Magnetic Fields in Large-scale Jets

Volker Gaibler
Theoretical Structure Formation Group
MPE Garching

Max Camenzind (LSW Heidelberg)
Martin Krause (MPE Garching)
Sadegh Khochfar (MPE Garching)
Outline

- Jet – Galaxy/ISM interaction
- X-ray cavities
- Turbulent cocoons
- Efficient thermalization
- Magnetic fields: stabilization & amplification of fields
- Ongoing work

most results:
Gaibler, Krause, Camenzind (submitted to MNRAS, 2009)
Why Jets?

➢ Massive elliptical galaxies formed already at high redshift. Most massive SMBH also form early.

➢ Can AGN feedback get it done?
   ▪ quench star formation in massive ellipticals (*negative feedback*)
   ▪ trigger star formation by jet activity (*positive feedback*)

➢ Open questions (cf. Joe Silk's talk):
   ▪ star formation efficiency depends on turbulence in ISM
   ▪ magnetic fields important to regulate SF
   ▪ evidence for jet-triggered star formation: is that an option for early and strong SF?

➢ → Jet feedback has to be examined in detail (resolved!)
Jet – Galaxy Interaction

- well-collimated beams
- only minor interaction with galaxy once they broke out???

Cyg A @ 5 GHz
Perley+ 1984
(with giant elliptical overlay, M87)
Jet – Galaxy Interaction

- well-collimated beams
- only minor interaction with galaxy once they broke out???

No!
Whole galaxy contained in cocoon

Cyg A @ 5 GHz
Perley+ 1984

Cyg A @ 327 MHz contour overlay
Lazio+ 2006
High-z Radio Galaxies

- Extended Emission Line Regions aligned with jets
- Outflows
- Highly turbulent motion (~ 1000 km/s)

Nesvadba+ 2008
Morphology

Cyg A
Ambient Gas & Cavities

- Thermal ambient gas: ICM in bremsstrahlung
- Cavities: ambient gas displaced by cocoon
- Relativistic particles synchrotron & inverse compton (beam and cocoon)
Jets and Cavities

Perseus A  
(Fabian+ 2006)  
z=0.0183  
pV ~ 2 x 10^{59} \text{ erg}  
power 10^{44-45} \text{ erg/s}

Cygnus A  
(Wilson/Carilli/Perley)  
z=0.0561  
enthalpy 3 x 10^{60} \text{ erg}  
power 1.3 x 10^{45} \text{ erg/s}
Very Light Jets

- Important: Density contrast: $\eta = \frac{\rho_{\text{jet}}}{\rho_{\text{ambient}}}$

- AGN jets:
  - despite their power very underdense on large scales!
  - mildly relativistic speeds of the beam plasma
  - but propagation much slower than jet speed
  - strong backflow
  - wide cocoons (Norman+ 1983)

- Estimate jet densities:
  - jet power, mass flux and jet speed
  - comparison to Eddington accretion limit
  - hotspot pressures (ram pressure)
  - propagation speeds

our study: $10^{-1} \ldots 10^{-4}$

under-dense jets

generally $\eta < 10^{-2}$
Density Contrast

“Heavy” $\eta = 10^{-1}$

“Light” $\eta = 10^{-3}$

Density

Simulated X-ray emission

Volker Gaibler: Magnetized AGN Jets
Cocoon Pressure

- Selfsimilar models:
  \[ p_c \propto L_j^{2/3} \text{ length}^{-4/3} \]
  Aspect ratio = const

- Simulation:
  \[ p_c \propto \text{length}^{-1} \]
  Slower decline in cocoon pressure!

- Approaches ambient pressure then:
  Aspect ratio should rise!

Observations: (Mullin+ 2008)

Our Results:
Jet – Galaxy Interaction

- well-collimated beams
- only minor interaction with galaxy once they broke out???

Cyg A @ 5 GHz
Perley+ 1984

Cyg A @ 327 MHz  contour overlay
Lazio+ 2006

No!
Whole galaxy contained in cocoon
Cocoon Turbulence

- strong backflow
- highly turbulent cocoon!
- interaction with ISM
- Creation of multi-phase turbulence in cocoon (M. Krause)

[animation]
waves and ripples in Perseus A
Fabian+ 2006

- travelling sound waves in shocked ambient gas
- weak bow shock softly turns into sound wave!
- dissipation / heating?
Energy Budget

- light jets:
  high thermalization efficiency
  hot radio plasma cavity
  & heated ambient gas (hot phase)

- thermalization ~ 80%
  (half cocoon, half ambient)
  Zanni+ 2005:
  up to 75% irreversibly dissipated

- several percent of total power
  contained in cocoon turbulence
  may stir up ISM
Location of the Emission Line Gas

O III FWHM
km/s

project with N. Nesvadba
multi-phase medium
simulations: Martin Krause
Magnetic Fields

➢ Why magnetic fields?
  ▪ synchrotron emission → they must be there!
  ▪ what is their effect?

➢ Topology:
  ▪ infer from polarization measurements
  ▪ mostly axial in beam, perpendicular at hotspots
  ▪ stretched tangled fields? helical fields?

➢ Assume helical fields
  ▪ effects found should also be relevant for tangled fields
  ▪ resolve magnetic field structure well
  ▪ magnetic field confined to jet (by setup)
  ▪ sub-equipartition
Magnetic Fields: Stabilization

- M3: plasma beta = 8.1 (injected)

- comparison HD – MHD
  - damp KH shear instability (field lines resist bending)
  - less entrainment
  - stabilization in cocoon not enough?

M3 density

\[ \text{no magnetic fields} \]

\[ \text{with magnetic fields} \]
Step 1: Beam Rotation

- initially: beam has no rotation, but helical field

- plasma rotation: “MHD angular momentum conservation” (exchange of magnetic field and plasma angular momentum)
Step 2: Shearing and Field Generation

- **backflow:** plasma streams off the axis
- **angular momentum conservation:** differential rotation
- **shearing:** kinetic → magnetic amplifies fields

3D field lines in jet beam

M2 @ 1.3 Myr
Magnetic Field Magnitude

- cocoon:
  much stronger fields than expected from flux conservation

- expectation in 3D:
  also strong fields, but balance poloidal/toroidal, turbulent distribution of magnetic fields in cocoon
Poloidal Magnetic Field

➢ strong in beam
➢ highly turbulent
➢ poloidal component artificially weak in 2.5D cocoons → 3D
The Question of Equipartition

- Often assumed: equipartition between magnetic field and relativistic particles
- Here: check magnetic field and plasma pressure (plasma beta)
- Beam: beta constant across shocks
- Cocoon: spread

![Pressure Diagrams](image)
Ongoing Work

➢ Physical mechanism examined by axisymmetric simulations
➢ 3D simulations of jets in clumpy medium for extended emission line regions in HzRG
➢ Interaction with cosmological environment
   Self-consistent evolution of jet activity (accretion, spin, ...)

![Graph and image of simulated jet activity]
cocoon turbulence excites sound waves, interaction with ISM thermalization very efficient for very light jets

magnetic fields stabilize jet head, suppress entrainment

helical fields & shearing generate magnetic energy: damp KH instability and magnetize cocoon

3D simulations necessary for realistic turbulent interaction with ISM and cosmological environment