Large Scale Anisotropic Expansion of AGN Outflows in Cosmological Simulations

Paramita Barai

Collaborators: Joël Germain, Hugo Martel
Université Laval
Québec City, Canada

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The Interface between Galaxy Formation and AGNs (Vulcano, Italy)
Introduction

- Outflows observed in a large fraction of AGNs

Goal: Calculate the volume fraction of the Universe filled by AGN outflows over the Hubble time

- Energy density
- Magnetic field
Motivation

Previous studies

Our Improvement
- Anisotropically expanding outflow
- Implement in cosmological simulations

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Cosmological outflows expand anisotropically in large scales. Away from high-density regions, into low-density regions, along the path of least resistance (Martel & Shapiro 2001, RevMexAA, 10, 101)
Outflow Geometry

- Bipolar spherical cone
- Spherical coordinates \((r, \theta, \phi)\)

Radius = \(R\)
Opening angle = \(\alpha\)
Direction of Outflow = \(\hat{\mathbf{e}}\) (unit vector)

\[
\begin{align*}
  r &\leq R \\
  0 &\leq \theta \leq \frac{\alpha}{2} , \text{or, } \left(\pi - \frac{\alpha}{2}\right) \leq \theta < \pi \\
  0 &\leq \phi < 2\pi
\end{align*}
\]
**Direction of Least Resistance (DLR)**

- In large-scale filamentary structures, outflow direction is obtained from pressure of surrounding medium.

**Implementation**

- Find DLR around density peaks.
- Taylor expansion of density around a peak inside sphere of radius $R^*$.
- Rotate Cartesian coordinates to make cross-terms vanish.

\[
\delta(x',y',z') = \delta_{\text{peak}} - Ax'^2 - By'^2 - Cz'^2
\]

- Largest of the coefficients $A$, $B$, $C \Rightarrow DLR$
Methodology

N-body Cosmological Simulation

Semi-analytical model of AGN outflows

Cosmological AGN population from observed luminosity function

Distribute AGN in the simulation volume (at density peaks)

Evolve AGN and their outflows within Simulation Box

Compute the volume of the cosmological box filled by the outflows
Cosmological Simulation

- N-body simulations of a cosmological volume
- Box size (comoving) = 128 $h^{-1}$ Mpc
  - Triply periodic boundary conditions
  - Expanding with the Hubble flow
- 256$^3$ dark matter particles
- 512$^3$ grid
- Evolve from $z=25$ up to $z=0$
- $P^3M$ code (particle-particle/particle-mesh)
- Grav. softening length
  - $= 0.3 \times$ cell size
  - $= 75 \, h^{-1} \, \text{kpc}$
- Particle mass
  - $= 1.32 \times 10^{10} \, M_{\odot}$
- $\Lambda$CDM model:
  - $\Omega_M = 0.241$
  - $\Omega_B = 0.0416$
  - $\Omega_\Lambda = 0.759$
  - $H_0 = 73.2 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$
  - $n_s = 0.958$
  - $T_{CMB} = 2.725 \, \text{K}$
Assume: baryonic gas distribution follows dark matter in the simulation box

**Ambient gas density:**

\[
\rho_x(z, \vec{r}) = \frac{\Omega_B}{\Omega_M} \rho_M(z, \vec{r})
\]

**Pressure:**

\[
p_x(z, \vec{r}) = \frac{\rho_x(z, \vec{r})KT_x}{\mu}
\]

**Temperature (assuming a photoheated medium):**

\[
T_x = 10^4 \text{ K}
\]

**Mean molecular mass:**

\[
\mu = 0.611 \text{ a.m.u.}
\]
Redshift & Luminosity Distribution

- Observed AGN bolometric luminosity function

\[ \varphi(L) = \frac{\varphi_*}{(L/L_*)^{\gamma_1} + (L/L_*)^{\gamma_2}} \]

- Constant AGN lifetime, \( T_{\text{AGN}} = 10^8 \) yr
- Fraction of AGN hosting outflows = 0.2

- Number of AGN
  \[ dN = f_{\text{outflow}} \varphi(L) d[\log L] V_{\text{box}} \]

- Locate AGN at local density peaks
- Filter density above a minimum halo mass
Bolometric Quasar Luminosity Function

\( \phi (L) \) vs. \( L / L_\odot \)

- \( z = 0.1 \)
- \( z = 0.5 \)
- \( z = 1 \)
- \( z = 1.5 \)
- \( z = 2 \)
- \( z = 2.5 \)
- \( z = 3 \)
- \( z = 4 \)
- \( z = 5 \)
- \( z = 6 \)
All Sources in Box from QLF. $N_{\text{AGN, total}} = 929805$

$10^8 < L / L_\odot < 10^9$
$N_{\text{AGN}} = 710181$

$10^9 < L / L_\odot < 10^{10}$
$N_{\text{AGN}} = 163699$

$10^{10} < L / L_\odot < 10^{11}$
$N_{\text{AGN}} = 42450$

$10^{11} < L / L_\odot < 10^{12}$
$N_{\text{AGN}} = 11507$

$10^{12} < L / L_\odot < 10^{13}$
$N_{\text{AGN}} = 1954$

$10^{13} < L / L_\odot < 10^{14}$
$N_{\text{AGN}} = 14$
New AGN locations in a slice of box at $z = 0.5$

Black - Particles (PM), blue - Peaks, red - AGNs
Active-AGN Life

Jet Kinetic power

\[ L_K = \varepsilon_K L_{bol} / 2, \]

with, \( \varepsilon_K = 0.1 \)

Jet advance

\[ \frac{L_K}{\rho_x \rho} = \rho_x \left( \frac{dR}{dt} \right)^2 \]

Energy

\[ E = 2L_K t_{age} \]

Pressure

\[ pV = (\Gamma - 1)E \]

Relativistic outflow with \( \Gamma = 4/3 \)

Overpressured: \( p >> p_x \)
Post-AGN Evolution

- Anisotropic Expansion when overpressured, $\rho > \rho_x$
  - Sedov-Taylor adiabatic expansion

- Total AGN energy

- Adiabatic loss

- Bipolar conical outflow

When reach pressure equilibrium, $\rho = \rho_x$

- Passive Hubble evolution, $R_{\text{comoving}} = \text{Constant}$

\[ E_{\text{AGN}} = 2L_K T_{\text{AGN}} \]

\[ pR^{3\Gamma_x} = \text{constant} \]

\[ V = \frac{4}{3} \pi R^3 \left( 1 - \cos \frac{\alpha}{2} \right) \]

\[ R = \xi_0 \left( \frac{E_{\text{AGN}} t_{\text{age}}^2}{\bar{\rho}_x} \right)^{1/5} \]
Volume Filled

- Count mesh cells in the simulation box occurring inside the volume of one/more outflow.
- Total number of filled cells, $N_{AGN} = \text{total volume of box occupied by outflows}$
- Express the total volume filled as a fraction of volumes of various overdensities in the box.

\[
N_\rho = N(\rho > C\rho_{\text{mean}})
\]

\[
\rho_{\text{mean}} = (1 + z)^3 \Omega_M \frac{3H_0^2}{8\pi G}
\]
Fractional Volumes of box of various overdensities filled by AGN outflows

\( N_\rho \) with \( c = 0, 1, 2, 3, 5, 7 \)
Volume Averaged Energy Density

\[ \langle u_E \rangle = \frac{\sum u_E V}{\sum V} \]

Graph showing the volume averaged energy density \( \langle u_E \rangle \) as a function of distance \( z \). The graph includes lines for different angles: \( \alpha = 60 \text{ deg} \), \( \alpha = 120 \text{ deg} \), \( \alpha = 120 \text{ deg, } \varepsilon_K = 0.05 \), and \( \alpha = 180 \text{ deg} \). The y-axis represents \( \langle u_E \rangle \) in erg/cm\(^3\), ranging from \( 10^{-18} \) to \( 10^{-12} \).
Volume Averaged Magnetic Field

\[ \langle B_c \rangle (\text{Gauss}) \]

- \( \alpha = 60 \text{ deg} \)
- \( \alpha = 120 \text{ deg} \)
- \( \alpha = 120 \text{ deg}, \varepsilon_K = 0.05 \)
- \( \alpha = 180 \text{ deg} \)

\( z \)
Summary

- Implemented a semi-analytical model of anisotropic AGN outflows in N-body simulations
- AGN outflows pervade 13 – 24% of the volume of the Universe by the present
  - In some cases occupy 100% of the overdense regions by z > 0
- Volume averaged quantities in the filled regions at z = 0
  - Energy Density = $5 \times 10^{-18}$ erg cm$^{-3}$
  - Magnetic field = $10^{-9}$ Gauss
References