The Physics of Jet Dissipation

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Overview

- Motivation and Basic Principles
- Global Dissipative Processes
  - Underlying Instabilities
  - Non-Linear Evolution and End State
  - Role of Magnetic Fields
  - Applications
- Local Dissipative Processes
- Lobe Death
- Implications

Jet Dissipation

- Dissipation/Destruction:
  - Self Inflicted
  - Due to Interaction with Environment
- Types:
  - Global
  - Local
  - Induced
  - Inevitable

Jet Dissipation – Related To:

- Radio Source Morphology/Type
- Extragalactic Emission Lines
- Metallicity of the Early IGM and ICM
- “Alignment Effect” in High-z Objects
- X-Ray Knots and Hot Spots
- Evolution of YSO Jets

Jet Interaction with Environment

- Most Important Form of Dissipation
- Mediates Energy, Mass, and Momentum Transfer Between Jets and Their Environment
- May be a Way to Determine:
  - Jet Content
  - Jet Bulk Flow Speeds
  - Jet B Fields
  - And Thus Constrain AGN Models

Dissipation Via Surface Instabilities

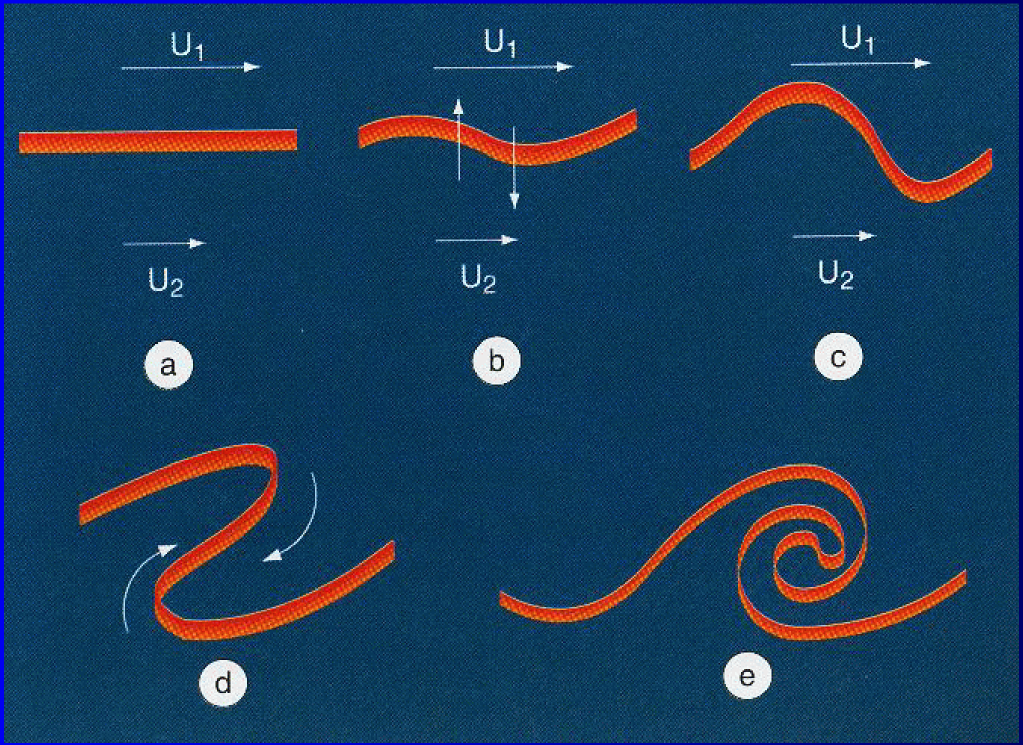
- Universal
  - Present at Some Level in All Jets in All Environments
- Global
  - Involve Most of Jet Surface for Long Times
- Inevitable (?)
  - Very Special Circumstances Required to Prevent Occurrence

Dissipation 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

Hydrodynamic Dissipation

- 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

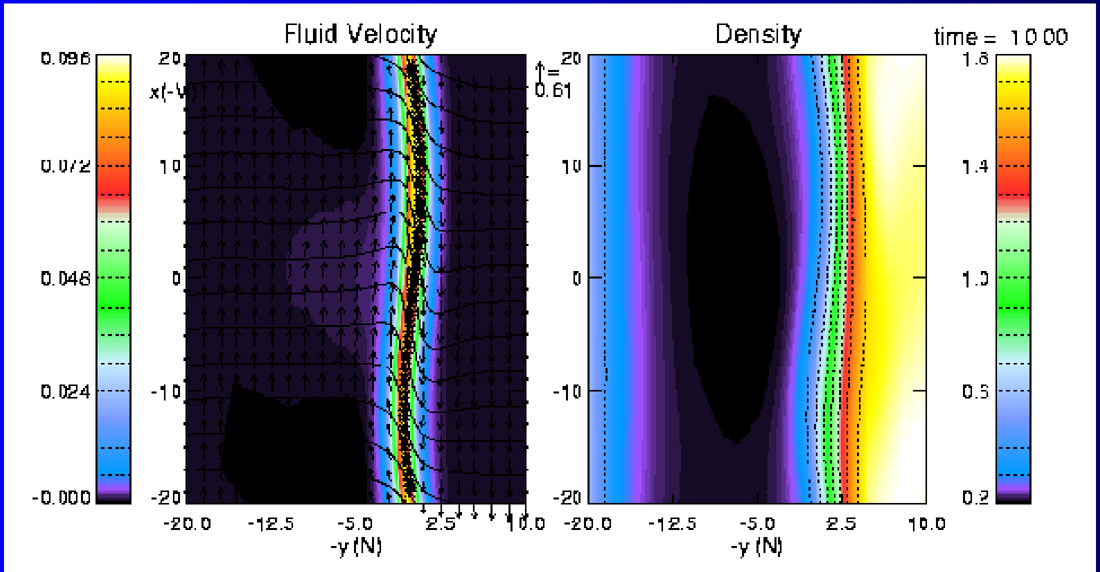
    $$\Delta U^2 \geq [2(\rho \ + \rho_2)/\rho_1\rho_2]\{T(\rho_1 - \rho_2)\}^{1/2}$$

  - Shortest Wavelengths Most Unstable

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

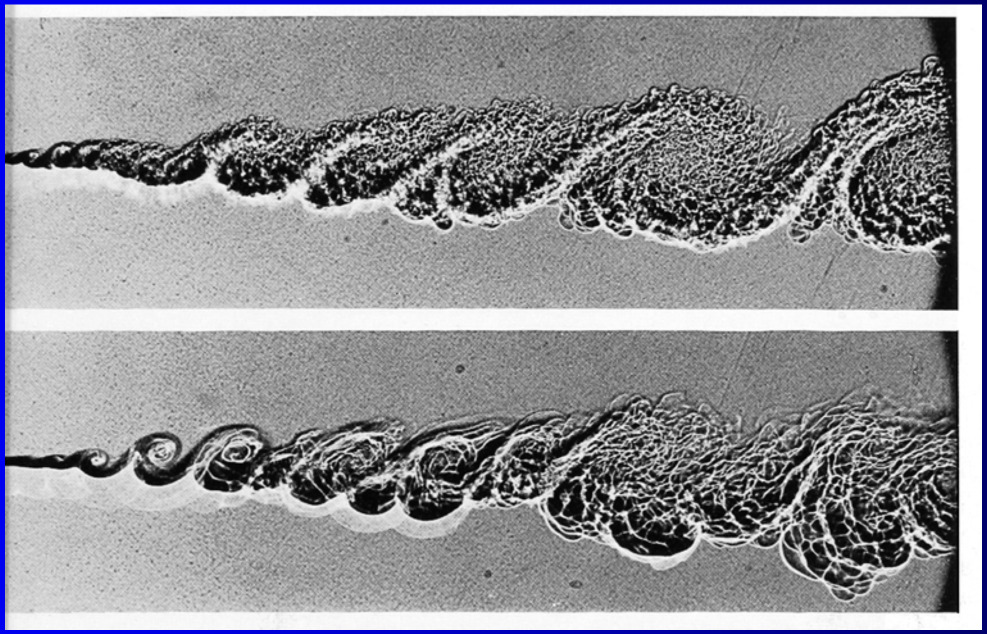
K-H Instability

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



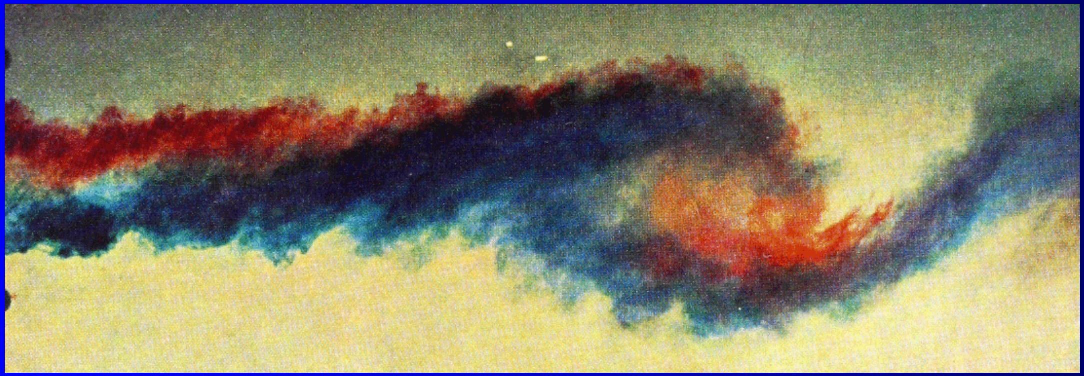
K-H Instability

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



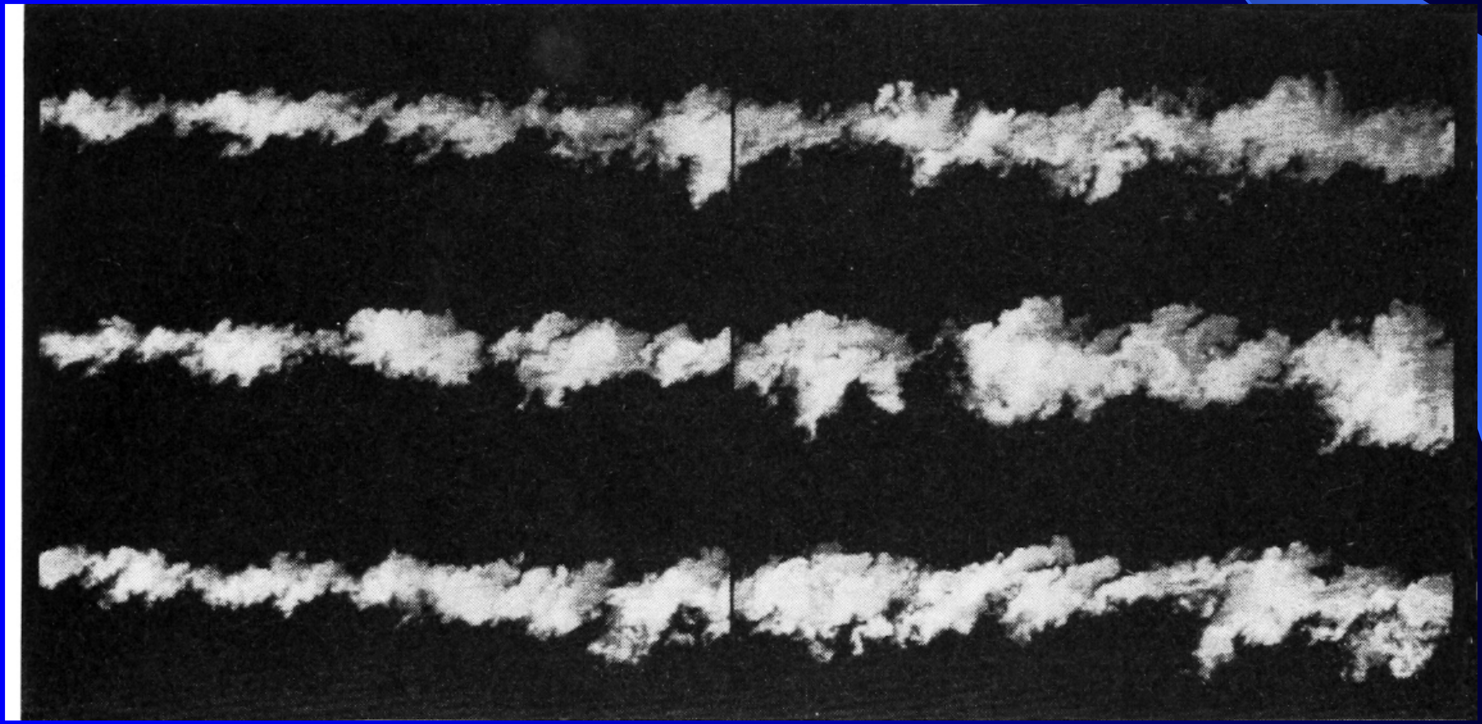
Mixing Layers

- Entrainment Very Effective
  - “Ingest – Digest” Process



Mixing Layers

- K-H Instability and Mixing Layers in Supersonic Flows



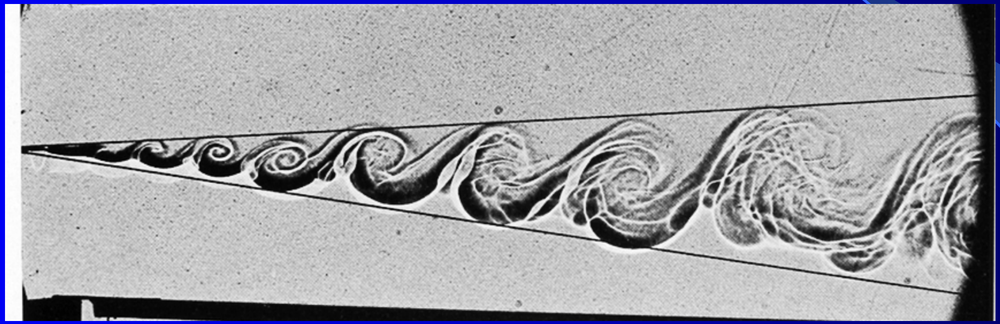
Mixing Layers

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

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

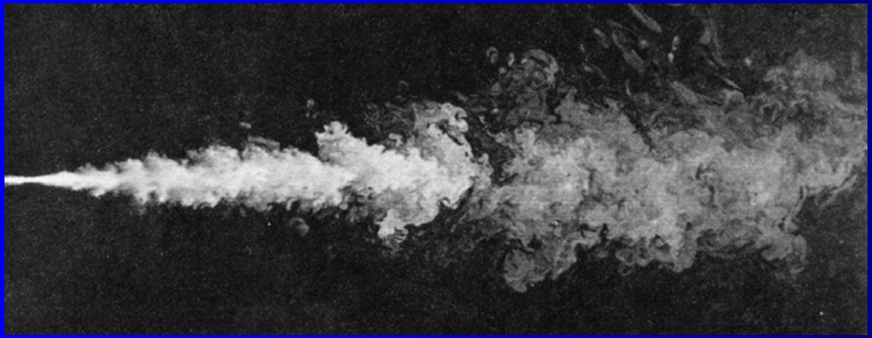
Mixing Layers

- Thickness Grows with Distance/Time



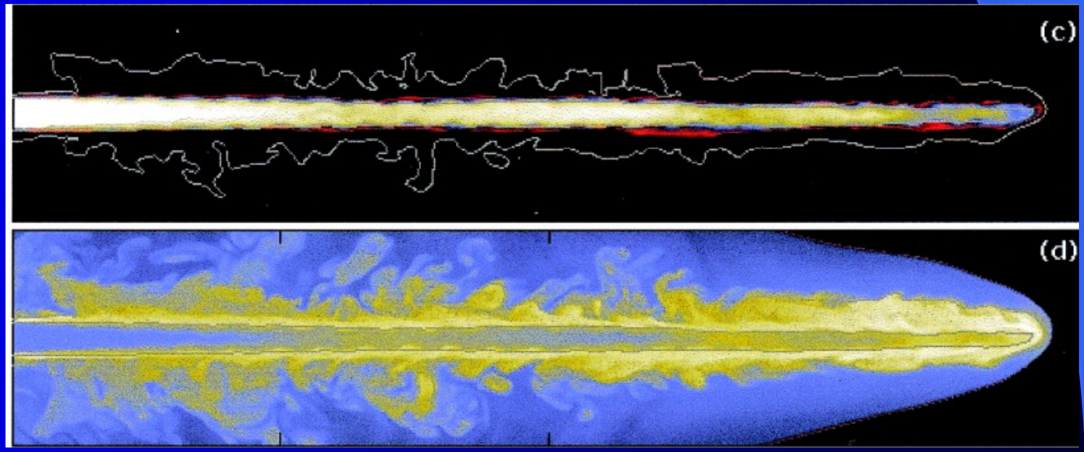
$$\tan \phi = C\,(\rho_L/\rho_H)^{\alpha}\,(v_{REL})^{-\beta}$$

- Mixing Layer Can Permeate Entire Jet



Relativistic Jets

- Data Very Sparse
- Use Numerical simulations
  - (Marti et al., Aloy et al., 1999-2003)
- 3d Simulations Show:
  - No "Backflow"
  - Development of Shear/Mixing Layers
  - Deceleration



The Effect of Magnetic Fields

- Remove Isotropy
- Add Viscosity
- Stabilize – In Principle

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

  - or, stable if

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

  - for

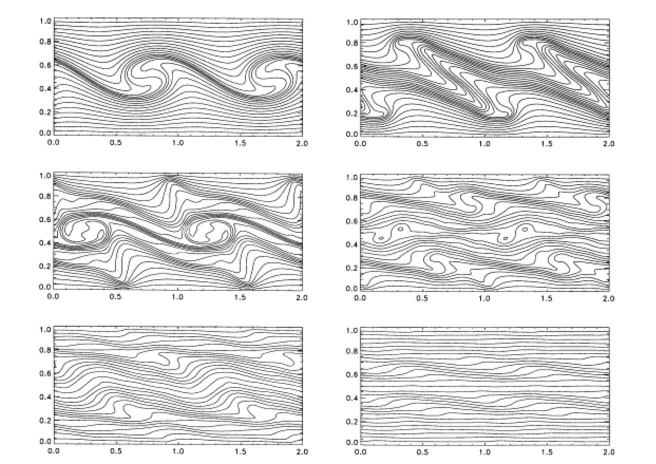
$$\mathbf{k} \| \mathbf{B} \| \mathbf{U}_R$$

The Effect of Magnetic Fields

- What are "Reasonable" Field Strengths?
- What Are the Field Strengths in Jets?
- What is the Origin of Jet Magnetic Fields?
  - Global Value of Beta >> 1.0
- Empirical Data Scarce
  - ICM Values Imply Beta ~ 100 - 1000

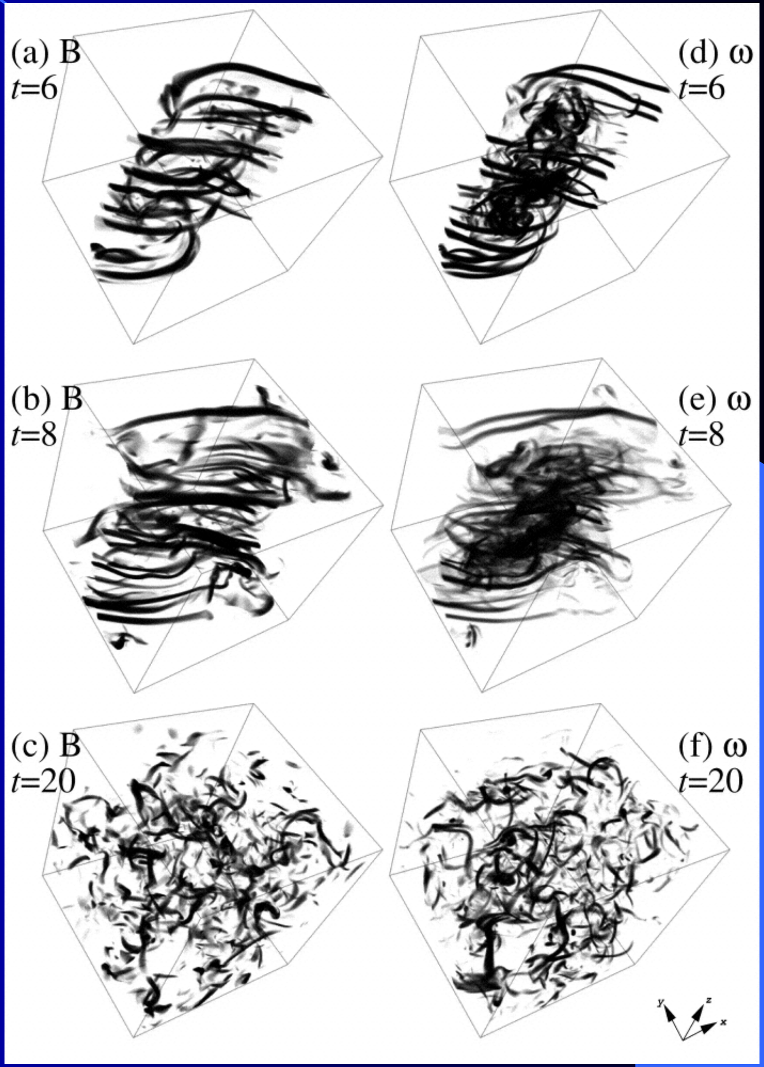
The Effect of Magnetic Fields

- Numerical Simulations Required
  - Jones et al. 1996 – 2000
- Two Dimensional MHD
  - Still Mixes for Beta > 10
  - 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"



Jet Dissipation

- 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

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

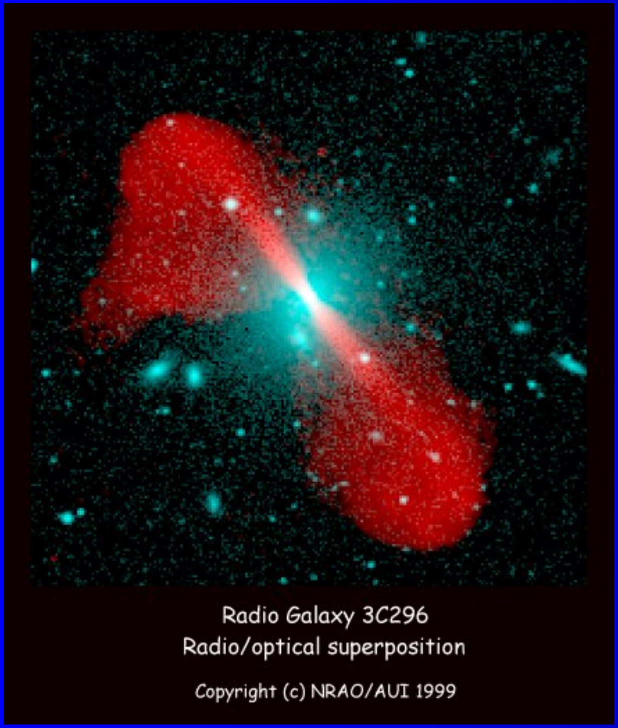
- At This Point Jet Is Fully Mixed, Turbulent

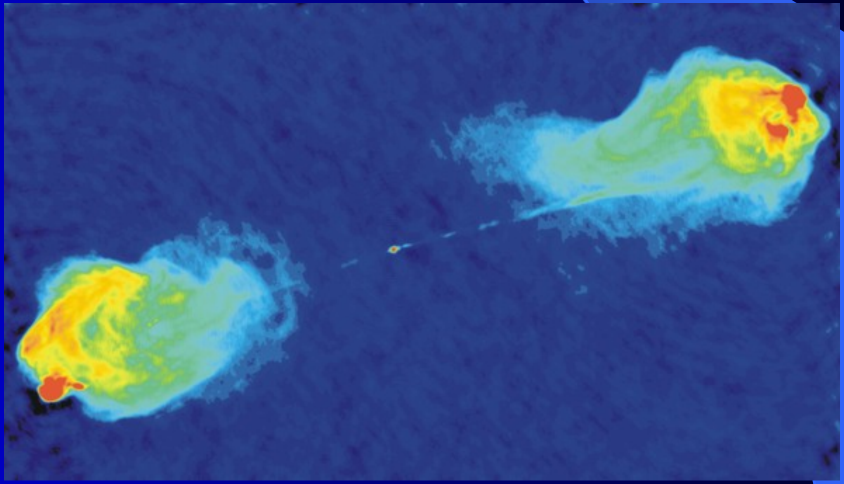
Jet Dissipation

- 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

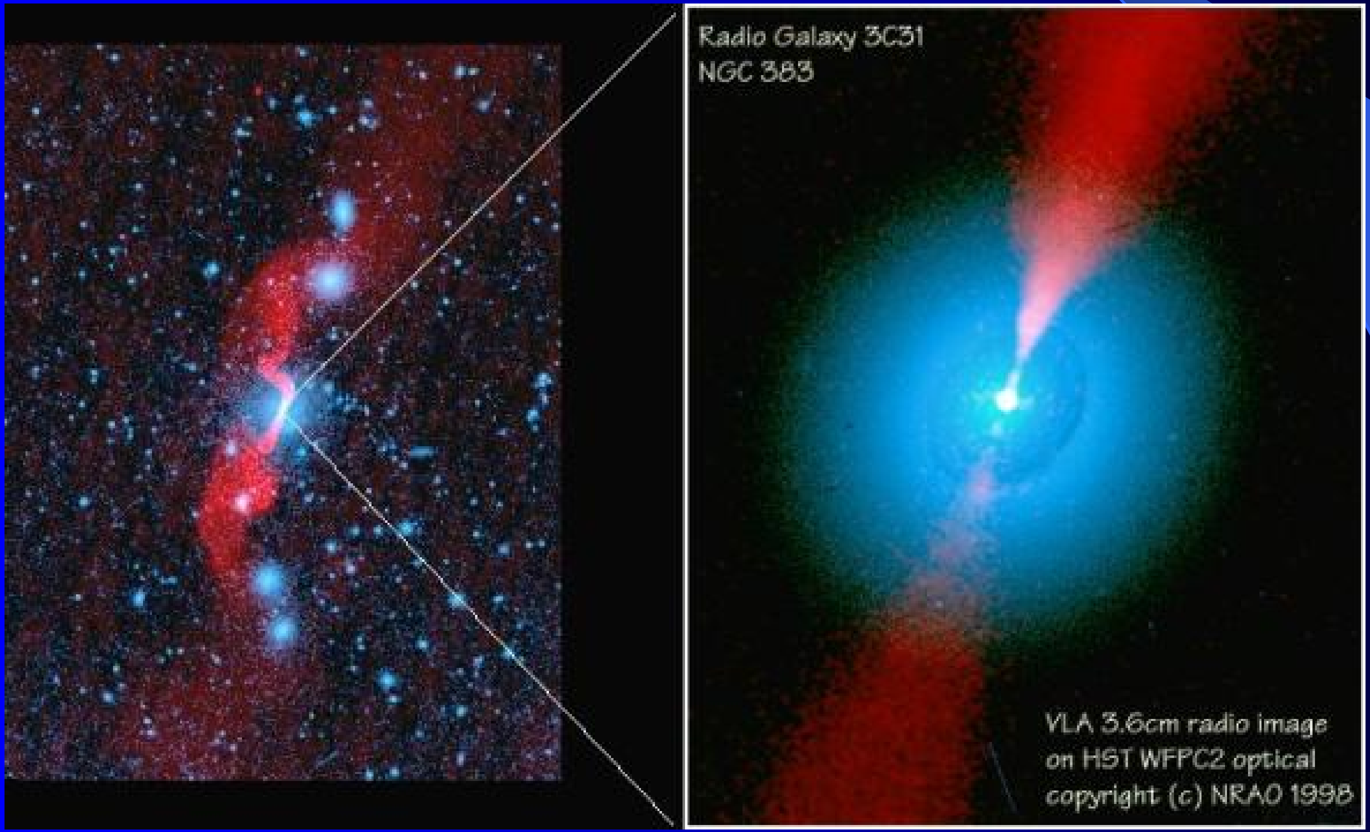
- Could Explain FRII – FRI Dichotomy
  - (De Young 1993, Bicknell 1995, Liang 1996)





Saturated Mixed Jets

- And The FRII – FRI Dichotomy

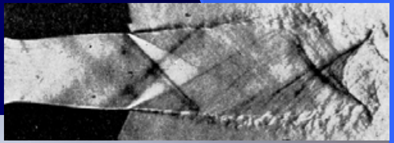


Saturated Mixed Jets

- 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 Dissipative Processes: Internal Shocks

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



Internal Shocks: Effects

- Partial Thermalization of Flow
- Particle Acceleration (J.Kirk)
- Magnetic Field Compression

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

- Radiation
  - Thermal

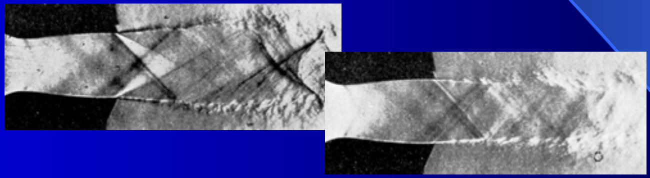
$$T_1 \approx T_0(2\gamma M_0^2)/(\gamma+1)^2$$

  - Non-Thermal

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

Internal Shocks: Dissipation

- Internal Shocks Along Jet:
  - Mostly Oblique

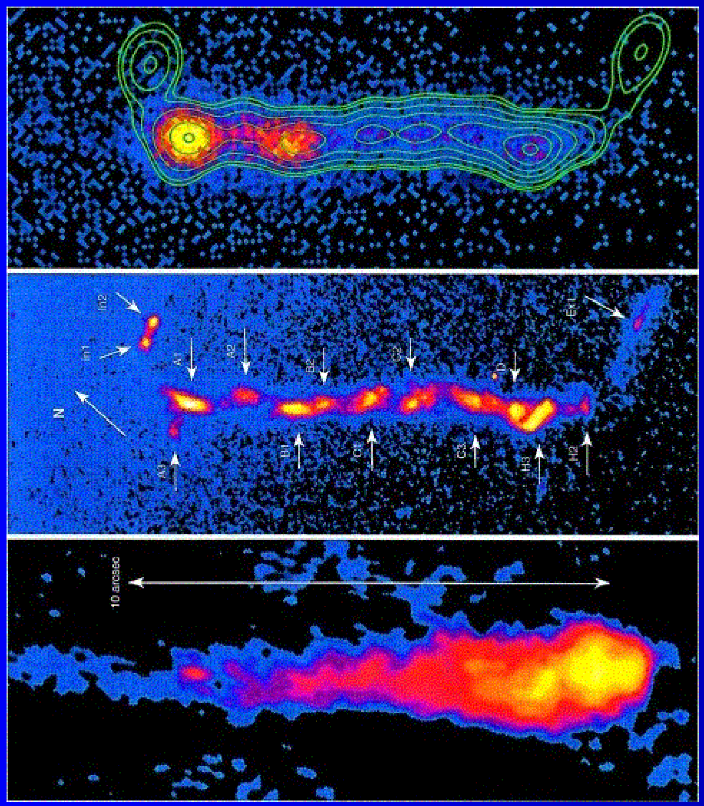


  - Mostly Redirect Flow – Internal “Weather”
    - Not Disruptive

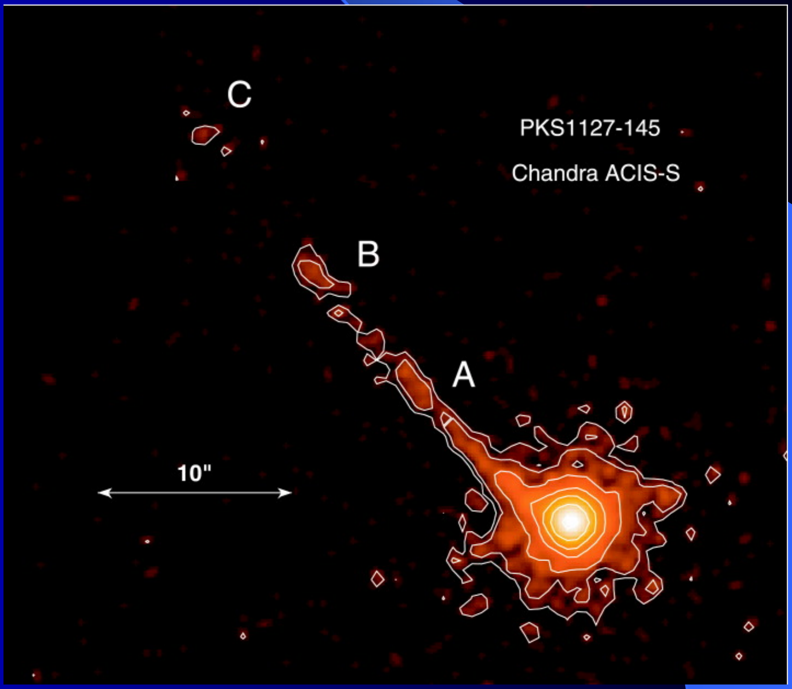
  - Mostly Convert Energy

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

Extragalactic Internal Shocks



Marshall et al. 2001



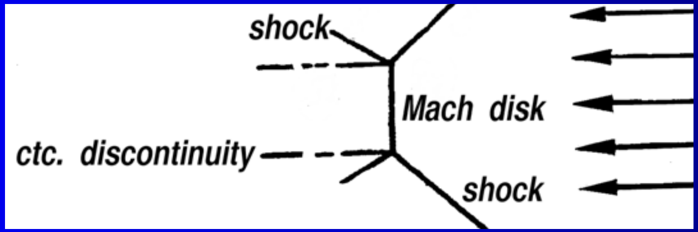
Siemiginowska et al, 2002

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 Provide Evidence for Jet Flow Speeds
  - SSC vs. IC on CMB

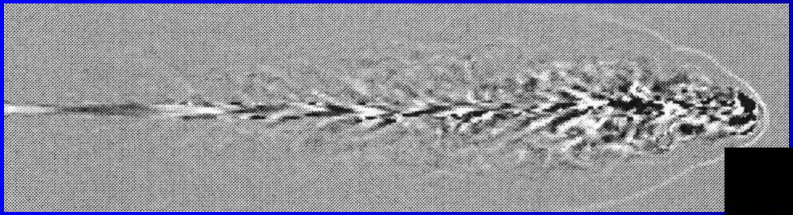
Termination Shocks

- Ideal:



  - (Beware Axisymmetric Calculations)

- Actual:



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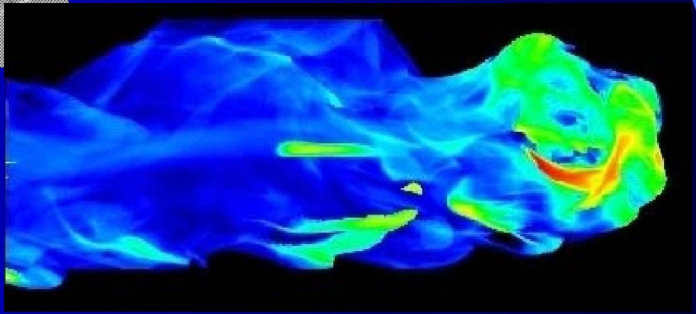
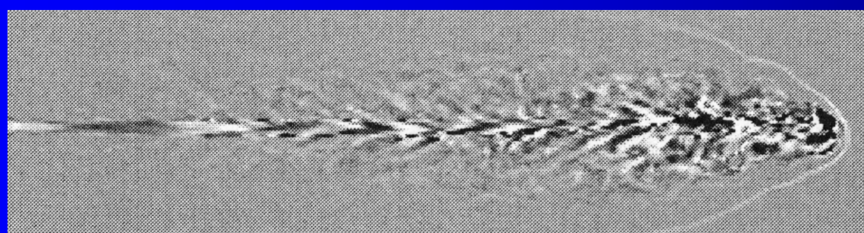
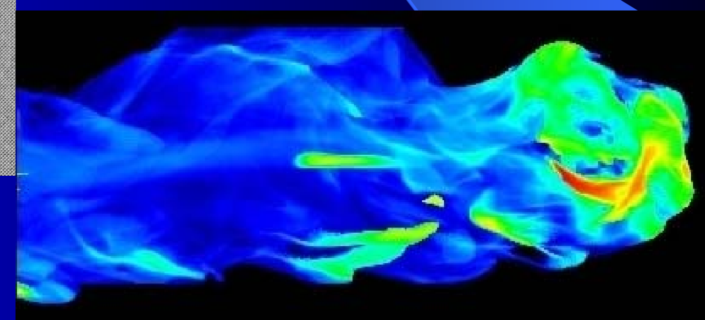


Tregillis & Jones

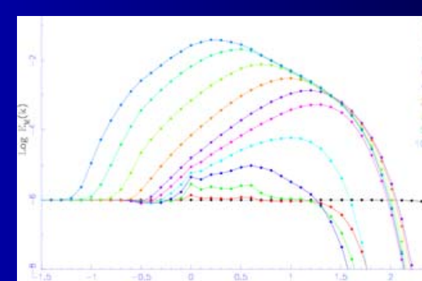
Termination Shocks

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





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



Conclusions

- Primary Jet Dissipation Mechanisms
  - Surface Mixing Layers
  - Termination Shocks
  - Turbulence
- Dissipation Processes Can Lead To:
  - Enrichment of IGM/ICM
  - Amplification of B Fields
  - Particle Acceleration?
  - Distant Emission Lines, Star Formation

Conclusions

- The Magnetic Field Problem
  - Origin
  - Strength
  - Geometry
  - Evolution and Amplification

- A Problem for Both Jets and Lobes

Conclusions

- A Remaining Mystery