Synthetic X-Ray and Radio Observations of Simulated Jets:
Insights and Opportunities

X-ray and Radio Connections
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Overview

- Introduction: A new approach
- Background: The simulations
- Opportunities: Synthetic Observations
  - What, Why, How?
- Insights
  - Dynamics
  - Field properties
  - Energy partitioning
- Conclusion: Opportunities

Introduction: A New Approach

- *Self-consistent* acceleration and transport of cosmic ray (CR) electrons within 3D MHD jet simulations
- Synthetic synchrotron radio and inverse-Compton X-ray observations (IC/3K, SSC)
- Standard observational analyses
  - Tregillis et al. ApJ, v601 n2 February 1 2004
- The fun part:
  - *Do we recover accurate source properties?*

Our Approach to CR Transport

(Jones et al. ApJ, 512, 105)

- Physical scales for acceleration << dynamical scales
- Broad electron distribution f(p) enables “finite volume” approach in momentum space:
- Use test-particle model for fast Fermi acceleration at shocks
- Solve kinetic equation for downstream transport

$$n_i = 4\pi \frac{f_{i-1/2}\, p^3_{i-1/2}}{q_i - 3}\left[1 - \left(\frac{p_{i-1/2}}{p_{i+1/2}}\right)^{q_i - 3}\right]$$

$$q = \frac{3r}{r-1} \qquad \left(\alpha = \frac{q-3}{2}\right)$$

$$\frac{dn_i}{dt} = 4\pi\left(\frac{1}{3}\nabla\cdot u - \frac{qD}{p^2} + \frac{p}{\tau_s p_0}\right) p^3 f \,\Big|_{p_{i-1/2}}^{p_{i+1/2}}$$

One Jet…

(Tregillis et al. ApJ, 557, 475)

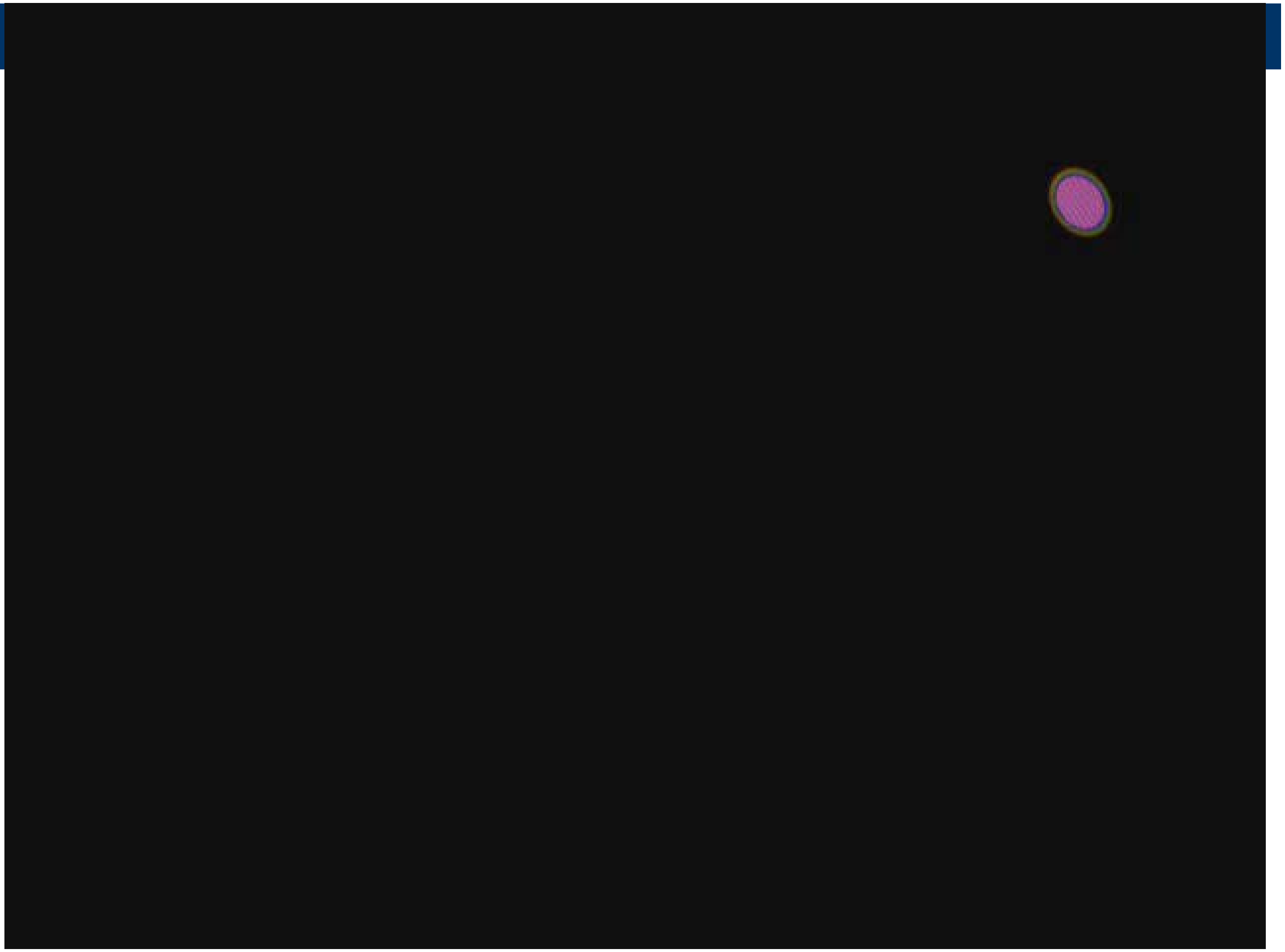
- Light, supersonic (nonrelativistic) 3D MHD jet
- $M_j=8$, $\eta=\rho_j/\rho_a=0.01$; pressure matched in uniform background
- Helical magnetic field; $\beta_0 = 100$ on axis
- Symmetry broken with 5^o precession
- 15 zones across jet core for accurate shock identification

…Three Scenarios

(Tregillis et al. ApJ, 557, 475)

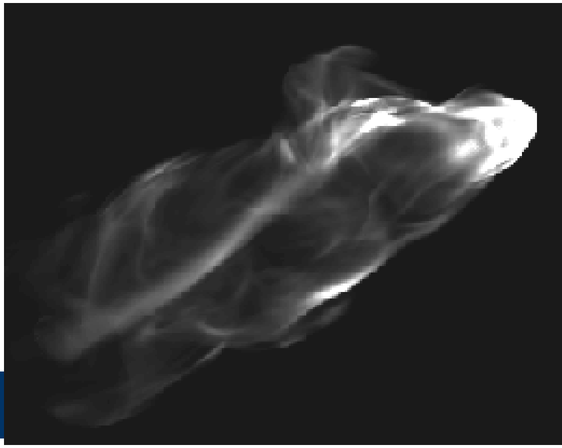
- Model 1: “Control”
  - No injection of fresh particles at shocks
  - Negligible radiative aging
- Model 2: “Injection”
  - Minimal CR population carried down jet
  - Fraction ($\varepsilon=10^{-4}$) of thermal electron flux “injected” at shocks
- Model 3: “Cooling”
  - Radiative lifetime for 5 GeV electrons ~ simulation duration
  - Spectra experience considerable aging

Particles…



…and Fields

Synthetic Observations



Particles

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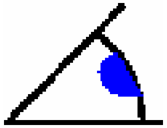
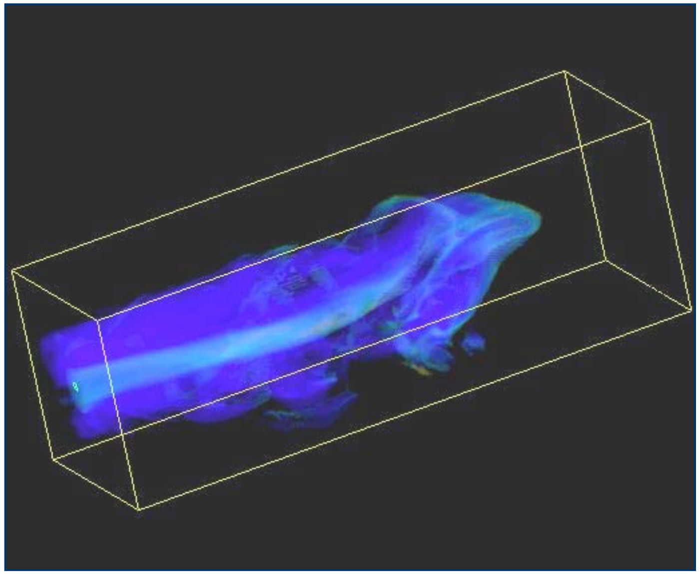
Fields

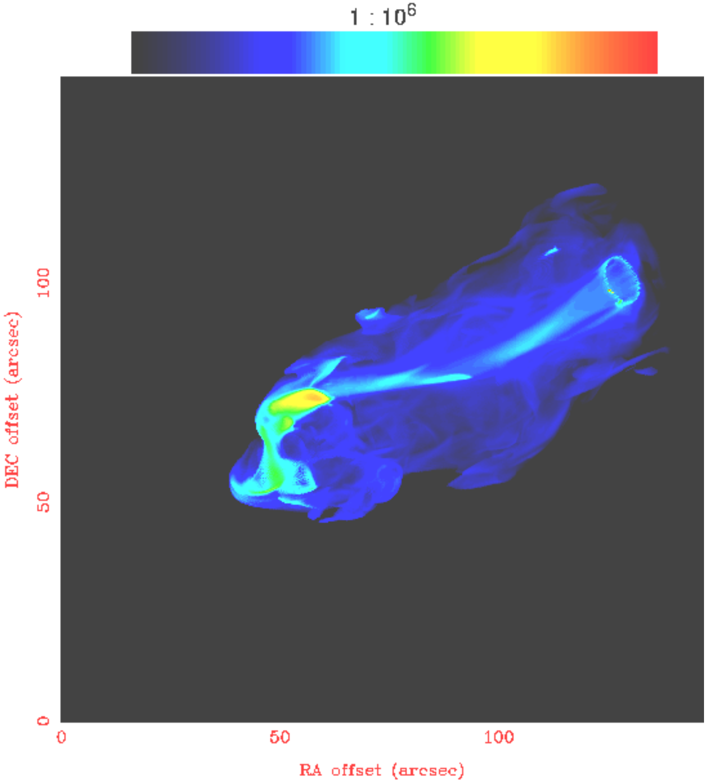




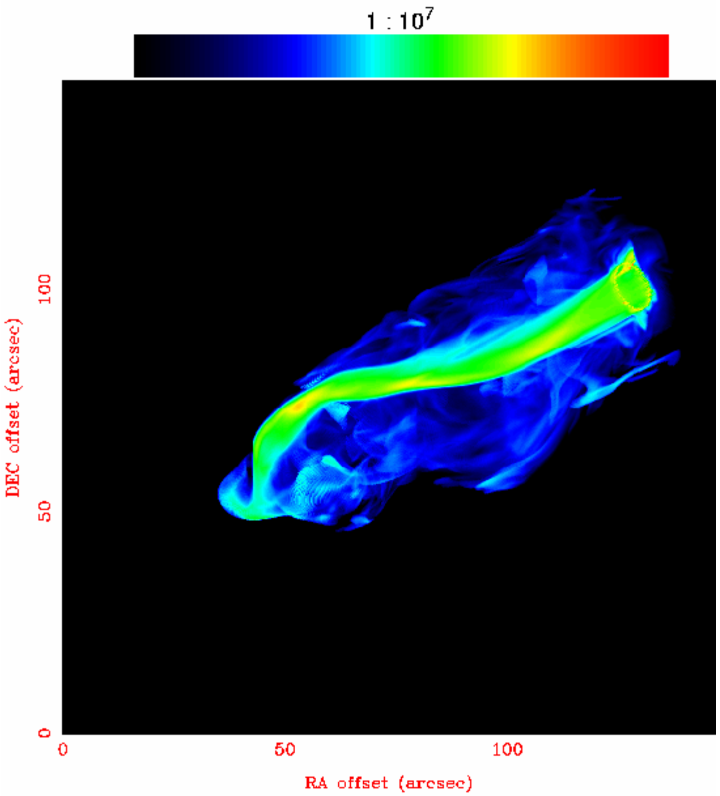
Synthetically-observable quantities include:

- Radio synchrotron surface brightness and spectral index
- IC/3K and SSC X-ray surface brightness
- Radio polarimetry (Stokes Q, U); Faraday rotation & RM

Example: Radio Surface Brightness, 1.4 GHz



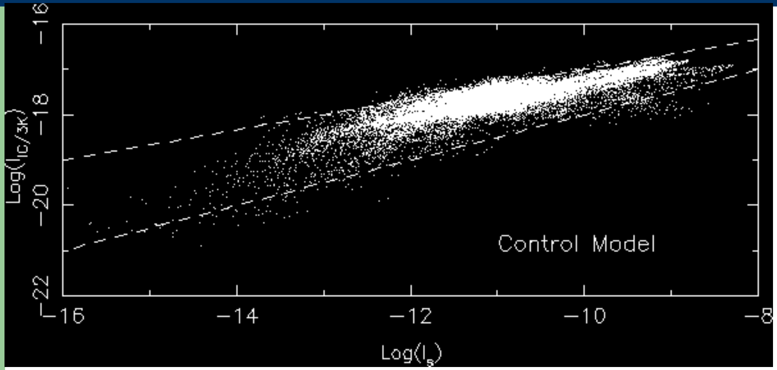
Injection



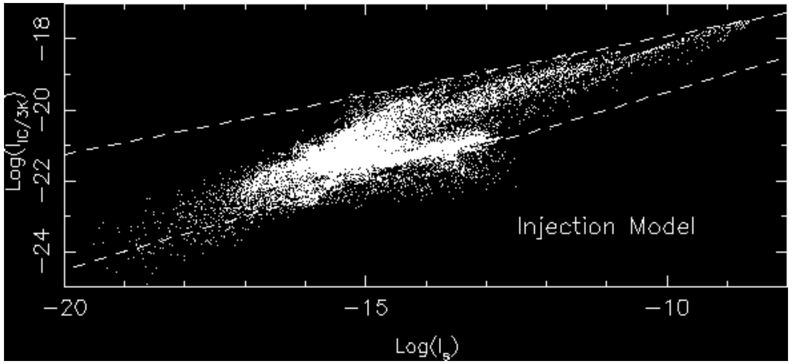
Cooling

Combined Observations (finally): Dynamical Insights

(Tregillis et al. ApJ February 1, 2004)

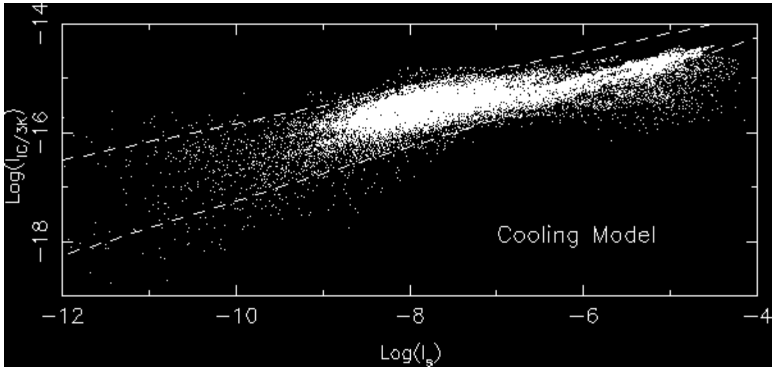


$I_{IC/3K} \propto I_S^m$; m = 1/3 – 1/2



$I_s \propto n_e D B^{1+\alpha}$ $\alpha \sim 0.5 - 1.0$

$I_{IC/3K} \propto n_e D$ $B \propto n_e^b$



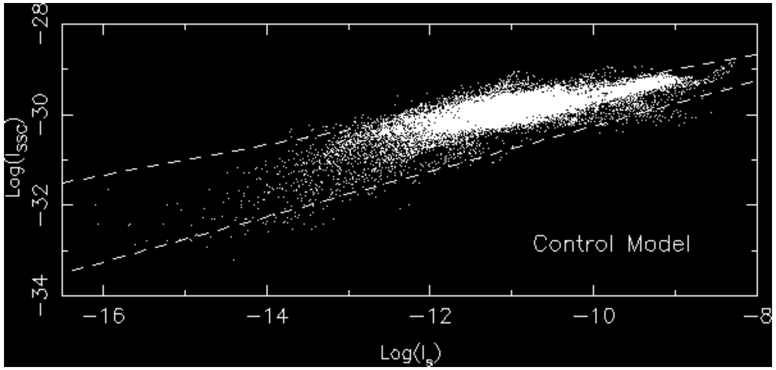
Compression (tangled) : $B \propto \rho^{2/3} \Rightarrow \underline{m \sim 0.5 - 0.43}$

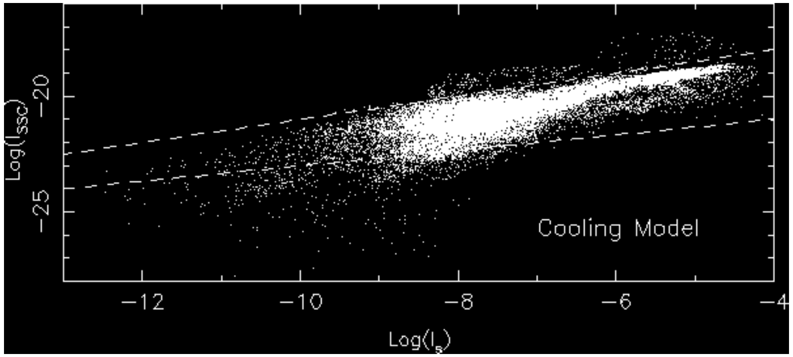
Perpendicular shocks: $B \propto \rho \Rightarrow \underline{m \sim 0.4 - 0.33}$

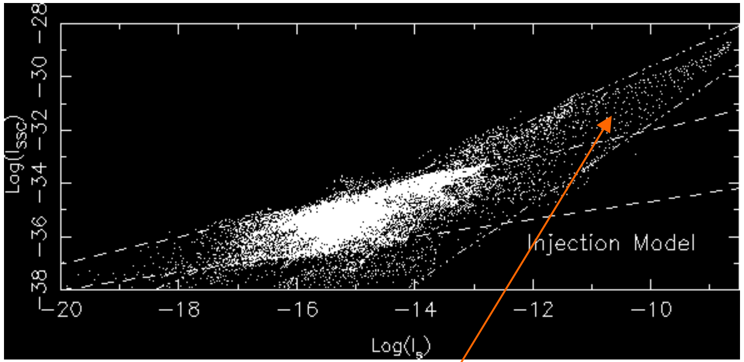
Dynamical Insights, continued

(Tregillis et al. ApJ February 1, 2004)

$I_{SSC} \propto I_S^m$; $m = 1/3 – 1/2$







$I_{SSC} \propto I_S^m$; $m = 1.0 – 1.5$

Locally dominated radiation field:

$\Phi \propto I_S \quad \Rightarrow \quad \underline{m \sim 1.47}\ \ (\alpha \sim 0.65)$

Combined Observations: Magnetic Field Strengths

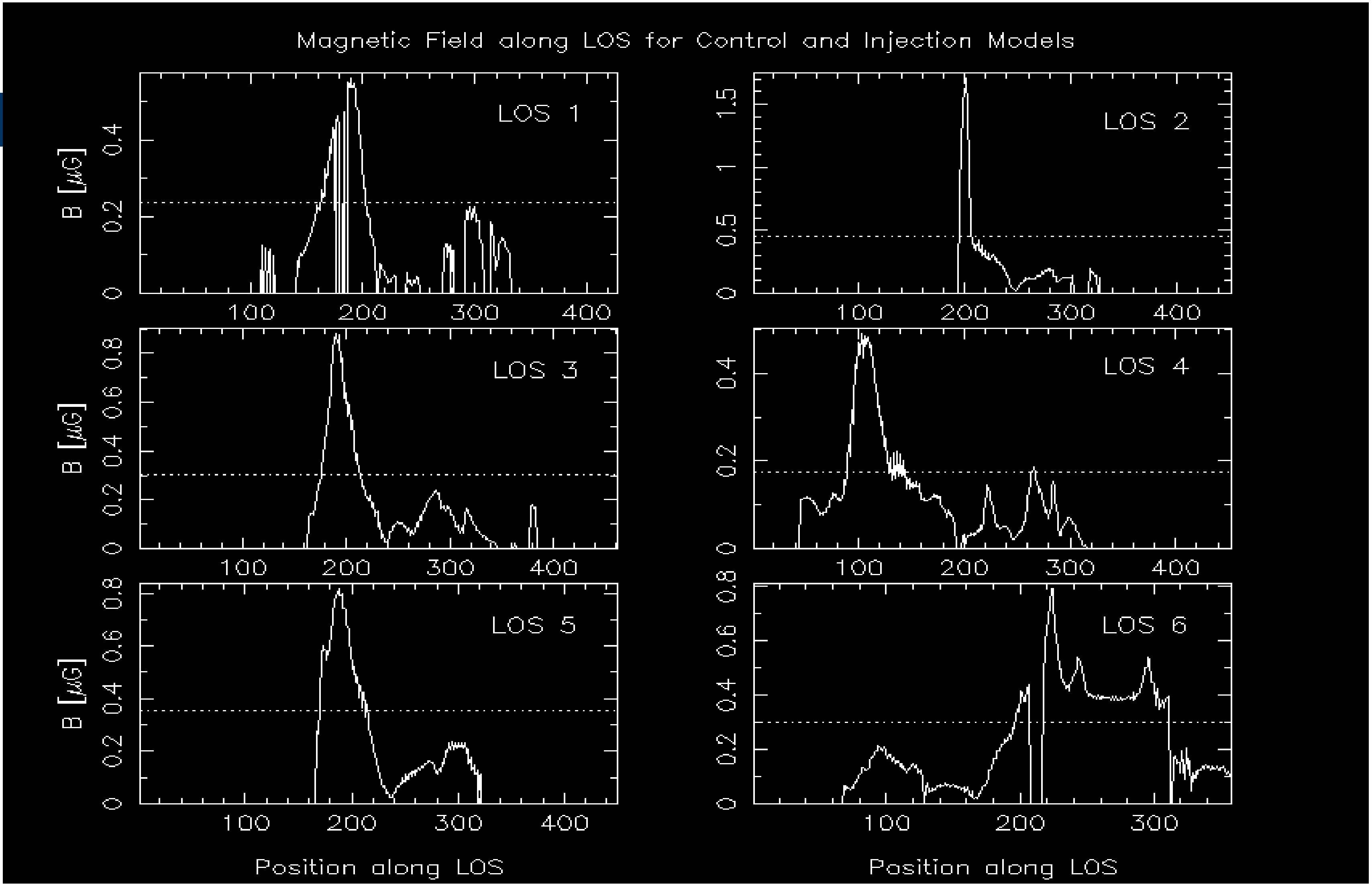
Radio:

$$B_{me} = 5.69 \times 10^{-5} \left[\left(\frac{1+k}{\eta} \right) \frac{(1+z)^{3+\alpha}}{\theta_x \theta_y l \sin^{3/2} \vartheta} \frac{F(\nu_0)}{\nu_0^{-\alpha}} \left(\frac{\nu_2^{1/2-\alpha} - \nu_1^{1/2-\alpha}}{1/2-\alpha} \right) \right]^{2/7}$$

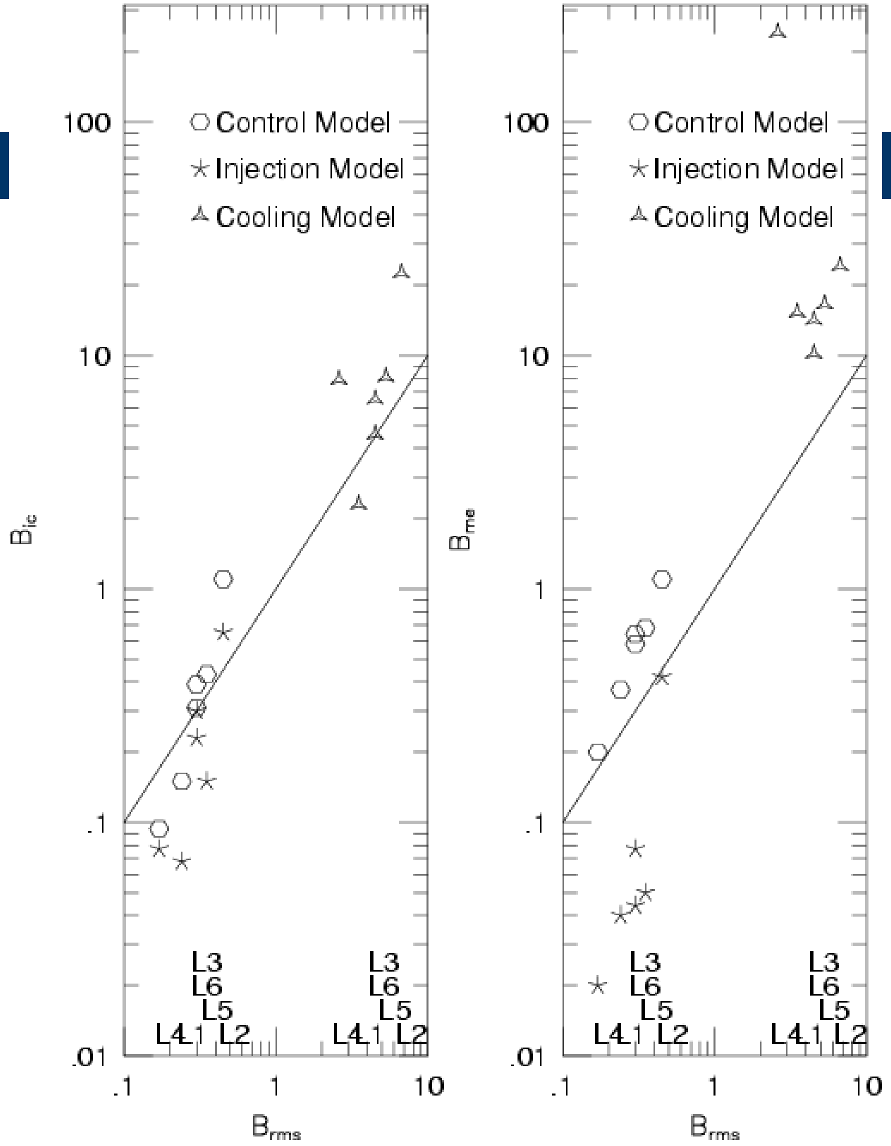
Radio & X-ray:

$$B_{ic}^{1+\alpha} = \left(\frac{j_{\alpha 0}^{BC}}{j_{a0}} \right) (1+z)^{3+\alpha} \left(1.06 \times 10^{-11}\right) \left(2.09 \times 10^{4}\right)^{\alpha-1} \left(\frac{\nu_r}{\nu_x} \right)^{\alpha} \frac{I_s(\nu_r)}{I_{ic}(\nu_x)}$$

The Gritty Reality…



…and Derived Values



Combined Observations: Energy Partitioning

$$d \equiv \frac{U_B}{U_E} = d_{\min}\left(\frac{B}{B_{me}}\right)^{7/2} \; ; \quad d_{\min} = \frac{3}{4}(1+k)$$

- B_{me} is inferred from the radio emission
- B is the true field value in the ideal case
- So, if B_{ic} is a useful estimator of B, why not…

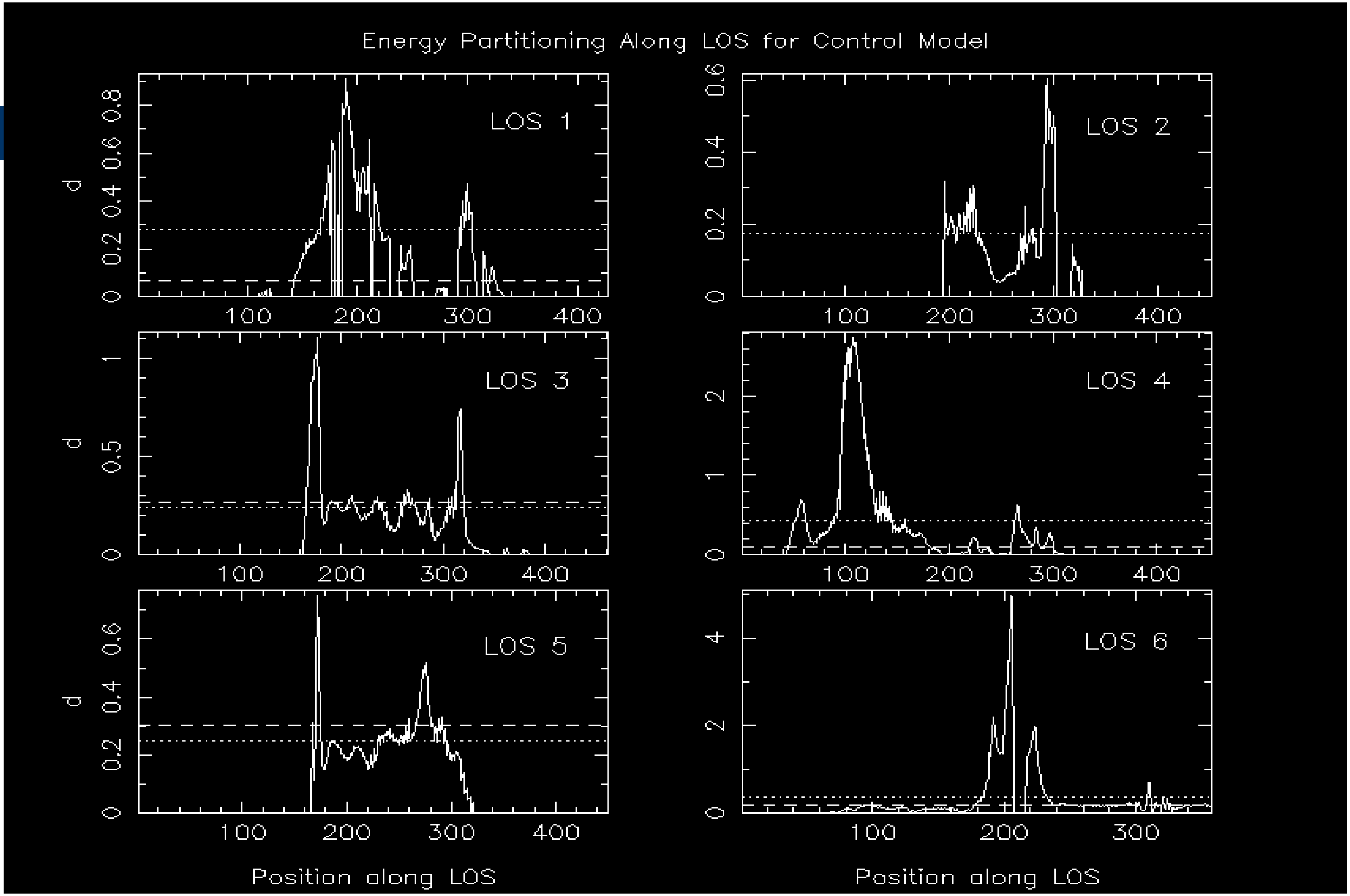
Replace B with B_{ic} and get a direct estimate of d?

Best Case Scenario:
High Degree of Uniformity

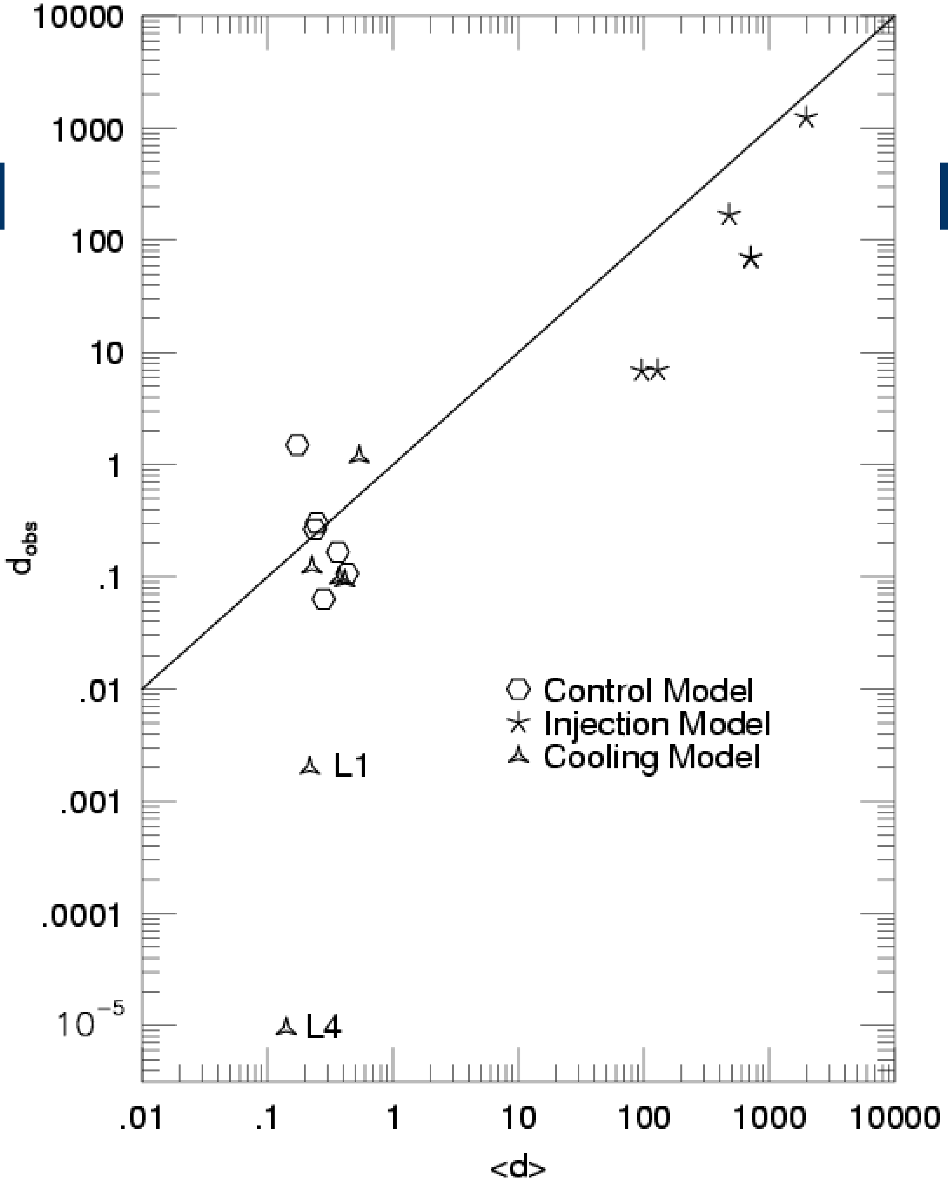
We know *d* exactly at the base of the jet…

d	Control	Injection	Cooling
Initial Conditions	1.6×10^{-1}	1.6×10^{3}	1.6×10^{-1}
Derived from B_{ic} and B_{me}	1.7×10^{-1}	1.2×10^{3}	9.2×10^{-2}

More Gritty Reality



…and More Derived Values



Conclusions & Future Work

Combined synthetic X-ray and radio observations of simulated jets reveal:

- Dominant dynamical and transport effects
- Good estimates for local field strengths
- Direct, independent estimates for the energy partitioning

All of this information is crucial groundwork for understanding the long-term evolution and dissipation of extragalactic jets on cosmological scales.