Jet Structure

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Relativistic Jets

Krakow June 2006

Overview

- Why Structure
- Observable “Structures”
- Origins of Global Structures
  - Implications for Jet Dynamics
    - Focus on Plasma Dominated Jets
- Origins of Local Structures
  - Implications for Jet Dynamics
- Summary –
  - Steps Toward the Nature of Jets

Jet Structures

- Observed Structure
  - Radiative Signature
  - May be Misleading
    - Is What You See What You Get?
- Physical Structure
  - Intrinsic Structure
    - Produced at Source
  - Induced Structure
    - Produced by Environment

Why Structure?

- We Know Very Little About Jets
  - Collimated – Somehow
  - Emit Non-Thermal Radiation
    - Relativistic Electrons and Magnetic Field
- We Don't Know
  - Outflow Speed (Inferred)
  - Content (Charge Neutralizing Species, Plus…)
  - Lifetimes
  - Particle and/or Field Energy Spectra (Cf. L. Rudnick)
  - Therefore No Basic Kinematics

Why Structure?

- If We Knew What We Don't Know…
  - Intrinsic Jet **v**, n, t: dE/dt, dM/dt at Source
  - Energy Spectra: Details of Production Processes
  - Strong Constraints on "Central Engine"
    - Acceleration Processes, B Field Production
    - Evolution of BH and Accretion Structures
  - Constraints on Evolution of Parent Galaxies

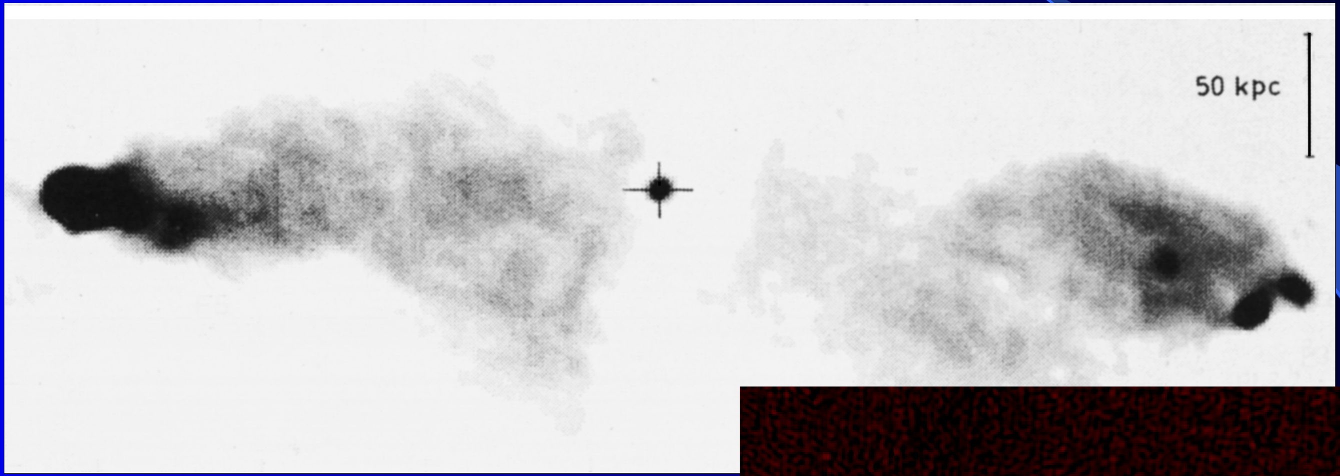
Why Structure?

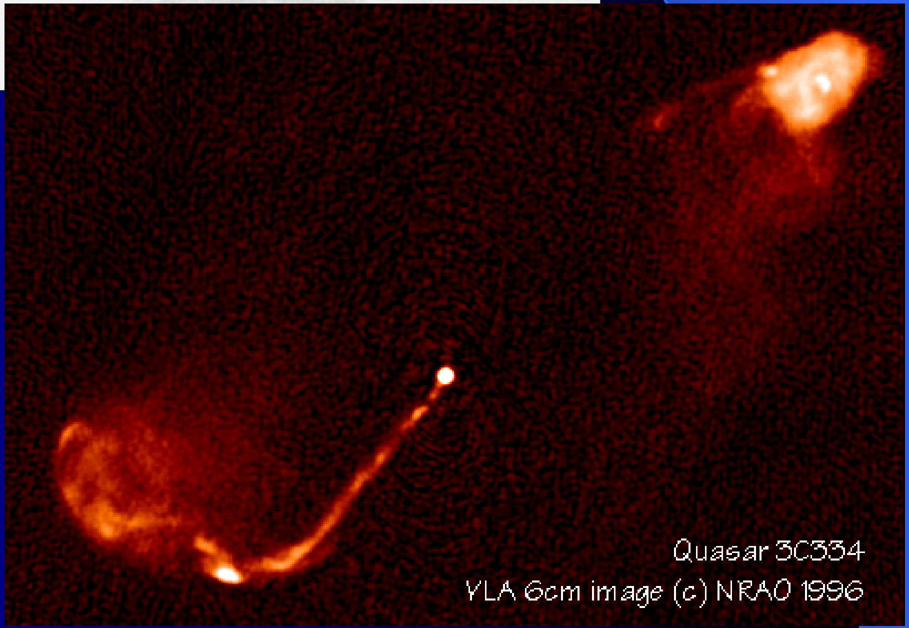
- How to Know What We Don't Know
  - Jet Structure
    - Results from a Combination of:
    - Intrinsic Jet Properties
    - Interaction With Environment
  - Jet Structure + Known Environment + Physics of Interaction
- May Yield What We Don't Know
    - (Or at Least Some of It)

Unresolved Issues

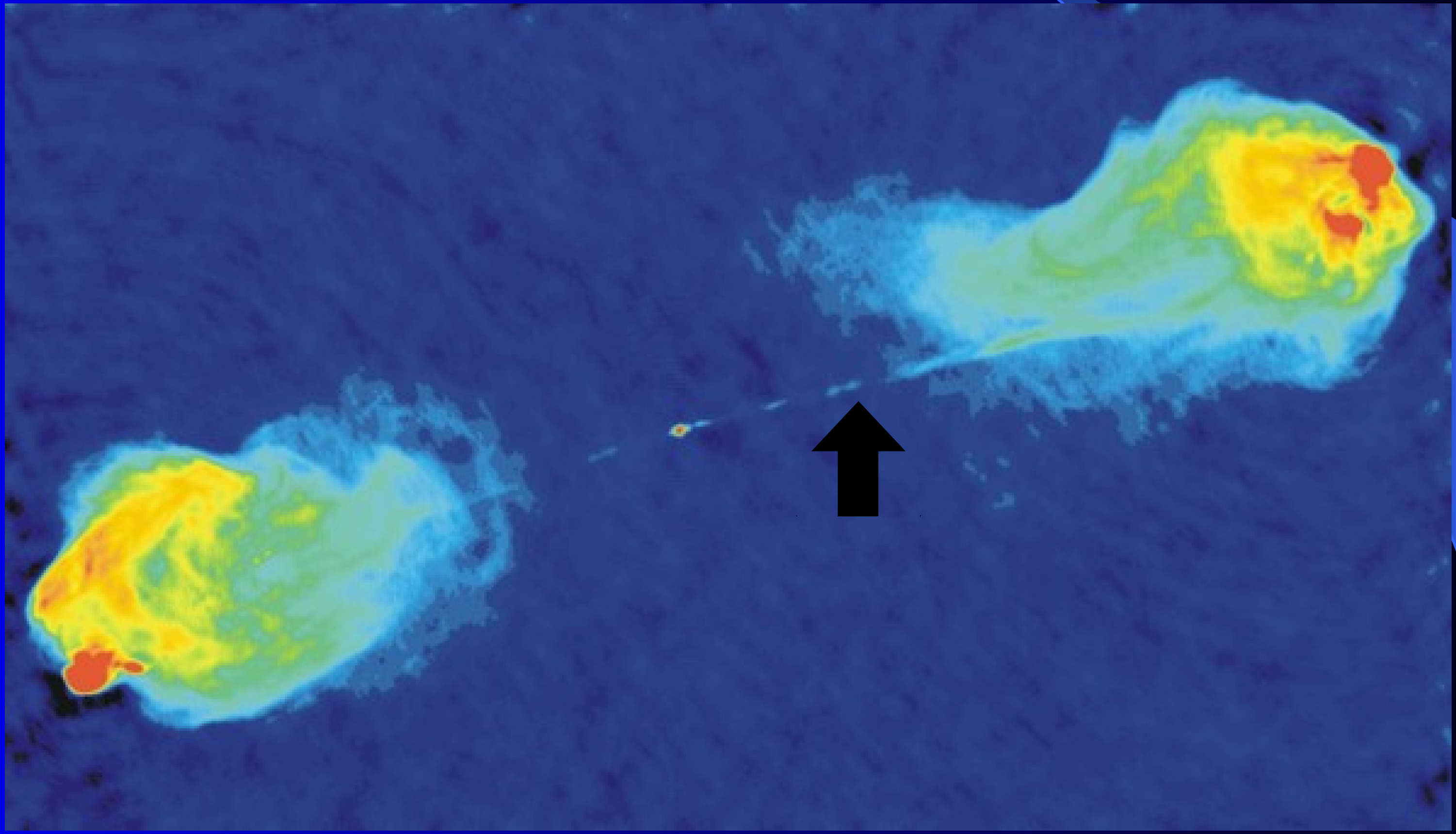
- Creation of Relativistic Power Law Population
- Jet Formation and Collimation
- Jet Content
- Outflow Speeds
- Stability
- Lifetimes and Reacceleration

Global Jet Structures: FR-II Radio Sources





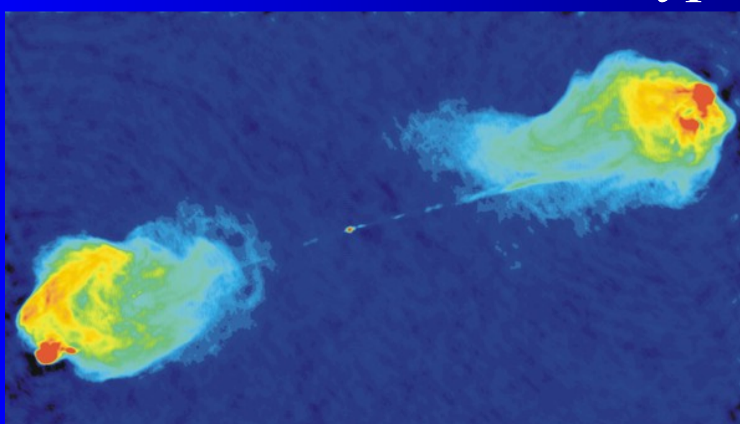
FR-II Radio Sources

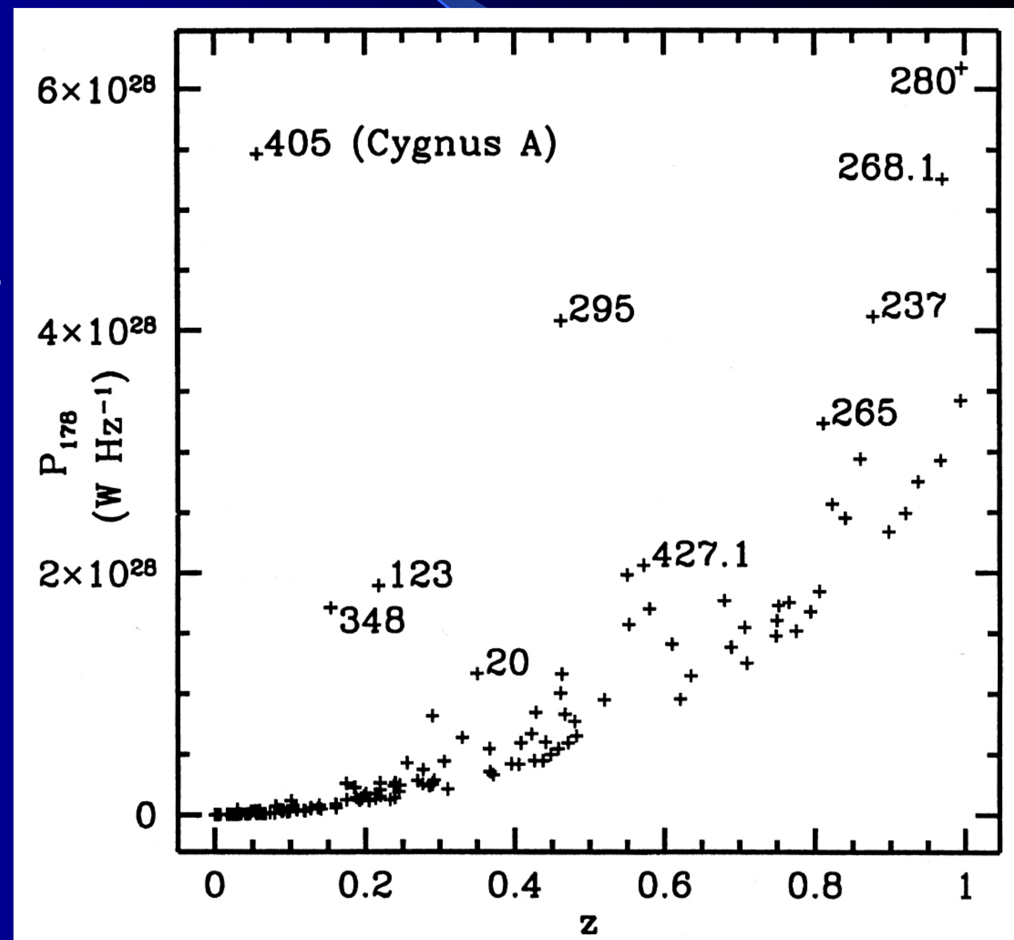


FR-II Radio Sources:

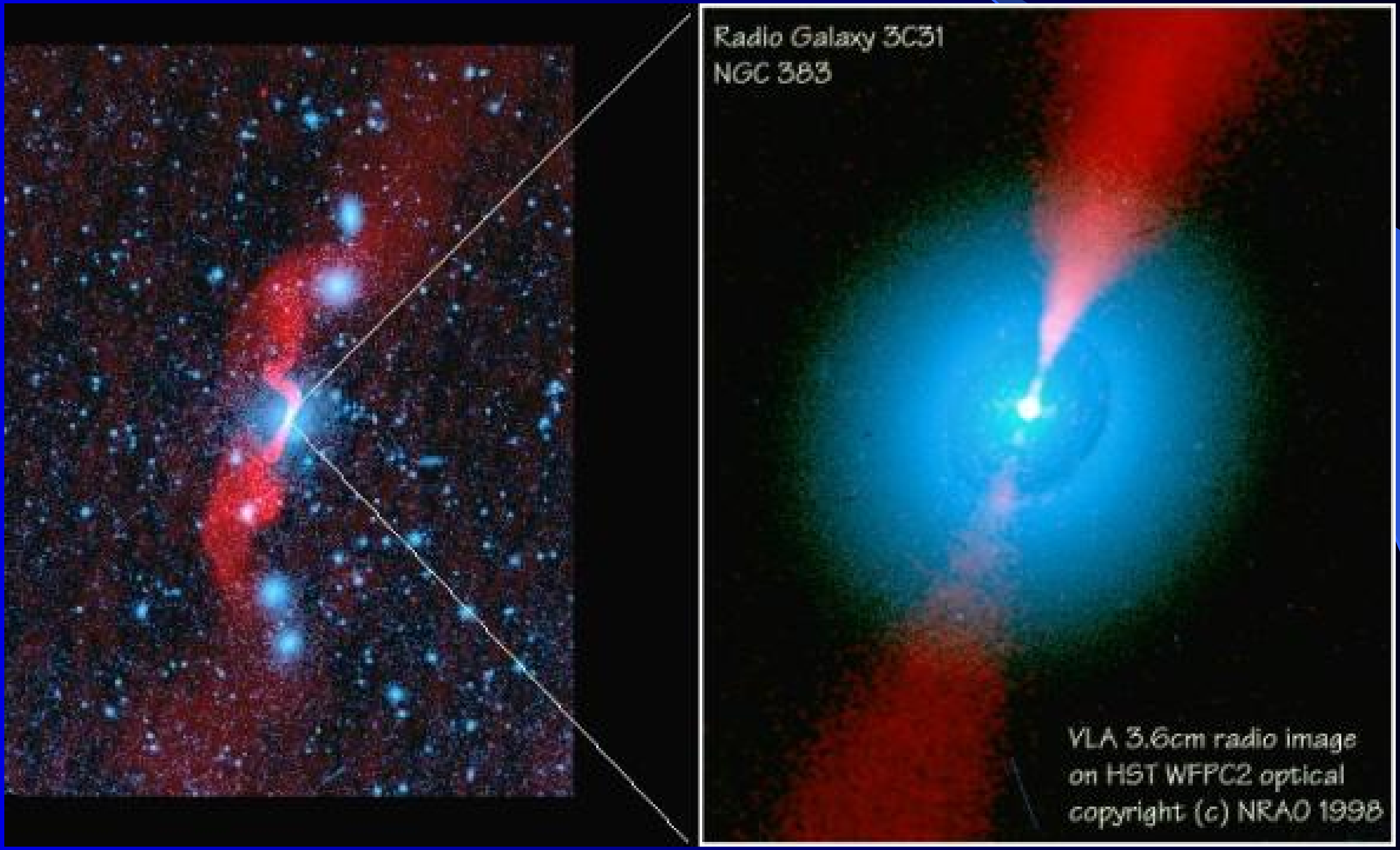
- Not "Typical" Radio Sources
  - Cygnus A:

    NOT "Archetype"

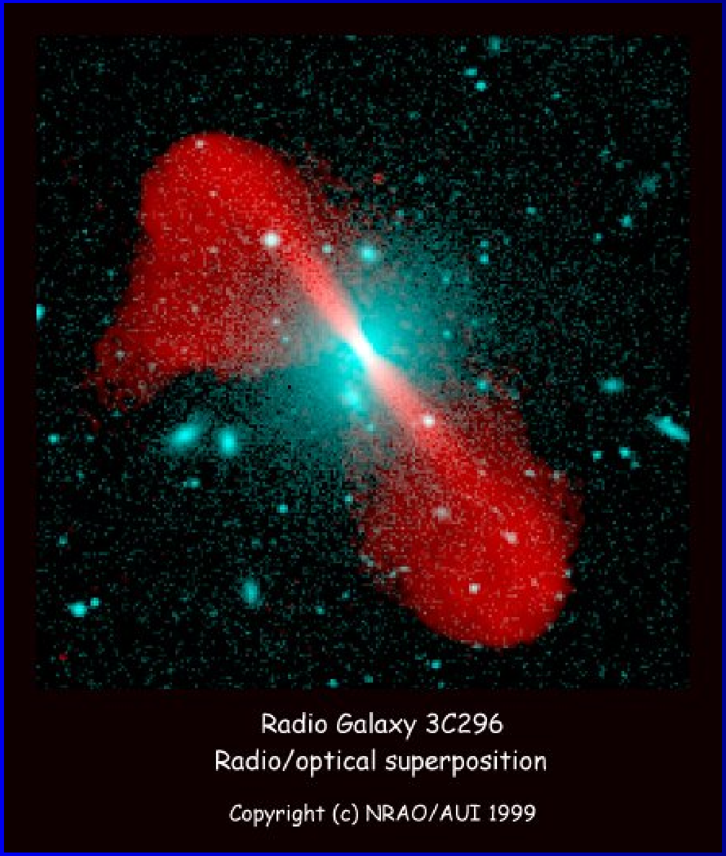


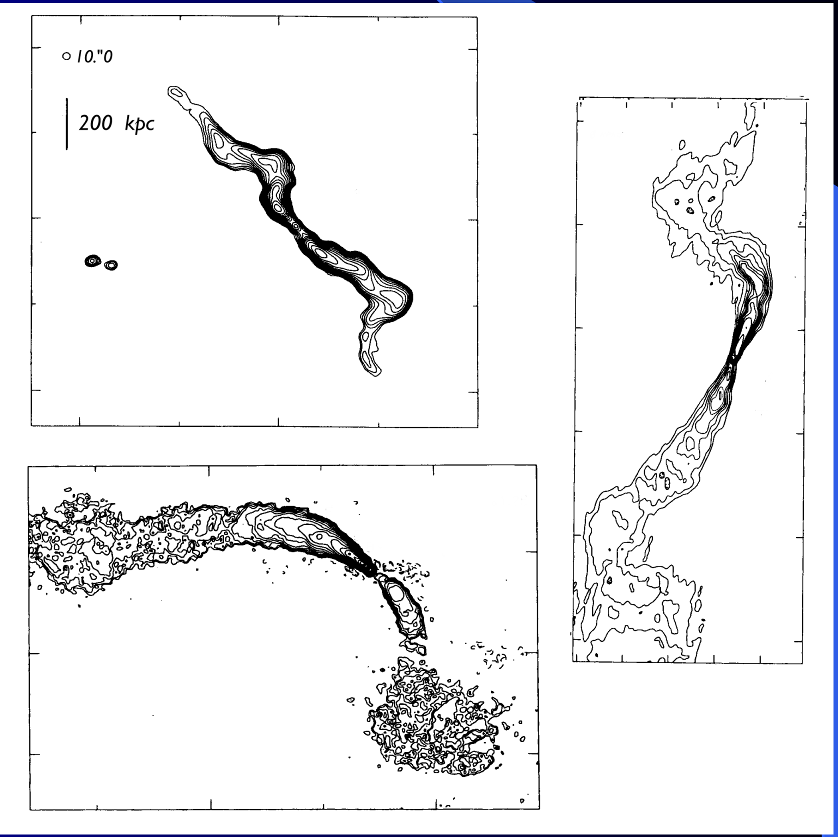


Global Jet Structures: FR-I Radio Sources



FR-I Radio Sources



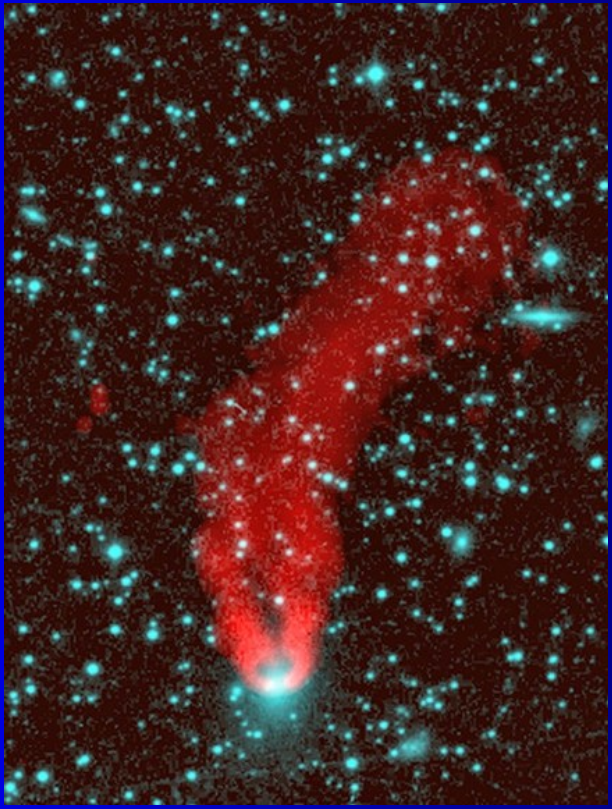


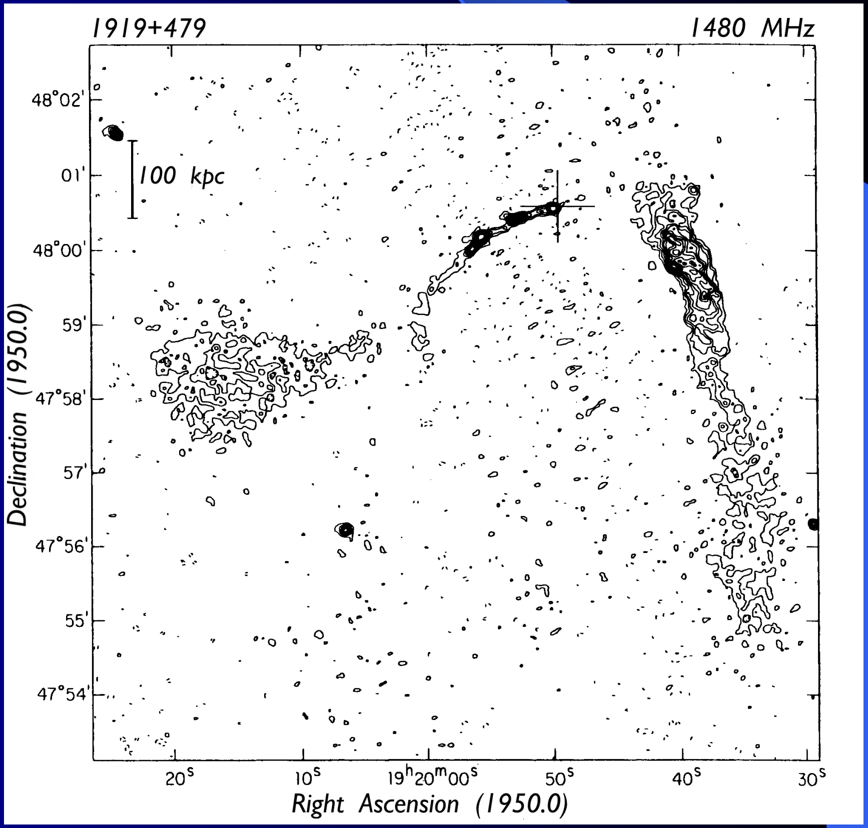
Extended Extragalactic Radio Sources

- FR-I / FR-II Statistics
- Space Densities: (to $z \sim 0.3$)
  - Spiral Galaxies: $\sim 3 \times 10^{-2}\ \mathrm{Mpc}^{-3}$
  - FR-I Sources: $\sim 3 \times 10^{-4}\ \mathrm{Mpc}^{-3}$
  - FR-II Sources: $\sim 1 \times 10^{-6}\ \mathrm{Mpc}^{-3}$
- Thus FR-I Objects are > 100 Times More Common than FR-II Objects

Global Jet Structures: Radio Sources in Clusters

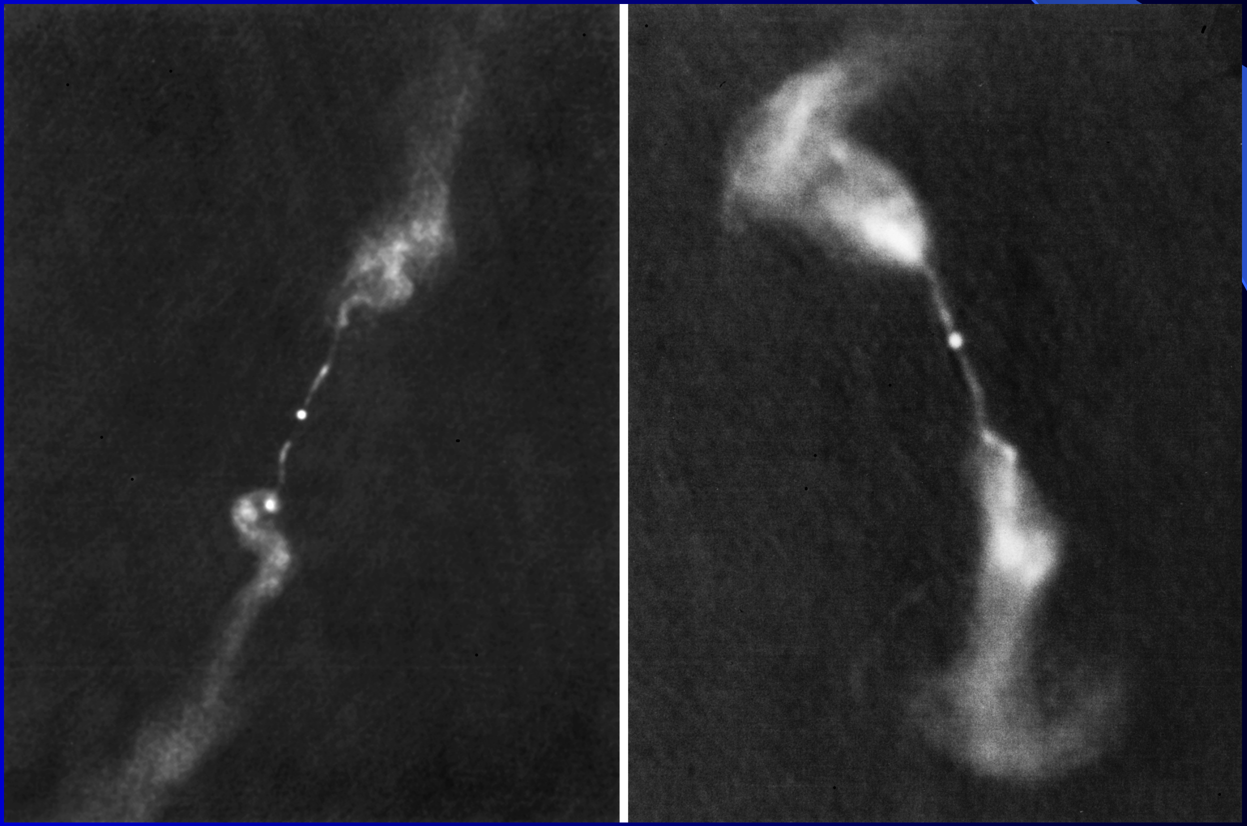
- Head-Tail Sources – A Known Interaction?





Radio Sources in Clusters

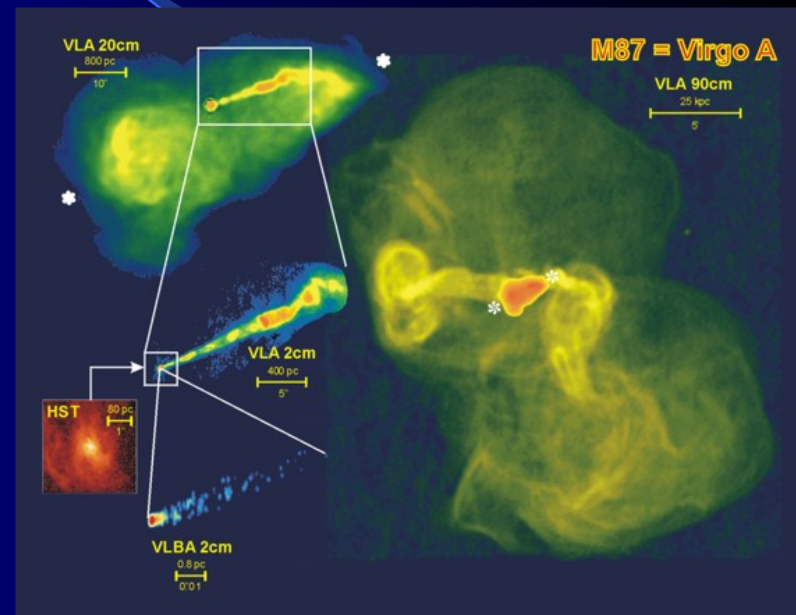
- Still Some Mysteries…

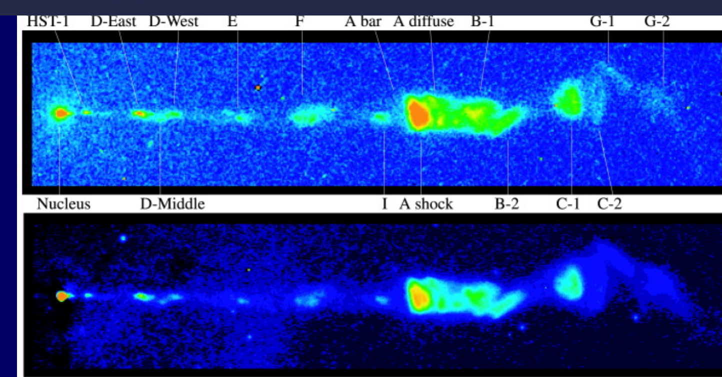


O'Donoghue, Owen & Eilek 1990

Special Cases: The Nearest Radio Sources

- Vir A, Cen A, Cyg A
- Biggest, Brightest
- Most Detailed Structure





Special Cases: The Nearest Radio Sources

- Richest Detail
- Stimulates Most Modeling
- How Representative?
  - Do ALL FR-I's Look Like M87? - no
  - Are ALL Fr-II's Like Cygnus A? - no
- But – Interesting Processes May be Seen
- But – How Much is Weather?

Observed Structures

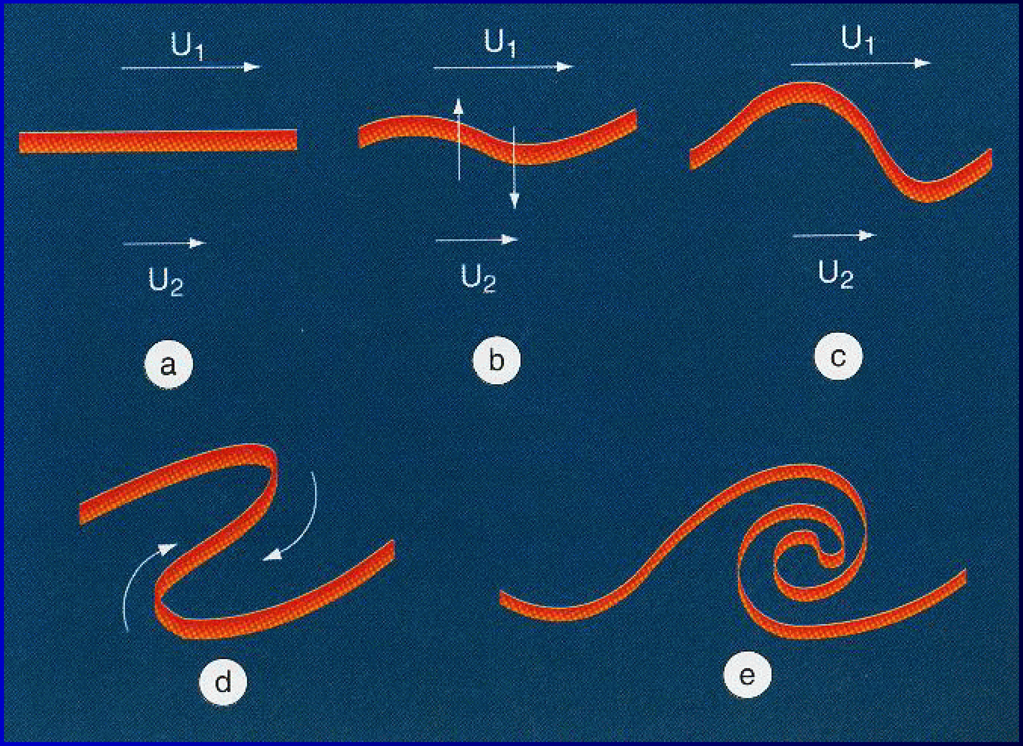
- Highly Collimated Jets (> 100 Jet Radii)
- Spreading Jets
- Bends, Wiggles, Plumes, Knots, Swirls, Flares, Filaments, Lines, Limb Darkening, Limb Brightening
- How Do They Arise?
- What Do They Mean?

Back to Basics

- Physical Origins of Structure
  - Intrinsic
  - Environmental
- Observe the Convolution of Both
  - How to Unravel/Deconvolve?
- Jet Interaction With the Environment
  - Mediates Mass, Energy and Momentum Transfer

Hydrodynamic Interaction

- Kelvin-Helmholtz Instability
  - Interface Between Fluids in Relative Motion



K-H Instability

- Linear Regime:
  - Perturbations Unstable at All Wavelengths in the Absence of Restoring Forces

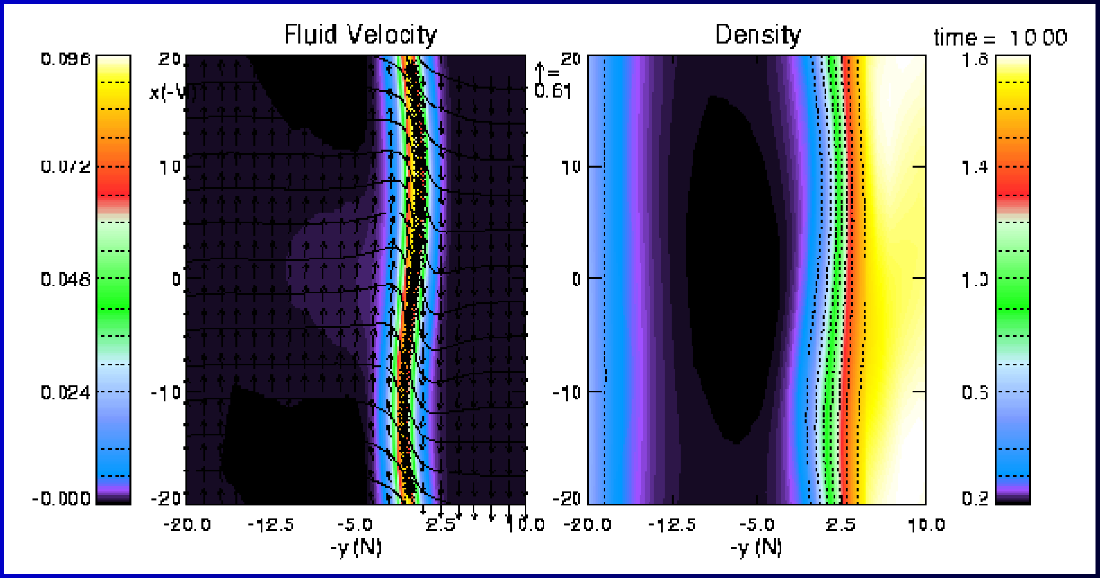
$$\Delta U^2 \geq [2(\rho \ + \rho_2)/\rho_1\rho_2]\{T(\rho_1 - \rho_2)\}^{1/2}$$

  - Shortest Wavelengths Most Unstable

$$\Gamma = k\Delta U(\rho_1\rho_2)^{1/2}/(\rho_1 + \rho_2)$$

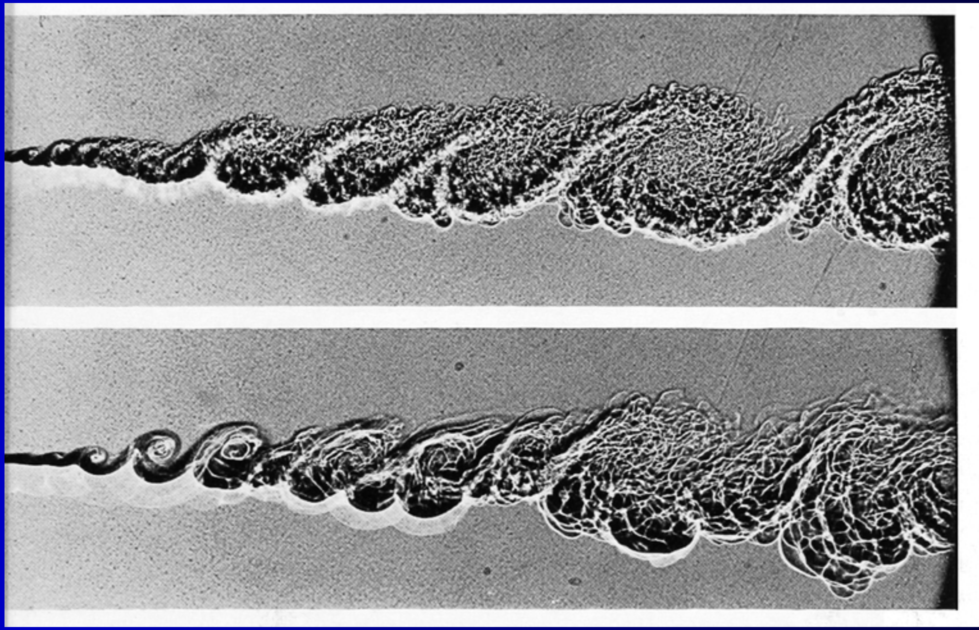
K-H Instability

- Quasi-Linear Regime:
  - Waves “Break”
  - Vorticity Created
  - “Cat’s Eye” Structures Form



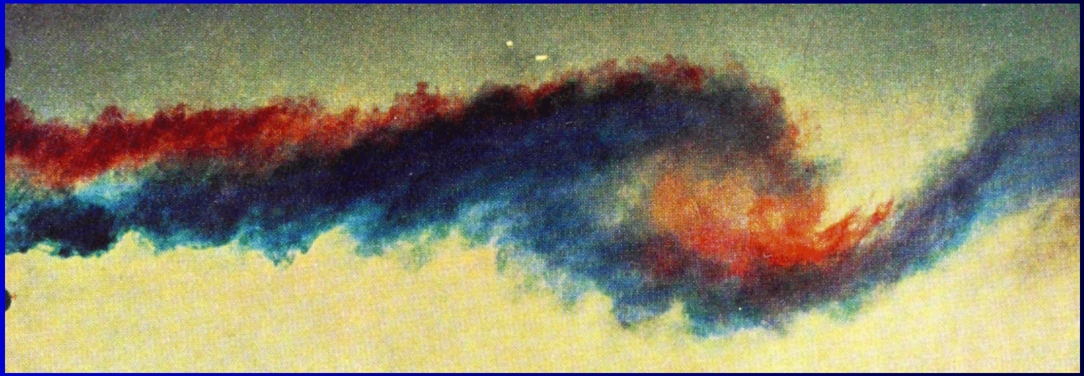
K-H Instability

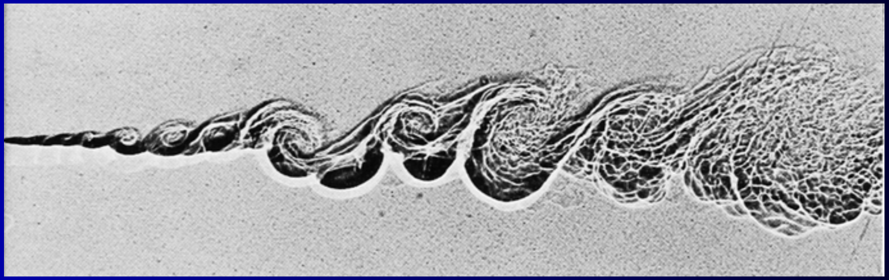
- Fully Non-Linear Regime:
  - Development of Turbulent Mixing Layer



Mixing Layers

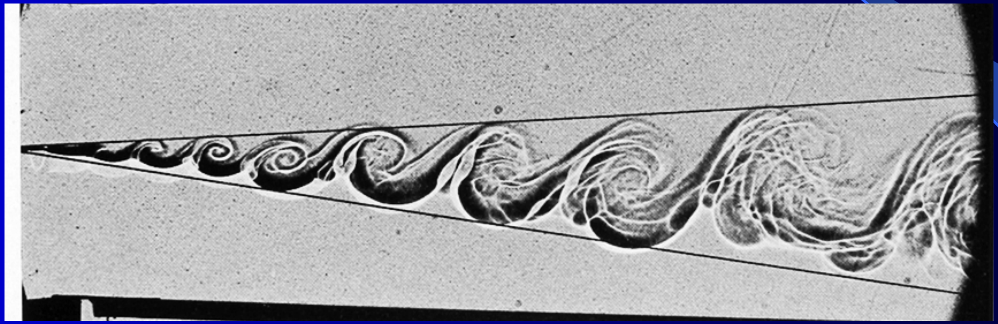
- Entrainment Very Effective
  - "Ingest – Digest" Process





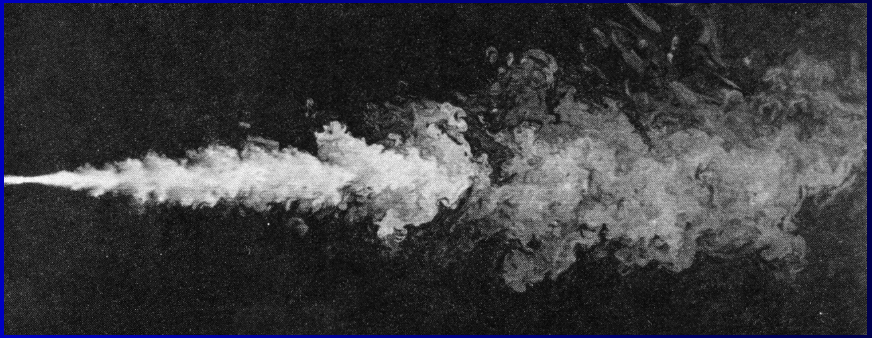
Mixing Layers

- Thickness Grows with Distance/Time



$$\mathrm{Tan}\ \phi = C\,(\rho_L/\rho_H)^{\alpha}\,(v_{REL})^{-\beta}$$

- Mixing Layer Can Permeate Entire Jet



Interaction Via Surface Instabilities

- Non-Linear Phase Creates Turbulent Mixing Layer
  - Entrains Ambient Medium
  - Transfers Momentum and Energy to Ambient Medium
  - Mixing Layer Can Penetrate Entire Jet Volume
  - Can Decelerate Jet to Subsonic Drift Motion
  - Can Be Fatal to Jet

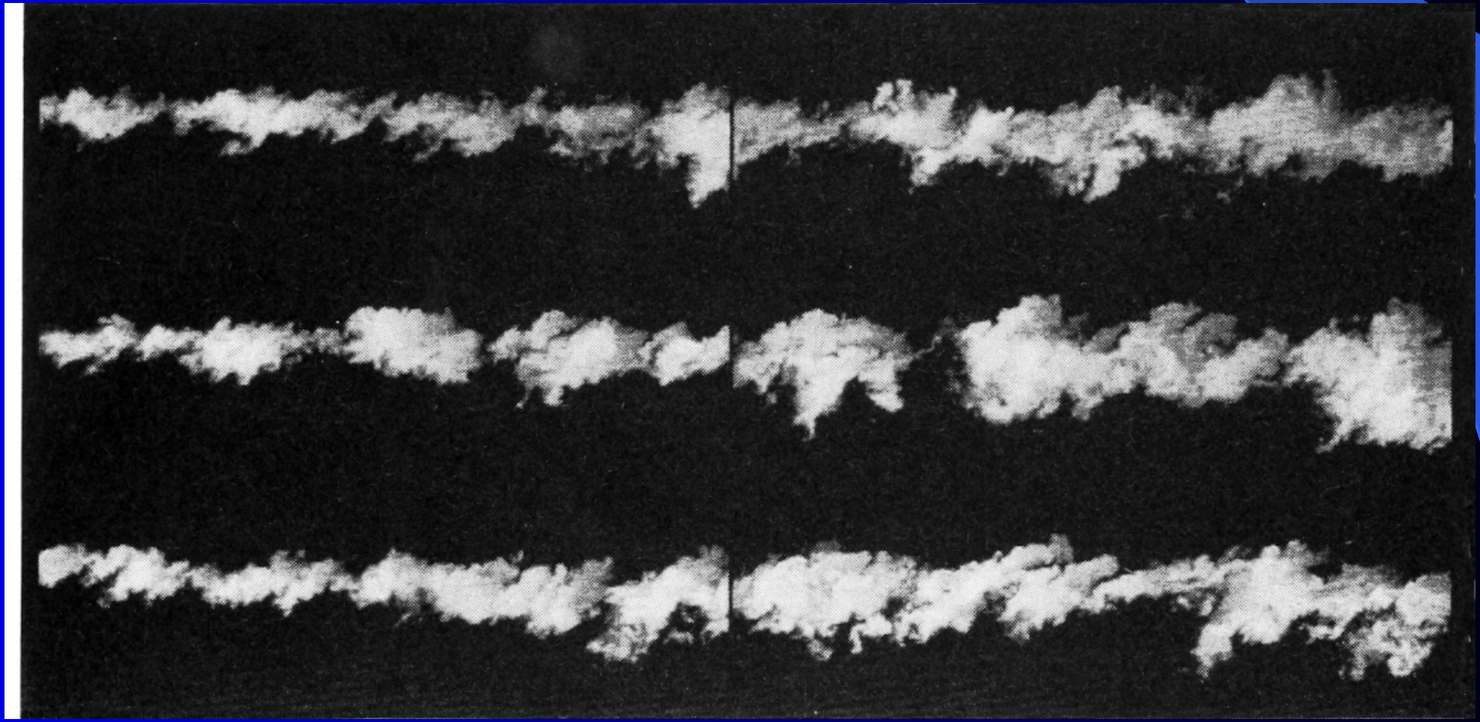
Mixing Layers

- Growth of K-H Instability and Mixing Layers is Inhibited By:
  - Compressibility
  - Spread of Initial Velocity Shear in Transverse Direction
  - Supersonic Relative Speeds

$$\mathrm{Tan}\,\phi \propto M^{-1}$$

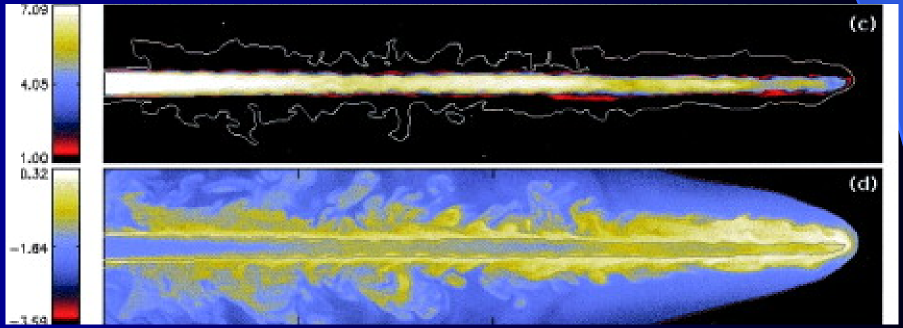
Supersonic Mixing Layers

- K-H Instability and Mixing Layers in Supersonic Flows



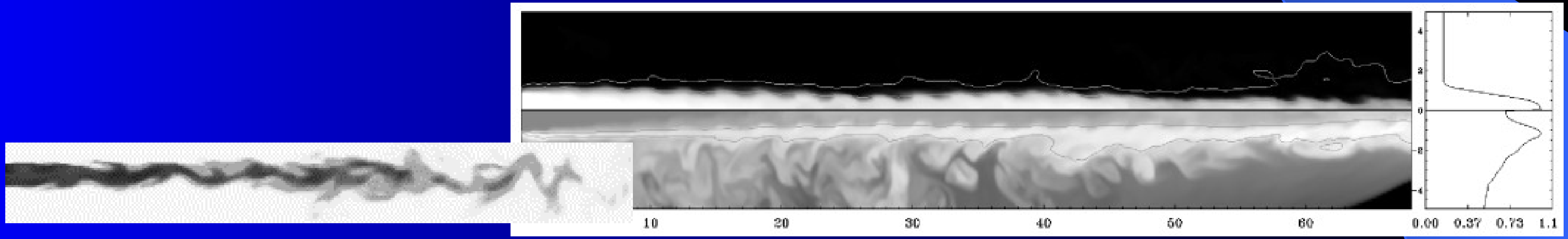
Relativistic Jets

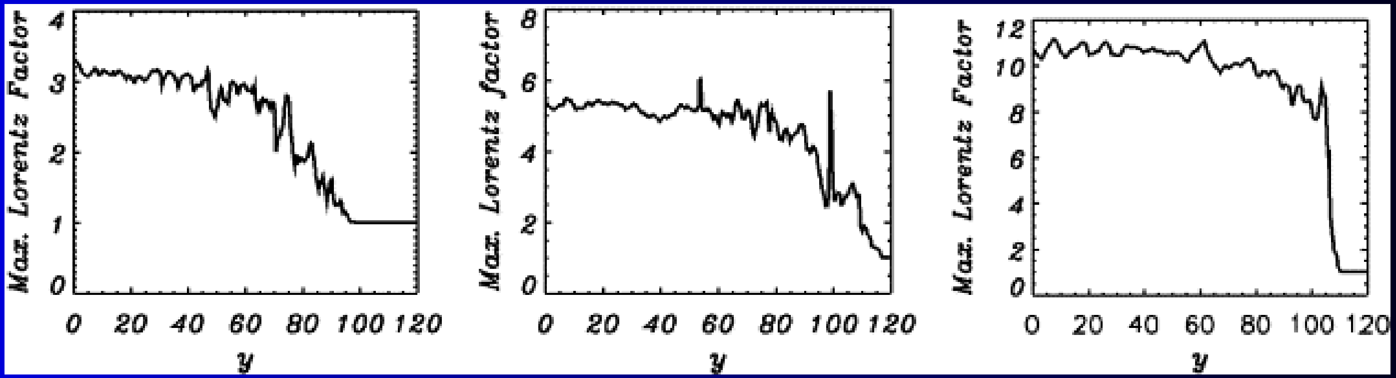
- Data Very Sparse
  - Use Numerical Simulations
    - (Marti et al., Aloy et al. 1999-2003)
- 3D Simulations Show:
  - Development of Shear/Mixing Layers
  - Rigidity
  - Deceleration



Relativistic Jets

- Deceleration Due to Surface Instabilities
- 3D Simulations
  - Aloy et al. 2000, Bodo et al.2003





The Effect of Magnetic Fields

- Remove Isotropy
- Add Viscosity
- Stabilize – In Principle

$$\Gamma = 0.5 | k \cdot U_R | [1 - (2 v_A k \cdot B)^2 / (k \cdot U_R)^2]^{1/2}$$

  - or, stable if

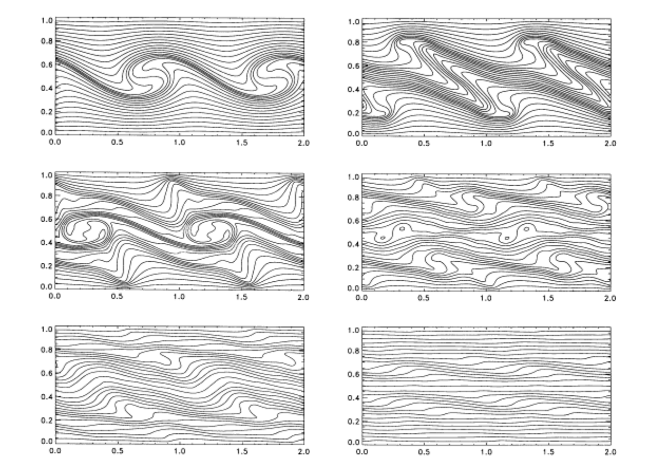
$$M_A = U_R / v_A \leq 2$$

  - for

$$k \| B \| U_R$$

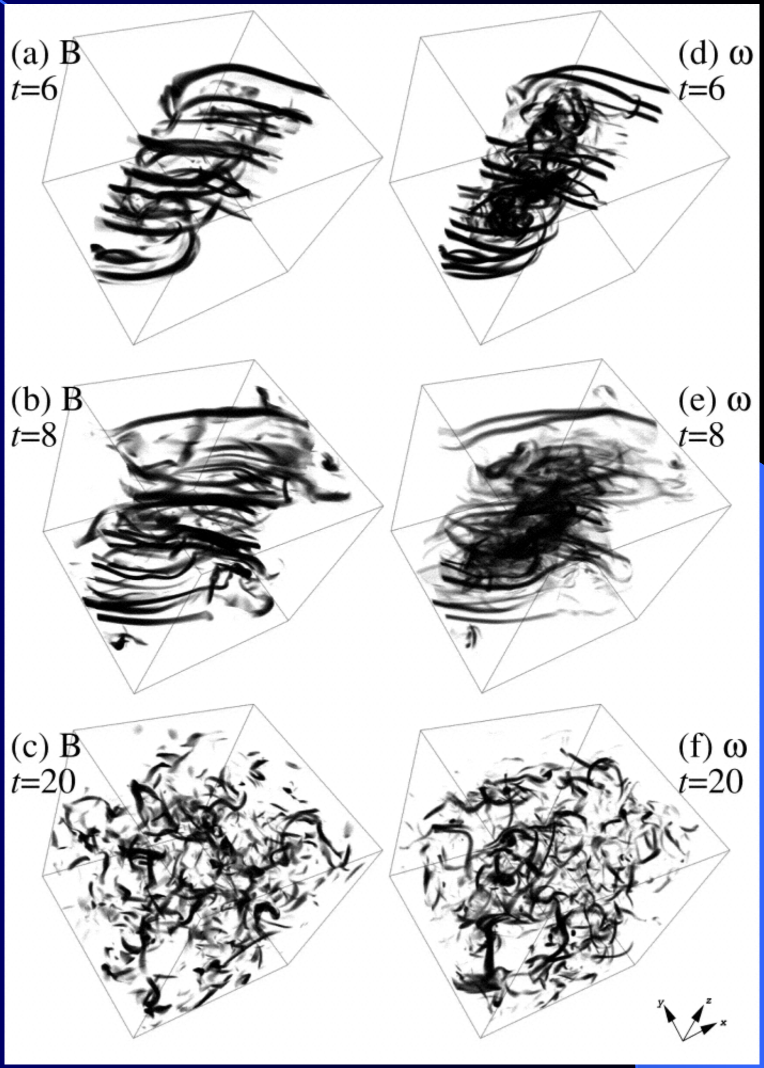
The Effect of Magnetic Fields

- Numerical Simulations Required
  - Jones et al. 1996 – 2000
- Two Dimensional MHD
  - Still Mixes for Beta > 1
  - Enhanced Local Fields
  - “Cat’s Eyes” Destroyed
  - Turbulence Suppressed by Geometry, Boundaries



The Effect of Magnetic Fields

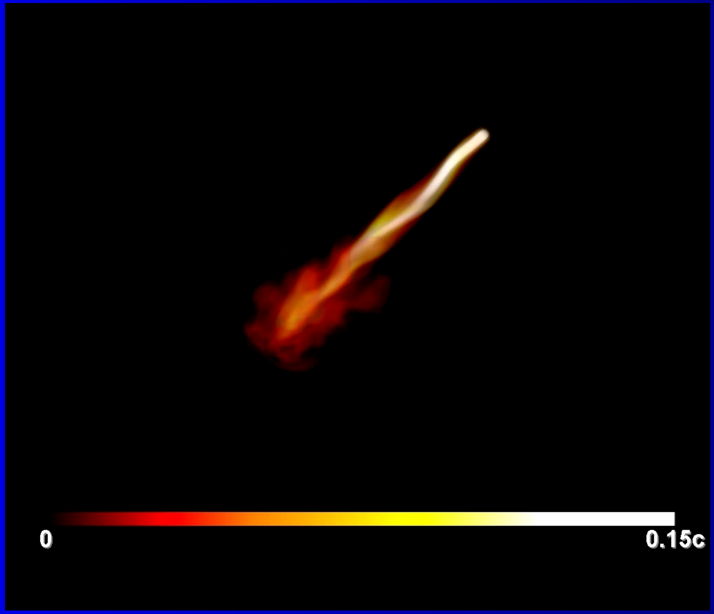
- Three Dimensional MHD
  - Enhanced Local Fields
  - For High Beta > 100
    - Evolves to Turbulence
    - Turbulent B Amplification
    - Enhanced Dissipation due to Magnetic Reconnection
    - Instability Remains "Essentially Hydrodynamic"



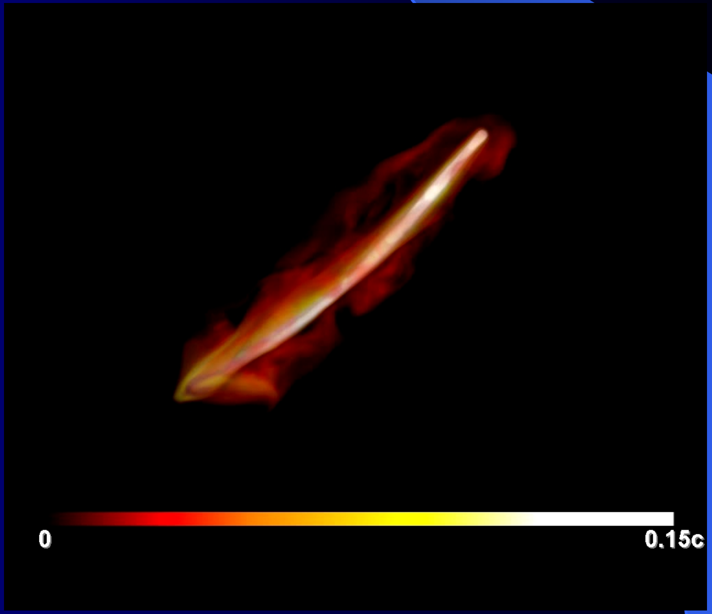
Ryu, Jones, & Frank 2000

The Effect of Magnetic Fields

- 3D MHD Simulations
  - (S. O'Neill, T. Jones, I. Tregillis, D. Ryu 2005)



M = 30



M = 120

Jet – Environment Interaction

- Penetration of Turbulent Mixing Layer Throughout Jet Volume
  - Since $\mathrm{Tan}\,\phi \approx C\,(\rho_J/\rho_{Amb})^{-\alpha}\,M^{-1}$
  - Then Mixing Layer Thickness = Jet Radius at

    $\Delta R = L_{MIN}\,\mathrm{Tan}\,\phi = R_{Jet}$
  - or

    $L_{MIN} \approx C'\,R_{Jet}\,M\,(\rho_J/\rho_{Amb})^{\alpha}$

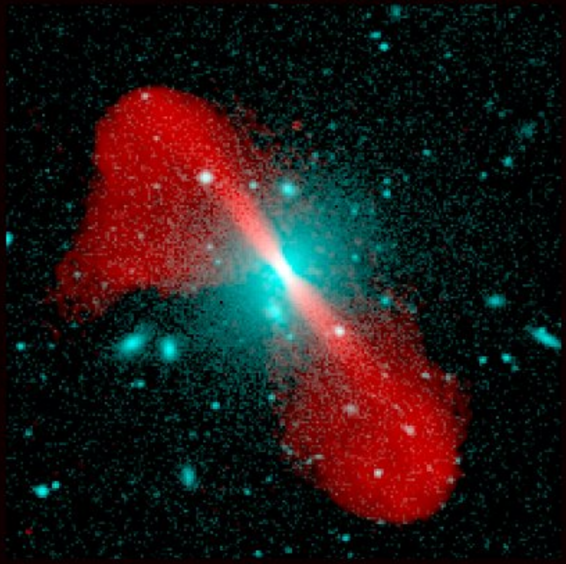
- At This Point Jet Is Fully Mixed, Turbulent

Induced Jet Structure

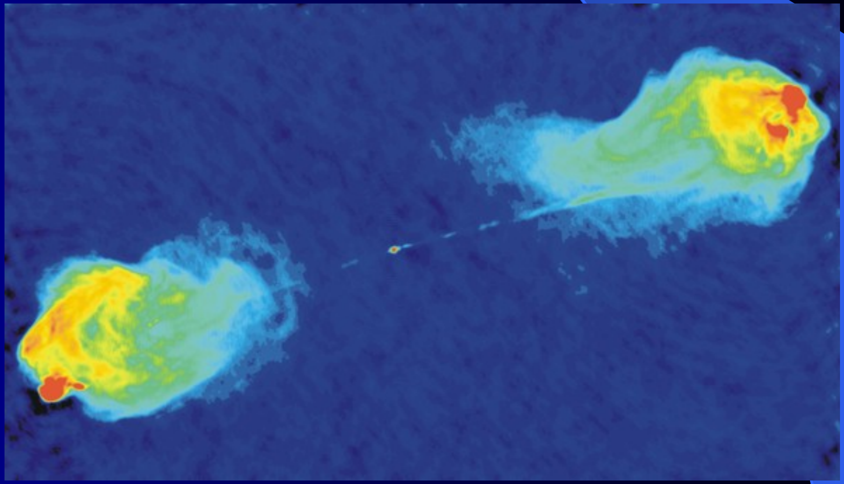
- Saturated, Turbulent Jet Has Now
  - Entrained Mass from Ambient Medium
    - (Bicknell 1984, De Young 1982, 1986)
  - Accelerated and Heated this Mass
  - Significantly Decelerated, Possibly to Subsonic Plume
  - Locally Amplified any Ambient or Entrained Magnetic Fields

Saturated Mixed Jets

- Could Explain FRII – FRI Dichotomy
  - (De Young 1993, Bicknell 1995, Liang 1996)

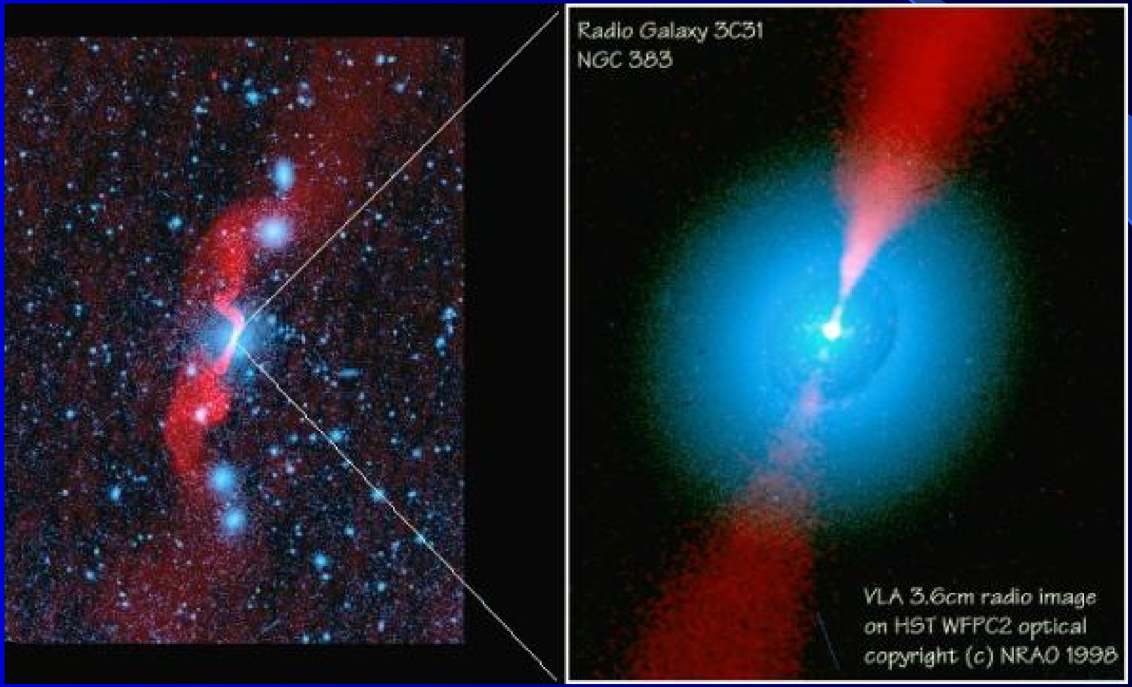


Radio Galaxy 3C296
Radio/optical superposition



Saturated Mixed Jets

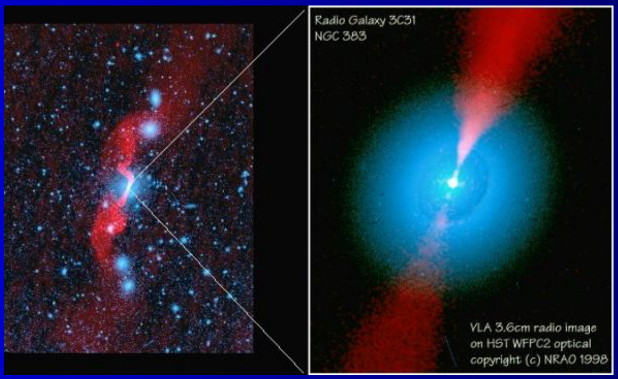
- And The FRII – FRI Dichotomy



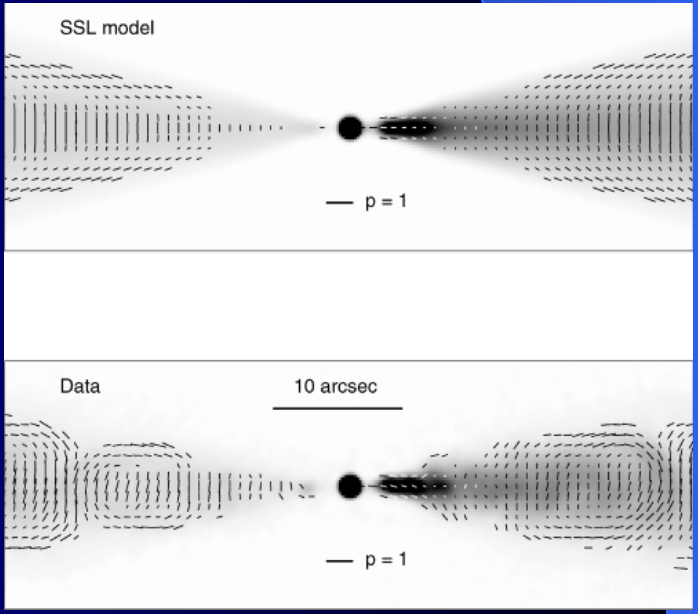
- Essential Inference: Decelerated, Subsonic Flow

Saturated Mixed Jets

- Decelerated Jet Modeling With Shear Layers - 3C31, 3C315
  - Laing et al. 2001 – 2006
  - Requires Some Additional Assumptions

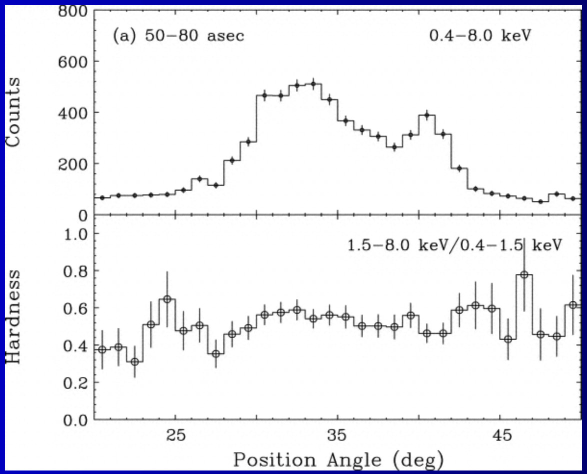


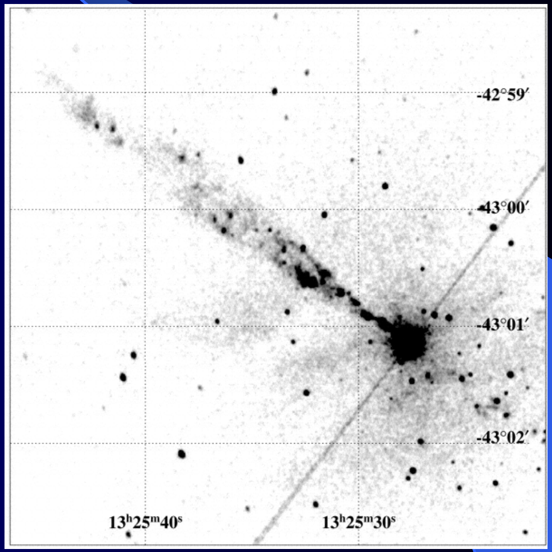
  - Laing & Bridle 2002



Saturated Mixed Jets

- Specific Example – Centaurus A
  - Kataoka, Stawarz, et al. 2006





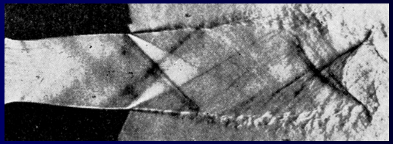
  - Limb Brightened in X-Rays
  - Spectra Consistent with Turbulent Acceleration

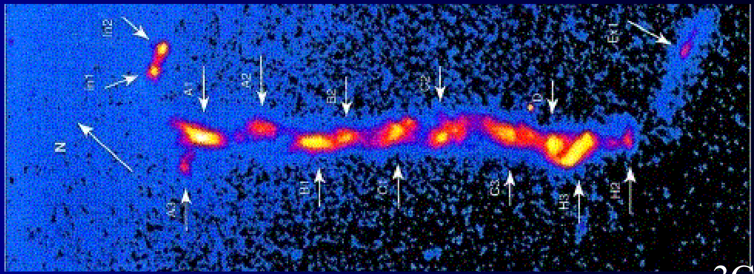
Saturated Mixed Jets

- Could Explain
  - Transport of Astrated Material to Extragalactic Scales via Mass Entrainment
    - Emission Lines in ICM and Outside Galaxies
    - Cooling and Jet Induced Star Formation
      - Extragalactic Blue Continuum
      - Dust Formation; Alignment Effect at Large z
    - Injection of Metals into ICM
    - Contamination of IGM at Very Early Epochs

Local Jet Structures: Internal Shocks and Hot Spots

- Require Special Circumstances:
  - Changing Jet Input
    - Impulsive or Driven
  - Local and Sudden Change in External Medium
    - Ambient Pressure Changes
    - Ambient Density Changes
      - Jet Expansion
      - Jet Bending
      - Jet Disruption





3C273

Internal Shocks: Effects

- Partial Thermalization of Flow
- Particle Acceleration
- Magnetic Field Compression

  $$B_1 \approx B_0(\gamma+1)/(\gamma-1)$$

- Radiation
  - Thermal

    $$T_1 \approx T_0(2\gamma M_0^2)/(\gamma+1)^2$$

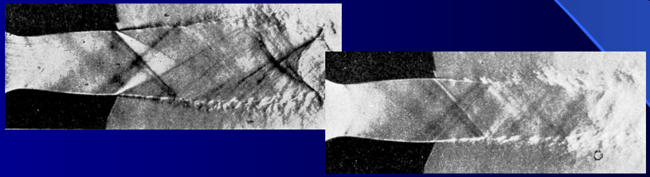
  - Non-Thermal

    $$P_{Synch} \propto B^2 E^2$$

- All Independent of Origin

Internal Shocks: Dissipation

- Standing Internal Shocks
  - Mostly Oblique



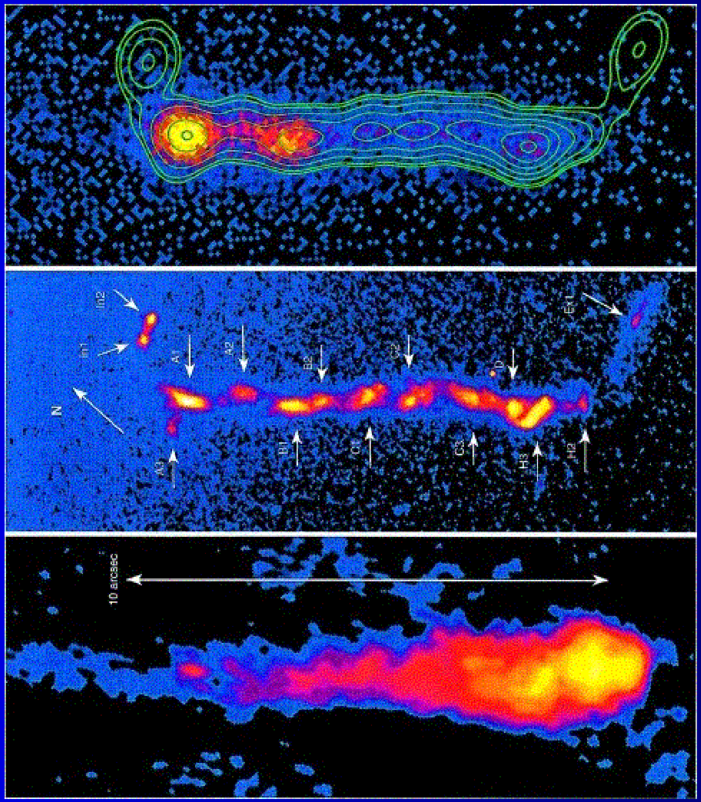
  - Mostly Redirect Flow – Internal “Weather”
    - Not Disruptive

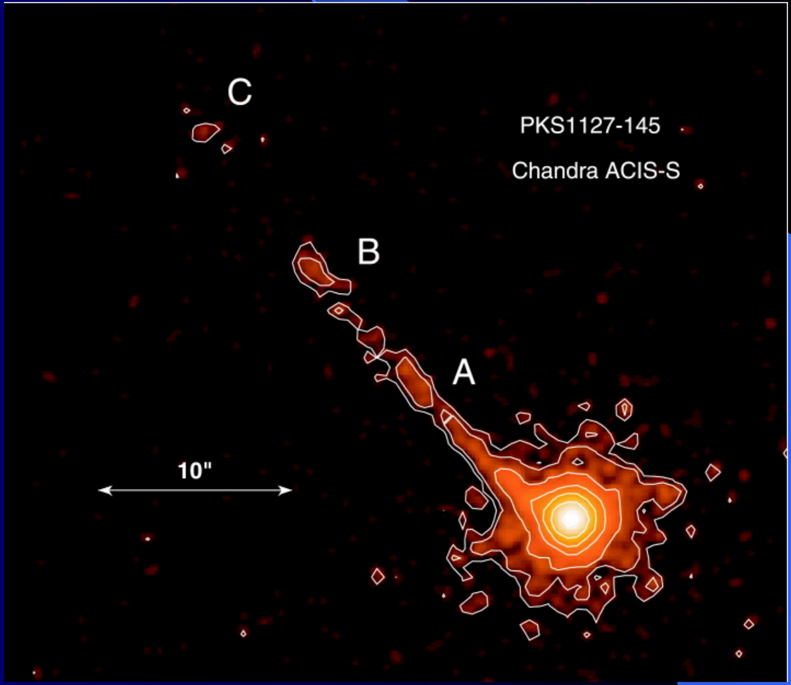
  - Mostly Convert Energy

$$\rho\ v^2 \rightarrow \Delta T, \Delta B^2, \Delta E$$

- Impulse Driven Internal Shocks - Transient

Extragalactic Internal Shocks





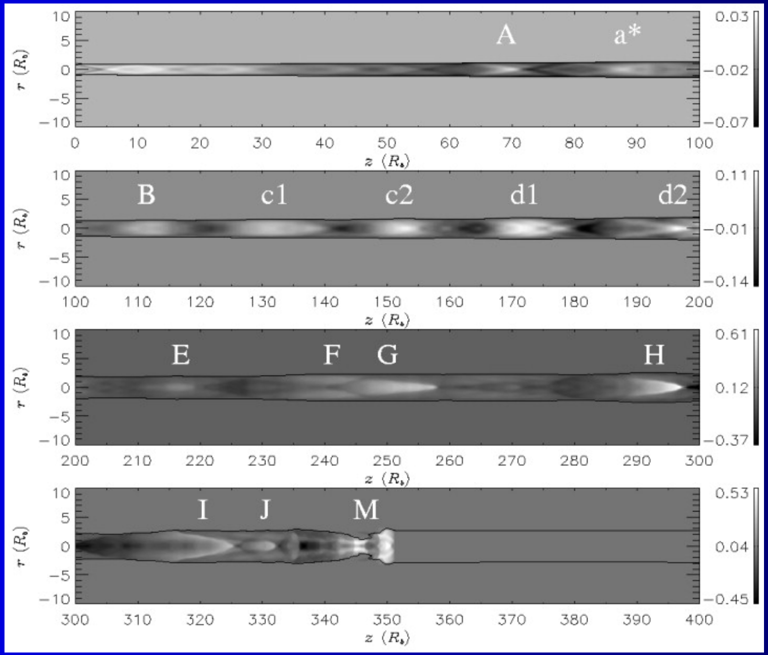
3C273 Marshall et al. 2001

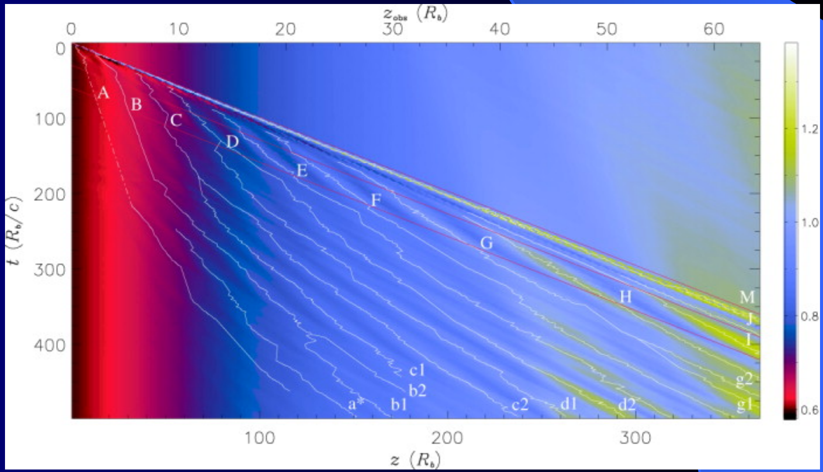
Extragalactic Internal Shocks

- Dissipative and Radiative Losses “Small”
  - Jet Not Disrupted, Hence:
  - Shocks Are Weak and/or Oblique
  - X-Ray and Radio Luminosities from Knots (Modulo Beaming) << Kinetic Energy Flux
- But - Emission May Be Indicators of Jet Flow Speeds and Particle Acceleration
  - E.g. SSC vs. IC on CMB

Extragalactic Internal Shocks

- Modeling of Induced Internal Shocks
  - Via Variations in Output of Central Engine

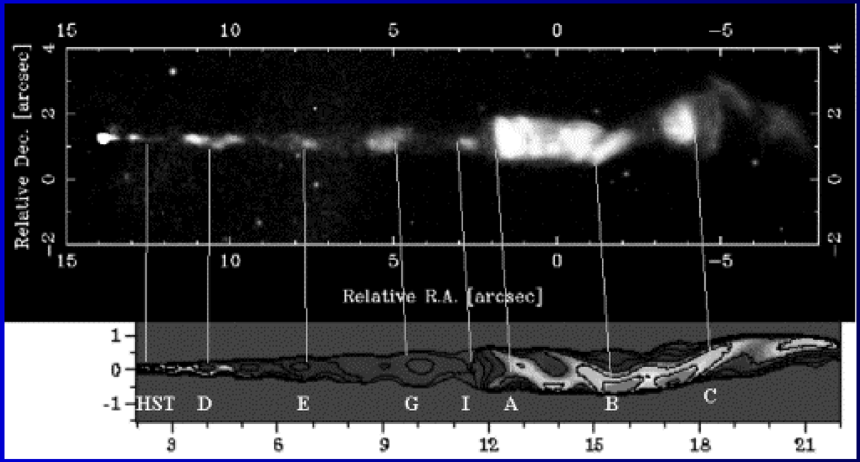




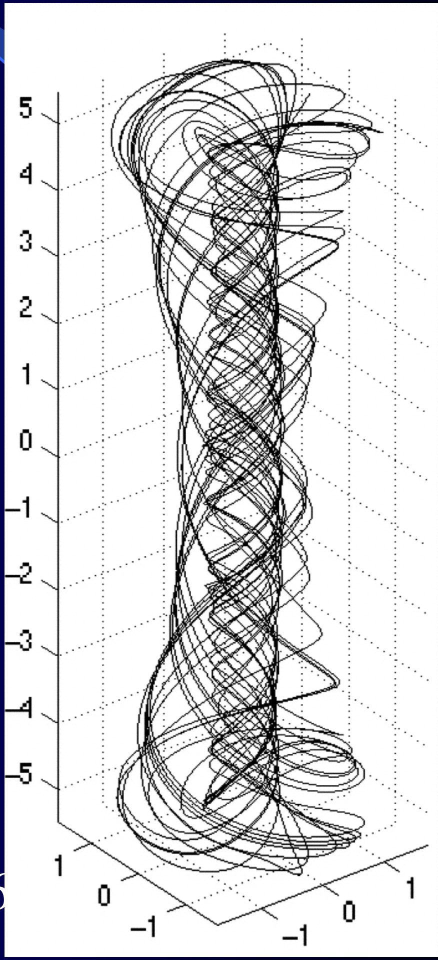
Agudo et al. 2001

Specific Jet Internal Structures

- M87 Jet – Internal Hotspots
  - "Double Helix"
    - Lobanov, Eilek & Hardee 2003



  - Linear K-H Instability – OR ….

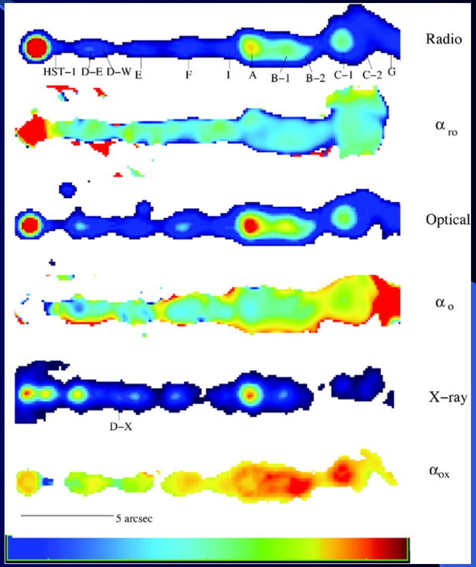


Li et al. 2006

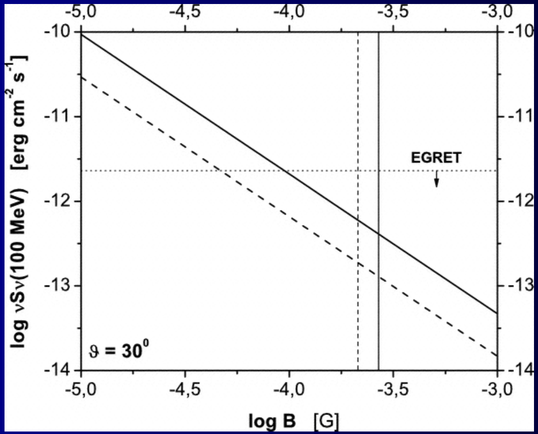
Specific Jet Internal Structures

- M87 Jet - Internal Hotspots
  - Spectral Index Distributions
    - Particle Acceleration/Injection

Perlman et al. 2004

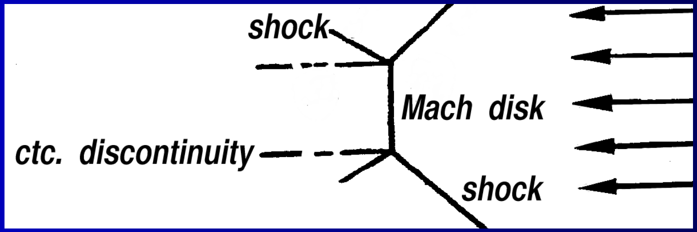


  - Inverse Compton Processes
    - B Field Limits
      - Stawarz et a. 2005



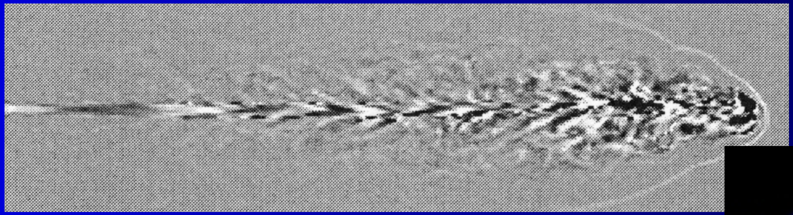
Termination Shocks

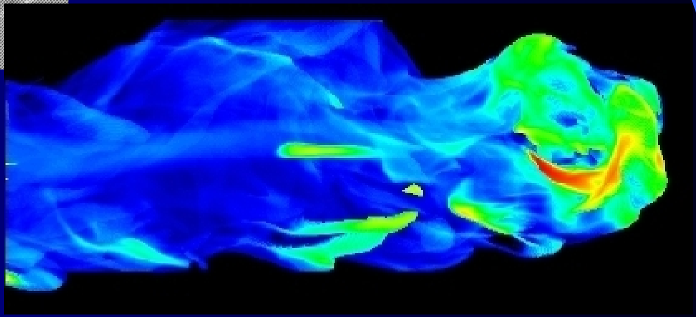
- Ideal:



  - (Beware Axisymmetric Calculations)

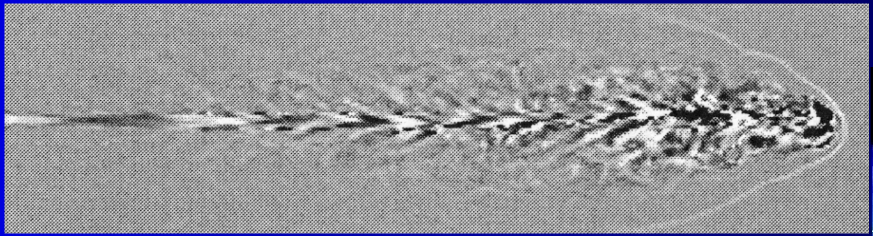
- Actual:

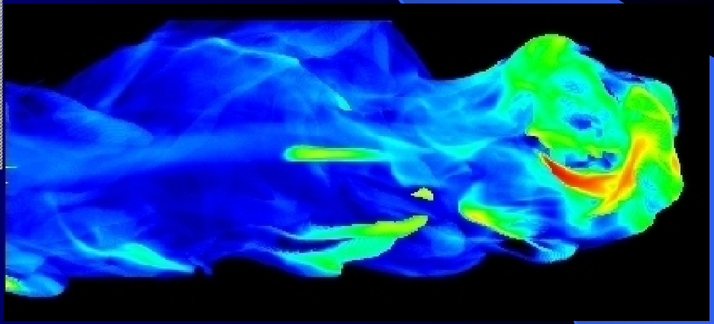




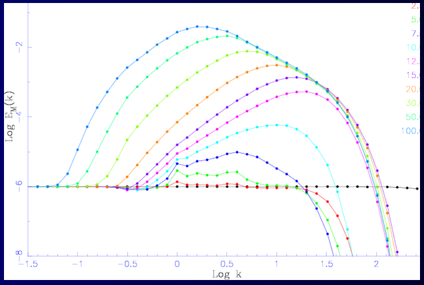
Termination Shocks

- May Be The Major Source of Energy Dissipation for Non-Infiltrated Flows



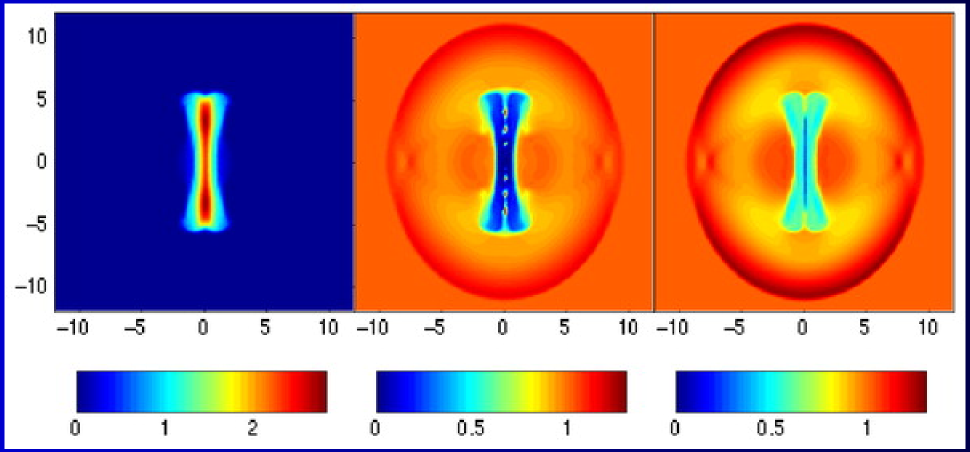


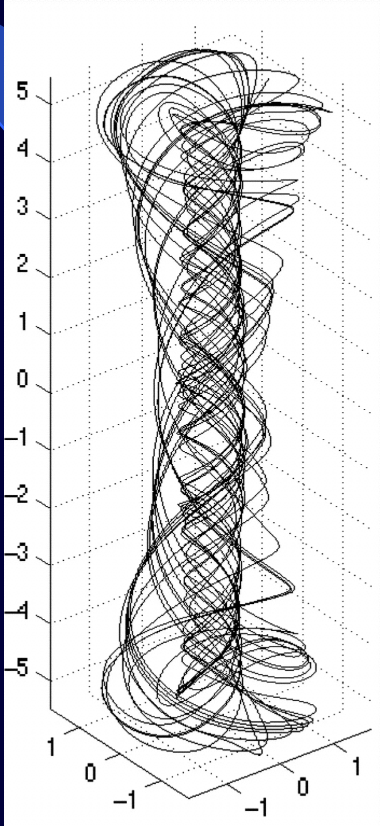
- May Be The Major Source of Turbulent Energy in Radio Lobes



Other Jet Structures

- "Poynting Flux" Jets
  - Very Interesting Alternative
  - But – More Work Needed

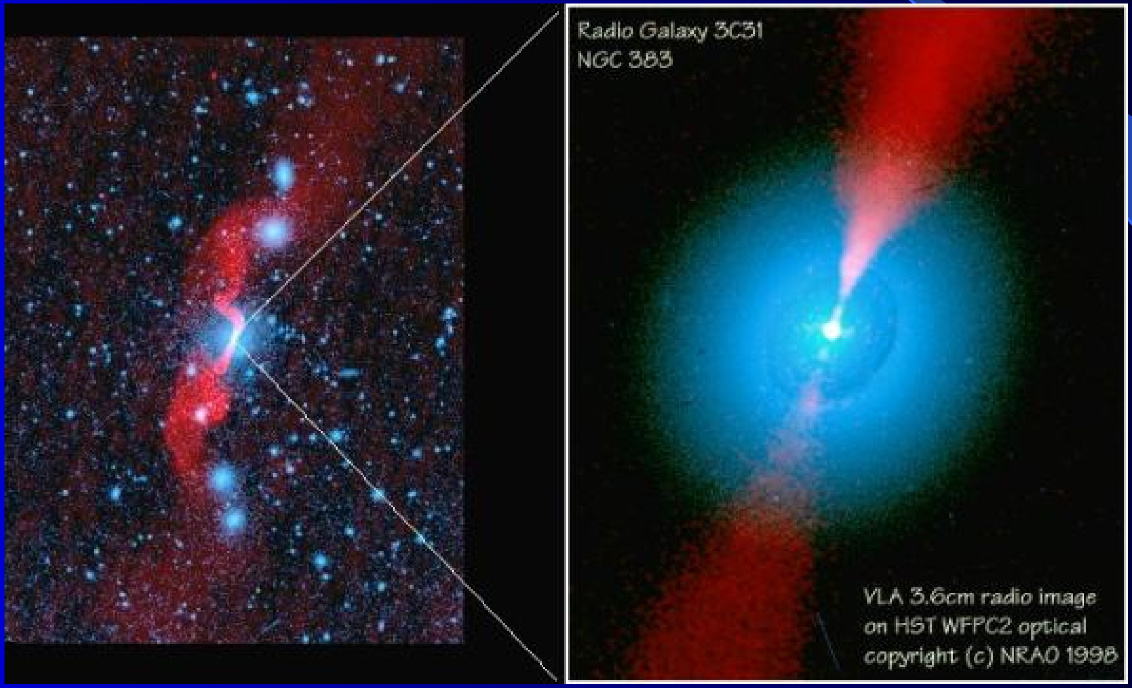




- Li et al. 2006

Other Jet Structures

- Can Poynting Flux Jets Do This?



Conclusions – Jet Structure

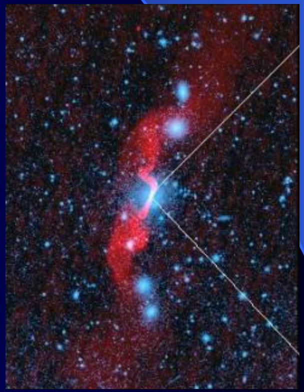
- Induced Structures – Interaction with Environment
  - Production of Mixing Layers Seems Universal
  - Basically Hydrodynamic for $\beta > 1$
  - Strong Mixing
    - Deceleration
    - Turbulence
    - Transport of Astrated Material Outward

Conclusions – Jet Structure

- Small Scale Structures – Knots, Bumps, and Wiggles
  - Can be Intrinsic, Can be Induced
  - If Induced (Pressure, Density Gradients) -Probably “Weather”
  - If Intrinsic – (Changes in dE/dt, dM/dt ..) - Can be Significant Indicators of “Central Engine” Parameters

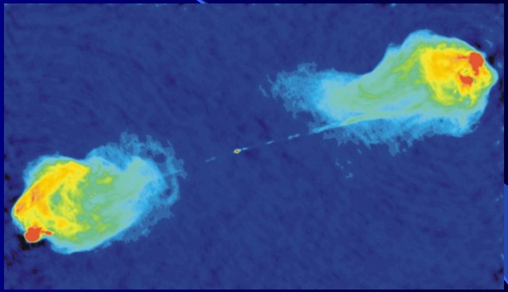
Conclusions – Jet Structure

- Strong Interaction with Environment
  - Can Produce Fully Mixed, Turbulent Jets
    - (Particle Dominated Jets)
- Can Basically Reproduce FR-I Geometry
    - Fast & Light – Not for Long
- This Accounts for 99% of Extended Extragalactic Radio Sources



Conclusions – Jet Structure

- The FR-II Problem



- Heavy or Very Relativistic Jets?
  - Enormous dE/dt, total E
- "Poynting Flux" Jets ?
- Are FR-I and FR-II Objects Intrinsically Different?