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

\[
\tan \phi \propto M^{-1}
\]
Mixing Layers

- Thickness Grows with Distance/Time

\[ \tan \phi = C \left( \frac{\rho_L}{\rho_H} \right)^\alpha (v_{REL})^{-\beta} \]

- 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

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

- or, stable if

\[ M_A = \frac{U_R}{v_A} \leq 2 \]

- for

\[ k \parallel B \parallel U_R \]
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 $\sim 100 - 1000$
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 \( \tan \phi \approx C (\rho_J/\rho_{Amb})^{-\alpha} M^{-1} \)
  - Then Mixing Layer Thickness = Jet Radius at
    \[ \Delta R = L_{MIN} \tan \phi = R_{jet} \]
  - 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
    \[ P_{\text{Synch}} \propto B^2 E^2 \]
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:

M. Norman

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