Ultra High Energy Cosmic Rays Produced by Jets Around Massive Black Holes

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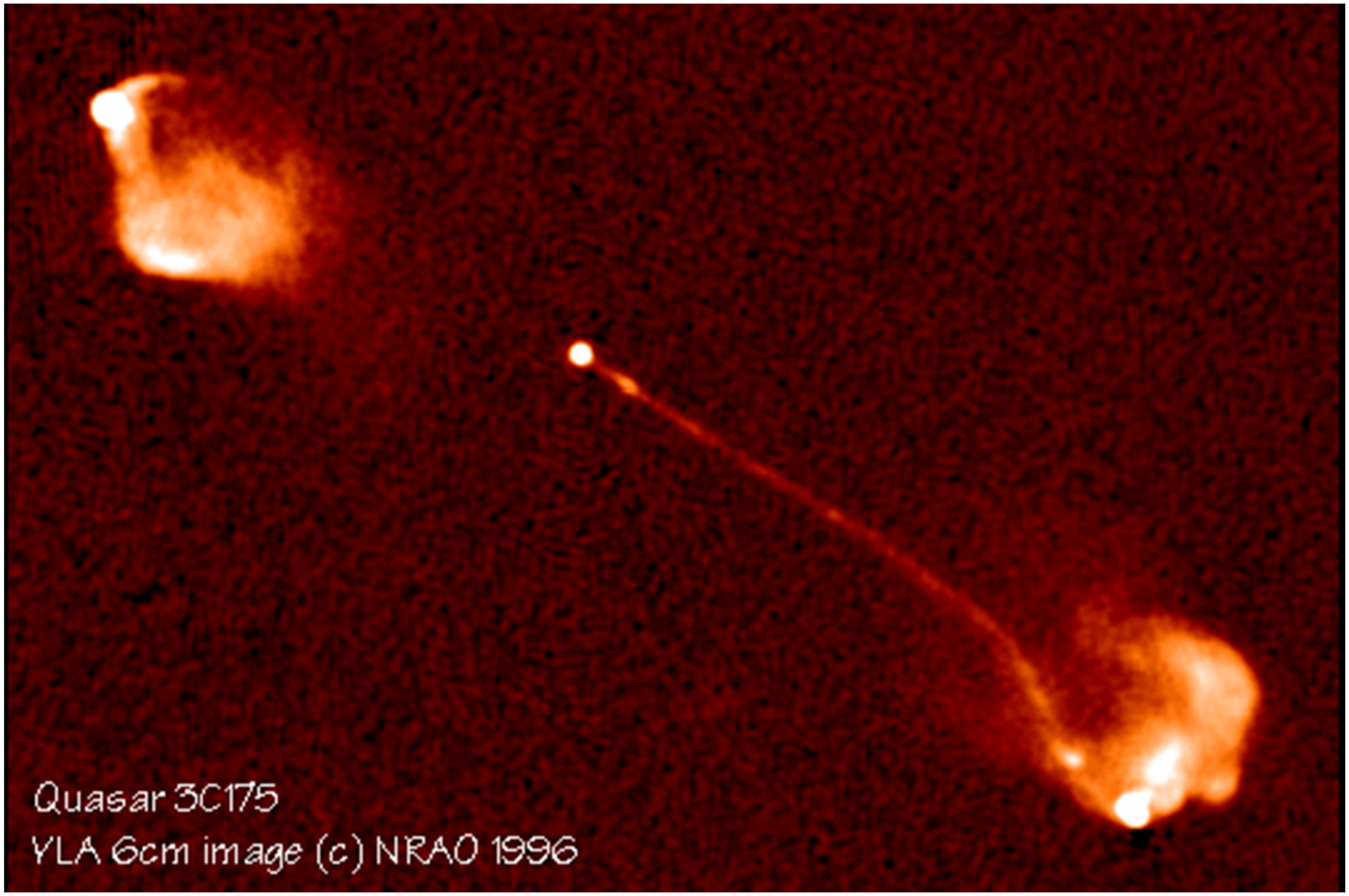
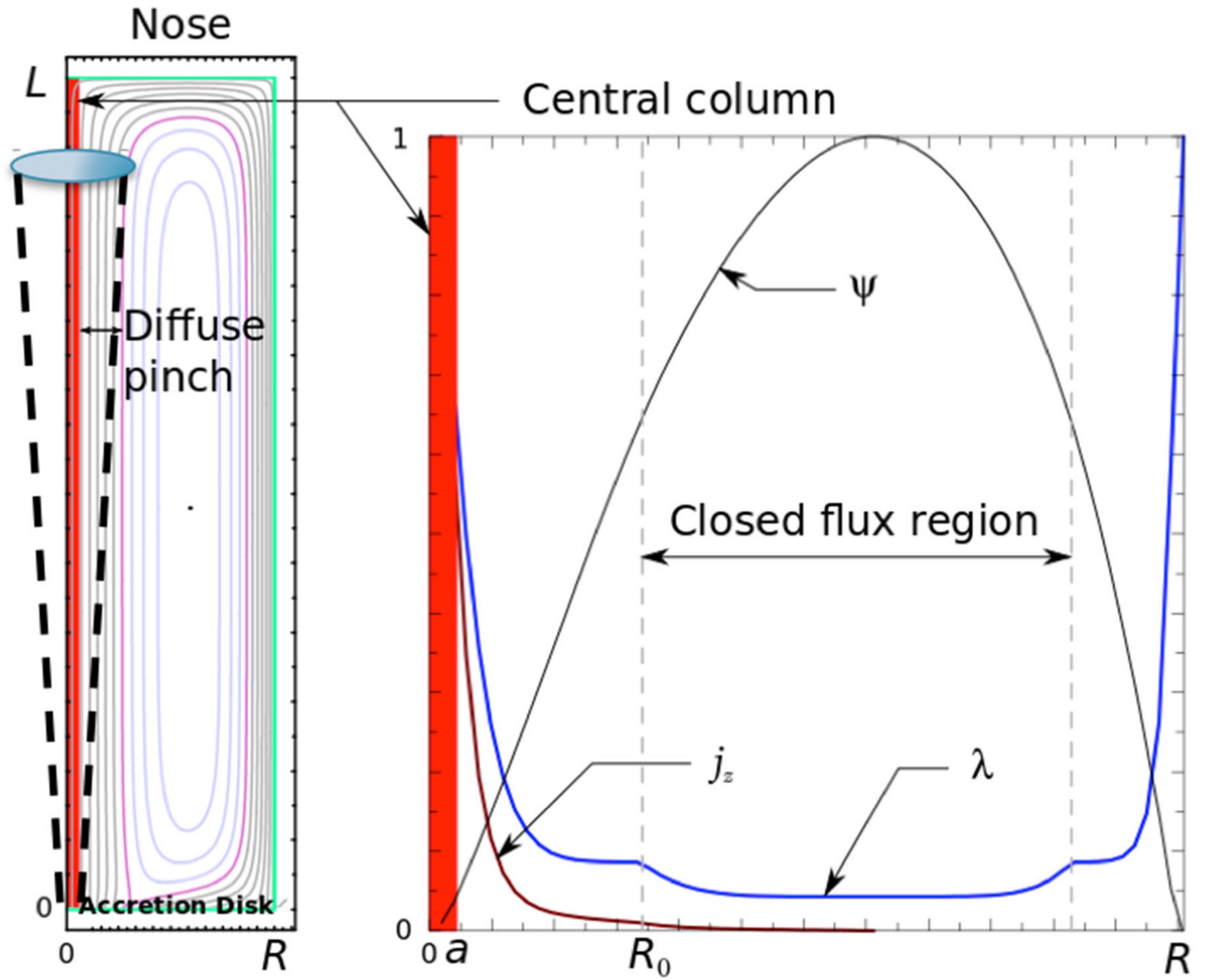
- AGN jets could be powerful cosmic ray accelerators [S. A. Colgate and H. Li, Comp. Ren. Phys. **5**, 431 (2004)]



We have developed an analytical model of AGN jets

- **Accretion disk jets in:** S. A. Colgate, T. K. Fowler, H. Li, J. Pino, ApJ **789**,144 (2014)
- **Jet stability in:** S. A. Colgate, T. K. Fowler, H. Li, E. B.Hooper, J. McClenaghan, Z.Lin, ApJ **813**, 136 (2015)
- **Jet as UHE cosmic ray accelerator in:** T. K. Fowler & H. Li, J. Plas. Phys. **82**, 595820503 (2016)
- **Model predictions in:** "Hyper-Resistive Model of Ultra High Energy Cosmic Ray Acceleration by Magnetically-Collimated Jets Created by Active Galactic Nuclei," T. K. Fowler, H.Li, R. Anantua, Submitted ApJ: **ArXiv 1903.06839 (March 2019)**

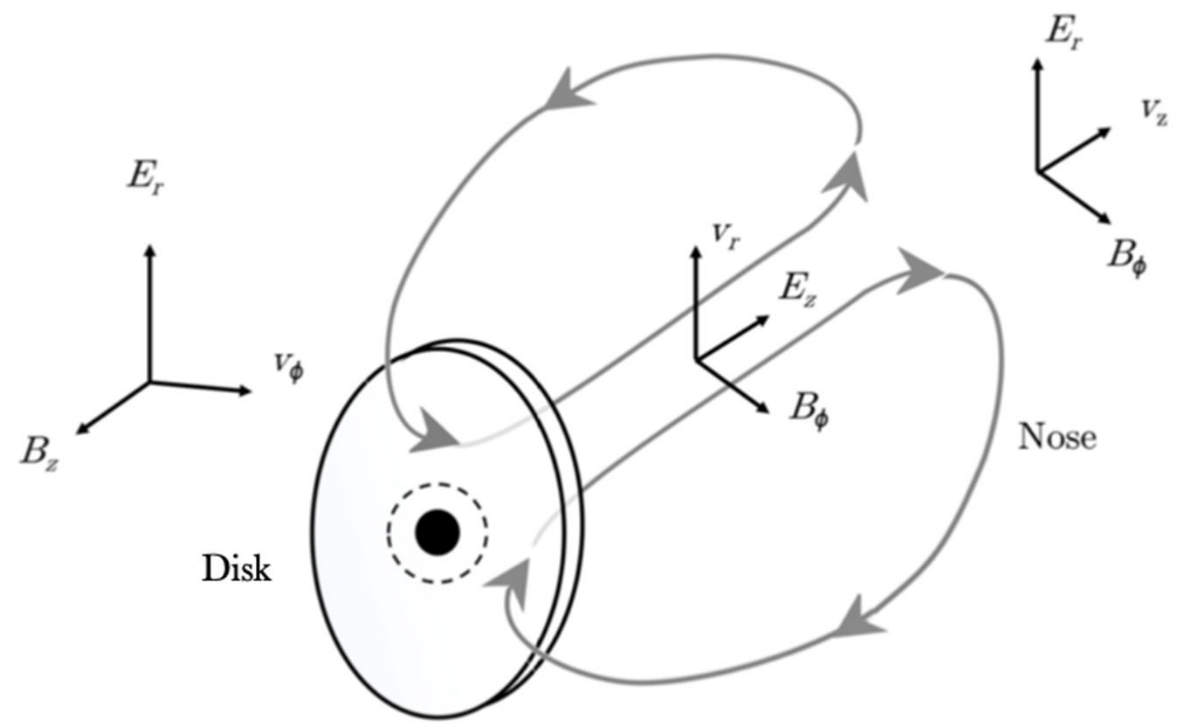
Model leads to Magnetic Tower as Ultra High Energy Cosmic Ray Accelerator



Nose
L
Central column
1
ψ
Diffuse
pinch
Closed flux region
j_z
λ
0
Accretion Disk
0
R
0
0
a
R_0
R

(a)
(b)

Current loops creating a magnetically collimated jet with large inductance



New Result

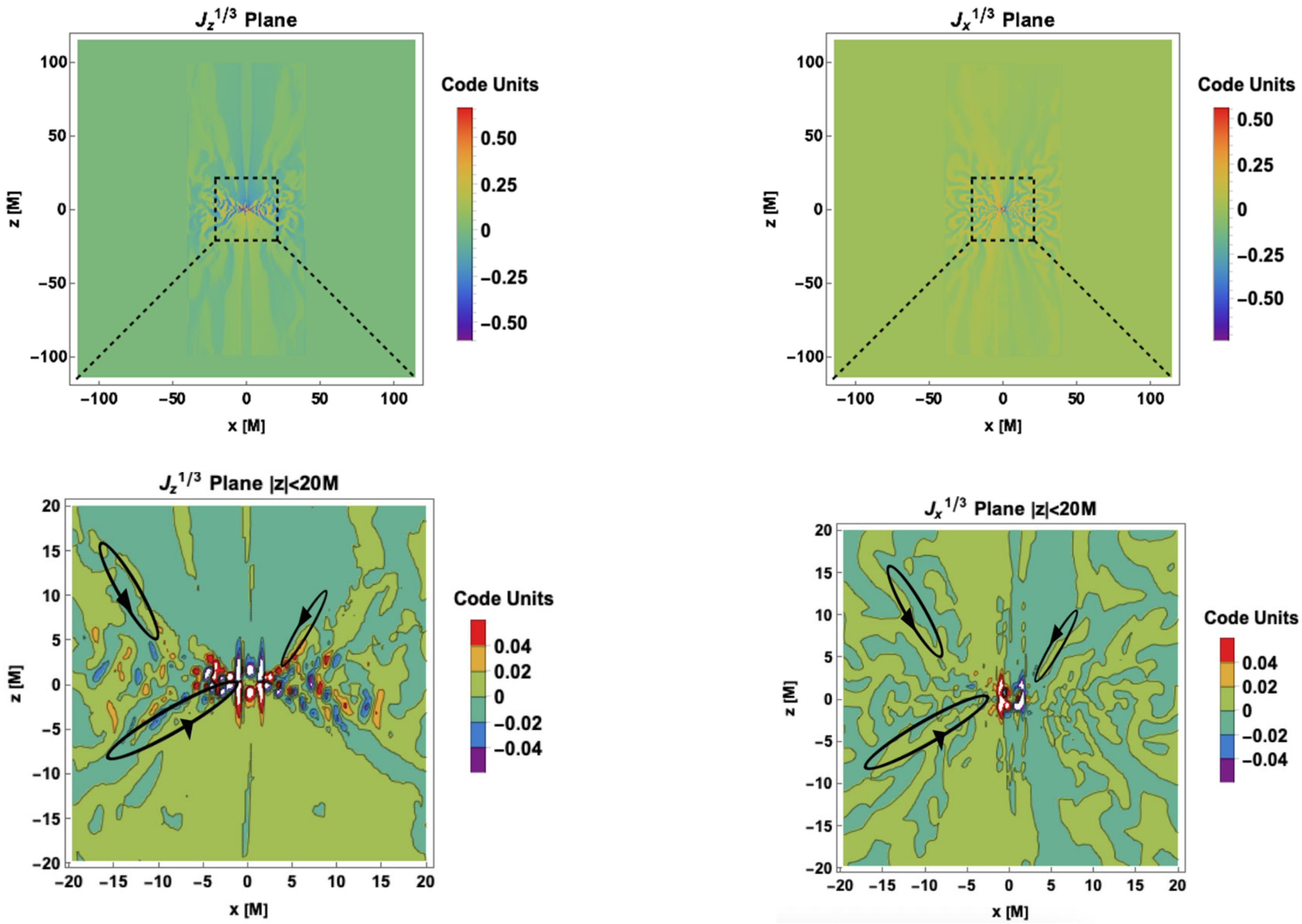
Example I:

- **GRMHD simulations show that an accretion disk launches a jet at:**

  $$B_\phi = r^{-1}\int_0^r dr\, r(4\pi j_z/c) = E_r = -(v_z/c)B_\phi\,;\ v_z = dL/dt = c$$

- **But we find that MRI causes B_ϕ in the disk to grow smoothly from $B_\phi = 0$ to $B_\phi >> E_r$**
- **Persistence of $B_\phi = E_r$ in the jet as $B_\phi >> E_r$ in the disk requires short-circuit in the disk corona**
- Preliminary evidence of short-circuit in disk corona appears in GRMHD simulation

Evidence of Short-Circuit



Other New Results

- **Example 2:**

  Relativistic effect could cancel jet acceleration:

  $$E_{||} - c^{-2} u_{||e}(\mathbf{u}\cdot\mathbf{E}_e)$$

  But **two-stream instability** gives $u_{||e} \approx 0$
- **Example 3:** Radiation inhibits acceleration in the jet but the **Drift Cyclotron Loss Cone (DCLC)** in the nose accelerates ions > 10^{20} eV
- **Example 4:** DCLC transport theory gives observed UHECR power spectrum $\mathbf{I(E) \propto 1/E^3}$

Magnetic Tower: Numbers

Input: Black hole

Mass M; jet life $\tau = 10^8$ yrs ($dM/dt \approx M/\tau$)

Parameters: Central Column radius a, field B_a

Current $I = (aB_a c/2)$; voltage $V = 5(a\Omega_a/c)aB_a$

Constraints: ($M_8 = 10^8$ Suns):

$\frac{1}{2}(M/\tau)\,\Omega_a = aB_a{}^2$; $IV = f\,[\frac{1}{4}(M/\tau)\,c^2]$; $f = \frac{1}{4}$

(with $\Omega_a = (MG/a^3)^{1/2}$; $R_S = 2MG/c^2 = 3\text{x}10^{13}\,M_8$ cm)

Results: $a = 10R_S$; $(a\Omega_a/c) = 1/5$; $B_a = 1500\,M_8{}^{-1/2}$

$I = 0.7\text{x}10^{28} M_8{}^{1/2}$ esu/s; $V = 1.4\text{x}10^{20} M_8{}^{1/2}$ volts

Inductive slowing down: $dL/dt = \frac{1}{4}\,c/(\ln R/a) = 0.01\,c$

Magnetic Tower: 9 Predictions

Jet: (1) $L = 0.01c\tau = 10^{24}$ cm; (2) $R = 0.1\ L$

UHE Cosmic Rays reaching Earth:

(3) Max. Energy = $1.4\ \text{x}10^{20}\ M_8^{1/2}$ eV;

(4) Energy spectrum $I(E) \propto 1/E^3$

(5) A few sources could explain observed intensity: ($1/\text{km}^2$ century) for $E > 6\ \text{x}10^{19}$ eV

Synchrotron:

(6) $\lambda < 10$ cm; (7) $(E_e)_{MAX} \approx 20\ \text{TeV}\ M_8^{5/8}$

(8) 1% luminosity; (9) Light cone ≈ 0.01rad

Magnetic Tower accelerator: 1st Stage

Central Column current drives MHD kink modes

Kink modes known to accelerate ions (Rusbridge et al. Plas.Phys.Contr.Fusion 39, 683 (1997)):

– Self-Correlated turbulence:

$E_{||} = D_{||} = - c^{-1}\langle \mathbf{v_1} \times \mathbf{B}_1 \rangle = (D_r^H / ca) B_\phi = 0.01$ V/L

Twisting field (B_ϕ, B_z) produces radiation limits:

$dp/dt = e[E_{||} - 2/3\, e(\gamma_L^4 / a^2)]$; $\gamma_L < 3.4 \times 10^7 M_8^{5/8}$

-- **Electron energy** < 20 TeV $M_8^{5/8}$

-- **Ion energy** $< 3 \times 10^{16}$ eV $M_8^{5/8}$

2^{nd} Stage: DCLC in the Nose

DCLC requires hole in $f(p_\perp) = \int dp_{||} f$:

$$\text{hole at } (p_\perp/m\gamma_L c)B_\phi < m\gamma_L c^2/r$$

Onset: $r_L = (E_{ion}/eB_\phi) > \Delta\,[0.4(\omega_{ci}{}^2/\omega_{pi}{}^2)^{2/3}]$

$$\Delta = (n/\nabla_z n); \qquad B_\phi = B_a\,(a/r)$$

Accelerator:

$$E_r = D_r = (D_z{}^H/c\Delta)B_\phi \approx C(V/r) \approx 0.1\,(V/r)$$

Cosmic Rays: $\boldsymbol{I(E) = \int_{nose} dx\, f\, D_z{}^H\,(\kappa/\Delta^2)}$

Cosmic Ray Energy Spectrum

- $\partial f/\partial t \quad = \partial/\partial p_r\,[-eE_{accel} f + D_p \partial f/\partial p_r] + \partial/\partial z\, D_z^H \partial f/\partial z$

For DCLC, $E_a < E < E_{MAX}(r) = \int_a^r dr E_{accel}$; $E = E_a$ entering nose

- $f \;=\; C \exp \int dp_r\, (eE_{accel}/D_p) \;\propto (1/E_{MAX}) \exp (E/E_{MAX})$

Flux width grows to: $\Delta = r_L(r)_{MAX} = r(E_{MAX}/eV)$

- **$I(E) \quad = \quad \int_{nose} Adr\; n\; \partial/\partial z\; D_z^H\, \partial f/\partial z$; $\qquad n = (I/Aev)$**

$= \quad (I/e) \int_{E/eV}^{1} dY\, (r/D_r^H) D_z^H (\kappa^*/\Delta^2) f(Y)$; $Y = (E/E_{MAX})$

$= \quad \kappa\, (eV/E)^3 (1/e^2V) \int_{E/eV}^{1} dY\, Y^2 \exp Y$; $\kappa =$
$\kappa^*(D_z^H/D_r^H)$

$\approx \quad$ **$(eV/E)^3\;\; [\kappa\, (I/e)\, (1/eV)]$**

Cosmic Ray Intensity on Earth

κ from energy conservation:

$\frac{1}{2}$ IV = $\int_{E*}^{eV} dE\, E\, I(E)$ = IV [κ(eV/E*)] ; $E^* < E_a$

κ = $\frac{1}{2}$ (E*/eV) ; $E^* < E_a$

Intensity above energy $E_1 = 6\mathrm{x}10^{19}$ eV:

$N[\int_{E1}^{eV} dE\, I(E)/4\pi R_S^2\,]$ = 1/[km^2 century]

κ (I/e) $\frac{1}{2}$ [(eV/E_1)^2 – 1] = ($R_{MPc}{}^2$/N) 4 x 10^{30}

Approximate agreement: N > 1, R_S > 10 MPc

Evidence that Jet is a Magnetic Tower

- RadioAstron collimated images (Giovaninni et al. Nat. Astron. **2**, 472 (2018))
- Collimated current, radius about a = 10 R_S by Faraday rotation measurements (Kronberg et al. ApJL,**741**, L15 (2011))
- Collimation near the black hole (Zamaninasab et al. Nature **510**, 126 (2014))

Does Theory Produce a Tower?

Jet as a Non-Maxwellian Vlasov fluid:

$$\partial \mathbf{j}/\partial t \quad + \quad \nabla\cdot \Sigma\int d\mathbf{p}\; q\mathbf{uu}\, f \quad =$$

$$\Sigma\int d\mathbf{p}\; f\, (e^2/m\gamma_L)[\mathbf{E} - c^{-2}\, \mathbf{u}\, (\mathbf{u}\cdot\mathbf{E}) + c^{-1}\, \mathbf{u} \times \mathbf{B}]$$

$$(\mathbf{u} \;=\; \mathbf{p}/m\gamma_L; \quad q = +/- e)$$

$$\partial \mathbf{P}/\partial t \;+ \nabla\cdot \Sigma\int d\mathbf{p}\; \mathbf{pu}\, f \quad =$$

$$c^{-1}\, \mathbf{j} \times \mathbf{B} \;+ \sigma\mathbf{E} \;-\; \rho\nabla V_G \;-\; \nabla p_{amb}$$

$$(\sigma \;=\; \nabla\cdot\mathbf{E}/4\pi)$$

Hyper-Resistive MHD

Average over 3D fluctuations giving hyper-resistivity **D**:

- $E_\perp + c^{-1}\mathbf{v} \times \mathbf{B} = - c^{-1}\, \partial \mathbf{A}_\perp/\partial t - \nabla\Phi + c^{-1}\mathbf{v} \times \mathbf{B} = D_\perp$
- $E_{||} - \langle c^{-2}\, u_{||}\, (\mathbf{u}\cdot\mathbf{E})\rangle = D_{||}$ relativistic accelerator
- $\partial \mathbf{P}/\partial t + \nabla\cdot n\mathbf{p}\mathbf{v} = c^{-1}\mathbf{j} \times \mathbf{B} + \sigma\mathbf{E} = c^{-1}\mathbf{j}^* \times \mathbf{B}$
- $(dM/dt)\Omega = \int ds\, \partial/\partial s \langle rB_\phi B_{POL}\rangle$; $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1$
- $c^{-1} j_\phi B_z = (1/8\pi r^2)\partial/\partial r\, r^2\, (B_\phi^2 - E_r^2)$ FFDE

Magnetic Tower in 3 Steps

- **Step 1: MRI in Disk:** $\mathbf{D} = c^{-1} \langle \mathbf{v}_1 \times \mathbf{B}_1 \rangle$

  $-\partial A_r/\partial t = [v_z B_\phi - cD_r]$

  $-\partial A_\phi/\partial t = [v_r B_z - cD_\phi]$

- $E_r/B_\phi = -[(v_\phi/c)B_z/B_\phi] \rightarrow (v_\phi/c)(v_z/v_r)(-D_\phi/D_r)$

- $E_r/B_\phi \ll (-D_\phi/D_r)$

  $= |\langle v_{1z} B_{1r} - v_{1r} B_{1z} \rangle / \langle v_{1z} B_{1\phi} - v_{1\phi} B_{1z} \rangle| \approx 1$

Magnetic Tower in 3 Steps

Step 2: Growing disk current at constant jet curent requires temporary short-circuit **j***:

$\nabla\cdot n\mathbf{pv} = c^{-1}\mathbf{j^*} \times \mathbf{B}$; $I = I_\perp = 2\pi r\Delta_z j_r{}^*$

$I_\perp = 2\pi r\Delta_z \, [(\partial/\partial z \; np_z v_z)/B_\phi]$

$= \tfrac{1}{2}\, I(v_{\perp z}/v_A)^2 \approx \tfrac{1}{2}\,(dL/dt/c)^2\, I$

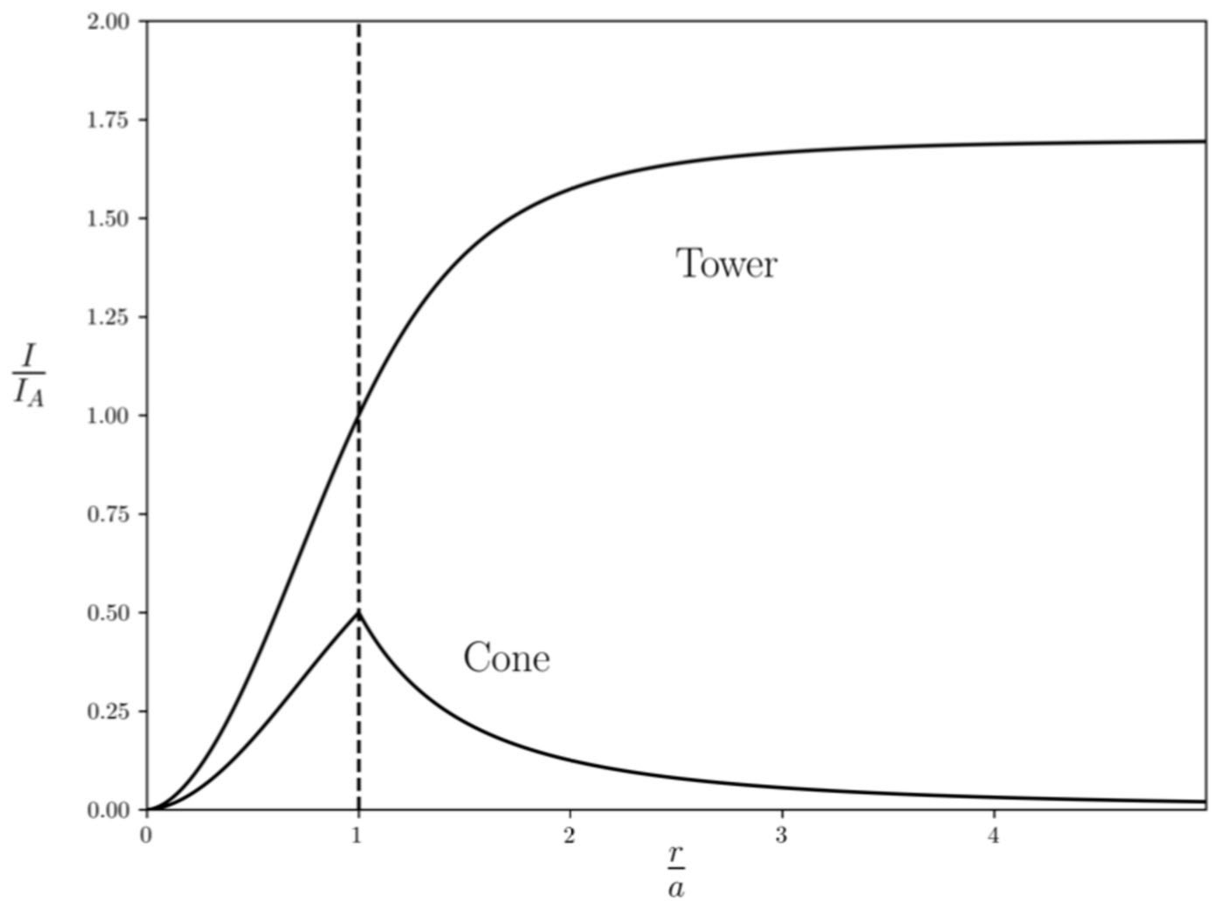
:

Step 3: Conical jets may eventually slow down by inductance alone, giving dL/dt << c, hence:

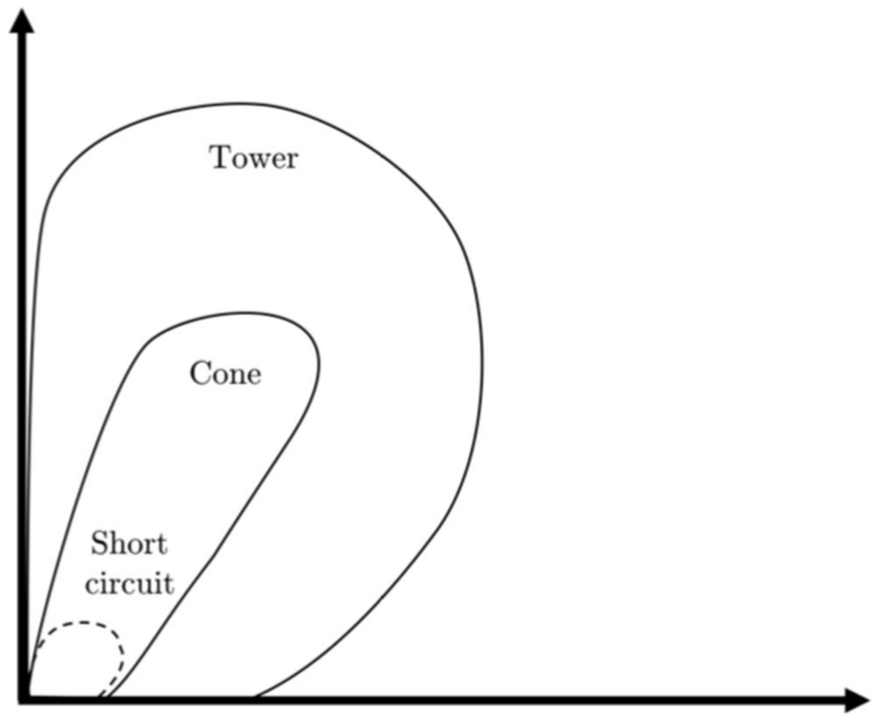
$I_\perp \rightarrow 0$; $E_r = (v_z/c)B_{\phi;} << B_\phi$

Hence $\mathbf{j} \times \mathbf{B} = 0$ (magnetic tower)

Cone Comes First



Jet evolution: cone to tower



Jet Synchrotron Radiation

All electrons radiate at $\mathbf{B = B_a}$:

$\frac{1}{2} M^*\Omega_a = aB_a^2 = \langle r\, \delta B_\phi\, \delta B_{POL} \rangle$, $\boldsymbol{\delta B_{POL} \approx B_a}$

Opening angle Θ is wandering field lines:

$d\xi/dt = \omega_A \xi = (c/\gamma_0)$; $\omega_A = \omega_0(\gamma_0/\gamma_L)^{1/2}$

$\gamma_L = [1 - (v^2 + \xi^2\omega_A^2)/c^2]^{-1/2}$; $\gamma_0 = (1 - v^2/c^2)^{1/2}$

$= \gamma_0/[1 - (\xi^2\omega_0^2\gamma_0^2/c^2)(\gamma_0/\gamma_L)]^{1/2}$

$\boldsymbol{\Theta = \xi/z}$ $= [(c/\gamma_0)t/(dL/dt)t]$ $=$ $\boldsymbol{100/\gamma_0 \approx 0.01}$

Recycling with the Ambient

- Spectrum $I(E) \propto (1/E^3)$ implies exchange of ambient ions and cosmic ray ions at the nose:

$I_{RECYCLE} = \int_{E*}^{eV} dE\, I(E) \approx \frac{1}{4}(I/e)(1/\kappa) >> I/e$

Recycling occurs by adjustments of DCLC vertical transport (approximated by κ). Requires snow-plowing ambient over annulus near $R_{ac} = 10^5 a$.

HOW DETECT?