Extragalactic circuits, black holes, and the ultimate energy transfers

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by

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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 ~ $10^8 M_\odot$ 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 $P = I^2Z$, watts, where $Z \sim 30$ Ohms, which is O the *impedance* of free space $Z(\varepsilon_0, \mu_0)$, (ε_0, μ_0) being the permittivity and magnetic permeability. These, in turn, uniquely determine *c.* The electrical potential drop (~ $10^{20} V$) 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

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

BH (magnetic + CR) energy output ($\gtrsim 10^{60}$ ergs) is "captured" within a few Mpc,

compare with

η (photons), ≈ 10%of $M_{BH}c^2$ (<u>not</u> captured) appears comparable to η (CR + B),

2147+816 giant radio galaxy

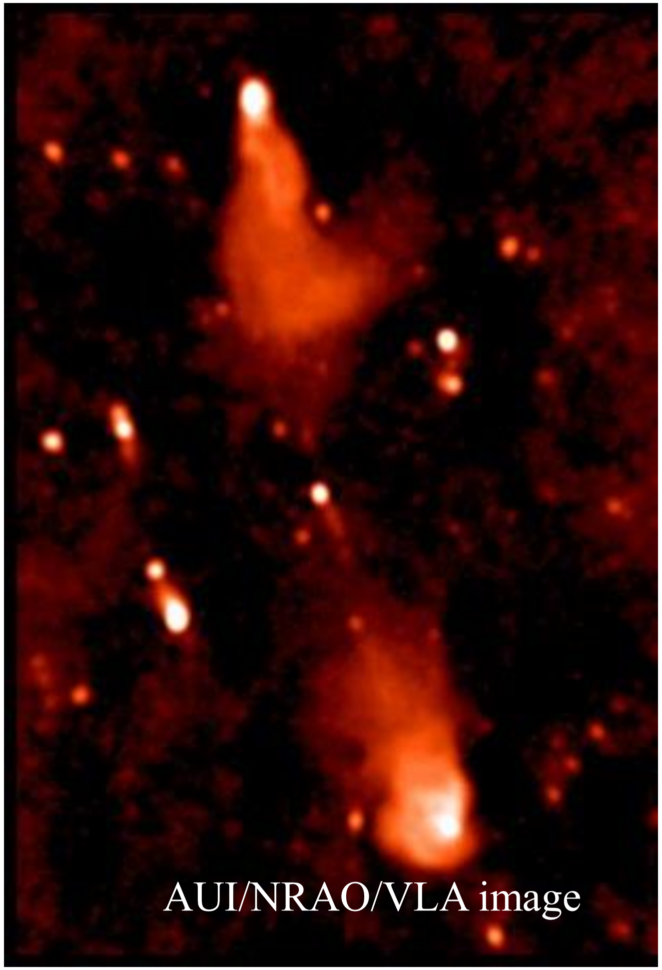
Analysis of ≈ 70 GRG images
Kronberg, Dufon, Li, Colgate
ApJ 2001

z=0.146

2.6 Mpc

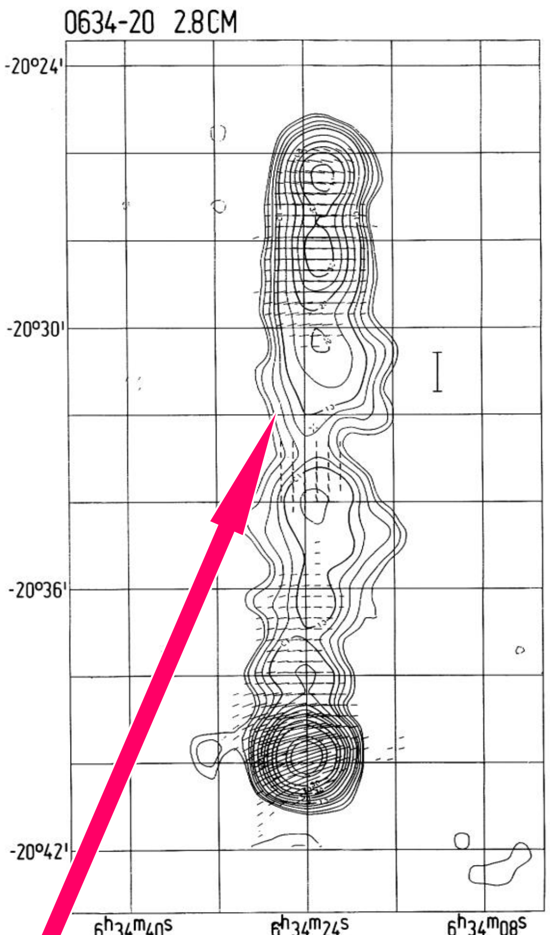
8 FRII-like GRG's, w. detailed,
multi-λ obs. & analysis
Kronberg, Colgate, Li, Dufton ApJL 2004

- Willis & Strom, 1978,80
- Kronberg, Wielebinski & Graham.1986,
- Mack *et al.* A&A 329, 431, 1998
- Schoenmakers *et al.* 1998,2000
- Subrahmanian *et al*. 1996
- Feretti *et al* 1999
- Lara *et al*. 2000
- Palma *et al*. 2000

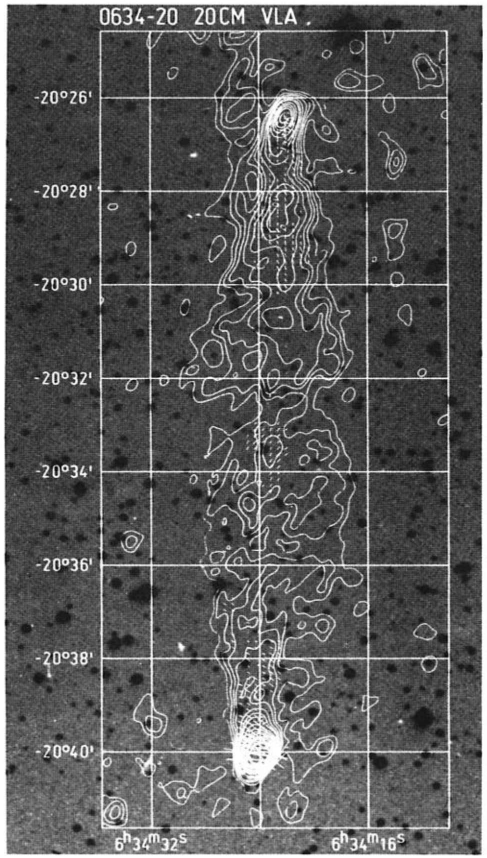


Indications for distributed acceleration of CR's within Mpc-sized radio lobe volumes

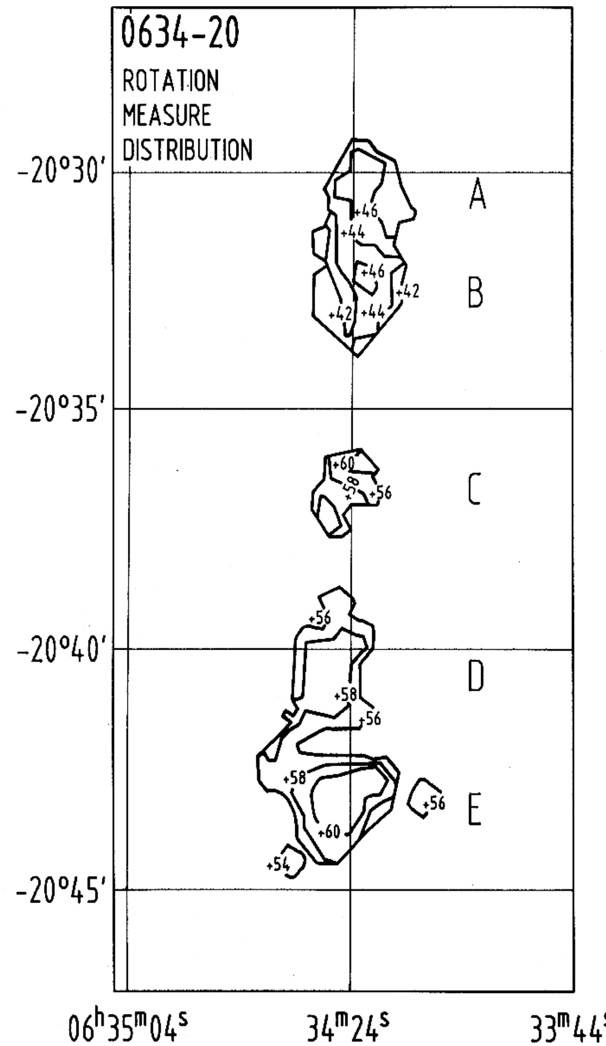
10 GHz



1.4 GHz



Faraday RM(radians/m²)



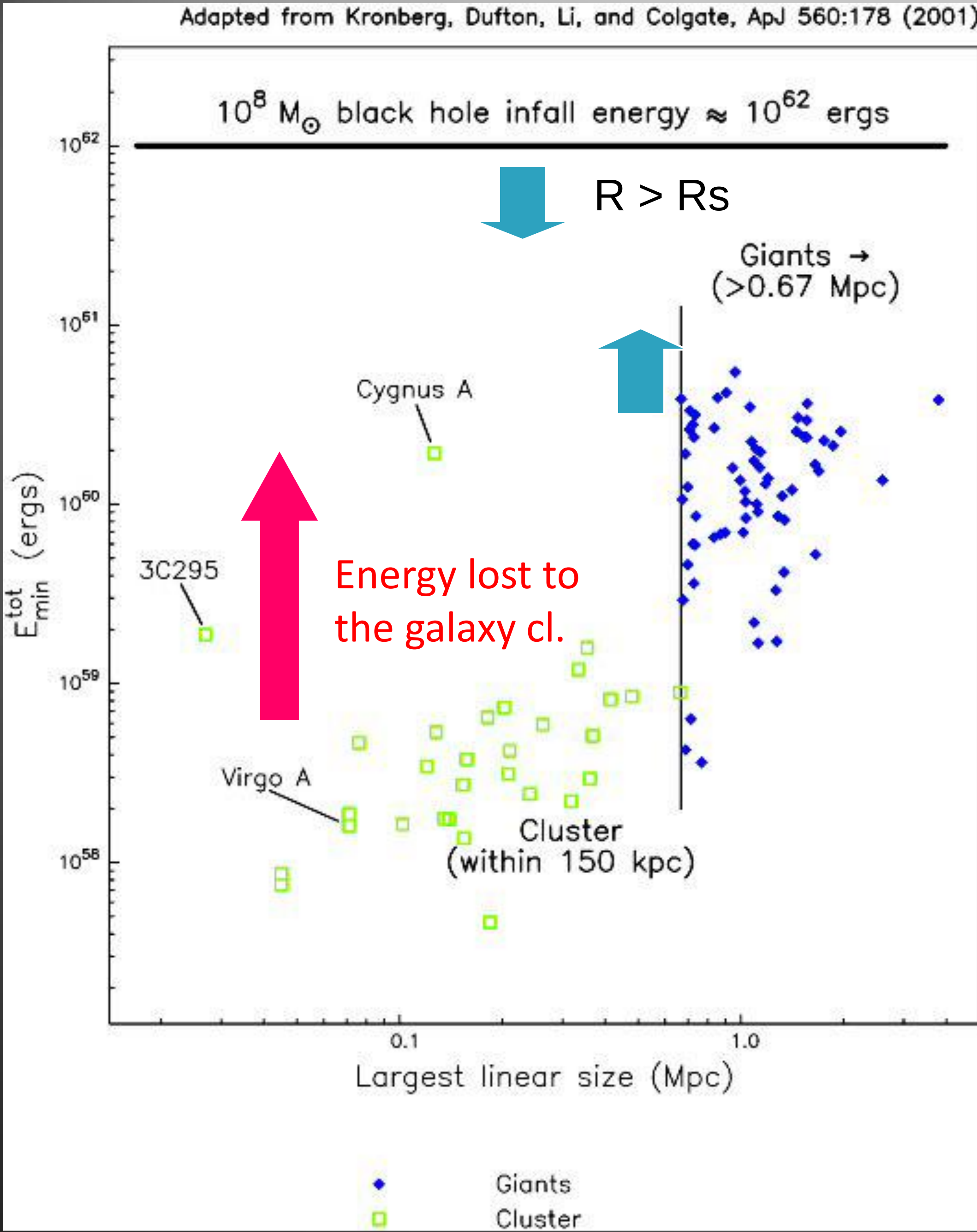
Effelsberg 100m.
Telescope 10.6 GHz

VLA 1.4GHz

Freshly accelerated,and
“starved” of thermal plasma

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

$$E_{CR} \approx 10^{19}\left(\frac{B}{3\mu G}\right)\left(\frac{L}{1\ \mathrm{Mpc}}\right)\ \mathrm{eV}$$



ENERGETICS:

$= M_{BH}c^2$

Mind the gap!!

Accumulated energy
$(B^2/8\pi + \varepsilon_{CR})$ x (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

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 .**

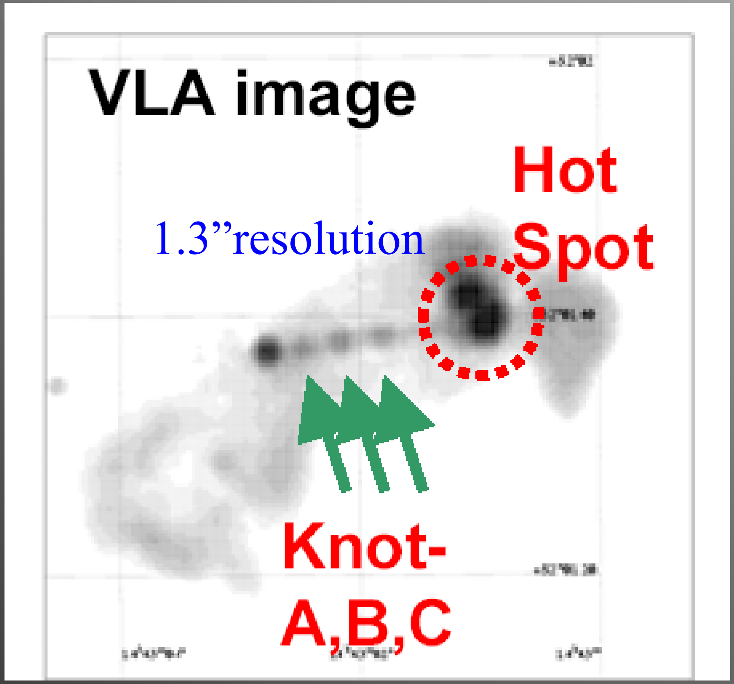
Knots and Hotspots of 3C303 (z=0.141, D ~ 600 Mpc)

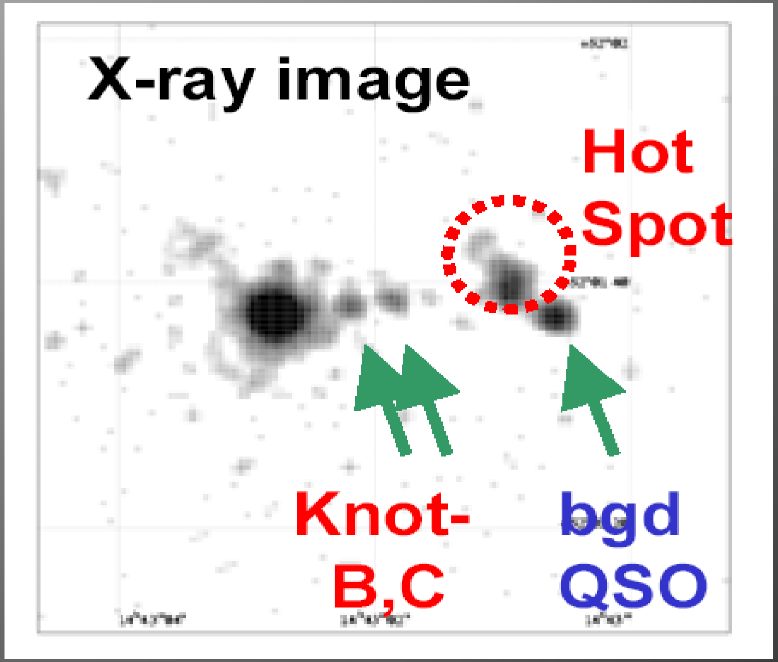
Radio (VLA) and X-Ray (CHANDRA)

P. Kronberg, Can.J. Phys ***64****, 449, 1986*

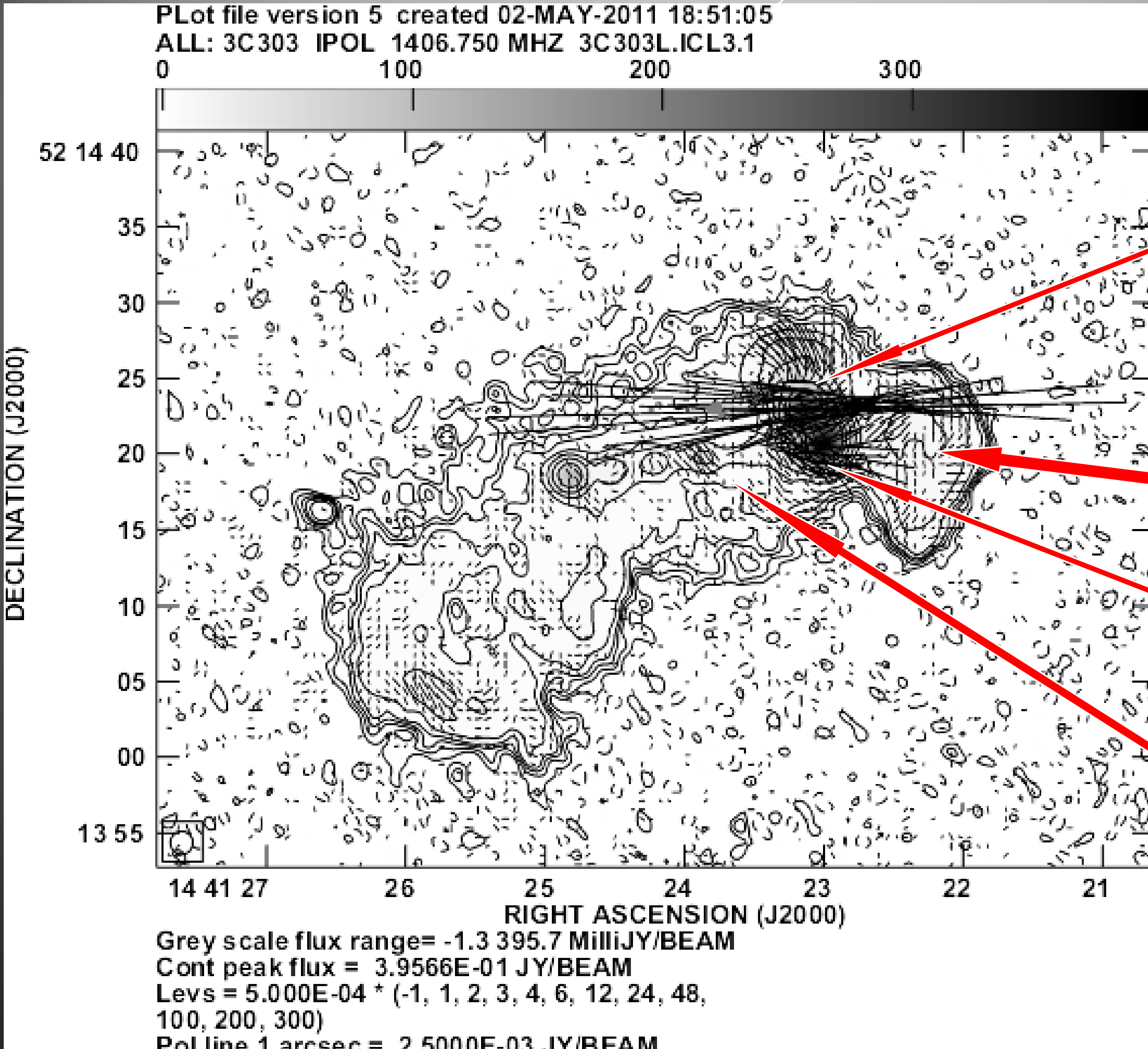
P. Leahy & R. Perley, Astr. J. ***102****, 537, 1991*

J. Kataoka, P. Edwards,
M. Georganopoulos, F. Takahara,
& S. Wagner A&A ***399****, 91, 2003*





3C303 1.4GHz, 1.4” resolution



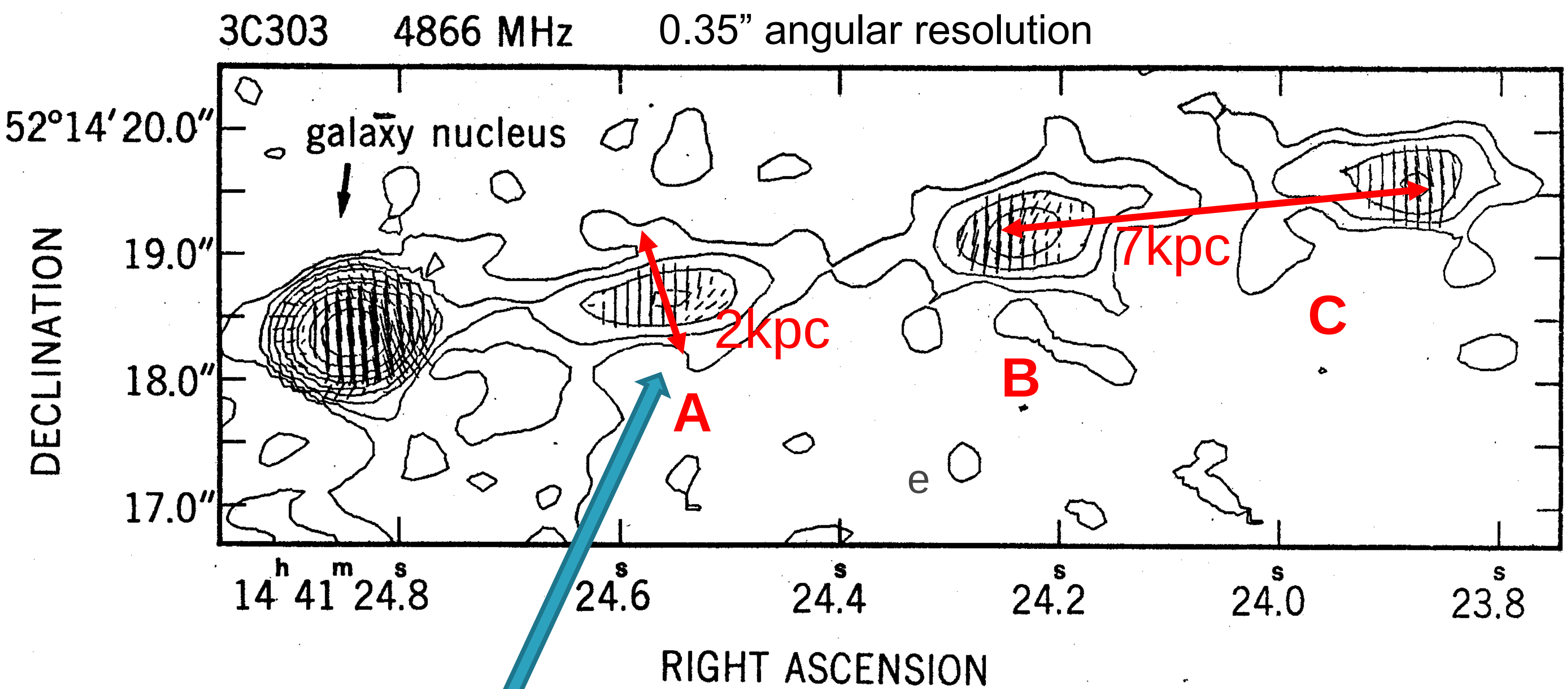
3 spheroid ``islands”
Each has high
Mag field ordering
& current signatures

jet continues
to here

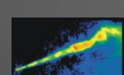
jet disruption
point

Knot ``E3’ has a
measured ∇RM
vector

4.9GHz VLA image at 0.3” resolution



Compare scales!



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

M87 Knot cocoons are ~ 12,000 times (vol.) smaller than those in 3C303!
SMBH-powered jets are very *scale-independent* systems!

Plasma Diagnostics of the 3C303 jet

*Lapenta & Kronberg ApJ **625**, 37-50, 2005*

(1) <(Total energy flow rate)> = $E^{T}_{min}/\tau \approx$ **2.8×10^{43}** τ_7^{-1} erg/s

(2) Jet's total photon luminosity radio → X-ray = **1.7×10^{42}** erg s^{-1}

→ Radiative dissipation from the jet is ≈10% of the energy flow along jet!

(3) Measure **knots'** synchrotron luminosity & size (D_{knot}) → **$B^{knot}_{int} = 10^{-3}$G**

(4) Measure Faraday rotation isolated in the knots, **RM** $\propto n_{th} \times B^{knot}_{int} \times D_{knot}$

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

(3) & (4) → estimate of V_A within knots : $V_A^{knot} \propto B^{knot}_{int}$ $n^{-0.5}$

RESULT: $V_A^{knot} \approx c$. *i.e.* in the *relativistic* range -- V_A^{rel}

How to estimate the jet current? -- *what measurements are required :*

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

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

2. High resolution X-ray image (~ kev) gives estimated ***T*** and ***ρ*** of gas surrounding the jet

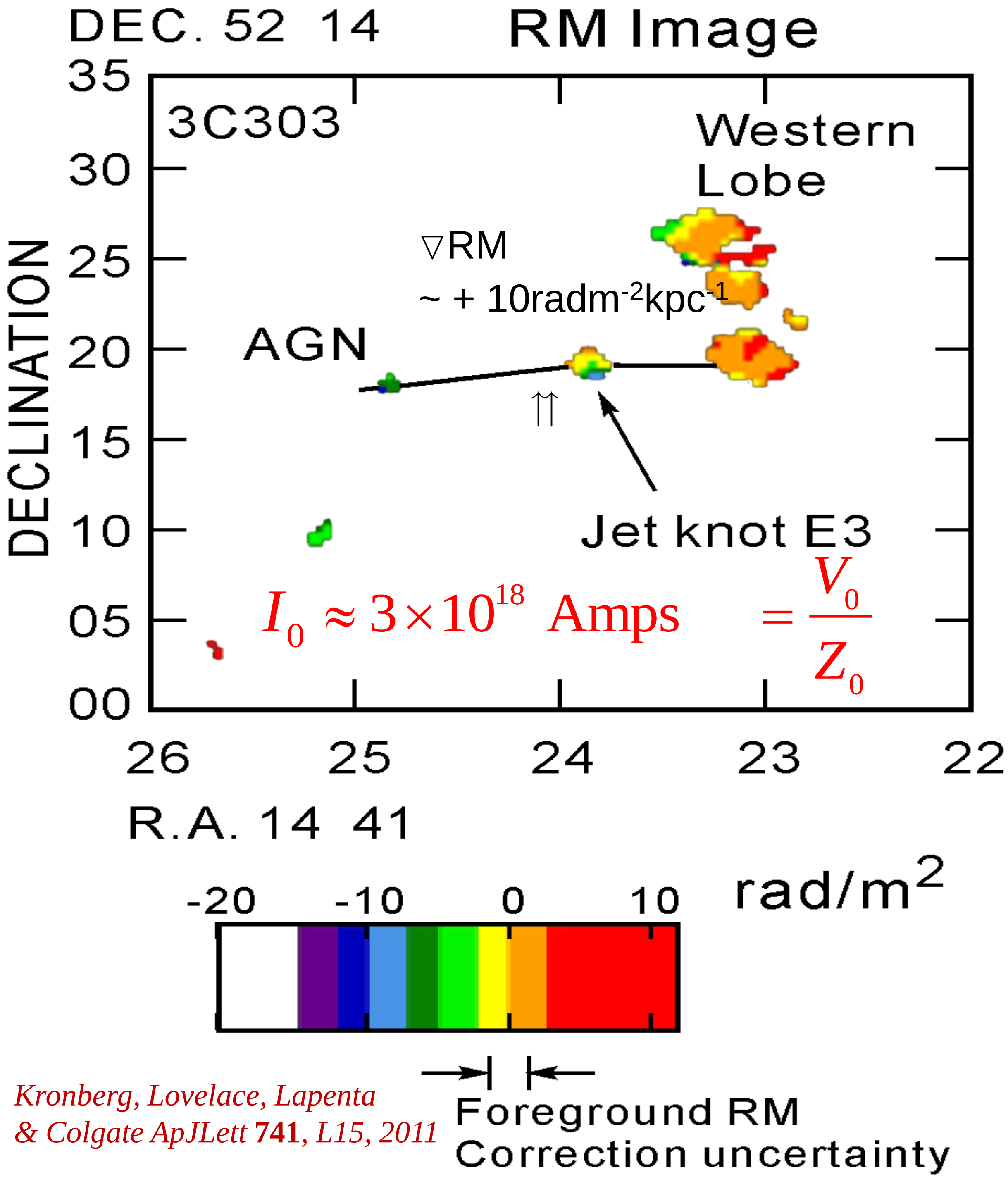
4. Need nearby sky RM's to establish the zero-level of RM

   i.e. subtract <$RM_{backgnd\ sources}$> from the RM's in the jet image

   (*normally only feasible outside a galaxy cluster*)

P.P. Kronberg Can J. Phys ***64****, 449, 1986 (original results)*

P.P. Kronberg, R.V.E. Lovelace, G. Lapenta, & S.A. Colgate, ApJL ***741****, L15, 2011*



Kronberg, Lovelace, Lapenta & Colgate ApJLett ***741****, L15, 2011*

Transmission line analogy:

Line Voltage:

$$V_0 = -\frac{1}{2} r_0 \int_0^{\bar{r}_2} d\bar{r} E_r(\bar{r}) \quad = \quad \frac{r_0}{3^{1/4}} \frac{B_0}{\sqrt{\mathcal{R}}}$$

= 3.4 x 10^20 beta Volts

Axial current:

$$\mathcal{R} \equiv r_0 / r_g \gtrsim 1.$$

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

= 3.8 x 10^18 A

This leads to a straightforward electrical circuit analogue for BH energy transfer into ``empty'' space

P.P. Kronberg. R.V.E. Lovelace, G. Lapenta & S.A. Colgate ApJL ***741***, *L15 2011*

R.V.E. Lovelace & P.P. Kronberg. MNRAS **430**, *2828-2835, 2013*

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

- ***P*** ~ 10^{37} watts of directed e.m. power, and ***I*** =3.3×10^{18} ampères of axial current, directed (in this case) away from the BH (Sign of ∇RM gives the ***I*** direction).

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

$$I_0 = c r_2 B_{\phi(r_2)} = \frac{V_0}{Z_0} \approx 3\times10^{18} \text{ Amps (MKS)}$$

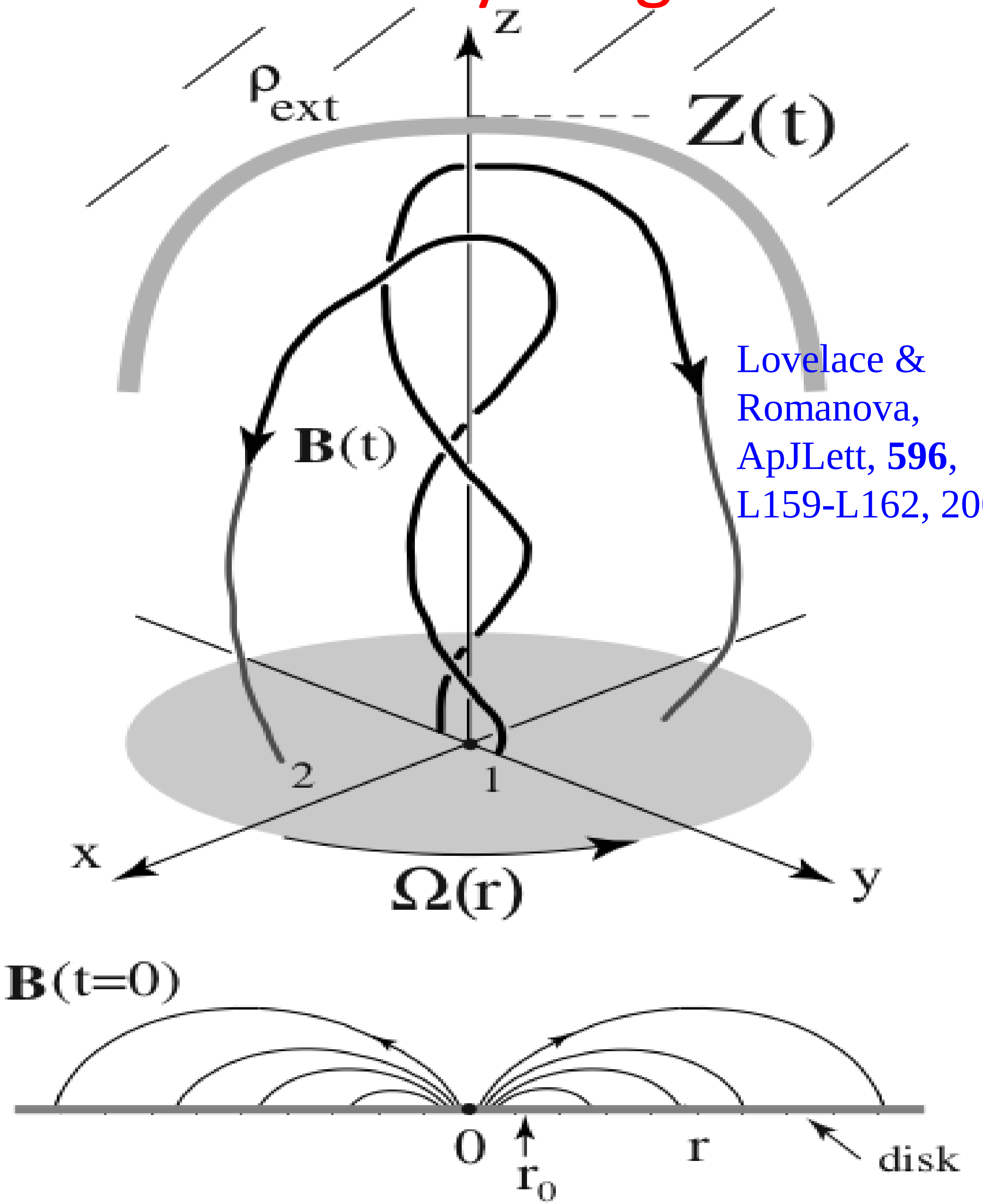
$$Z_0 = \frac{3}{c}\beta \text{ (cgs)} = 90\beta \text{ Ohms (MKS)}$$

$$V_0 = \frac{r_0 B_0}{3^{1/4}\sqrt{R}} = 2.7\times10^{20} \text{ Volts(MKS)}$$

$\beta = \frac{U_z}{c} \lesssim 1$, where *r1*, *r2* are the inner & outer transmission line radii (*Lovelace & Ruchi, 1983*)

Concept of Poynting flux-dominated energy flow from a BH accretion disc

Relativistic Poynting Flux Jets



Lovelace & Romanova, ApJLett, **596**, L159-L162, 2003

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,

$$\frac{\partial \Delta V}{\partial t} = -\frac{1}{C}\frac{\partial \Delta I}{\partial z} \ , \qquad \frac{\partial \Delta I}{\partial t} = -\frac{1}{L}\frac{\partial \Delta V}{\partial z} \ , \tag{20}$$

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

O. Heaviside, Electromagnetic Theory 1893

Van Nostrand NY,

$$\left(\frac{\partial^2}{\partial t^2} - u_\varphi^2 \frac{\partial^2}{\partial z^2}\right)(\Delta V,\ \Delta I) = 0 \ , \tag{21}$$

where

$$u_\varphi = \frac{1}{\sqrt{LC}} = c\left[1 + \frac{1}{2\Gamma^2} + \frac{1}{2\Gamma^2}\ln\left(\frac{r_3}{r_2}\right)\right]^{-1/2} \ , \tag{22}$$

Lovelace & Kronberg MNRAS **430**, *2828, 2013*

Magnetic Insulation:

It breaks down (less common):

when |**E**| ≥ |**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 ΔI and Δ*V* are no longer exactly in phase. This can create |**E**| ≥ |**B**|, for some distance and time period Δ*t*,--- *e.g. ~1000yr in the 3C303 jet*, --

   --- creating conditions for coherent particle acceleration

Why are jet currents so difficult to measure?

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

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

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

This detectability problem gets worse at higher z

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

LOFAR frequencies down to ~200MHz can detect RM's at low $n_{\rm IG}$ and $B_{IG} \leq 10^{-6}$ G

Future magnetoplasma probes of jets will require::

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

Low freq. telescopes ($\lesssim$1GHz) will achieve these goals

recent references:
R.V.E. Lovelace & P.P. Kronberg, *MNRAS* **430**, 2828, 2013
P.P. Kronberg & R.V.E. Lovelace, *EPJ Web of Conf.* **99**,13005, 2015

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,

END