Connections between Radio and High Energy Emission in AGN

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**Motivation:**

* Partition of Black Hole Gravitational Power into:

  - Disk emission
  - Coronal emission / Advection Dominated Accretion Flows (ADAFs)
  - Jets and Winds

* Parameters of jets in radio-loud objects close to black hole

* Launching of jets from black holes
Origin of X-ray emission

Two main possible emission mechanisms:

• Comptonization of soft disk photons by hot corona

• Synchrotron or Inverse Compton emission from jet

Shastri et al. ’93
Black Hole Fundamental Plane

Merloni & Heinz ’03
Falcke ’04

5 GHz core luminosity vs 2-10 keV luminosity

Offset in Galactic and Extragalactic correlations due to black hole mass

\[ \log L_R = 1.05 \log L_X + 0.78 \log M + 7.33 \]
Panessa et al 2007

Low luminosity Radio Galaxies

Seyfert galaxies (radio quiet)

Difference of 3 orders of magnitude in radio luminosity but same slope

\[ L_X \propto L_R^{0.97} \]
Panessa et al. 2011 - Correlation lost at VLBI resolution

Suggests correlation with jet power rather than luminosity
INTEGRAL Sample

- INTEGRAL 20-40 keV sample; 88 sources (Malizia et al. ’09)
- 2-10 keV X-ray data (Malizia et al. + literature)
- NVSS radio data (Maiorano et al. in prep.)
Different modes of X-ray and radio emission

- Disk and corona dissipate gravitational power rapidly
- Jet Poynting flux-dominated, non dissipative
- Jet power manifest on kpc scales
Relationship between radio power and jet power

Not simply a conversion of jet power into luminosity

Model-dependent, e.g. Shabala et al. ’05: Expansion of radio source into 2-component background medium

Model for Seyferts motivated by observations of NGC 4051
NGC 4051: Giroletti & Panessa ’09

~ 19 kpc bubble on large scales fed by jet on small scales
Jet – Interstellar Medium interaction

Powerful $10^{45}$ ergs s$^{-1}$ jet in 1 kpc fractal medium
Luminosity of bubble

Emissivity

\[ j_\nu = \text{Numerical Factors} \times K B^{(a+1)/2} \nu^{-(a-1)/2} \]

\[ N(\gamma) = K \gamma^{-a} \]
Luminosity of bubble

Emissivity

\[ j_\nu = \text{Numerical Factors } \times \frac{KB^{(a+1)/2}}{\nu^{(a-1)/2}} \]
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Luminosity of bubble

Emissivity

\[
\dot{j}_\nu = \text{Numerical Factors} \times K B^{\frac{(a+1)}{2}} \nu^{-\frac{(a-1)}{2}}
\]

\[
N(\gamma) = K \gamma^{-a}
\]

K estimated from electron pressure

\[
K \approx \frac{3p_{\text{tot}}}{m_e c^2} \left( \frac{p_e}{p_{\text{tot}}} \right)^{\gamma_1} (a-2)
\]
Luminosity of bubble

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Lower cutoff
Luminosity of bubble

Emissivity

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K estimated from electron pressure

Radius and pressure of bubble

\[ R = At^{3/5} \]
\[ p_{\text{tot}} = \frac{12}{25} \rho_a A^2 t^{-4/5} \]

\[ A = \left[ \frac{125}{384\pi} \frac{FE}{\rho_a} \right]^{1/5} \]
Luminosity of bubble

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Ambient density

Jet energy flux

Lower cutoff
Luminosity - Jet Power relation

\[ P_ν = j_ν \times \text{Volume} \]

\[ B = \text{Equipartition with total pressure} \]
Luminosity - Jet Power relation

\[ P_\nu = j_\nu \times \text{Volume} \]

\[ B = \text{Equipartition with total pressure} \]

\[ P_\nu \approx \text{Numerical Factor} \times \rho_a^{3(a+1)/20} F_{E}^{(a+11)/10} t^{(4-a)/5} \nu^{(3-a)/2} \]
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\[ n_a \sim 1 \text{ cm}^{-3} \]
Luminosity - Jet Power relation

\[ P_\nu = j_\nu \times \text{Volume} \]

\[ B = \text{Equipartition with total pressure} \]

\[ P_\nu \approx \text{Numerical Factor} \times \rho_\alpha^{3(a+1)/20} F_E^{(a+11)/10} t^{(4-a)/5} \nu^{(3-a)/2} \]

\[ n_\alpha \sim 1 \text{ cm}^{-3} \]

\[ t \sim 3 \times 10^8 \text{ yr} \]
Luminosity - Jet Power relation

\[ P_\nu = j_\nu \times \text{Volume} \]

\[ B = \text{Equipartition with total pressure} \]

\[ P_\nu \approx \text{Numerical Factor} \times \rho_a^{3(a+1)/20} F_E^{(a+11)/10} t^{(4-a)/5} \nu^{(3-a)/2} \]

INTEGRAL sample: \( \nu = 1.4 \) GHz

\[ n_a \sim 1 \text{ cm}^{-3} \]

\[ t \sim 3 \times 10^8 \text{ yr} \]
Radio power -> Luminosity

Strongest dependence is on energy flux

\[ P_{\nu} \propto \frac{F_E^{(a+11)/10}}{10} \]

\Rightarrow F_E \propto \frac{P_{\nu}^{10/(a+11)}}{P_{\nu}^{0.76}} \text{ for } a = 2.2
Almost linear correlation between jet power and X-ray luminosity

\[ F_E \propto L_X^{1.04} \]

Somewhat misleading since alternative regression =>

\[ L_X \propto F_E^{0.6} \]

Jet power \(~ 0.5\%\) of X-ray luminosity – with large deviations from mean
Main points on disk-dominated X-ray AGN

• Need to understand better the relationship between radio and X-ray emission in both radio-loud and radio quiet sources where the X-ray emission is clearly disk coronal emission.

• Important to focus on jet power rather than radio luminosity when considering the partition of gravitational power among various modes.

• Consideration of the large scale source structure and dynamics useful way of estimating jet power.
X-ray jet emission in the Radio-Loud Galaxy Centaurus A

SED of core from Lenain et al ’09
Interaction of jet with ISM

Radio and X-ray Images from Hardcastle et al 2003 and 2007
Interaction of jet with ISM

Radio and X-ray Images from Hardcastle et al 2003 and 2007
Interaction of jet with ISM

Radio and X-ray Images from Hardcastle et al 2003 and 2007

Radio knot SW of nucleus

Approaching side

Receding side

Friday, 27 July 12
Velocity of [SiVI] – 0.12” SINFONI – VLT
Neumayer et al. 2007

Corrected for rotation:
Why is [SiVI] blue-shifted?

Redshifted emission on approaching side and blueshifted on receding side at first counterintuitive

Expect entrained clouds to be moving with jet
z-y plane defined by jet and observer
Shock models (MAPPINGS)

- Precursor
- Shock
- Shock + Precursor

Blue Cloud

Log $[\text{SiVI}/\text{Br}]$

Log $[\text{CaVIII}/\text{Br}]$

$\beta = 0.1$

$\beta = 1$

$\beta = 10$

1000 km/s

750 km/s

500 km/s

350 km/s

220 km/s

170 km/s

1000 km/s

$\beta = 0.1$

$\beta = 1$

$\beta = 10$

Total
High energy emission from the core
Synchrotron + Inverse Compton model fits to the high energy emission from the core of Cen A – Lenain et al. 2009

Model Lorentz factor = 15
Inclination ~ 25°

Estimates from VLBI observations (Tingay et al. 01)

Lorentz factor > 1.12
Inclination between 45° and 80°
Parameters of photoionization models

\[ U = \frac{\text{No. density of ionising photons}}{\text{Atomic no. density}} = \frac{n_{\text{ph}}}{n} \]

\[ \alpha = \text{Spectral slope of flux density} \]

Flux density \( F_\nu \propto \nu^{-\alpha} \)

Typically \( \alpha \approx 1.4 \)

and \( \log U \approx -2 \)

Lenain et al. models of X-ray synchrotron => \( \alpha \approx 0.39 \)
Flux of ionizing photons

\[ \delta_{\text{obs}} = \frac{1}{\Gamma(1 - \beta \cos \theta_{\text{obs}})} \]

\[ \delta_{\text{cl}} = \frac{1}{\Gamma(1 - \beta \cos \theta_{\text{cl}})} \]

Doppler factors:

Lorentz factor
Ionizing flux (cont.)

\[ N_{ph} = \int_{\nu_0}^{\infty} N_{ph}(\nu) \, d\nu \]

\[ = \frac{1}{c} \left( \frac{D_A}{D_{cl}} \right)^2 \left( \frac{\delta_{cl}}{\delta_{obs}} \right)^3 \int_{\delta_{obs}}^{\infty} \frac{F_{obs}(\nu_{obs})}{h\nu_{obs}} \, d\nu_{obs} \]

\[ \frac{D_A}{D_{cl}} = \frac{\text{Distance to Cen A}}{\text{Distance of cloud from core}} \]

\[ = \frac{\sin(\theta_{obs} + \theta_{cl})}{\psi_{cl}} \]

Projected angular distance of cloud from core
Results of photoionization calculations

Optimal MAPPINGS model very close to the slope derived from high energy models and ..... quite different from standard AGN models

log U = -1.9 typical of dusty photoionization models (Dopita et al. 2002)
Density and filling factor

Indicates modest Lorentz factors < 5
Density and filling factor

Typical filling factors for entire Narrow Line Region in AGN $\sim$ few $\times 10^{-2} - 10^{-4}$

Indicates modest Lorentz factors $< 5$
Conclusions for Centaurus A

• Blue-shifted cloud in the core of Centaurus A photoionized by high energy emission from base of jet

• But ... beamed emission from jet consistent with low Lorentz factor not 15 as claimed by high energy model

• Greater consistency with deductions from VLBI data

• Need for substantial revision of models for high energy emission