In the case of PKS0637, stronger limits could be found for the end of the radio jet, but we use the distance of the strong radio/X-ray knots 8″ from the quasar. With Γ=10 and $\theta = 5°$, we find a $max(\gamma)$ value of 1700.

PKS1127 has a redshift of z=1.16 so beaming models do not require a large Γ (Harris & Krawczynski 2002; Siemiginowska et al. 2002). Knot C is located 28″ from the core. For this source, there is not much difference between synchrotron and IC/CMB models insofar as our analysis is concerned. For $\theta = 20°$ and Γ=3, $max(\gamma)$ is 1600.

These limits on γ are sufficient to convince us that 'hot' pairs are not a viable candidate for the agent responsible for the energy/momentum flow of powerful jets. Since we find similar constraints for PKS0637 and for PKS1127, this conclusion does not rely on models that require largge values of Γ.

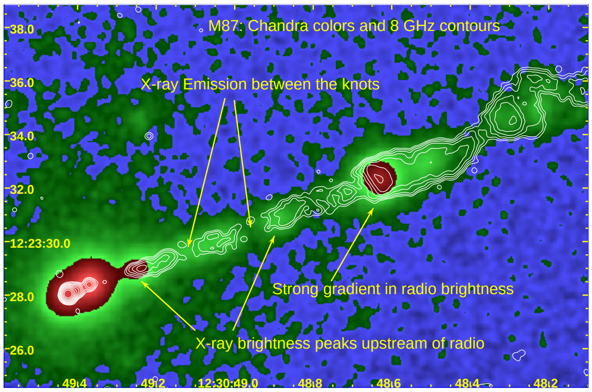

Fig. 2. A Chandra image of the M87 jet, with radio contours overlayed. The effective resolution of the X-ray data is about 0.57″ FWHM, whilst that of the radio is 0.24″ FWHM. With matching beams, the features illustrated do not change.

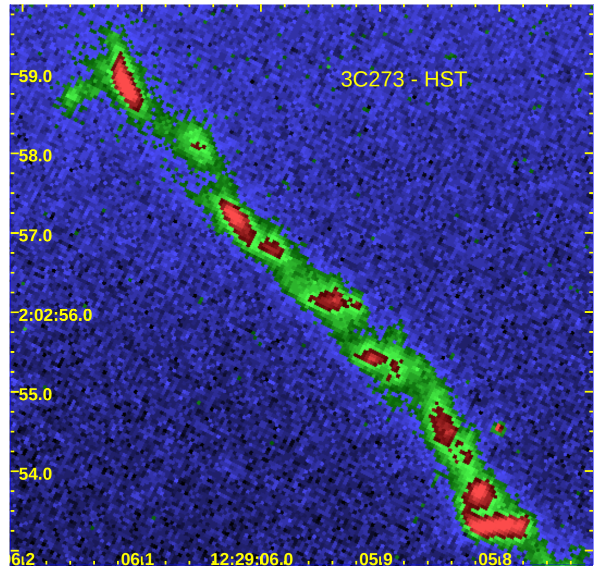

Fig. 3. An HST image of 3C273.

3. WHY DO JETS HAVE KNOTS?

3.1. *Synchrotron Models*

In this section we will consider knots in both low power and high power jets. Conventional wisdom has it that knots [a.k.a. marked brightness enhancements] occur because internal shocks accelerate particles, and these particles radiate. Good examples are M87/knot A and 3C120/k25 which show sharp gradients in radio brightness, often as an inclined linear feature.

However, there is also X-ray emission between the radio knots indicating that there must additionally be some distributed acceleration process to generate electrons with $\gamma \approx 10^7$ wherever X-ray emission is found (see Figure 2). This follows from the very short half-life (of order a year) of the electrons responsible for synchrotron X-rays.

3.2. *IC/CMB with beaming*

The main question for the IC/CMB model is why don't X-ray 'knots', once they appear, trail off downstream more gradually than the radio and optical since for IC/CMB, the half-life for the X-ray emitting electrons ($\gamma \approx 100$) is very much longer than for those producing optical and radio emission.

3.3. *General processes for producing knots*

- Doppler boosting: if the jet fluid follows a curved trajectory, (e.g. a helix as proposed for VLBI scale jets by Gabuzda, Murray, & Cronin 2004; Asada et al. 2002; Hong et al. 2004), we might see only segments of the trajectory for which the angle to the l.o.s. is small. The HST image of 3C273 (the kpc scale jet is shown in Figure 3), resembles the projection of a helix. This would work for either X-ray emission model although the large Γ's required for IC/CMB would mean that these jets would have higher contrast than lower Γ (synchrotron) jets like M87.

- Intermittent Ejection from the central engine - which would mean that kpc scale knots are moving, like pc scale blobs. This also works for both emission models.

- Acceleration and Deceleration - changes Γ so that more or less IC X-rays are produced because the effective photon energy density goes as Γ^2. This process would operate only for the IC/CMB model, but is most likely not feasible because any significant increase in Γ would require a large energy source. Furthermore, at the location of internal shocks where the radio emission is high (e.g. the radio knot A in the M87 jet) we would expect a deceleration of the jet fluid leading to less X-ray IC emission, contrary to the observed bright increase in X-ray emission.

- Massive expansion/contraction - If the disappearance of a knot is to be explained by expansion (which would certainly lower the emissivity for both models), we would expect a marked change in the ratio of IC to synchrotron emission. This follows because although the electron

Mechanism	Sync.	Key Element	IC/CMB
internal shocks	Y	offsets	N
Distrib. Accel.	Y	X-ray emis.	not required
Curved Traject.	Y	contrast	Y(?)
Intermittant Eject.	Y	(vlbi blobs)	Y
Accel./Decel.	N	source of energy	N(?)
Expand/Contract	Y	offsets	N

energy distribution, N(E), will suffer a uniform drop, there will also be a very strong effect of lowering the magnetic field strength: the synchrotron emissivity will decrease as B^2 and a fixed reception band will be sampling a higher energy segment of the N(E) power law which will have a smaller amplitude. Thus we would expect a sharper decrease of the synchrotron emissivity (radio and optical) than the IC emissivity (X-ray). Just the opposite is actually observed in many cases.

4. SUMMARY

- In both the synchrotron and IC/CMB emission models, hot electrons cannot be the main carrier of jet energy and momentum. That leaves Poynting flux, 'cold' electrons/positrons, or protons (hot or cold).
- In the table below we summarize the situation for generation of knots. If the IC/CMB process were responsibe for X-ray emission from powerful jets, then the most favored knot processes would be curved trajectories and/or intermittant ejection. If the X-rays come from synchrotron emission, then two additional processes are viable: internal shocks and expansion/contraction.

The classical explanation of knots as internal shocks does not account for the brightness differences between radio, optical, and X-ray images under the IC/CMB model, but is fully consistent with the synchrotron model. The only two knot production methods which we find to be consistent with both X-ray emission models are the intermittant ejection and curved trajectory scenarios (these are not mutually exclusive).

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