Lecture 2: Extragalactic Outflows
Outline

- General aspects of collimated outflows
- Thermal (sub-relativistic) and non-thermal (relativistic) flows
- Thermal outflows and their effect on AGN hosts and IGM
- Formation of relativistic jets, kinematics of compact jets
- Overview of the jet emission
- Jet models versus observables
- Relativistic shocks
- Plasma instabilities
- Nuclear opacity in jets
Collimated outflows

- Jets (bipolar outflows) are common. Range from YSO to QSO, found also in pulsars and even on the Sun.

- Generally: bipolar outflows solve the problem of transporting excess energy and angular momentum from compact, rotating, magnetized objects which accrete external matter.
Fundamental jet questions

- Formation and collimation of relativistic jets.
- Matter content of the jets and outflows
- Stability and propagation on spatial dynamic scales of $>10^5$
- Relation to accretion disks and black holes
- Contribution from the jets and outflows to ISM and IGM
AGN Energy Balance

- **Radiation:**
  - Quasar luminosity: $10^{44} - 10^{47}$ erg s$^{-1}$
  - Luminosity integrated over lifetime: $10^{57} - 10^{62}$ erg

- **Relativistic jets:**
  - Jet power: $10^{43} - 10^{47}$ erg s$^{-1}$
  - Jet power integrated over lifetime: $10^{57} - 10^{62}$ erg

- **Sub-relativistic outflows (winds):**
  - Total wind power: $10^{43} - 10^{46}$ erg s$^{-1}$
  - Wind power integrated over lifetime: $10^{56} - 10^{61}$ erg

- **Starburst-induced superwinds**
  - Reliable quantitative assessment is difficult
Sub-relativistic Outflows
Outflows

- Jets: non-thermal, relativistic flows: $v \lesssim c$, present in ~10% of AGN

- Broad-absorption-line (BAL) outflows: $v \lesssim 50000 \text{ km/s}$, present in ~50% of low-L AGN and ~20% of high-L AGN.

- Wide-angle winds in Seyfert galaxies (OIII cones): ~20-40% of Sy galaxies
Outflows: Interpretations

- Radiation-driven winds from accretion disk
- Thermally-driven winds from BLR or torus
- Magnetically-driven winds from accretion disk
Outflows: Where it all begins

Open Issue: Characterise the geometry and mode of the accretion flow.

- Kerr black hole
- Hot corona
- Poynting flux
- Jet
- Open Issue: Characterise the geometry, and velocity of the outflow/jet particle content.
- Open Issue: Characterise the geometry and velocity of the outflow/wind, and its impact on the host galaxy and cluster.
- Open Issue: Characterise the geometry and mode of the accretion flow.
Relativistic Outflows
Jets: Current paradigm

A. Lobanov

- **r~1pc**
  - “Core”: the nuclear region, highly variable, weakly polarized, optically thick – standing shock? location at which the jet emission becomes optically thin?

- **r~10pc**
  - “Compact jet”: curved trajectories, rapid variations of velocity and flux density, “transverse” magnetic field – dominated by relativistic shocks?

- **r~100pc**
  - “Hectoparsec-scale jet”: straighter trajectories, apparent accelerations, weaker changes of emission, “longitudinal” magnetic field – dying shocks? plasma instabilities?
Formation

1. Lorentz factors:
   \[ \gamma_j \sim 10^3 - 10^4, \quad \Gamma_j \leq 15 \]

2. Thin/thick accretion disks:
   \[ \dot{M} \leq 0.5 \dot{M}_E \text{ or } \geq \dot{M}_E \]

3. MHD and magnetized disks:
   \[ B_G \sim 10^2 - 10^4 \, \text{G} \]

Collimation and Acceleration

Pressure/density/B-field gradients

\[ z_{\text{col}} = \alpha_c R_G, \quad R_G = \frac{2GM_{\text{BH}}}{c^2}, \]
\[ \alpha = 10^2 - 10^3 \]

Collimated width:
\[ r_{\text{jet}} = R_G (B_G / B_{ex})^{1/2} \]

Dynamics

Stationary flows, shocks, plasma instability

\[ (\rho \nabla) \Gamma_j p^{1/4} = 0, \quad \Gamma_j (z_{\text{col}}) \approx 1.22 \]
\[ N(\gamma) d\gamma = N_0 \gamma^{-s} d\gamma, \quad B(z) \propto z^{-m}, \quad N(z) \propto z^{-n} \]
Jet kinematics

Superluminal motions and relativistic effects

Apparent speed: $\beta_{\text{app}} = \frac{\beta \sin \theta}{1 - \beta \cos \theta}$; $\beta = v/c$, $\gamma = \frac{1}{(1 - \beta^2)^{1/2}}$

Relativistic transformations:
$t = \delta^{-1} t'$, $\nu = \delta \nu'$, $I_{\nu}(\nu) = \delta^3 I'_{\nu'}(\nu')$, with $\delta = [\gamma (1 - \beta \cos \theta)]^{-1}$

Useful relations for $\beta_{\text{app}} = \beta_{\text{app}}(t)$

Jet with constant viewing angle ($\theta = \text{const}$):
$$\beta(t) = \frac{\beta_{\text{app}}(t)}{\sin \theta + \beta_{\text{app}}(t) \cos \theta}$$

Jet with constant rest frame speed ($\beta = \text{const}$):
$$\cos \theta(t) = \frac{\beta_{\text{app}}^2(t) \pm [\beta^2(\beta_{\text{app}}^2(t) + 1) - \beta_{\text{app}}^2(t)]^{0.5}}{\beta(\beta_{\text{app}}^2(t) + 1)}$$

Minimum kinetic power condition:
$$\gamma_{\text{min}} = (1 + \beta_{\text{app}}^2)^{1/2} \quad \beta_{\text{min}} = \cos \theta \quad \delta_{\text{min}} = (1 + \beta_{\text{app}}^2)^{1/2}$$
Jet kinematics

Rest frame kinematics

Luminosity distance

\[ D_L = \frac{c}{H_0 q_0} \left[ q_0 z + (q_0 - 1) \left( (1 + 2q_0z) \right)^{1/2} - 1 \right] \]

Apparent speed

\[ \beta_{app}(t) = \mu(t) D_L (1 + z)^{-1} \]

Distance travelled in the rest frame of the jet

\[ R(t) = (1 + z)^{-1} \int_0^t \frac{\beta(t)}{1 - \beta(t) \cos \theta(t)} dt \]

Rest frame time

\[ \Delta t' = (1 + z)^{-1} \int_0^t \delta(t) dt \]

Rest frame viewing angle

\[ \cos \theta'(t) = \frac{\beta(t) - \cos \theta(t)}{1 - \beta(t) \cos \theta(t)} \]
Overview of Jet emission
Jet emission: Overview

Radio / optical / X-ray
Synchrotron radiation emitted by relativistic electrons and positrons

X-ray / γ-ray
Inverse Compton scattering of electrons and low energy photons
Particle cascades induced by ultrarelativistic protons.
Shock acceleration – additional mechanism for producing energies needed for γ-ray emission
Jet emission: Synchrotron

single electron: \[ P_s = 2\sigma_T c\gamma_e^2 u_B \sin^2 \psi \]
\[ \sigma_T = \frac{(8\pi e^4)}{(3m_e c^4)} \]

particle energy distribution: \[ N(\gamma) d\gamma = N(\gamma_0) \gamma^{-s} d\gamma \]

Lorentz factors: \( \gamma_l < \gamma < \gamma_u \)

Frequencies: \[ \omega_{l,u} = \gamma_{l,u} \Omega_e \sin \psi \]
\[ \Omega_e = \frac{(e B)}{(\gamma m_e c)} \]

emissivity: \[ j_\nu = c_5(\alpha)(2c\gamma_1)^\alpha N_{\gamma_0}(B \sin \theta)^{\alpha+1} \nu^{-\alpha} \]

self-absorption: \[ I_\nu = j_\nu / \kappa_\nu \left[ 1 - \exp(-\kappa_\nu L) \right] \]

for \( \tau \gg 1, \kappa_\nu \propto j_\nu \nu^{-5/2} \)

\[ I_\nu = I_0 \left( \frac{\nu_1}{\nu_0} \right)^{\alpha} \left( \frac{\nu}{\nu_1} \right)^{5/2} \left( 1 - \exp \left[ - \left( \frac{\nu_1}{\nu_0} \right)^{5/2-\alpha} \right] \right) \]

\( \alpha = \frac{1-s}{2} \)
\[ \nu_m = \tau m^{1/(\alpha-2.5)} \nu_1 \approx 1.097(-\alpha)^{-0.386} \nu_1 \]
Synchrotron: Spectral turnover

\[ S_m = \frac{\pi}{6} C_S(\alpha) N_0 B^{1-\alpha} \nu_m^\alpha d_\Omega^3 D_L (1+z)^{\alpha-1} \delta_j^{3-\alpha} \]

\[ \tau_m = C_T(\alpha) N_0 B^{1.5-\alpha} \nu_m^{-(2.5+\alpha)} d_\Omega D_L (1+z)^{\alpha-4.5} \delta_j^{2.5-\alpha} \]

\[ B = 10^{-5} C_B(\alpha) d_\Omega^4 \nu_m^5 S_m^{-2} \delta_j (1+z)^{-1} \]

\[ N_0 = C_N(\alpha) D_L^{-1} d_\Omega^{4\alpha-7} \nu_m^{4\alpha-5} S_m^{3-2\alpha} (1+z)^{6-2\alpha} \delta_j^{2\alpha-4} \]
Synchrotron: Spectral turnover

Turnover frequency from VLBI data

Case B

Case A

VLBI data

true $v_m$

fitted $v_m$

~1–10 MHz

~1 GHz

1 GHz

43 GHz

~1000 GHz

Flux Density

$S \sim v^{2.5}$
Turnover frequency imaging

- Turnover frequency distribution diagnoses plasma in the jet.

3C345: Mapping the turnover frequency distribution in the jet.
Jet models
Information from VLBI images

- **Observations**: 1D (routinely), 2D (SoA)

- **Models (relativistic)**
  - Analytical: 2D (routinely), 3D(t) (SoA)
  - Numerical: 3D (routinely), 3D(t) (SoA)

- **Problems**: connecting predictions \((p, v, \rho)\) to observables \((S_v, \alpha, \beta_{app})\). Elusive \(B, \Gamma, \text{and } M_j\)

- **Solution**: find a way to extract reliable 2D information from images! High-fidelity images and novel reduction and analysis techniques are much needed!

(Hughes et al. 1994)
Models vs. Observations

Model:

\[ S_m \propto \nu_{\nu m}^p, \]
\[ \nu_{\nu m} \propto r^{\epsilon}, \]
\[ \delta \propto r^b, \]
\[ B \propto r^{-m}, \]
\[ N \propto r^{-n}. \]

Observables:

\[ \beta_{\text{app}}(t), \]
\[ S(t), \]
\[ S_m(t), \nu_{\nu m}(t). \]
Jet models: Analytical

A. Lobanov

1. Shock-in-jet models

- Relativistic beaming (Shkolnisky 1963)
- Accretion (Linden Bell/Salpeter/Zeldovich 1964)
- Relativistic jet (Rees, 1969)
- Relativistic shock (Blandford & Rees, 1978)
- Plasma instability (Reynolds 1982, Hardee, 1982)
- Shock-in-jet model (Marscher & Gear 1985)
- Two-fluid model (Sol, Pelletier & Asseo 1989)
- Poynting flux jet (Lovelace & Romanova 1992)
- “Electric current” jet (Camenzind 1993)

2. Oblique shock models

- Ambient medium \( \beta < 1 \)
- Relativistic flow \( \beta \approx 1 \)

3. Two-fluid models

- \( \beta \approx 0.4 \) jet
- \( \gamma \approx 10 \) beam

Shocks: compressed regions with enhanced magnetic field

Oblique shocks (possibly due to interactions with non-relativistic medium)

Kelvin-Helmholtz instabilities and/or shocks

Hardee & Norman (1988);
Bicknell & Begelman (1995)

Sol et al. (1989); Laing (1989); Hardee et al. (1994)(1995)
Numerical era:

-- began in late 1960s from essentially 1D works,
-- continued through 2DMHD and 2DRMHD
-- the goal now 3D RMH(E?)D... + rotating, transversally stratified outflows
-- problem: detailed comparison to observations
Shocks and Instabilities
Relativistic shocks

Shock in a conical jet with a half-opening angle \( \phi \). \( x \ll R \)

Approximations: \( B \propto R^{-m}, \quad N \propto R^{-n}, \quad \delta \propto R^b \)

Received spectrum: \( S(\nu) \propto R^\xi \nu^{-\zeta \delta (s+3)/2} \),

\( \zeta \) and \( \xi \) depend in the dominant energy loss mechanism.

Turnover flux density: \( S_m \propto B^{-1/2} \nu_m^{5/2} R^2 \propto R^{(4+m)/2} \nu_m^{5/2} \)

Turnover frequency: \( \nu_m \propto R^{[\xi-(4+m)/2+b(s+3)/2]/[5/2+\zeta]} \)

Stages of shock evolution:

1) Compton-loss stage \( \xi = [(11 - s) - m(s + 1)]/8 \quad \zeta = s/2 \)
2) Synchrotron-loss stage \( \xi = -\lfloor 4(s - 1) + 3m(s + 1) \rfloor/6 \quad \zeta = s/2 \)
3) Adiabatic-loss stage \( \xi = [2(5 - 2s) - 3m(s + 1)]/6 \quad \zeta = (s - 1)/2 \)
Shock model: application

- Shock model explain successfully the spectral evolution in one of the moving features in the jet in 3C345.
- Fitting simultaneously the spectral and kinematic changes is problematic – possibly due to rapid shock dissipation.

![3C345: trajectory of C5](image1)

![Turnover frequency evolution in C5 (3C345)](image2)
Jet models: K-H instability


Low frequency limit (longest unstable wavelength):

$$\lambda_{\text{lim}}^1 = \frac{4 n \Gamma_j R_j (M_j^2 - 1)^{0.5}}{(n + 2m - 0.5)}$$

High frequency limit (resonant wavelength):

$$\lambda_{\text{lim}}^* = \frac{4 n R_j M_j \beta_w^*}{\eta^{0.5} \beta_j (n + 2m + 0.5)}$$

Resonant modes propagate at:

$$\beta_w^* = \varepsilon \beta_j, \quad \varepsilon = \frac{\eta^{0.5}}{\Gamma_j^{-1} + \eta^{0.5}}$$

In the low and high frequency limits:

$$\lambda^* \propto R_j, \quad \lambda^1 \propto R_j$$

Constant frequency ($\omega = \text{const}$) regime: and $\lambda_\omega$ may not depend on $R_j$.

- Can estimate basic parameters ($M_j, a_j, M_x, a_x, \eta, \rho_j/\rho_x$)
- Can also predict the behavior of the instability modes, and reproduce the jet structure.

Pressure structure of Es mode

Jet crosssection

(Hardee 2000)
Instabilities on pc scales

- Linear regime of K-H instability

\[
\lambda_{HS} = 18.0, \quad \lambda_{Es} = 12.0, \quad \lambda_{Eb1} = 4.0, \quad \lambda_{Eb2} = 1.9
\]

\[
G_j = 2.1, \quad M_j = 3.5, \quad \eta = 0.02, \quad a_j = 0.53, \quad v_w = 0.21
\]

Nuclear Opacity
Compact jet properties

Properties of ultra-compact jets can be described by the following set of condition:

- A power-low particle distribution
  \[ N(\gamma_e) = N_0 \gamma_e^{-s} \text{ for } \gamma_{\text{min}}(r) < \gamma_e < \gamma_{\text{max}}(r) \]
  \[ \alpha = \frac{(1 - s)}{2} \]

- Jet expansion
  \[ R = a r^\varepsilon \quad (\varepsilon \leq 1) \]

- Magnetic field evolution along the jet
  \[ B = B_1 (r_1/r)^m \]

- Particle density evolution along the jet
  \[ N = N_1 (r_1/r)^n \]

The case \( m=1, \ n=2 \) corresponds to the equipartition regime
The "core" of a VLBI jet is located in a region where emission turns optically thin at a given frequency. Hence the core position depends on the observing frequency.

Optical depth in the jet

\[
\tau_s(r) = C'(\alpha)N_1 \left( \frac{eB_1}{2\pi m_e} \right)^{\epsilon} \frac{\delta^\epsilon \phi_o}{r(\epsilon m+n-1)\nu^{\epsilon+1}}
\]

The condition \(\tau_s=1\) determines the location of the core

\[
r[pc] = (B_1^{k_b} F/\nu)^{1/k_r}
\]

\[
F = (1 + z)^{-1} [6.2 \cdot 10^{18} C_2(\alpha) \delta_j^\epsilon N_1 \phi_o]^{1/(\epsilon+1)}
\]

\[
k_b = (3 - 2\alpha)/(5 - 2\alpha)
\]

\[
k_r = ((3 - 2\alpha)m + 2n - 2)/(5 - 2\alpha)
\]
Nuclear opacity: Core shift

- Position offset of the optically thick "core" of a VLBI jet can be used to estimate physical conditions in the nuclear region of AGN

Core location:

\[ r[\text{pc}] = (B_1^{k_b} F/\nu)^{1/k_r} \]  
(Königl 1981)

Core offset measure:

\[ \Omega_{\nu\nu} = 4.85 \cdot 10^{-9} \frac{\Delta r_{\text{mas}} D_L}{(1 + z)^2} \cdot \frac{\nu_1^{1/k_r} \nu_2^{1/k_r}}{\nu_2^{1/k_r} - \nu_1^{1/k_r}} \]

Derived magnetic field and distance from the central engine to the core:

\[ B_1 = (\Omega_{\nu\nu}/ \sin \theta)^{k_r/k_b} F^{-1/k_b} \]

\[ r_{\text{core}}(\nu) = \Omega_{\nu\nu} \left[ \nu^{1/k_r} \sin \theta \right]^{-1} \]
Summary

- Jets are formed in the immediate vicinity of supermassive black holes.
- Jets transport excess energy and momentum away from SMBH.
- Dynamic evolution and emission properties of compact jets are described well by synchrotron emission.
- Shocks and plasma instabilities affect strongly the dynamics and emission of the jets.
- Multifrequency studies involving spectral imaging and opacity measurements in the nuclear regions offer a good opportunity to assess physical properties in the jet plasma.