Outflows and relativistic jets in AGNs

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The two AGN classes

• Radio-quiet (Seyferts, QSO)
  - Relatively weak radio emission (but > normal galaxy)
  - No collimated jet (but bipolar flows, ionization cones)
  - No gamma-ray emission >MeV (Dermer & Gehrels ‘95)

• Radio-loud (Radio galaxies, quasars)
  - Intense radio Emission (synchrotron)
  - Powerful jets
  - Gamma-ray emission >MeV, up to tens of TeV...
Jets in radio-loud AGNs

- Large scale (>kpc) one or two sided
  - FR I weak jets, not well collimated
    • Beamed counterparts: BL Lacs?
  - FR II powerful jets, well collimated (hot spots)
    • Beamed counterparts: FSRQ?

- Superluminal motion observed at pc scale (VLBI/VLBA), always one-sided
  
  Apparent V between 5 and 10 c
  No clear difference between BL Lacs and FSRQ!
Superluminal motions

- Statistics on known sources (Vermeulen & Cohen ‘95)
- Compatible with a constant $\beta \sim 10$
- Some larger values discovered?
- Responsible also for Doppler boosting, enhanced variability...

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Gamma-ray emitting blazars (grazars)

Gamma-ray luminosity can dominate the e.m. spectrum ($10^{48}$ erg s$^{-1}$)

Strongly variable, often correlated with other wavelengths, but not in a simple way

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Extreme blazars (>100 GeV)

Still more variable (<30?)

Extreme spectrum:
- Synchrotron peak in X rays dans les X
- Compton peak at TeV

Correlated variability

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«Standard» model for gamma-ray emission

Gamma-ray opacity constraint: lower value of Bulk Lorentz factor, need for relativistic bulk motion

Leptonic processes favoured: Inverse Compton on synchrotron or external photons $e^-(\frac{\gamma mc^2}{2}) + h\nu \rightarrow e^-(\frac{\gamma' mc^2}{2}) + h\nu'$

Sources of soft photons
- accretion disk
- optical lines
- synchrotron (SSC)

Relativistic jet $\beta = 10$

Relativistic particles injection $\gamma^2 \approx 10^3 - 10^5$
Internal Shocks

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Generation of relativistic jet?

Powerful jets can be extracted from accretion disks through Magneto-Hydrodynamical process (Blandford & Payne '82, Pelletier & Pudritz '92, Ferreira & Pelletier '93)

Referred also as «winds» or «outflows»

- Ideal MHD
- Resistive MHD
Self-similar Accretion Discs driving Jets (Ferreira, Pelletier...)

- \( B \approx \) equipartition
- Ejection efficiency \( \dot{M}_{\text{acc}} \propto r^{\boxed{0.01}} \)
**Influence of ejection parameter**

- Disc SED modified by ejection
  \[ T_{\text{eff}} = r q \]
  \[ q = \frac{3}{4} \]

- Jet terminal velocity
  \[ V_{\text{jet}} = L_0 r_0 \sqrt{2 \theta} \]
  \[ \theta = 1 + \frac{1}{2\sqrt{\theta}} \]

Low ejection efficiency \( \theta \) \( \Rightarrow \) powerful jets and disks

High ejection efficiency \( \theta \) \( \Rightarrow \) weak jets and disks
**«Two flows» model**

**But** Relativistic jets difficult to produce and collimate with equipartition $V_{\text{jet}} \approx V_{\text{Kepler}}$

No high $g_b$ solution!

**Two flows model** : 2 distinct flows (Sol, Pelletier, Asséo 1985)

- MHD jet $e^- p^+$ mildly relativistic
- Highly relativistic pair plasma

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Two-flow model

Account for some contradictions from small scale to large scale jets.

Example = 1928+134

- Two-sided jet @ kpc scale
- One sided jet @ pc scale
- Superluminal motion, $v_{app} = 6 \, c$

Either $q$ is varying by $\sim 50^\circ$
Or $q$ is varying from 7 to 1.08...
Bulk acceleration of pair plasma

- Compton effect transfers energy and impulsion

- In an anisotropic photon field, directed force (\sim radiation pressure)

- Vanishes in some frame due to relativistic aberration.

\[ b < b_{\text{eq}} \quad \text{Frad} > 0 \quad \text{acceleration} \]

\[ b = b_{\text{eq}} \quad \text{Frad} = 0 \quad \text{equilibrium} \]

\[ b > b_{\text{eq}} \quad \text{Frad} < 0 \quad \text{braking (Compton drag)} \]
O'Deill's Compton Rocket effect

- In the vicinity of an accretion disk, $\gamma_{eq}$ increases with the distance $r \sim (z/R_\text{g})^{1/4}$

Hot plasma: same $\gamma_{eq}$ but the force is $X$ by $\gamma_{eq}^2$
(Compton Rocket effect)
Saturation velocity is reached later and is larger

Cold pair plasma: $\gamma_{b}$ increases but reaches a plateau when $T_{\text{acc}} > T_{\text{dyn}}$

$\gamma_{b} \sim \frac{T_{\text{soft}}}{4\mu m_{\text{e}} c^3 R}$

But cooling faster than acceleration (Phinney) !!
Rocket effect with continuous heating

- standard disk, \( L = \text{Ledd} \)
- power law distribution
  \( n(\ell) = n_0 \ell^{-s}, 1 < \ell < \ell_{\text{max}} \)  
  (Renaud Henri 1998)

\[
M = 10^8 \text{ M}_{\odot}
\]

\[
M = 10 \text{ M}_{\odot}
\]
Generation of pair plasma

In situ generation of pair plasma

Feedback on gamma-ray emission
- Some relativistic particles
- X-ray and gamma-ray emission by IC and/or SSC
- $e^+e^-$ annihilation forms new pairs
- Continuous reacceleration by MHD turbulence

- Processus must stop! Add a prescription on maximal random Lorentz factor, balancing an acceleration rate $g_0$ with synchrotron and Compton losses
Some results

• Spectral fits

Particle and disk photon density along the jet

Multiwavelength spectrum
Pair production threshold

- For a given geometry and B field, the solutions depend on initial particle density and the acceleration rate.

Very sharp transition of jet power when pair production starts: highly non-linear

Steady-state solutions probably unphysical, variability expected.
A time-dependent model

- Assume a time-dependent acceleration rate
- Parametrized by \( g_0(t) \)
- Assume \( \frac{d}{dt} g_0 = Q_{\text{inj}} - P_{\text{jet}} \)

\begin{align*}
\text{acceleration} & \quad \text{turbulence} & \quad \text{energy injection} \\
\text{e^+e^- pairs} & \quad \text{pair production} & \quad \text{pair production} \\
\text{quenching} & \quad \text{IC process/cooling} & \\
\end{align*}
Spontaneously variable solutions

For some values of Qinj (corresponding to the «wall(s)») time-dependent solutions exhibit spontaneous flaring behavior.

At least qualitative agreement with observations.
Flares associated with the ejection of discrete components
The particle distribution function

Spectra usually fitted with power laws

\[ N(\mu_g) \propto \mu_g^{-s} \]

but sometimes in very narrow ranges

Extreme blazars can be fitted equally well with pile-up (quasi-Maxwellian) distributions

\[ N(\mu_g) \propto \exp(-\mu_g/\mu_{\text{max}}) \]

More naturally predicted by bulk turbulence acceleration

Pian et al '98
\[ S=1 \]
\[ \mu_{\text{min}} = 4 \times 10^5 \]
\[ \mu_{\text{max}} = 3 \times 10^6 \]
First results with pile-up distribution

Extremely sharp pair transition

Pair creation directly on synchrotron X-ray photons

Violent variability expected
Some conclusions

Pair model can reproduce the qualitative features and the quantitative SED of AGNs.

Need for simultaneous multi wavelength and time-resolved spectra to better test the models: leptonic/hadronic, homogeneous/inhomogeneous, pairs or not, particle distribution function...

High sensitivity and energy coverage of GLAST extremely valuable for temporal and spectral resolution, encourage multi-campaigns.