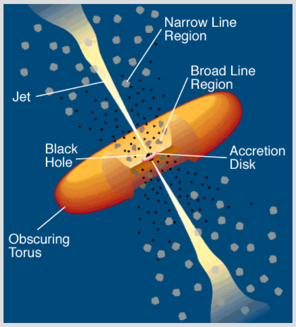
Introduction Active Galactic Nuclei

Jets



Radio Galaxies and radio-loud Quasars

Radio galaxies & radio-loud quasars:
the most powerful radio sources

(Usually) extended (or very extended!) radio emission with common characteristics (core-jets-lobes)
Typically hosted by an elliptical (early-type) galaxy

Amazing discovery when they were identified with extragalactic, i.e. far away, objects

⇓

Unexpectedly high amount of energy involved!
The radio contribute only to a minor fraction of the energy actually released by these AGNs.
(ratio between radio and optical luminosity ~10^{-4})
However, the kinetic power in jets can be a significant fraction of the accretion energy

Why study radio-loud AGN?

They show most of the phenomena typical of AGNs
(e.g. optical lines, X-ray emission etc.)
⟶ very interesting objects in (almost) all wavebands

In addition they have
spectacular radio morphologies

But they are quite rare!

Local Space Densities of Some Objects

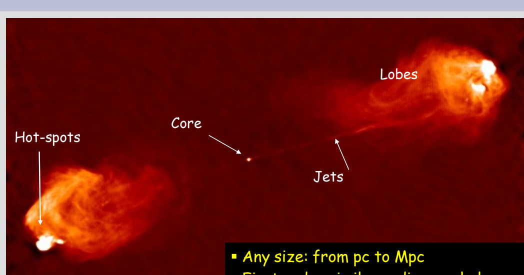
Object		*Gpc*$^{-3}$
Spiral Galaxies	$M_V < -20$	5×10^6
	$M_V < -22$	3×10^5
	$M_V < -23$	3×10^3
Elliptical Galaxies	$M_V < -20$	1×10^6
(incl. S0)	$M_V < -22$	1×10^5
	$M_V < -23$	10^4
Rich Clusters of Galaxies		3×10^3
Radio Galaxies	$P_{1.4\,GHz} > 10^{23.5}$ W Hz^{-1}	3×10^3
	$P_{1.4\,GHz} > 10^{25}$ W Hz^{-1}	10
Radio Quasars	$P_{1.4\,GHz} > 10^{25}$ W Hz^{-1}	3
Radio Quiet Quasars	$M_V < -23$	100
	$M_V < -25$	1
Sy 1	$M_V < -20$	4×10^4
Sy 2	$M_V < -20$	1×10^5
BL Lac	$P_{1.4\,GHz} > 10^{23.5}$ W Hz^{-1}	80
Strong IRAS Galaxies	$L_{IR} > 10^{12}\,L_\odot$	300

Some Radio surveys

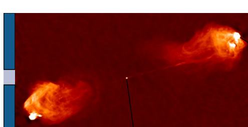
Start: 3CR (Cambridge Telescope) → 328 sources with $\delta > -5^o$
flux above 9 Jy @ 178 MHz
(1 Jy= 10^{-26} W m^{-2} Hz^{-1})

4C	2Jy	178 MHz	Cambridge (+5,6,7C)
PKS	~3Jy	408 MHz	Parkes
			Molonglo
B2	0.25	408 MHz	Bologna (+B3)
NRAO	0.8Jy	1.4-5GHz	NRAO
PKS	0.7Jy	2.7 GHz	Parkes
NVSS	2.5 mJy (45" res.)	1.4 GHz	NRAO VLA Sky Survey
FIRST	1mJy (~5" res)	1.4 GHz	Faint Images Radio Sky at Twenty centimeters
WENSS		300 MHz	WSRT

A prototypical radio galaxy



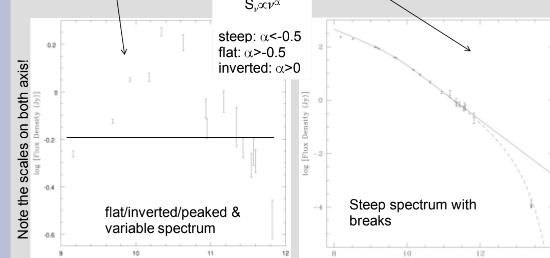
- Any size: from pc to Mpc
- First order similar radio morphology
  (but differences depending on radio power, optical luminosity & orientation)
- Typical radio power 10^{23} to 10^{28} W/Hz



Radio Spectrum

$S_\nu \propto \nu^\alpha$

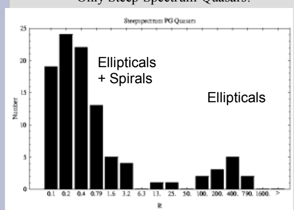
steep: α<-0.5
flat: α>-0.5
inverted: α>0



Carilli et al. (1999)

Radio-Dichotomy

Only Steep-Spectrum Quasars!



R=radio/optical flux

Kellermann et al. (1989)
Falcke, Sherwood, Patnaik (1996)

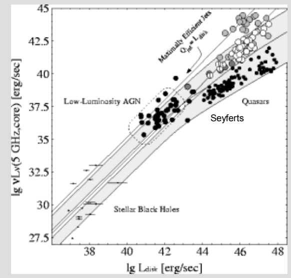
- Optically bight quasars come in two flavors: radio-loud and radio-quiet
- This is seen in a homogenous optically selected sample (e.g. PG/BQS quasar sample).
- Normalizing the radio emission (jet) by the optical luminosity (disk): only 10% of quasars are radio-loud.
- In both groups radio comes from jets! Why the difference in efficiency?
- It is not clear whether that persists also at lower masses and accretion rates…

Jet-Disk Symbiosis
(looking at radio core only!)

- Jet power scales with accretion disk power

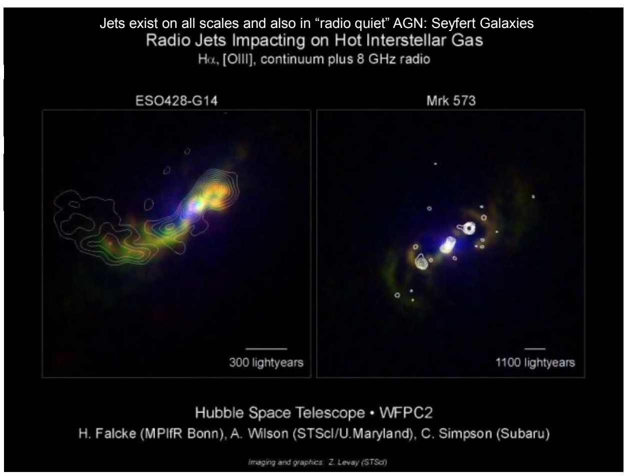
$Q_{jet} = q_{j/l} \cdot L_{disk}$
$\Rightarrow S_{radio} \propto L^{17/12}$

- Model applicable to
  - quasars
  - LLAGN
  - X-ray binaries

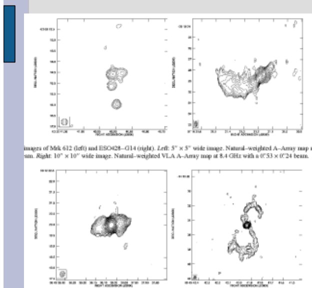


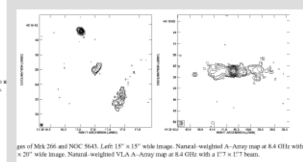
Radio Core Luminosity

Accretion disk luminosity
Falcke et al. (1994-2000)

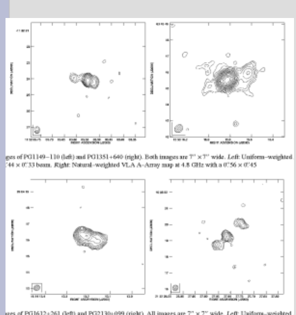


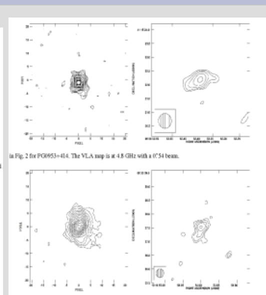
Radio Structures in Seyferts





VLA Observations of RQQs (Radio Quiet Quasars)

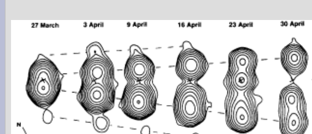




Leipski, C.; Falcke, H.; Bennert, N.; Hüttemeister, S. (2006)

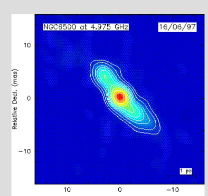
Jets exist on all scales

X-ray binaries



Mirabel & Rodriguez (1994)

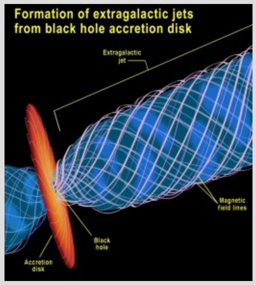
Low-Luminosity AGN



VLBI: Falcke, Nagar, Wilson et al. (2000)

Jets

- Not well understood
- Emitted from axis of rotation
- Acceleration through magnetic fields
- Acceleration of charged particles from strong magnetic fields and radiation pressure
- Synchrotron Radiation
  - Produces radiation at all wavelengths especially at Radio wavelengths
- Possible source of Ultra high energy cosmic rays and neutrinos

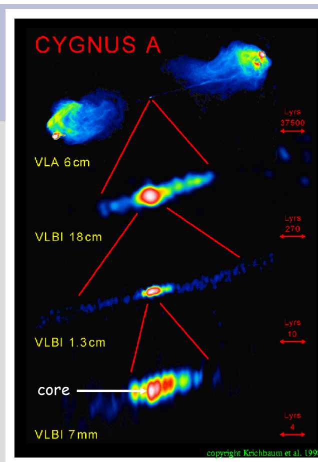


Jets

Often the radio emission is more symmetric on the large scale and <u>asymmetric on the small scale</u>

The core is defined based on the spectral index: flat ($\alpha \sim 0$)

[to find which component is the radio core is not always easy: free-free absorption can complicate the story!]

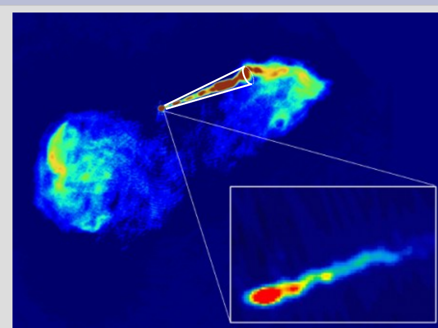


Jet in M87

- Discovery of AGN jet (Active Galactic Nucleus) in M87 (Curtis 1918)
- "...curious straight ray..."
- Is: optical synchrotron radiation from relativistic plasma jet ejected from black hole
- Hubble shows super-luminal motion v~6c

HST: Biretta et al. (1999)

Black Hole powered jet in M87

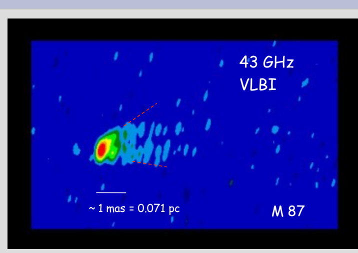


Reid et al. (1999, Space VLBI)

Jets Collimation

Going very close to the BH to see how the collimation of the jet works.

rapid broadening of the jet opening angle as the core is approached on scale below 1 mas (0.1 pc).



The jet does not seem to reach a complete collimation until a distance of many tens of Schwarzschild radii (escape velocity = *c*)

Jet emanating from the accretion disk, not yet collimated

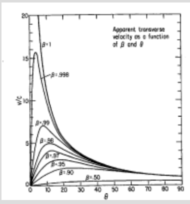
Monitoring of the quasar 3C120 with VLBI

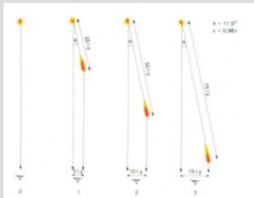
VLBA 22 GHz Observations
of
3C120

José-Luis Gómez	*IAA (Spain)*
Alan P. Marscher	*BU (USA)*
Antonio Alberdi	*IAA (Spain)*
Svetlana Marchenko-Jorstad	*BU (USA)*
Cristina García-Miró	*IAA (Spain)*

Superluminal motions

Read old jet lecture on superluminal motion and beaming!





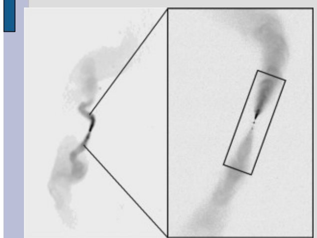
These projection effects explain:

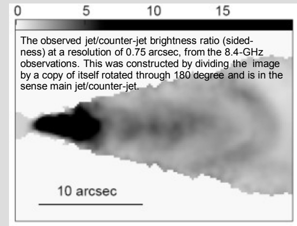
- the apparent superluminal motion
- the asymmetry between the two jets, also the flux of the approaching and receding components are affected by projection (Doppler Boosting)

These are among the methods used to find out the orientation of a source

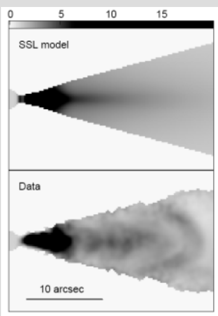
Jet to Counter Jet Ratios: boosting & de-boosting

The jet to counter jet ratio of the inner jet can be modeled by a relativistic, decelerating jet with a fast spine and a slower shear layer (Laing & Bridle 2002).





3C31: Jet to Counter Jet Ratios

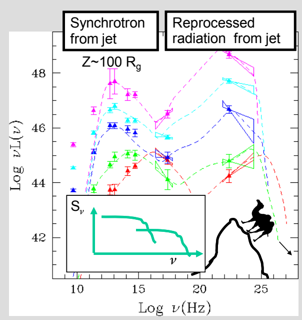


Quantity	opt	SSL min[a]	max[b]	Gauss
Angle to line of sight θ (degrees)	52.4	48.9	54.1	51.4
Jet half-opening angles (degrees)[c]				
inner region ξ_i	6.7	–	–	6.6
outer region ξ_o	13.2	–	–	13.0
Boundary positions (kpc)				
inner r_1	1.1	–	–	1.1
outer r_0	3.5	–	–	3.6
arbitrary fiducial r_f	9.6	–	–	9.8
Spine half opening angles (degrees)				
inner region ζ_i	4.06	3.1	6.5	–
outer region ζ_o	2.79	0.7	4.5	–
On – axis velocities / c				
inner jet β_i	0.87	0.83	0.93	0.20
inner boundary β_1	0.77	0.68	0.83	0.76
outer boundary β_0	0.55	0.45	0.63	0.54
outer fiducial β_f	0.28	0.25	0.33	0.27
velocity exponent H	9.5	3.6	>	8.8
Fractional velocity at edge of jet[d]				
inner jet v_i	0.06	0.0	1.15	–
inner boundary v_1	0.74	0.4	1.30	0.97
outer boundary v_0	0.67	0.51	0.87	0.63

BL Lacs – looking down the jet

Read old jet lecture on superluminal motion and beaming!

- BL Lacs are thought to be beamed FRI radio galaxies ponting at us.
- Relativistic beaming will lead to an enhancement of the core emission by a huge factor (10^3)
- In BL Lacs the emission is completely dominated by the innermost jet.
- The spectrum is "flat" in $S\nu$ and rising linearly with ν in a $\nu S\nu$ plot.
- There is no evidence for a disk spectrum (probably because FRIs have a radiatively inefficent disk/ADAF).
- The spectrum resembles a „camel's back".
- Radio - optical: synchrotron emission from jet
- X-ray – TeV: inverse Compton or hadronic cascades (e-γ, p-γ)



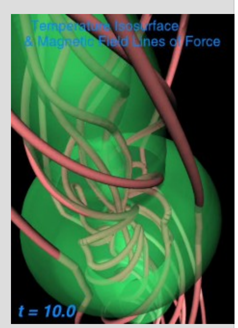
Fossati et al. (1998)

Jet Formation

- All relativistic cosmic jet sources may be connected by a common basic mechanism
  - A promising model for that is magnetohydrodynamic acceleration by rotating, twisted magnetic fields
    - "Spin Paradigm" can explain qualitatively a number of statistical properties of AGN
  - Geometrically thick accretion flows are more efficient at launching jets
    - In Microquasars this principle may explain the correlation between the production of a jet and the presence of a hot, geometrically thick accretion flow
    - This also may be testable in some Seyfert AGN as well
  - Slow acceleration and collimation of these jets is probably the norm
    - There is some evidence for this in AGN jets
  - Highly relativistic jet flows may be produced by strong, straight magnetic fields
- All galactic cosmic jet sources, including supernovae and gamma-ray bursts, may be connected by a common origin as well: different outcomes of the last stage of evolution in a massive star

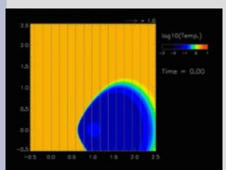
Basic Principles of **Magnetohydrodynamic** Jet Production

- Basic MHD mechanism:
  - Blandford (1976); Lovelace (1976)
  - Acceleration by rotating black holes (Blandford & Znajek [1977])
  - Acceleration by rotating [thin] accretion disks (Blandford & Payne [1982])
- First numerical simulations: Uchida & Shibata (1985)
- **Key ingredients** in their "Sweeping Pinch" mechanism
  - Thick accretion disk or torus
  - Keplerian differential rotation ($\Omega \propto R^{-3/2}$)
  - Initial strong vertical magnetic field (strong enough to slow disk rotation)
  - $\mathbf{J} \times$ B force splits up into magnetic pressure and tension: $-\nabla\,(B^2/\,8\pi)\ +\ (\mathbf{B} \bullet \nabla\mathbf{B})\,/\,4\pi$



Basic Principles of Magnetohydrodynamic Jet Production (continued)

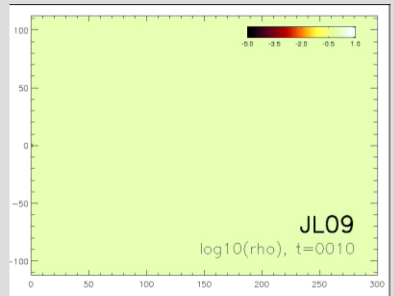
- Typical results (e.g., Kudoh et al [1998]; Uchida et al. [1999])
  - Differential rotation twists up field into toroidal component, slowing rotation
  - Disk accretes inward, further enhancing differential rotation and
  - Greatest field enhancement is at torus inner edge



- Magnetic pressure gradient (dB_φ^2 / dZ) accelerates plasma out of system
- Magnetic tension [hoop stress] ($-B_\varphi^2/R$) pinches and collimates the outflow into a jet
- Outflow jet speed is of order the escape velocity from the inner edge of the torus ($V_{jet} \sim V_{Alfven} \sim V_{esc}$)
- Jet direction is along the rotation axis

Kudoh, Matsumoto, & Shibata (2002)

Simulated jet evolution in the ISM

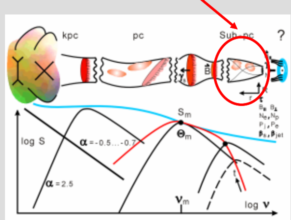


The basic jet emission model for the flat-spectrum core

Blandford & Königl (1979), Falcke & Biermann (1995)

- Plasma freely expanding in a supersonic jet
- $B \propto r^{-1}$, $n \propto r^{-2}$, $\gamma_e \sim$ const
- superposition of self-absorbed synchrotron spectra
- at each frequency one sees the $\tau = 1$ surface as the "core"$\Rightarrow$flat spectrum
- subject to rel. boosting

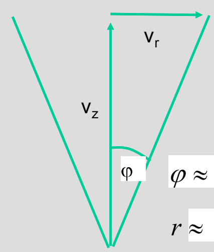
Jets are messy - their radio cores are simple



The Spectrum of Jet-Cores: Free Expansion Approach

- Plasma propagates at a constant proper speed $\Rightarrow v_z = \gamma_j\beta_j c$.
- The (isothermal) plasma expands with sound speed $\Rightarrow v_r = \gamma_s\beta_s c$.
- The resulting shape is a cone with Mach number

$$M = \frac{\gamma_j\beta_j}{\gamma_s\beta_s} \approx \gamma_j\sqrt{c}$$



$$\varphi \approx \frac{1}{M}$$

$$r \approx \varphi$$

The Spectrum of Jet-Cores: Particle and Energydensity Scaling

- Particle conservation:

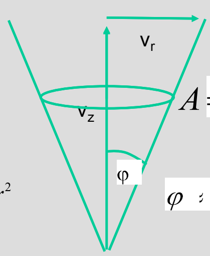
$$\dot M_j = \rho\cdot v\cdot A = m_p n(r)\cdot\gamma\beta c\cdot\pi r^2$$

$$\Rightarrow n(r) = \frac{\dot M_j}{m_p\cdot\gamma\beta c\cdot\pi r^2} \propto r^{-}$$

- Energy conservation:

$$\dot E_{j,mag} = \rho_B\cdot v\cdot A = \frac{B^2(r)}{8\pi}\cdot\gamma\beta c\cdot\pi r^2$$

$$\Rightarrow B(r) = \sqrt{\frac{8L_{j,B}}{\gamma\beta c\cdot r^2}} \propto r^{-}$$



$$A = \tau$$

$$\varphi \approx \frac{1}{M}$$

The Spectrum of Jet-Cores: Synchrotron Absorption

- Synchrotron Absorption:

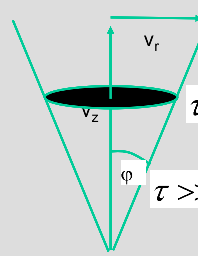
$$\alpha_{sync} \propto B^{\cdot}\nu$$

$$\tau \propto r\alpha_{sync}, \quad B \propto r^{-}$$

$$\tau \propto r^{-}\nu$$

- At a specific observing frequency we see the τ=1 surface; the location is frequency dependent:

$$r_{\tau=1} \propto \nu^{-1}$$



$\tau <<$

$\tau =$

$\tau >>$

The Spectrum of Jet-Cores: Synchrotron Emission

- Synchrotron Emission:

  $\varepsilon_{\nu,nc}(\nu) \propto {}^{3.5}\nu^{-0.5}$

  $\nu \propto {}^{-1}$, $B \propto {}^{-1}$

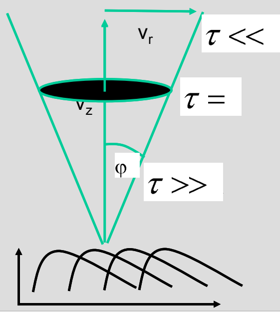
  $S_\nu \propto \cdot\,\varepsilon_{\nu,nc}$

- The emission is dominated by the τ=1 surface.

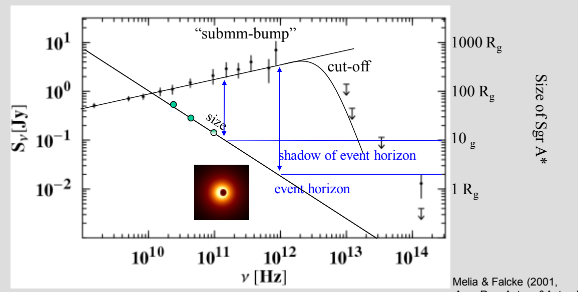
  $S_\nu \propto r\,{}^{3} r^{-\,.5} r^{0.5} =$ const

- For a conical jet the spectrum is flat!

NB: $B^2 \propto \dot{M}$ & $\nu \propto$ $\Rightarrow \varepsilon_{\nu,nc} \approx \dot{M}^{1.5}$



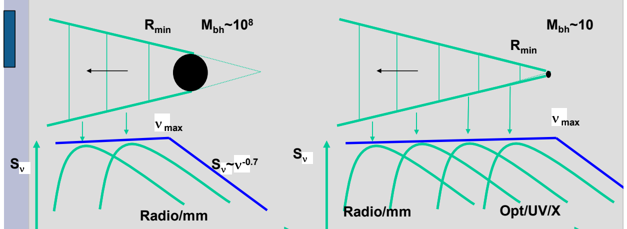
Size and Spectrum of Sgr A* (Galactic Center)



Melia & Falcke (2001, Ann. Rev. Astron.&Astroph)

The spectrum cuts off at the size scale of the event horizon!

The Synchrotron Spectrum of Jets



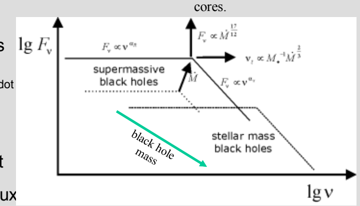
In jets $\nu \propto r^{-1} \Rightarrow \nu_{max} \propto r_{min}^{-1} \propto M_{bh}^{-1}$

$\Rightarrow$Turnover Frequency in stellar black holes >> blazars!

Scaling of Jets: large, small, powerful and faint

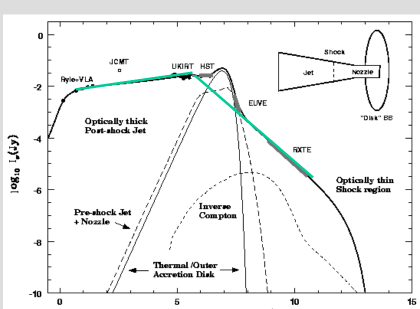
- The basic shape of the broad-band jet spectrum is (relatively) invariant to changes in black hole mass and accretion rate.
- Simple scaling laws with M_{dot} can be derived analytically.
- Assumption $M_{dot} \propto P_{jet}$!
- Radio/optical/X-ray ratio depends on M_{bh} **and** M_{dot}!
- ⇨ Smaller black holes peak at higher frequencies.
- ⇨ Increasing M_{dot} increases flux density non-linearly.

Scaling laws for Blandford & Königl jet cores.



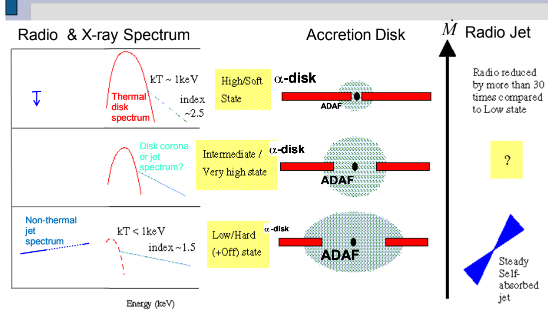
Falcke & Biermann (1995)
Markoff et al. (2003)
Falcke et al. (2003)
see also:
Heinz & Sunyaev (2003)
and Merloni et al. (2003)

Jet Model for the X-Ray Binary XTE J1118+480



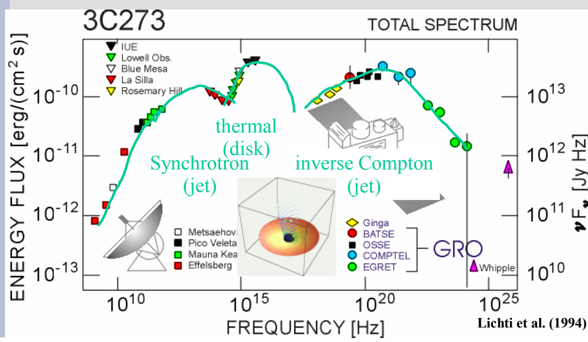
Markoff, Falcke, Fender (2001)

The Power-Evolution of XRBs



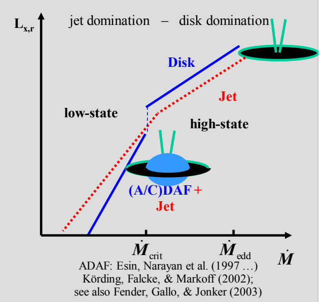
Fender (2000)

Spectrum of a Luminous Quasar



"JDAFs" Jet-Dominated Accretion Flows

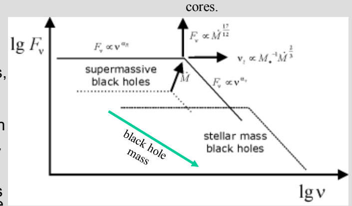
- The SED has jet and disk contributions!
- At lower accretion rates disks become less and less prominent, jets remain strong.
- Sub-Eddington black hole SEDs may be jet-dominated.



Scaling of Jets: large, small, powerful and faint

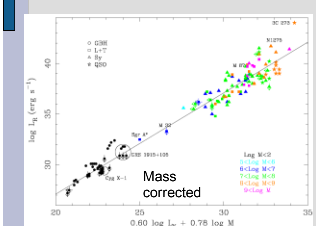
- Remember in the jet model:
  Radio/optical/X-ray ratio depends on M_{bh} **and** M_{dot}!
- Assuming that the scaling-laws are correct, radio, optical, mass, and accretion rate are connected: .
- E.g. one predicts that all jet-dominated BHs lie on a plane in the parameter space given by mass, accretion rate, and X-ray emission
- This means: if one simply plots radio vs. X-ray emission of BHs the data will be scattered (since there is a range in mass and accretion rate), however, if one scales the X-ray emission to a common mass, there will be more order in the chaos…

Scaling laws for Blandford & Königl jet cores.

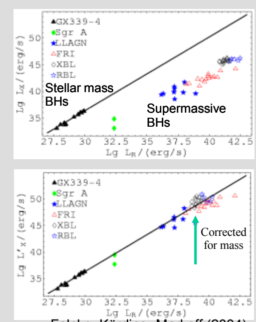


Falcke & Biermann (1995)
Markoff et al. (2003)
Falcke et al. (2003)
see also:
Heinz & Sunyaev (2003)
and Merloni et al. (2003)

Fundamental Plane: Radio, X-Rays, and Mass

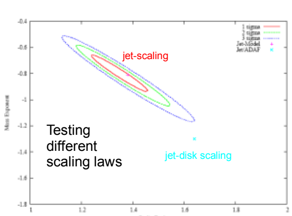


Merloni, Heinz, Matteo (2003)

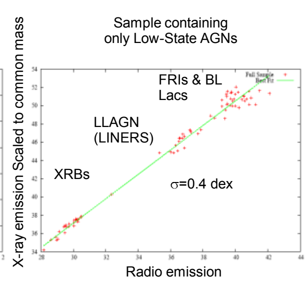


Falcke, Körding, Markoff (2004)

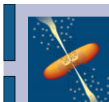
Restriction to Sub-Eddington BHs: XRBs, LLAGN, FRIs, BL Lacs



Sample containing only Low-State AGNs

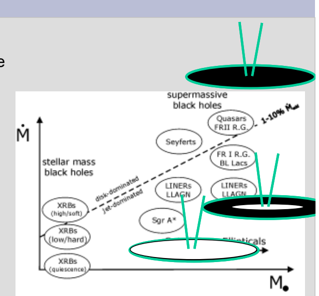


Falcke, Körding, Markoff (2004)
Körding, Falcke, Corbel (2005)



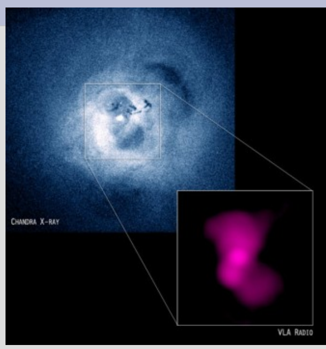
Power Unification

- Black holes have no hair!
- Stellar and supermassive blacks have more and more in come …
  - BH, Jet, disk, variability
  - Main parameters: $M_\bullet$, Mdot
- XRB state transitions seem to have their equivalent in AGN classes
- Sub-Eddington Black Holes may turn from disk- to jet-dominated.
  - Spectrum dominated by jet
  - Energy output dominated by (kinetic) jet power
- Fundamental plane of BH activity describes spectral evolution (best for sub-Eddington BHs)
- Radio quietness related to jet-quenching in High-state or not?



Falcke, Körding, Markoff (2004)

Feedback in radio-loud AGN?



Feedback of radio-loud AGN into the surrounding IGM (seen through X-ray here).

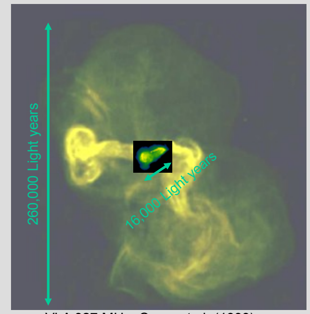
The kinetic impact of jets causes the X-ray gas to be displaced.

The consequence are holes in the X-ray emission.

Fabian et al.

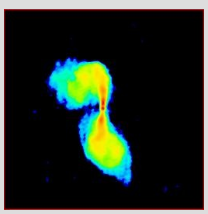
Black Hole powered jet in M87

- M87 is considered a low-luminosity AGN.
- Radio jet powers huge radio lobe and pushes out hot X-ray gas.
- Energy output from black hole dominates environment of galaxy.

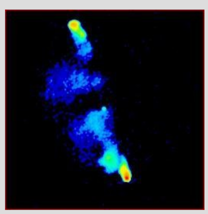


VLA 327 MHz: Owen et al. (1999)

Radio Loud AGN: FR I – FR II



Weak or no emission lines, no blue bump

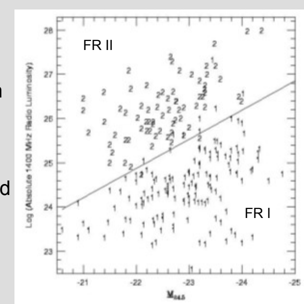


Strong emission lines, blue bumps seen

Radio Power

FR I/FR II division

- **Owen-Ledlow diagram**
  - 1 = FR II
  - 2 = FR I
- FRI and FRII radio galaxies delineated by sharp division in optical/ radio luminosity plane
- Bigger galaxies need more powerful radio galaxies for the jets to emerge unharmed by shear forces in the ISM.



Owen & Ledlow (last century)

Shock waves in jets

Lifetimes short compared to extent of jets

=> additional acceleration required.

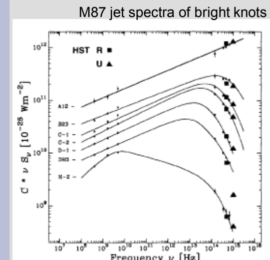
Most jet energy is ordered kinetic energy.

Gas flow in jet is supersonic; near hot spot gas decelerates suddenly

=> shock wave forms. Energy now in relativistic e- and mag field.

Particle Acceleration in jets: shocks and more

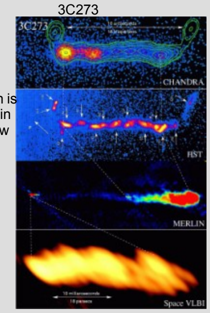
M87 jet spectra of bright knots



Meisenheimer et al. (1997)

Emission is typically in power law form

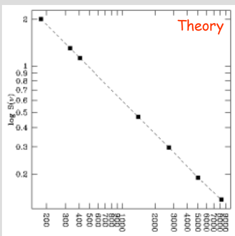
3C273

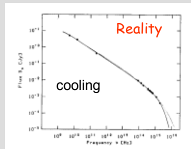


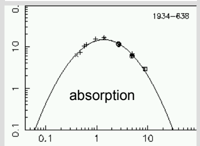
Optical and perhaps X-ray synchrotron require TeV electrons and continuous re-acceleration in the jet!

Radio Spectra: Age Effects

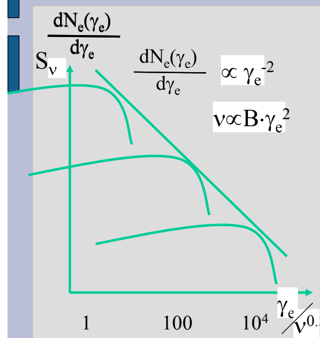
1. Energy loss
2. Self-absorption in the relativistic electrons gas
3. Absorption from ionized gas between us and the source (free-free absorption) -> torus!





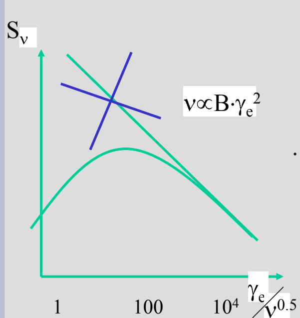


Electron Energy Distribution in Jets



- The typical energy distribution of relativistic electrons is a power-law in γ_e ($E=\gamma_e m_e c^2$).
- The energy of electrons is related to a characteristic frequency.
- A power-law in the energy distribution produces a powerlaw in the spectrum

Electron Energy Distribution in Jets



- Coincidentally in the inner jet region the low-frequency spectrum is self-absorbed.
- Hence, electrons with $1 \leq \gamma_e \leq 100$ remain invisible but they could make up 99% of the total electron content!

$$\frac{dN_e(\gamma_e)}{d\gamma_e} \propto \gamma_e^{-2} \Rightarrow N_{tot} \propto \gamma_{min}^{-1}$$

Energy loss

The relativistic electrons can loose energy because of a number of process (adiabatic expansion of the source, synchrotron emission, inverse-Compton etc.).

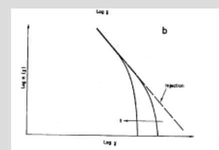
⇒ the characteristics of the radio source and in particular the energy distribution *N(E)* (and therefore the spectrum of the emitted radiation) tend to modify with time.

Adiabatic expansion: strong decrease in luminosity but the spectrum is unchanged

Energy loss through radiation:

$$\tau = \frac{E}{\dot{E}} = \frac{17yr}{(B/\mathrm{Gauss})^2 \gamma}$$

After a time t_0 only the particle with $E_0<E^*$ still survive while those with $E_0>E^*$ have lost their energy.

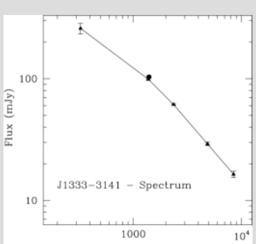


For $\nu < \nu_{break}$ the spectral index remains constant ($\alpha = \alpha_0$)

For $\nu > \nu_{break}$ ⇒ $\nu_{break} \sim B^{-3}\, t_{yr}^{-2}$ ⇒ $\alpha = (\alpha_0 - 1/2)$

Single burst
Continuous injection

Energy loss



- These energy lost affect mainly the large scale structures (e.g. lobes).
- Typical spectral index of the lobes → $\alpha = 0.7$

$$t_b(Myr) = 1.6 \cdot 10^3 (B/\mu G)^{-3/2} (\nu_b/GHz)^{-1/2}$$

Typically 20-50 Myr for B=10μG, freq 8-1 GHz

Unless there is re-acceleration in some regions of the radio source!

Self-absorption in the relativistic electron gas

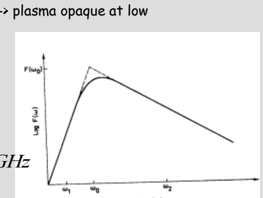
Optically thick case: the internal absorption from the electrons needs to be considered ⇒ the brightness temperature of the source is close to the kinetics temperature of the electrons.

The opacity is larger at lower frequency -> plasma opaque at low frequencies and transparent at high

$$\tau \gg 1 \qquad S(\nu) \propto \nu^{-5/2} B^{-1/2}\, d\Omega$$

Frequency corresponding to τ=1

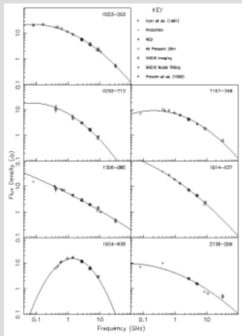
$$\nu_{max} \approx f(p) B^{1/5} S_m \theta^{-4/5} (1+z)^{1/5}\, GHz$$



Self-absorption in the relativistic electron gas

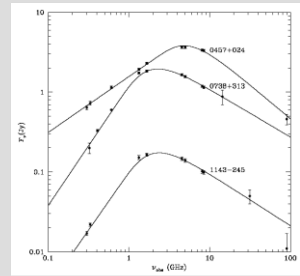
Affects mainly the central compact region or very small radio sources

Higher "turnover" frequency ⇨ smaller size of the emitting region.

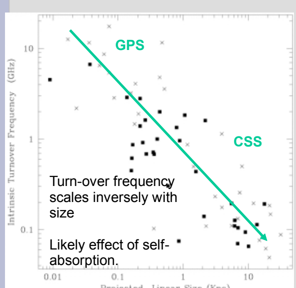


Gigahertz Peak Spectrum and Compact Steep Spectrum Sources

- GPS = Gigahertz Peak Spectrum – characterized by a peak in the radio spectrum at ~ 1 GHz
- CSS = Compact Steep Spectrum – have steep spectra at microwave frequencies but also have a peak in the spectrum in the 10-100 MHz range

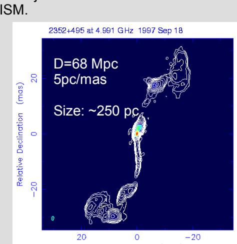


GPS & CSS Sources – young (and frustrated sources)



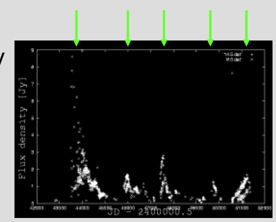
O'Dea 1998

GPS (GHz-Peaked-Spectrum) and CSS (Compact-Steep-Spectrum) sources are young radio jets that are still stuck in the dense ISM.



GPS at work: The "Seyfert" Galaxy III Zw 2

- Flux increase by factor 20-250 within years
- Outbursts roughly every 5 years
- Radio monitoring campaign set up in anticipation of current outburst

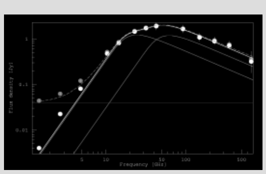


Aller et al., priv. com.

The Extreme Variability of the Seyfert Galaxy III Zw 2

- Flux increase by factor 40 (!) within 2 years
- Outburst peaks at 7mm
- Textbook-like self-absorbed spectrum (α=2-2.5)
- Fitted by two synchro-tron components.

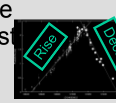
Millimeter-Peaked-Spectrum(MPS) λ=7mm

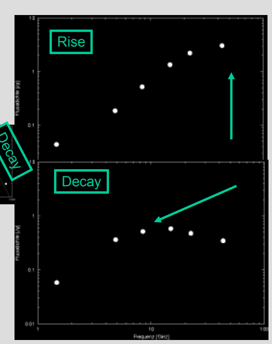


Falcke, Bower, et al. (1999, ApJL)

III Zw 2 - Spectral Evolution

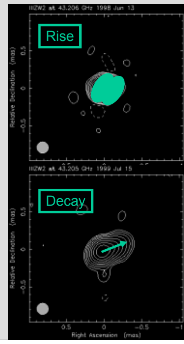
- The spectrum remained highly inverted, peaking at 43 GHz during the rise of the outburst
- Peak frequency dropped quickly after peak in 43 GHz lightcurve (decay).





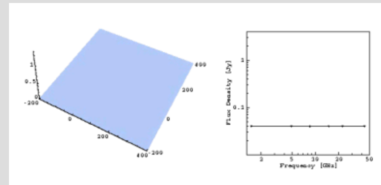
III Zw 2 - Structural Evolution

- The source remained ultra-compact during the rise, but requiring at least two compo-nents separated by 72μas (=0.1 pc).
- No other components found!
- Structural expansion seen during the decay.



Evolution of III Zw 2

Simultaneous VLBI and VLA observations



·VLBI monitoring
·superresolved (150μas)
·5 epochs interpolated

·VLA monitoring
·Monthly sampling
·13 epochs interpolated

Very close corres-pondence between spectral and struc-tural evolution!

Brunthaler, Falcke, Bower et al. (2000)

Polarization

Characteristic of the synchrotron emission: the radiation is highly polarized.

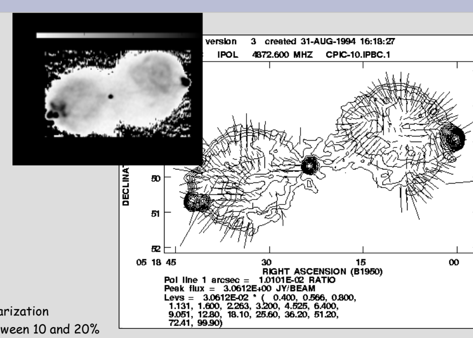
For an uniform magnetic field, the polarization of an ensemble of electrons is linear, perpendicular to the magnetic field and the fractional polarization is given by:

$$p = \frac{3p+3}{3p+7} \quad percent \Rightarrow 0.7-0.8 \quad \text{for} \quad 2<p<4$$

never!

Typical polarization from few to ~20% ⇒ Tangled magnetic field

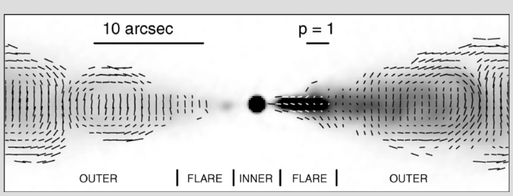
Polarization



Polarization between 10 and 20%
(some peaks at ~40% around the edge of the lobes)

Polarization

Example of polarization in radio jets.



Faraday rotation

Travel through a *plasma+magnetic field* (that can be internal or external to the source) changes the polarization angle

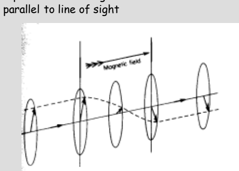
$$\Delta\theta = 2.6 \cdot 10^{-17} \lambda^2 \boxed{\int n_e B dl}$$

N_e = electron density of the plasma
dl = depth
B = component of the magnetic field parallel to line of sight

Rotation measure (RM)

RM can be derived via observations at different wavelengths

- If the medium is in front of the radio source: no change in the fractional polarization
- If the medium is mix in the radio source: depolarization dependence on wavelength (if due to Faraday rotation)



thermal electrons with density ~ 10^{-5} cm^{-3}

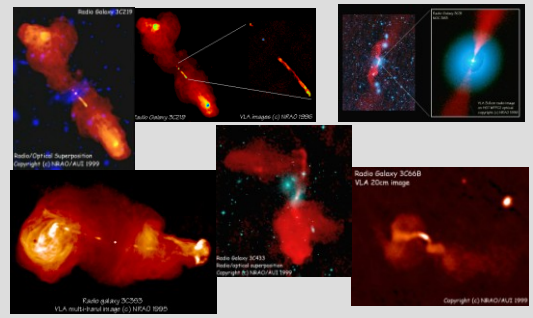
Depolarization happens also if the magnetic field is tangled on the scale of the beam of the observations

Different types of radio galaxies

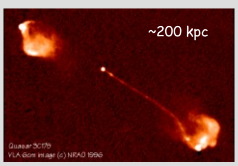
The morphology of a radio galaxy may depend on different parameters:

- radio power (related to the power of the AGN?)
- orientation of the radio emission
- intrinsic differences in the (nuclear regions of) host galaxy
- environment

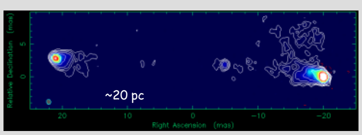
Different types of radio galaxies



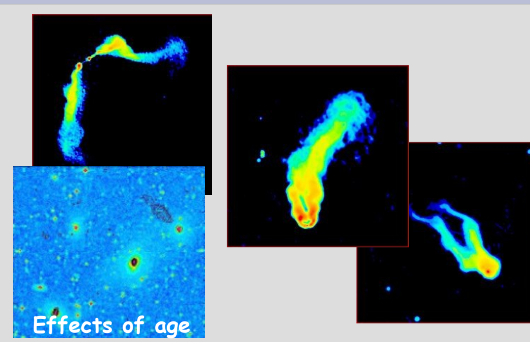
Different types of radio galaxies



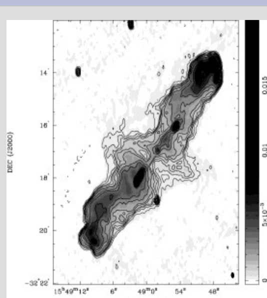
The morphology does not depend on size!

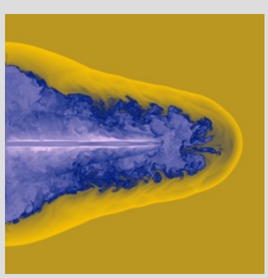


Effects of the interaction with the environment



Restarting Jets





V.L. Safouris, G.V. Bicknell, R.S. Sunrahmanyan & L. Saripalli, 2006, ApJ

Summary

- Jets are ubiquitous and are seen in almost all types of sources at all black hole masses and all accretion rates.
- They are hot, collimated plasma streams close to the speed of light, beaming plays a role
- They are launched close to the black hole.
- They can carry a few percent of the total accretion power in the form of kinetic energy.
- Emission ranges over the entire e.m. spectrum – main processes are synchrotron and inverse Compton emission.