AGN Outflows in Dynamic ICMs: Winds and Twists

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Outline

• AGN outflows (radio jets) are major dynamical & thermodynamical ICM components

• AGN/ICM interactions may provide insights to AGN & ICM physics

• Is binarity in radio mode AGNs useful as a tool in these investigations?
Dave DeYoung was keenly interested in AGN/ICM interactions (from 2007 Anchorage Workshop)

3D Buoyant Bubble – AGN-made ICM cavity: Role of the ICM magnetic field

DeYoung, O’Neill & Jones 2007

Bubble mass fraction

- $r_0 = 2 \text{ kpc}$
- $x_0 = 15 \text{ kpc}$
- $\rho_{\text{bub}}/\rho_{\text{icm}} = 0.01$
- 40x34x34 kpc
- $\Delta x = 0.13 \text{ kpc}$

DeYoung, O’Neill & Jones 2007
Radio AGNs are Common in Clusters

Cluster cores

X-ray w/ radio contours
Croston +

Cluster outskirts

X-ray (red) & radio (green)
Rudnick +
Importance:
Energy Input to ICM Can Be Large

![Graph showing cavity power vs. X-ray luminosity of ICM](image)

**Fig. 6.**—Cavity power of the central AGN vs. the X-ray luminosity of the ICM inside the cooling radius that must be offset to be consistent with the spectra ($L_{\text{ICM}} = L_X - L_{\text{cool}}$). The symbols and wide error bars denote the values of cavity power calculated using the buoyancy timescale. The short- and medium-width error bars denote the upper and lower limits of the cavity power calculated using the sound speed and refill timescales, respectively. Different symbols denote different figures of merit: circle: well-defined cavity with bright rims; triangle: well-defined cavity without bright rims; square: poorly defined cavity. The diagonal lines denote $P_{\text{cav}} = L_{\text{ICM}}$ assuming $pV$, $4pV$, or $16pV$ as the total enthalpy of the cavities.
Importance:
Dynamics Reflect ICM Motions/Structure

O'Dea & Owen \(\lambda\)21cm

\[ U_{gal} \sim 2000 \text{ km/s} \]
\[ \tau_{AGN} > 2 \times 10^8 \text{ yr} \]

NGC 1265

Sijbring & deBruyn \(\lambda\)49cm

\(~540 \text{ kpc}\)

3C 84

\(~540 \text{ kpc}\)
Some Known to be Binary  
(Many Might Be)  

Binary Example: 3C 75

A400  
NGC 1128  
~ 8kpc separation

Red (visible)  
Blue (radio)
Figure 1. The binary radio galaxies J0321−455N and J0321−455S. 2.4-GHz radio contours are overlaid on a combined $R$- and $V$-band optical image of the field made using the ANU 2.3-m telescope. The contours correspond to 4, 16, 64 and 128 times the rms image noise of 60 μJy beam$^{-1}$. Spectroscopy (see Table 2) reveals that the objects labelled c and d and the radio galaxies are at about the same redshift.
Binary Example: FIRST J1643+3156

~15 kpc separation

Figure 2. HST/ACS image of FIRST J1643+3156 in the F814W filter with an overlay of contours of the radio emission at 1.66 GHz. The two bright quasar nuclei are visible. The host galaxy of the radio-loud quasar is perturbed.
Given the commonality of AGNs in ICMs
The Challenge:

Decipher complex morphological (& other) clues
to establish useful dynamical diagnostics:

E.G.,
ICM flow properties
ICM magnetic field properties
Jet physical properties
Define key Jet/ICM interaction parameters

We’ve mostly explored through simulations
Previous Generation Jet Simulations in Static ICMs (3D MHD)  
e.g., O’Neill, Mendygral & Jones 2009

- Bipolar, collimated Mach 30 (internal) jet outflows  
  \( L_{\text{jet}} = 1.2 \times 10^{46} \text{ erg/s} \) (combined jets at full power)  
  Steady or intermittent (50%, 26 Myr cycle)  
  \( r_{\text{jet}} = 3 \text{ kpc} \)  
  \( \rho_{\text{jet}}/\rho_0 = 0.01 \)  
  Toroidal jet B field at source (\( \beta = P_g/P_M \sim 100; B_j \sim 10 \mu \text{G} \))

- Passive `CR’ electrons, shock injection & DSA  
  Adiabatic & radiative (synch, IC) losses

- AGN at center of \( \sim 4 \times 10^{14} \text{ M}_\odot \) cluster (NFW potential)  
  Static ICM, \( kT_{\text{ICM}} \sim 3 \text{keV} \) (\( \sim \) Perseus)  
  Double \( \beta \) profile with random density fluctuations  
  Tangled ICM magnetic field  
  \( \langle \beta_{\text{plasma}} \rangle \sim 100 \) (range \( \sim 30:1000 \)) \( \langle B_{\text{core}} \rangle \sim 7 \mu \text{G} \)  
  No radiative cooling of ICM
Illustration: Intermittent Jets

Magnetic Field Intensity

Blue (AGN plasma)
Red (ICM plasma)
Synthetically Observed’ & Actual Energetics Comparisons Good to ~ 50%
On the Other Hand: Real ICMs are Dynamic:

“Bullet Cluster” 1E 0657-56

Chandra + HST
Two Classes of More Realistic Simulations:

• AGN Jets in simple, but dynamic media
• AGN Jets in self-consistent ICMs
Example: Bipolar AGN Jets in a Turbulent ICM Wind:
Narrow Angle Tail (NAT) FRI Source
(Porter + 2009)

• Code: MHD TVD with passive CR electrons (CGMV)

• Box: 1 Mpc x 1 Mpc x 200 kpc
  2000×2000×400 = 1.6×10^9 zones
  Δx = 0.5 kpc

• Jet Power: 5×10^{44} erg/s
• Jet Radius: 5 kpc
• Bending Radius: ~ 20 kpc (M_j/M_{ICM} ~ 2)
• Simulation Duration: 215 Myr
• Tail Length: ~ 600 kpc
NAT Simulation Setup:

Emergent Jets:

\[ U_{\text{jet}} = 0.044c \]
\[ R_{\text{jet}} = 5 \text{ kpc} \]
\[ \rho_{\text{jet}} = 0.1 <\rho_{\text{icm}}> \]
\[ M_{\text{jet}} = \frac{U_{\text{jet}}}{s_{\text{jet}}} = 3 \]
\[ \beta_{\text{jet}} = \frac{P_{\text{mag}}}{P_{\text{gas}}} \sim 10 \]
\[ \text{(toroidal field)} \]

ICM:

\[ U_{\text{icm}} = 2000 \text{ km/s} \]
\[ \theta = 30 \text{ degrees} \]
\[ M_{\text{w}} = \frac{U_{\text{icm}}}{s_{\text{icm}}} = 1.5 \]
\[ P_{\text{icm}} = P_{\text{jet}} = 1.8 \times 10^{-11} \text{ dy/cm}^2 \]
\[ <n_{\text{icm}}> = 0.001 \text{ cm}^{-3} \]
\[ B_{\text{rms}} = 2.2 \mu \text{G} \]
\[ <\beta_{\text{icm}}> = 100 \]

Turbulent ICM:

Outer scale 20 kpc
Kolmogorov

Bending Radius:

\[ \frac{R_b}{R_j} \sim (\frac{M_j}{M_w})^2 (\frac{P_j}{P_i}) \]
for \( \frac{P_j}{P_i} = 1 \)
\[ R_b/R_j \sim (\frac{M_j}{M_i})^2 = 4 \]
So \( R_b \sim 20 \text{ kpc} \)
Kinetic Energy Deposition

KE in ICM
Rest Frame
Jet-wind plane
Vorticity (Shear, turbulence)

Volume Rendered

t = 215 Myr
Magnetic Field Injection/Amplification

Volume Rendered

$t = 215$ Myr
Synthetic Synchrotron Emission

178 MHz
215 Myr

(Using included Cre population)
Self-Consistent ICM Example:

Intermittent Bipolar AGN Jets in a Nominally Relaxed ICM
Extracted from Cosmological Simulation (SPH MHD):
Wide Angle Tail (WAT) FR II Source
Mendrygral + 2012

- Code: MHD TVD (grid-based) with passive CR electrons (CGMV)
- Box: 1 Mpc³; 1008³ zones
  \[ \Delta x = 1 \text{ kpc} \]
- Jet Power: \(6 \times 10^{44} \text{ erg/s}\)
- Jet Radius: 3 kpc
- Jet Velocity: \(v_j = 10^4 \text{ km/s}\)
- Jet Density: \(\rho_j = 4 \times 10^{-28} \text{ g/cm}^3\)
- Toroidal Magnetic Field (\(\beta = 1, 10, 100\))
- Cluster (7 Gyr since major merger):
  - Mass = \(1.5 \times 10^{14} M_\odot\); \(kT \sim 1.5 \text{ keV}\); \(c_s \sim 650 \text{ km/s}\)
  - \(B_{\text{core}} \sim 5 \mu \text{G}\)
Overview of Selected Cluster

$z = 0$

Density

Pressure

1 Mpc

0 Myr

0 Myr

200 kpc
Cluster Magnetic Field
Initial ICM Gas Entropy Slices with Velocity Vectors

Cross winds up to 450 km/sec

Bar shows jet axis
Evolution of AGN Cavity

Note distortions from axial symmetry

(‘Launch cylinder’ visible)
Synthetic X-Ray Image (divided by $\beta$-law)
Synthetic Radio Images

131.3 Myr

196.8 Myr
Back to Binary AGNs: 3C 75

Blue (X-ray) Pink (radio)

A400
Merging clusters
$\Delta v \sim 1000 - 2000$ km/s
Merging galaxies
$\Delta v \sim 400$ km/s
Projected separation $\sim 7$ kpc
Yokosawa & Inoue

$v_w = 1100 \text{ km/s} \\
(\text{almost in plane})

Orbital diameter 8\text{kpc}

Orbital period 110 \text{ Myr}

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Fig. 1. The coordinate system; $x$-$y$ plane is the orbital plane of the binary galaxy and $x$-axis is the major axis of the orbit. The plane of the sky is $S$ and $i$ is the inclination of the orbital plane $O$ from the line of sight.
General idea of Expected Behavior
(Yokosawa + Ballistic Model)

Fig. 2. Jet trajectories produced by the binary orbiting galaxy. $\varphi_{\text{phase}}$ is the orbital phase of the galaxy. The intergalactic wind flows to the left direction.
Yokosawa + Ballistic Model

Fig. 4. (a) Radio map of 3C 75 at 5 GHz (Owen et al. 1985) obtained with the VLA.
(b) Halftone simulation of the best-fitted jets, in which each point has been replaced by a random dot pattern with Gaussian cross section. The half-width of the cross section increases linearly with time. Parameters of the jet velocities and the orbital elements are represented in table 1.
Our MHD Simulation Set Up:

| Box: 500 kpc X 250 kpc X 500 kpc (1084 X 542 X 1084) grid |
| Δx = 0.5 kpc |

| ICM: |
| ρ_{ICM} = 5 \times 10^{-27} \text{ g/cm}^3 |
| P_{ICM} = 1.3 \times 10^{-11} \text{ dyne/cm}^2 |
| v_x = 1100 \text{ km/s} (v_y = v_z = 0) |
| v_x/c_s = M_{ICM} = 1.67 |
| Turbulent ICM: <v_{turb}>_{RMS} = 150 \text{ km/s}, <B_{turb}>_{RMS} = 2 \mu \text{G} |
| outer scale 30 kpc |

| Jets: (paired & orthogonal to AGN orbit) |
| r_j = 3 \text{ kpc} |
| v_j = 1.5 \times 10^4 \text{ km/s} |
| P_j = P_{ICM} = 1.3 \times 10^{-11} \text{ dyne/cm}^2 |
| \rho_j = 5 \times 10^{-28} \text{ g/cm}^3 |
| v_j/c_{sj} = M_j = 7.2 |
| \beta = P_g/P_M = 10 |
| L_j = 5 \times 10^{43} \text{ erg/s} |
| orbital diameter = 12 \text{ kpc (x-y plane)} |
| orbital period = 91 \text{ Myr} |
Crude Comparison

Simulation: Jet mass fraction

3C 75: radio in pink

t = 215 Myr

Roughly similar scales
t = 215 Myr (~ 2 binary orbits)

Jet mass fraction ‘color’

Jet break:

$l_b \sim \left( \frac{M_j}{M_{ICM}} \right)^2 r_j$

Varies during Orbit $(v_w + v_o)$

$< l_b > \sim 60 \text{ kpc}$

Tail lengths $\sim 300 \text{ kpc}$
Evolution of Mass Fraction
Thanks!