Acceleration in Active Galactic Nuclei II

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Why study jets?

- Jets major component of galactic energy budget, impact cosmology
- Diagnostic of hole, history and environment
- GRBs you can image!
- UHECR acceleration sites?
- GeV/TeV + RXO observations should enable great advances
Some Big Questions on Jets

- **Location**
  - TeV, GeV, Radio, X-ray…

- **Emission Mechanisms**
  - Leptonic vs Hadronic, Synchrotron vs Coherent

- **Composition**
  - EM, pairs, ionic plasma

- **Velocity Field**
  - Monolithic, vs laminar vs turbulent

- **Collimation**
  - Pinch vs inertial vs pressure

- **Particle acceleration**
  - Shocks vs reconnection vs stochastic…

- **Transport**
  - Power, thrust, discharge, current

- **Origin**
  - Black hole, relativistic accretion disk
Location

- **mm/submm VLBI resolve down to 10m (r~100m) in nearby low power sources**

- **γ-ray variability**
  - $t_{\text{var}}$~mins reported in MKN501, PKS2155-304 at 1TeV
    - Nearby low power galaxies
  - $<m!$ cf pulsars
  - $\Gamma>50!$ cf GRBs
  - Pair production opacity to external infrared photons $\Rightarrow r>100m$
  - Breaking shockwave??
  - Cross correlate TeV-GeV variations
  - Cross correlate with radio observations
  - OVRO 40m – up to 1000 sources per day
  - VLBI observations

- **Test hypotheses on whole sample**
Emission Mechanisms

- Radio emission - synchrotron radiation?
  - However, intraday variability is very hard to explain
    - $I_{\nu \Omega} = 2kT_B \nu^2/c^2$, defines Brightness Temperature
    - $T_B < 10^{12}K$; $S \sim \Gamma^3 t^2$
    - $\Rightarrow r(5GHz) \sim 10^{18}$cm in high power sources
    - $\Rightarrow \Gamma > 100 \Rightarrow$ radiatively inefficient
  - Or coherent emission eg cyclotron maser
    - Nonlinear opacity constraints
  - Or refractive interstellar scintillation
    - Most likely now?
    - Check with frequency studies
Emission Mechanisms

- **γ-ray emission**
  - Inverse Compton scattering of synchrotron photons
    - $10\text{TeV} \Rightarrow \gamma > 10^7 \Rightarrow$ soft photons are FIR photons
    - Soft photons also provide an opacity for escaping TeV photons
    - Test by determining location of emission
  - **Hadronic emission models**
    - Accelerate protons to $>30\text{ TeV}$
    - Pion produced $\gamma$-rays
    - Neutrinos!
    - Test with IceCube etc
Composition

- What carries the jet power?

- Electromagnetic field
  - **DC models**
    - Force-free
    - Rel. MHD
      - Add inertia, pressure of plasma
      - Dissipation?
  - **Energy initially Poynting Flux?**
    - $E \times B$
      - Plasma supplies currents and charge
      - Inertial effects expected to become more important with $r$

\[
\begin{align*}
\frac{\partial B}{\partial t} &= -\nabla \times E \\
\frac{\partial E}{\partial t} &= \nabla \times B - j \\
\rho &= \nabla \cdot E \\
\nabla \cdot B &= 0 \\
\rho E + j \times B &= 0 \Rightarrow E \cdot B = E \cdot j = 0 \\
\rho E \times B &= (\nabla \cdot E)E \times B + (B \cdot \nabla \times B - E \cdot \nabla \times E)B \\
B^2
\end{align*}
\]
DC/AC Models

- Where do the currents close?
  - Near hole?
  - At end of jet?

- How do they close?
  - Dissipatively $j \cdot E \Rightarrow$ Heat
    - Hot spot?
  - Non-dissipatively $j \times B \Rightarrow$ Plasma Momentum
    - Fluid jet

- AC models
  - tangled field
  - Rapidly changing disk field polarity
Pair plasma

- **Pairs easy to make**
  - GV voltages out of EV-ZV
    - GeV gamma ray + keV X-ray -> pairs
  - Pair annihilation just as easy until energy density falls

- **Pure pair jet cannot escape radiation field close to black hole**
  - Something else must carry momentum
Electron-ion plasma

- Ions carry energy, momentum
  - Do not radiate

- Surely entrained into jet eventually

- If original jet ionic, probably originates from disk not hole

- Problems
  - Cold electrons moving with relativistic ion beam, with $\Gamma \sim 10$, create (unseen?) Compton-scattered X-rays
  - Depolarization of radio emission

- EM -> pairs -> ions? Where?
Velocity Field

- **Doppler blinding**
  - Optically thin stationary flow, \[ j_ν \propto \left( \frac{2\Gamma}{1 + \Gamma^2 \theta^2} \right)^{2+\alpha} \]

- **Jet shear is natural**
  - Spine-sheath structure?
  - AMR gas-dynamical simulations exhibit turbulent sheaths

- Beaming?, Absorption?, MHD?
Collimation

- Jets overpressured with respect to external gas => magnetic confinement
  - Toroidal field
    - eg $B_\phi \sim R^{-1} \Rightarrow (P_{\text{ext}}/P_{\text{int}}) \sim (R_{\text{max}}/R_{\text{min}})^{-2}$
    - => Faraday rotation gradients across jet
      $$\Delta \Phi = \int \frac{\omega^2 \omega_{G\parallel} dl}{\omega^2 c}$$
      - VLBI polarimetry
      - How far does current flow?
  - Inertial confinement requires ions
Particle acceleration

- Need $\gamma \sim 10^8$ for X-rays, $\gamma$-rays

- Natural accelerator is shock
  - Internal due to disturbance at source
  - External due local instability

- Relativistic shocks
  - Gas dynamical: $P = e/3 \Rightarrow \beta_- \beta_+ = 1; \beta_s = 3^{-1/2}$
  - RMHD; $\beta_s \rightarrow 1$, less dissipative
  - Force-free emission fronts
    - $B^2 - E^2$ can change sign $\Rightarrow$ catastrophic pair production emission
UHECR

- EMF $\sim (LZ_0)^{1/2}$
  - $\sim ZV$ for quasars, Cyg A etc
- Are lower power AGN Auger sources?
- Is EMF sufficient?
- Can currents flow to region where protons can escape without photopion production?
- Must field be regenerated?
Homogeneous acceleration

- **Required by X-ray observations eg M87**
  - Electrons cool between shocks
    - $t_{\text{cool}} \sim B_{\text{mG}}^{-3/2} \, \text{yr}$

- **Stochastic acceleration**
  - Relativistic MHD wave modes/weak shocks
  - Second order process

- **Relativistic reconnection**
  - Poorly understood but likely to be efficient
  - Non-realtivistic reconnection better understood now
Transport

- **What is energy, momentum, mass, current carried by jets**
  - \( F = w \Gamma^2 B + E \times B \)

- **Important for environmental impacts**

- **Measure jet properties**
  - Sample average \( \rightarrow \) angle average

- **Measure calorimetrically using radio lobes**
  - Important correlations with proxies are emerging
Origin

- What can we learn about the hole/disk?
- VLBI observations
  - mm/submm observations
  - VSOP2 (2012)
  - R~ few m in M87, Cen A Sgr A*
- Internal shocks?
  - Correlated features in both jets?
- Understand current flow
- Test Central Dogma
On the Electrodynamics of Moving Bodies

Even field
Odd current

\( \frac{L_H}{L_D} \sim \left( \frac{1}{\alpha D \beta D} \right) \left( \frac{\Omega_H}{\Omega_D} \right)^2 \left( \frac{s_D}{c} \right) \)
Pictor A

Electromagnetic Transport
$10^{18}$ not $10^{17}$ A
DC not AC
No internal shocks
New acceleration mechanisms

Current Flow

Nonthermal emission is ohmic dissipation of current flow?
Pinch stabilized by velocity gradient
Equipartition in core
Evolution of Mass Supply, Hole

- **Disk begins at accretion radius**
  - $R_a \sim GM/\sigma^2 \sim (c/\sigma)^2 m \sim 10^6 R_{in} \sigma_{300}^{-2}$

- **Supply rate**
  - $\sim (\sigma^3/G)f_{\text{gas}} \sim 4 \times 10^{29} \sigma_{300}^{-3} f_{\text{gas}} \text{ g s}^{-1}$

- **Inflow time**
  - $R_a/\sigma \sim 2 \times 10^{-3} M_6 \text{ Myr}$
  - $> \text{Jet flow time}$

- **Mass increment**
  - $\Delta \mu \sim f_{\text{gas}}$
  - Spin evolves stochastically
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