Extragalactic circuits, black holes, and the ultimate energy transfers

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Abstract

Energy, and electrical circuits in Space, and their connection to supermassive black holes

• A non-negligible fraction of Supermassive Black Hole's (SMBH) rest mass energy gets transported into extragalactic space -- by remarkable processes in jets which are not completely understood. The bulk of the energy flow from the SMBH (e.g. $\gtrsim 10^7 M_\odot$) appears to be electromagnetic, rather than via a particle beam flux. Also, remarkably, these jets contain current flows that remain largely intact over multi-kpc distances. Accretion disk models have independently calculated that a $\sim 10^8 M_\odot$ SMBH should generate $\mathcal{O} 10^{18} - 10^{19}$ Ampères in the vicinity of the SMBH.

• I describe the first and best yet observational estimate of the current flow along the axis of a jet that extends from the nucleus of the active elliptical galaxy in 3C303. This is $I \sim 10^{18}$ Ampères at a projected 40 kpc from the AGN. This points to the existence of cosmic scale electric circuits. The power flow is $P = I^2 Z$, watts, where $Z \sim 30$ Ohms, which is $\mathcal{O}$ the impedance of free space $Z(\varepsilon_0, \mu_0)$, $(\varepsilon_0, \mu_0)$ being the permittivity and magnetic permeability. These, in turn, uniquely determine $c$. The electrical potential drop ($\sim 10^{20} V$) across the jet diameter (which is $\approx$ a few times $r_g$ of the SMBH) is, interestingly $\approx$ that required to accelerate the Ultra High Energy Cosmic Rays (UHECR).

• Jets and high energy outflows have different progenitors, forms, sizes, luminosities, and ambient environments

• This talk focuses on
  1. electromagnetically dominated (Poynting flux) jets from supermassive BH's
  2. located in a rarified intergalactic environment - i.e. not in rich galaxy clusters
BH (magnetic + CR) energy output ($\gtrsim 10^{60}$ ergs) is “captured” within a few Mpc,

compare with

$\eta$ (photons), $\approx 10\%$ of $M_{BH}c^2$ (not captured) appears comparable to $\eta$ (CR + B),

$Z_0 = \frac{3}{c} \beta$

2147+816 giant radio galaxy

Analysis of $\approx 70$ GRG images
Kronberg, Dufon, Li, Colgate

z=0.146
2.6 Mpc

8 FRII-like GRG’s, w. detailed,
multi-\(\lambda\) obs. & analysis
Kronberg, Colgate, Li, Dufton ApJL 2004
• Willis & Strom, 1978,80
• Kronberg, Wielebinski & Graham.1986,
• Schoenmakers et al. 1998,2000
• Subrahmanian et al. 1996
• Feretti et al 1999
• Lara et al. 2000
• Palma et al. 2000

AUI/NRAO/VLA image
Indications for distributed acceleration of CR’s within Mpc-sized radio lobe volumes

Effelsberg 100m. Telescope 10.6 GHz

VLA 1.4GHz

Kronberg, Wielebinski & Graham
A&A 169, 63, 1986

\[ E_{CR} \approx 10^{19} \left( \frac{B}{3 \mu G} \right) \left( \frac{L}{1 \text{ Mpc}} \right) \text{ eV} \]
ENERGETICS:

\[ R > R_s \]

Accumulated energy
\[ \left( \frac{B^2}{8\pi} + \epsilon_{GR} \right) \times \text{(volume)} \]
from "mature" BH-powered radio source lobes

Giant Radio Galaxies (GRG) capture the highest fraction of the BH energy released to the IGM

GRG’s are the best BH energy calorimeters available

Energy lost to the galaxy cl.
Overview of radio observational aspects

• Kpc-scale jets are likely electromagnetically dominated: \( P = I^2 Z \)

• Important measurables are power flow and current \( (I) \)

• Jets and lobes that proceed from a Supermassive Black Hole (SMBH) are good candidates for Hadron acceleration to the highest energies

• Why measurements of jet current are currently difficult at resolution scales of e.g. the NRAO JVLA.
Knots and Hotspots of 3C303 (z=0.141, D ~ 600 Mpc)

**Radio** (VLA) and **X-Ray** (CHANDRA)


**VLA image**

1.3” resolution

**X-ray image**

Hot Spot

Knot-A, B, C

Hot Spot

Knot-B, C

QSO
3C303 1.4GHz, 1.4” resolution

- 3 spheroid “islands”
- Each has high Mag field ordering & current signatures
- Knot “E3” has a measured $\mathbf{\nabla} \mathbf{RM}$ vector
- Jet continues to here
- Jet disruption point
M87 Knot cocoons are $\sim 12,000$ times (vol.) smaller than those in 3C303! SMBH-powered jets are very scale-independent systems!

The M87 jet on the physical scale of one 3C303 “knot”
Plasma Diagnostics of the 3C303 jet


\[(1) \quad \langle \text{Total energy flow rate} \rangle = \frac{E_T}{\tau} \approx 2.8 \times 10^{43} \tau^{-1} \text{ erg/s} \]

\[(2) \quad \text{Jet’s total photon luminosity radio } \rightarrow \text{X-ray } = 1.7 \times 10^{42} \text{ erg s}^{-1} \]

\[\rightarrow \quad \text{Radiative dissipation from the jet is } \approx 10\% \text{ of the energy flow along jet!} \]

\[(3) \quad \text{Measure knots’ synchrotron luminosity & size } (D_{\text{knot}}) \rightarrow B_{\text{knot int}} = 10^{-3} \text{ G} \]

(4) Measure Faraday rotation isolated in the knots, \[\text{RM } \propto n_{\text{th}} \times B_{\text{knot int}} \times D_{\text{knot}} \]

gives \[n_{\text{th}} \text{ in knots for 3C303) } \rightarrow n_{\text{th}} \approx 1.4 \times 10^{-5} \text{ cm}^{-3} \text{ (a low, extragalactic - level density!)} \]

(3) \& (4) \rightarrow \text{estimate of } V_A \text{ within knots: } \[V_{A_{\text{knot}}} \propto B_{\text{knot int}} n^{-0.5} \]

RESULT: \[V_{A_{\text{knot}}} \approx c, \text{ i.e. in the relativistic range } -- V_{A_{\text{rel}}} \]
How to estimate the jet current? -- what measurements are required:

1. Need sub-arcsec resolution, + adequate sensitivity in Stokes IQU at $\geq 2$ frequencies,

2. Faraday RM distribution over the jet $\frac{\Delta \chi}{\Delta \lambda^2}(x, y)$ at a common angular resolution

3. High resolution X-ray image ($\sim$ kev) gives estimated $T$ and $\rho$ of gas surrounding the jet

4. Need nearby sky RM’s to establish the zero-level of RM
   \textit{i.e.} subtract $<\text{RM}_{\text{backgnd sources}}>$ from the RM’s in the jet image
   \textit{(normally only feasible outside a galaxy cluster)}

\textit{P.P. Kronberg Can J. Phys} \textbf{64}, 449, 1986 (original results)
\[ I_0 \approx 3 \times 10^{18} \text{ Amps} = \frac{V_0}{Z_0} \]

Transmission line analogy:

**Line Voltage:**

\[
V_0 = -\frac{1}{2} r_0 \int_{0}^{\bar{r}^2} d\bar{r} E_r(\bar{r}) = \frac{r_0}{3^{1/4}} \frac{B_0}{\sqrt{\mathcal{R}}}
\]

\[= 3.4 \times 10^{20} \text{ beta Volts}\]

**Axial current:**

\[
I_0 = -\frac{1}{2} c r_2 B_\phi(r_2) = \frac{V_0}{Z_0}
\]

\[= 3.8 \times 10^{18} \text{ A}\]
This leads to a straightforward electrical circuit analogue for BH energy transfer into “empty” space


- **Low thermal density around knots suggests dominance of a Poynting flux**

- **\( P \approx 10^{37} \) watts of directed e.m. power, and \( I = 3.3 \times 10^{18} \) ampères of axial current, directed (in this case) away from the BH (Sign of \( \nabla R M \) gives the \( I \) direction).**

**Poynting jet’s electrical properties: (current, impedance, voltage):**

\[
I_0 = cr_2B_\phi(r_2) = \frac{V_0}{Z_0} \approx 3 \times 10^{18} \text{ Amps (MKS)}
\]

\[
Z_0 = \frac{3}{c} \beta \text{ (cgs) = 90} \beta \text{ Ohms (MKS)}
\]

\[
V_0 = \frac{r_0B_0 \sqrt{r}}{3^{1/4} \sqrt{R}} = 2.7 \times 10^{20} \text{ Volts (MKS)}
\]

\[
\beta = \frac{U}{z} \leq 1, \text{ where } r1, r2 \text{ are the inner & outer transmission line radii} \quad (Lovelace & Ruchi, 1983)
\]
Concept of Poynting flux-dominated energy flow from a BH accretion disc
Relativistic Poynting Flux Jets

Pre 1900 - problem of telegraphic signal (energy) propagation over very long distances -- telegrapher’s equations:

Time and space-dependent perturbations of a Poynting-flux jet are described by the Telgrapher’s equations,

\[
\frac{\partial \Delta V}{\partial t} = - \frac{1}{C} \frac{\partial \Delta I}{\partial z} , \quad \frac{\partial \Delta I}{\partial t} = - \frac{1}{L} \frac{\partial \Delta V}{\partial z} ,
\]

where \((\Delta V, \Delta I)\) represent deviations from the equilibrium values \((V_0, I_0)\). The equations can be combined to give the wave equations

\[
\left( \frac{\partial^2}{\partial t^2} - u_\varphi^2 \frac{\partial^2}{\partial z^2} \right) (\Delta V, \Delta I) = 0 ,
\]

where

\[
u_\varphi = \frac{1}{\sqrt{LC}} = c \left[ 1 + \frac{1}{2\Gamma^2} + \frac{1}{2\Gamma^2} \ln \left( \frac{r_3}{r_2} \right) \right]^{-1/2} ,
\]

O. Heaviside, Electromagnetic Theory 1893
Van Nostrand NY,

Lovelace & Kronberg MNRAS 430, 2828, 2013
Magnetic Insulation:

It breaks down (less common):

when $|E| \geq |B|$

Example: where B approaches zero on some surface. At this point, normal Resistive MHD does not apply.

Specific examples:

1. In a magnetic reconnection layer, **or** (relevant here)

2. If an electromagnetic jet encounters a “load” with an inductive component, the reflected $\Delta I$ and $\Delta V$ are no longer exactly in phase. This can create $|E| \geq |B|$, for some distance and time period $\Delta t$, --- e.g. $\sim 1000\text{yr}$ in the 3C303 jet, ---

--- creating conditions for coherent particle acceleration
Why are jet currents so difficult to measure?

Jet-associated $\Delta RM$ (& VRM) are intrinsically small.

They also need to be isolated from other source-intrinsic, and ambient (e.g. cluster ICM) emission

*example*: $\Delta RM$ only $\sim 10\text{rad m}^{-2}$ across the 3C303 jet. Even for $I \sim 10^{18}$ A at $z = 0.14$, & $10\text{rad m}^{-2}$, the angle of rotation is only $25^\circ$ at 1 GHz.

This detectability problem gets worse at higher $z$

e.g. for 3C9 at $z = 2.012$, $\Delta RM = 10\text{rad m}^{-2}$ becomes $\frac{10}{(1 + 2.012)^2} = 1.1 \text{ rad m}^{-2}$ - undetectable!

LOFAR frequencies down to $\sim 200\text{MHz}$ can detect RM's at low $n_{IG}$ and $B_{IG} \leq 10^{-6}$ G
Future magnetoplasma probes of jets will require:

1. Much higher resolution (\(<\sim 1\)”) transverse to the jet “spine”.
2. higher brightness sensitivity.
3. frequency ranges \(<\sim 1\) GHz for Faraday RM imaging.

*Low freq.* telescopes (\(<\sim 1\)GHz) will achieve these goals

*recent references:*
Summary:

1. We have estimated the circuit parameters for a supra-galaxy--scale jet.

2. Applied it to observations of the jet in radio galaxy 3C 303.

3. We have developed a simple transmission line model for extragalactic Poynting flux jets.

4. Introduced the concept of magnetic insulation, relevant to VHE particle acceleration, and applied it for a jet-ambient plasma $\beta \approx 10^{-5}$.

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