Implications of the enthalpy flux carried by powerful quasar jets*

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Relativistic Jet Power: Why we care

1. Enthalpy flux of jets can reverse the cooling flow catastrophe in clusters of galaxies

2. Jet power significant in black hole energy budget – indicates available energy which may be manifested in other channels (e.g., winds)

3. Comparable or greater than the black hole luminosity: supports calculations of super Eddington accretion & rapid growth at large redshift.
Power: aka kinetic flux, Enthalpy Flux

Definition*: $\Gamma^2 \times \text{velocity} \times \text{Area} \times \text{Density of \{Relativistic enthalpy + Poynting flux – rest mass\}}$

$$= \Gamma^2 \beta c \text{ Area } \left[ 2B^2/8\pi + (1-1/\Gamma)(1+k_2) \rho c^2 \right]$$

X-ray observations of kpc scale jets allow us to estimate $B$ and $\Gamma$

- For relativistic jets
- Inverse Compton scattering the CMB

IC/CMB interpretation

Extension of the radio-emitting synchrotron electrons to lower energy produces IC x-rays by scattering off the $\Gamma^2$ enhanced CMB

**Relativistic jet $\delta = 1/(\Gamma (1-\beta \cos \theta))$**

Cannot solve for all three quantities $\Gamma$, $\delta$, and $\theta$

1. Use $\Gamma = \delta$
2. Set $\Gamma$ = some number
3. Parameterize as a function of $\theta$

Relate $B$ to the relativistic particle density via minimum energy

Usual assumptions of uniformity, isotropy in rest frame, electron cutoff below $\gamma_{min} = 30$, $r_{jet} = 2kpc$, are there $p$ or $e^+$?

Proton energy = electron energy

Supersnapshot transformation: Volume = $V_{obs}/(\delta \sin \theta)$

Felten-Morrison (’66) IC formulas give combination of $\delta$ & $\Gamma$
Comparison of Proton (orange) and Positron (blue) jets, for $\Gamma = \delta$
Γ = δ (triangles) gives reasonable results for enthalpy flux.

Power vs. angle to line of sight, for δ ≠ Γ
X-ray Jets, $\delta=\Gamma$

- Left graph: Enthalpy Flux ($10^{46}$) vs. Radiative Luminosity
- Right graphs: X-ray Jets with Protons and Positrons, $\delta=\Gamma$

- X-ray Jets with Protons: Black Hole Mass [$10^8 M_\odot$] vs. Luminosity
- X-ray Jets with Positrons: Black Hole Mass [$10^8 M_\odot$] vs. Luminosity
Summary
X-ray jet results from a Chandra Quasar Survey

Jet Enthalpy flux ~ bolometric radiation of quasar

Assuming $\Gamma = \delta$ gives reasonable results for B, electron density, enthalpy flux, lengths and Lorentz factors for the survey properties

Jets are at small angles to line of sight, $\leq 10$ degrees

Kinetic flux $5-10 \ E46 \ erg/s$ for proton jets, $1-2 \ E46$ for $e^{+/-}$ jets, for minimum energy conditions