The physics of AGN jets from 3D simulations

Salvatore Cielo
IAP, Paris
with:

J. Silk (IAP|JHU)
M. Volonteri (IAP)
V. Antonuccio-Delogu (INAF)
A. V. Macciò (NYU)
Active Galactic Nuclei

Brightest source! $10^{48}$ erg/s

**Powered by SMBH**

**unified model!**

**Interesting for:**
- MHD, GR
- BH accretion/growth
- UHE-CR (extragalactic)
- high-z “flashlights”
- … feedback!

---

Figure 1.3: How the unified AGN model explains the spectral features of these objects. Note the multiscale structure, spanning several orders of magnitudes in size (image not to scale). The color coding differentiate the structures; order-of-magnitude estimates of the structures’ scale are indicated in light green; the spectral features (mostly emission) are highlighted in blue. Image adapted from: Astronomical Society of the Pacific (1995).

**Figure 28.4** A sketch of the continuum observed for many types of AGN:

- **Turnover**
- **IR bump**
- **Radio loud** ~ 10%
- **Radio quiet** ~ 90%

---

**Molecular/dusty Torus**
- Rec-processed IR emission - obscures inner disk if seen edge-on; AGN continuum emission evaporates/fomizes its inner edge, creating material for BLR and NLR

**Extended lobes (Hot Spots/Plumes)**
- Resolved (imaging) radio emission also seen as cavities in X-ray imaging.
- Determine total jet power (pV work) and other kinematic parameters (shape)

**SC PhD thesis**

---

**Hot corona around disk**
- $\sim 0.1$ parsec
- Thermal + Compton re-process emission up to hard X-ray

**Narrow Line Region (NLR)**
- $\sim 100$ parsec
- Cold gas emission from clouds - yield AGN redshift

**Winds/outflows**
- $\sim 1$ parsec
- Broad and Narrow Absorption Lines (BAL and NAL) - blue-shifted, evidence of strong outflows

**Accretion disk**
- $0.001-0.1$ parsec
- Thermal emission - optical/UV to soft X-ray (Big Blue Bump)
- Cyclotron-synchrotron emission - when resolved (e.g. Sgr A* at 310 GHz)
- Broad 6.4 keV emission line - Fe Kα line from inner accretion disk; yields BH spin measures

**Broad Line Region (BLR)**
- $\sim 10$ parsec
- Cold gas emission from clouds - yields cloud velocities, broadening and position (reverberation mapping), hence BH mass.
- Intensities correlate with jet luminosity.

**Inner jet (continuum) region**
- $\sim 1$ parsec
- Synchrotron emission: [radio] jet passes from accretion-dominated to matter-dominated in a few pc.
- Inverse Compton emission - hard X-ray; the jet accelerates electrons up to $10^{15}$ eV; the Compton Self-Compton (SSC) or Internal Compton (IC).

---

B.W. Carroll, D.A. Ostlie
An introduction to modern astrophysics

---

12 Nov 2015

Salvo Cielo, IAP - AGN Catania
on AGN Feedback

Radio Galaxy Cyg A
(nasa.gov)

Chandra's Perseus cluster
(from Fabian12)

mechanical
(jets, cavities)

AGN everywhere!

McConnell & Ma '13

BH/gxy co-evolution.
Is it feedback?

AGN Catania

12 Nov 2015
Salvo Cielo, IAP -
AGN feedback in simulations 1/2

Launching (AU scale)

Hawley, Fendt + 15

- (GR)MHD jets from BH/disks
- BZ/BP process; accretion efficiency sets jets or winds.

Sadowsky+15

In isolated halos (10-100 kpc)

- Jets reproduce source shapes
- “Gentler” winds create cyclic starforming cold gas phase

Gaspari + 13

Li + 15

12 Nov 2015 Salvo Cielo, IAP - AGN Catania
AGN feedback in simulations 2/2

Gxy formation and cosmology [Mpc and more]

SF is suppressed.

Jet Feedback may be

Negative (e.g. Tortora + '09)

Positive (e.g. Gaibler+12 Bieri+15)

AGN feedback avoids overcooling, though often subgrid.
E.g. Sijacki+15, Dubois+14
Our Simulation Model

DM + Hot Gas + Cold Clumps + Bipolar Jet

Physics: hydro + gravity + radiative cooling

Software: FLASH, Adaptive Mesh (75 pc res.)

Geometry: multiple (up to 5) jet events, random angles few Myr break

Next: add stars.

Galactic: \( \sim 10^{13} \, M_{\odot} \)

T.I.S. \( 10^4 \, K \)

\( 5 \times 10^6 \, K \)

\( 10^{44} \, \text{erg/s} \)
Why flipping jets?

X-ray cavities in clusters

Chandra's Perseus "Halloween" ~ 150 kpc

- constrain jet parameters (e.g. Guo + '14)
- multiple pairs

x-shaped radio galaxies:

- SMBH spin flip or backflows

12 Nov 2015

Salvo Cielo, IAP - AGN Catania
Cavities = hot air balloons

Paris, 1783
Recap: with a single Jet (Cielo+14)

1. Bow shock region develops

2. Turbulent “cocoon”

3. Jets open into “radio” lobes/bubbles (if jet stops)

2.1 Myr
Many Jets!
(in prep.)

cold clumps
• Stop jet for a bit
  → asymmetry
• Compressed/heated
  → +/- feedback

“flipped” jets
• More isotropic feedback
• Trigger much backflow

Density slice ~50 kpc
Results: **cold** gas mass

Steady positive feedback

**BUT** < 1% total → quite dense!
Results: cold gas compression

![Graph showing cold gas compression]
Results: **cold gas compression**

![Graph showing cold gas compression](image)
Results: outflow velocity

10 Myr

- 75000 km/s jets
- ~2000 km/s cocoon

28 Myr

- Mach 1 bow-shock
- Mach 20 jets (by constr.)

- Is it X-shaped? (I'd say yes)
- Is it flip or backflow? → Need synchrotron maps!
U.F.O.s (Do you believe?)

Cooling efficiency
Important for cosm. simulations where this is all subgrid!

Compton? Only above $10^{10}$ K

12 Nov 2015

Salvo Cielo, IAP - AGN Catania
Results: backflows (one jet)

Potential fuel for the SMBH...
(but accretion disk not resolved)

Sketch by V. Antonuccio

Accretion Disk

Z Velocity (cm/s)

$t_{\text{age}} / \text{Myr}$

$M_{1\text{kpc}}^{100pc} / M_{\odot}$

- 150p6
- 200p5
- 200p6
- 250p6
- d+200p6
- d+250p6
- dj–200p6

Cielo+14

12 Nov 2015

Salvo Cielo, IAP - AGN Catania
Results: backflows (many jets)

Same rate of $\sim 1 \, M_{\text{sun}} \, y^{-1}$

lasts 25 Myr instead of 1
Results: soft-xray images
Conclusions

AGN jets

• produce energy-conserving outflows
• backflows can shape galaxy

Multiple jets

• reproduce multiple X-ray cavities
• greatly enhance backflows

Our cold gas model

• is compressed → positive feedback
• is very dense!

Thank you!