Galaxies with radio and optical jets

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Less than 10% of galaxies have an active nucleus. 10% of AGN have **Radio jets** (« Radio-Loud »)

Every galaxy has a black hole but the activity time-scale is short, ~ 10-40 million yrs

According to the angle of the line of sight: the jet is seen, or relativistic motions, broad lines exist, or are hidden by the molecular torus (type 2, scattering, polarisation)
Distinction between jet and wind

The wind comes from the heated disk, which can evaporate. Or the magnetic pressure is too strong.

Turbulence in the disk
MRI instability
**Activity cycles**

Separation of lobes $\sim 100$ kpc, 
$V \sim 1000$ km/s 
$\Rightarrow$ age $\Delta t \sim 10^8$ yrs

Several cycles?

Other way to estimate the duration of the activity cycles of AGN 
$\Delta t \sim$ (galaxy life)(% active time) 
$\sim (10^{10}$ yrs)(1% of galaxies active with jets) $\sim 10^8$ yrs
Two types of morphologies for the radio jets

**FR II (left) & FR I (right)**

High luminosity:
- 3C 219
- 3C 33.1
- 3C 47

Low luminosity:
- 3C 31
- 3C 296
- 3C 465

Hot spots in the center:
- 3C 31

Hot spots at the end:
- 3C 47

- 3C 465
Why only one jet?

3C133 Image VLA

Faraday depolarisation $\sim \lambda^2$

$\Rightarrow$ The visible jet is always towards the observer

Eliminated hypothesis
-- The jet is alternatively on one side or the other
-- Absorbing medium

Laing, 1988
Relativistic aberration, Doppler boost

Reference frame of the fluid
Isotropic emission

Reference frame of observer
Lorentz transformation

\[ \Gamma \gg 1 \]
\[ = \frac{1}{\sqrt{1 - v^2/c^2}} \]

\[ \sin \phi = \frac{1}{\gamma} \frac{\sin \phi'}{1 + \beta \cos \phi'} = \frac{1}{\Gamma} \quad \text{(for } \Phi' = \pi/2) \]

→ Already aberration at small speed (ex. rain) -- For AGN \( \Gamma \sim 5 \)

\[ D = \frac{1}{\Gamma(1 - \beta \cos \theta)} \]

→ Flux multiplied by \( D^2 \)
Total relativistic Doppler effect

Doppler factor \[ D = \frac{1}{\Gamma(1 - \beta \cos \theta)} \] \[ \Gamma \sim 5 \quad v/c \sim 0.98, \quad D \sim 9.9 \]

→ Aberration, Flux multiplied by \( D^2 \)
→ Effect of time dilatation, Flux multiplied by \( D \)

\[ \text{Time 1} \quad \text{Time 2} \quad \text{Time 3} \]

Source at rest

\[ \text{Time 1} \quad \text{Time 2} \quad \text{Time 3} \]

Source in motion

→ Doppler effect on frequencies, Flux in \( v^{-\alpha} \) (synchrotron \( \alpha = 1 \))
Flux multiplied by \( D^{3+\alpha} \sim D^4 \sim 9600 \)
Some \( \Gamma \) up to 100, \( D \sim 200 \), and \( D^4 \sim 16 \times 10^8 \)!!
Optical jets, various wavelengths

Quasar 3C 273
Hubble Space Telescope • ACS HRC Coronagraph

NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA • STScI-PRC03-03

Martel et al 2003
Superposition with Radio

Jet radio: contours // optical jet (HST)

67kpc long
3C273, the most nearby quasar
Jet detected at all wavelengths

Superposition of optical jet (HST) in X-rays (Chandra) and in radio cm (Merlin)
Jets can be super-luminal

P at velocity \( v \), with respect to O
\[ y = r \sin \theta \quad t = r/v \]

Light coming from P reaches us in less time than light coming from O.

Time observed for the object to go from O to P
\[ t_{\text{app}} = t - \frac{x}{c} \]
\[ t_{\text{app}} = \left( \frac{r}{v} \right) - \left( \frac{r}{c} \right) \cos \theta \]
\[ t_{\text{app}} = \left( \frac{r}{v} \right) \left( 1 - \beta \cos \theta \right) \]

V apparent on the sky
\[ v_{\text{app}} = \frac{y}{t_{\text{app}}} \]
\[ v_{\text{app}} = \frac{(v \sin \theta)}{(1 - \beta \cos \theta)} \]

For \( v \ll c \), \( \beta = \frac{v}{c} \sim 0 \) \( \Rightarrow \) \( v_{\text{app}} = v \sin \theta \)
For \( v \sim c \), \( v_{\text{app}} \gg v \) and even larger than \( c \)
Relativistic jets: a large range of scales

High resolution Space Telescope + radio jet (VLA)
Black hole in rotation: origin of Radio jets?

If the black hole is rotating, energy can be extracted from it, by the Penrose process.
Penrose process

E2 > E1

E1

Projectile initial

Fragment récupéré

Axe de rotation

Désintégration

Limite statique

Ergosphere

Horizon

Fragment capturé

E<0

up to 29%

Jean-Pierre Luminet
Mechanism of Blandford-Znajek

The goal is to extract energy and angular momentum from the black hole in rotation. The electromagnetic field around the hole is perturbed by magneto-spherical currents, which produce a torque ⇒ Slow down the black hole

- Poloidal B field, Ω and B same sense
- Described by the potential vector A
- H Horizon
- Particles in T can only fall in the hole
- The positrons are quickly absorbed by the hole, The atmosphere is of negative charge
Blandford-Znajek (following)

Poynting vector $S = \frac{E \times B}{\mu}$
Electromagnetic extraction of rotational energy

Plasma dominated by magnetic energy

horizon

ergosphere

Flux of Poynting vector

Blandford and Znajek 1977
Extraction MHD and not only MD

Plasma dominated by magnetic energy

Region dominated by particles

Equatorial plane

Punsly & Coroniti 1990
Torque slowing down the black hole: $\mathbf{J} \times \mathbf{B}$

Meridian plane

Angular momentum $\mathbf{L}$

Punsly & Coroniti 1990
Numerical simulations: MD & MHD

Monopole field (Komissarov 2001, McKinney 2005)

- Le flux of Poynting corresponds to model of Blandford-Znajek stationary state

→ The energy is extracted from BH, the introduction of particles MHD does not change the phenomenon MD

MHD very similar to MD model

\[ a=0.9 \]
\[ \Gamma \text{ from } 0 \text{ to } 14 \]
Ergosphere and B field in simulations

Simulations MD, uniform field *(Komissarov 2004)*

All field lines entering the Ergosphere are in rotation up to 0.5 times $\Omega$ of hole

The dissipative layer in the equatorial plane is the source of energy

The energie is extracted from the region between horizon and ergosphere (=processus of Penrose)
Jets are confined by magnetic fields

Collimation over 8 orders of magnitude in scales
The differential rotation twists the field lines which slows down rotation and allows more accretion.

Magnetic pressure and thermal pressure accelerate the jet.

Magnetic tension collimates.

Uchida et al 1999
Ejection mechanisms

A black hole in rotation ($a \sim 1$) accretes ionized and magnetized gas.
The gas falls in the hole, and some electromagnetic energy is ejected along the rotation axis.
This energy flux (Poynting) will be charged with particles, to form a relativistic jet.

→ Similarity with the processus of Blandford-Znajek

The reaction of the magnetic field is to accelerate the plasma in counter-rotation of the hole.

→ Arrival of $L < 0$
The radio galaxies are in general Ellipticals, may be because $M_{BH} \sim M_{\text{bulge}}$. 
Galaxies host of FR-Is and FR-IIs

The radio galaxies FR I and FR II are Giant ellipticals with dust lanes. The FRI are often cD galaxies at the center of rich clusters.
The majority of quasars are observed in galaxy mergers.

Violent gas shocks \(\rightarrow\) fueling of the black hole
Ejection of plasma: radio lobes in ellipticals, results of mergers

Cygnus A

Image radio, VLA

Optical image, HST
A double quasar, just merging: 3C75, $z=0.023$

Optical image HST

Image radio, VLA

25,000 ly
Radio lobes, galaxies in motion

Galaxies move at a velocity up to 1000km/s in galaxy clusters
How two radio lobes can merge in a single one

NGC 1265, Perseus cluster
Weaker radio sources: more diffuse lobes

NGC 1316 in Fornax
**Origin of radio mission:**

- Power-law spectrum decreasing with frequency (slope 0 at nucleus, then -1)
- linearly polarised emission (at least 30%, which is a lot)

⇒ **Synchrotron radiation** emitted by electrons in relativistic motion in a magnetic field

For an electron of energy

\[ E = \gamma m_e c^2 \quad \text{avec} \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]

The characteristic frequency of emission is

\[ \nu_c \sim 4.2 \times 10^6 \gamma^2 B \ \text{Hz} \]

With \( B \) in Gauss
Emission gamma (TeV) from a blazar

Very high energy photons are emitted by radio AGN, when their jet is oriented towards the observer ➔ blazar & « Flat Spectrum Radio Quasar » (FSRQ)  Doppler factors of 20-50!
Jets in Gamma: high variability

Radiation mechanisms:
synchrotron, SSC  
(synchrotron self-Compton)  
& EIC (external inverse Compton)
At low power: SSC  
At high power: EIC

Variability on time scales down to minutes
The blazar sequence

The highest luminosity blazars have the softest spectra

Electrons of high energy
In low power objects “injection” between
\( \gamma_{\text{min}} = 10^{4.5} \) to \( 10^{6.7} \)
At high \( L \), \( \gamma_{\text{min}} \) is smaller
Mechanisms of photons in culture

1. Seed high-energy photon
2. Pair production
3. Compton scattering
4. Pair production
5. Compton scattering

Multiplication of high energy $\gamma$ rays, as soon as
(1) high energy photons are injected
(2) there exists a B field transverse or chaotic
(3) an isotropic radiation field (BLR at $10^{17}$ cm)
(4) the Lorentz factor of the jet $\Gamma \sim 4-10$

*Stern & Poutanen (2006, 2008)*
Why some AGN have radio jets and not others?

Frequency and circumstances: Most AGN have no jet, 90% are « Radio-Quiet »

10% of « Radio-Loud »: a true dichotomie

Are these different phases of an universal evolution?

Centaurus A
Blue: X-rays
Red: Radio

Kellerman 1989
Two sequences in the plane $L_B - L_R$
Same sequences in \((L_B/L_{\text{Edd}})-(L_R/L_{\text{Edd}})\) 

This time normalised to \(L_{\text{Edd}} \approx 10^{38} \times (M_{\text{BH}}/M_\odot)\) erg/s
$R \sim L_R/L_B$, $\lambda$ accretion rate $\sim L_{acc}/L_{Edd}$
Criteria for radio jets

1) The parameter $R$ increases when the accretion rate $\lambda = \frac{L_{\text{acc}}}{L_{\text{Edd}}}$ decreases.

2) This is verified for both sequences « radio-loud » and « radio-quiet ».

3) A saturation of the parameter $R$ occurs at low accretion rate $\lambda < 10^{-3}$. 
Dependence of $R$ on the mass of the BH

For powerful radio jets, $M_{BH}$ must be $> 10^8M_\odot$
The micro-quasars in our Galaxy: nearby, variable at human time-scale

SS433: micro-quasar

Objects of stellar masses
The end of life for massive stars
Rotation of the BH 1000 times per second
Microquasars & Quasars

**Microquasar**
- Jets: ≈ 300,000 km/s
- Nuages de plasma relativistes
- trou noir de masse stellaire en rotation
- Disque d'accrétion (~10^3 km)
- Etoile compagnon

**Quasar**
- Jets: ≈ 300,000 km/s
- Nuages de plasma relativistes
- trou noir supermassif en rotation
- Emission UV et optique
- Disque d'accrétion (~10^5 km)
- Galaxie hôte
Micro-quasar GRS 1915 superluminal velocity

X-Rays: red
Gamma-rays: green
Radio: blue

Ejection cycles of about one hour

A dizain per day
For low accretion rates, the radio luminosity increases with the accretion rate ($L_X$) like $L_R \propto L_X^{0.7}$ (Gallo et al. 2003)

But for higher accretion rates $\geq 0.01$ Edd, the jet production becomes intermittent (Fender et al., 2004)
The accretion phases vary for example Cyg X-1

Accretion High (H) (small truncation radius)
Accretion low (L) (higher truncation radius)
Transitions
⇒ Energy emitted in photons Compton
**The different phases**

**Micro-quasars & AGN**

The hard X are correlated with the radio emission.

In the high luminosity phase, the disk radiates efficiently, and electrons are not emitted.

In the low phase, ADAF

Truncation of the disk, formation of a corona where photons are comptonized (hard X-rays)

⇒ The corona is the jet base.
Several phases for the Seyfert

Seyferts 1 in general accrete at the Eddington limit
  – this corresponds to a high accretion rate, unstable
  -- oscillation time-scale of \( \sim 2 \text{ yr} \) \( (M/10^6 M_\odot) \)

Some Seyfert galaxies have no longer broad lines
“Narrow Line S1” example NLS1 PKS 2004-447
  – \( M = 5 \times 10^6 M_\odot \); could become a classical S 1 in \( < 10 \text{ yr} \)
  – A brighter AGN, broader lines
Criteria for radio jets

For AGNs as for micro-quasars, $L_R$ and $L_{\text{acc}}$ are related for the low accretion rates, and for high accretion rates, the production of jets become intermittent (e.g., Merloni et al., 2003, Nipoti et al., 2005)

But the relations are verified separately for spirals and ellipticals, as for two parallel relations

there exists an other parameter, related to the formation of these galaxies, and of their central black hole

The spin of the black hole?
The role of the black hole spin

If jets are produced by the extraction of the rotational energy of black holes and if elliptical galaxies have more luminous radio jets

-- does this mean that ellipticals have not enough gas to stop the jets?
-- or ellipticals have higher spin parameters (a)?

Ellipticals are formed by mergers of smaller galaxies, but more frequently by major mergers
A large number of minor mergers could arrive in the same final mass state, but the spin would be cancelled statistically
Minor & major mergers

The final angular momentum coming from several BH of random orientation cancels out

A residual spin is expected for the black hole resulting from a major merger
Simulations of jet formation

Brinkmann & Camenzind 2004
very high state

high state

low state

quiescent state

\( \dot{m} = \frac{\dot{M}_{\text{acc}}}{\dot{M}_{\text{Edd}}} \)

Esin et al. 1995

A. Müller (2004)
Unstable: Oscillations

$\Gamma > 2$

$\Gamma < 2$

Fender & Belloni 2004 ARAA
Conclusions

Properties of jets
-- relativistic boost, disymmetry
-- superluminal jets
-- analogy with micro-quasars
-- The radio power is 3 orders of magnitude larger in ellipticals relative to spirals

How are jets formed?
-- Extraction of the rotational energy of the BH (Blandford-Znajek) (processus of Penrose + B field)

-- the radio power increases when the accretion rate decreases

Ellipticals have black holes with a larger spin (a~1)
Could be due to their formation in major mergers