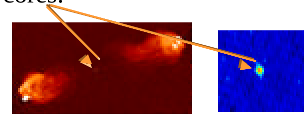
Radio Cores

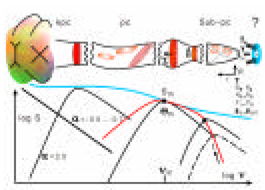
- All types of active black holes have compact, flat-spectrum radio cores:
  - Blazars
  - Quasars
  - Seyferts
  - Liners & LLAGN
  - The Galactic Center
  - X-ray binaries
- Potentially useful probes for BH physics



Radiogalaxy LLAGN

The Basic Jet Model

- 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" ⇒ flat spectrum
- subject to rel. boosting

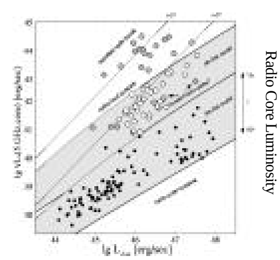


Jet-Disk Symbiosis

- Jet power scales with accretion disk power

  $Q_{jet} = q_{j/l} \cdot L_{disk}$

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



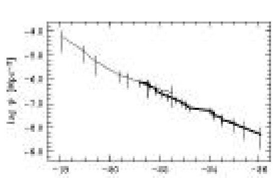
Radio Core Luminosity

Accretion disk luminosity

(Falcke, Malkan, Biermann 1995)

Luminosity Function of AGN

- The AGN luminosity function is steeply rising towards lower luminosities.
- The majority of AGN is rather silent.
- 1/3 of nearby galaxies are LLAGN (Ho et al. 1995-2000)



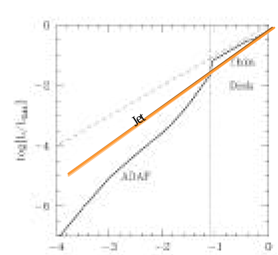
Köhler et al. (1997)

Disks may become radiatively inefficient …

- Below a critical accretion rate, disks may become radiatively inefficient (and become advection dominated: ADAFs, BDAFs, CDAFs …).

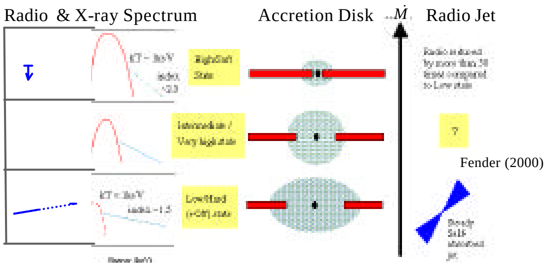
⇒ At lower accretion rates disks become less and less prominent.

⇒ What about the jets?



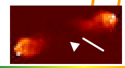
Esin, Narayan et al. (1997 …)

The Power-Evolution of XRBs



Suggestion: FR Is, BL Lacs, LLAGN are the low/hard state of supermassive BHs

The FR I Gap for Radio-Loud Quasars



- Why are there no FR I quasars? Are they sub-Eddington?
- Radio loud quasars are found almost exclusively in elliptical galaxies.
- Black hole masses $\geq 10^9 M_\odot$ (McLure, Dunlop et al.).
- R.L. quasars are almost exclusively of FR II type (the high-power one).

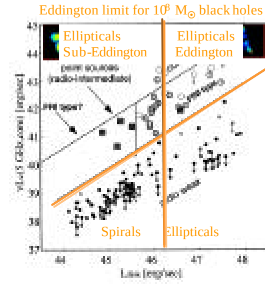


Figure: Falcke, Ghopal-Krishna, Biermann (1995)

The FR I Gap for Radio-Loud Quasars

- FR Is are missing in the sample because they have no disk spectrum.
- Analogy to XRBs:

  Are the FR I radio galaxies the low/hard-state of radio-loud AGN?

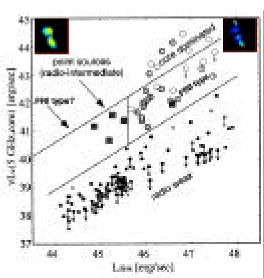
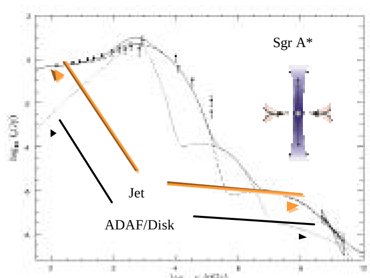


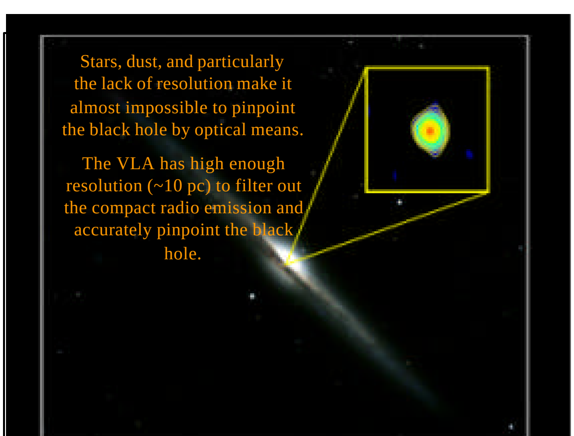
Figure: Falcke, Ghopal-Krishna, Biermann (1995)

JDAF Model for LLAGN: Jet-Dominated Accretion Flow

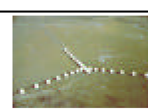
- Because $T_{e,disk} << T_{e,jet}$ the ADAF radiates only in the innermost region.
- Emission from the jet material dominates cm and X-ray emission
- Applied to Sgr A*, NGC4258



Yuan, Markoff, Falcke (2001)



VLA Survey of LLAGN



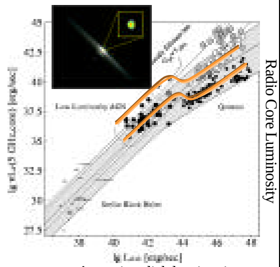
- Parent Sample: Ho et al. (1995)
- Sample A: 48 Liners
- Sample B: 95 active galaxies within 19 Mpc
- Survey: VLA @ 15 GHz, 0.15” resolution, 1 mJy (10σ) detection limit
- Goal: pick out flat spectrum cores

VLA - Very-Large-Array Survey of Nearby Galaxies

- 1/3 of galaxies in distance limited sample of LLAGN detected with the VLA at 15 GHz

	Number	Detected	Ratio
Seyferts	22	10	45%
Liners	37	16	43%
Transition	34	4	12%
Sum	93	30	32%

- Discovery of many new black holes in nearby galaxies
- Some of the least luminous black holes in the universe



Falcke et al. (1994-2000)

VLBA observations

- **Sample:** all sources brighter than 3 mJy at 15 GHz and compact structure
- **Observations:** VLBA phase-referencing at 5 GHz, detection limit ~ 1.5 mJy

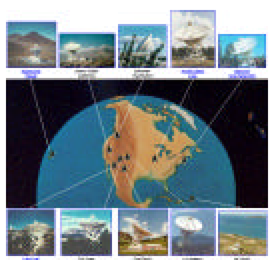
VLBA observations

Detection Rate:

18/19 sources = 95%

(non-detected core was steep-spectrum)

very effective selection!



VLBA observations

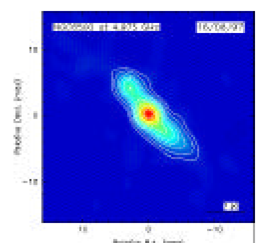
Morphology:

- 6 brightest cores: core-jet structure
- 10 fainter sources: point-like (dynamic range limited)

$T_b \geq 10^8$ K

⇒ genuine AGN cores

⇒ ≥40% of Liners are AGN



Falcke et al. (2000); Nagar et al. (2000)

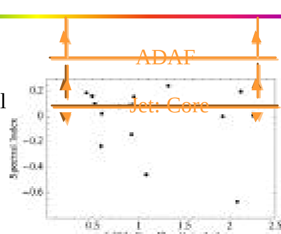
VLBA observations

Spectral Index:

- The VLBA/VLA spectral index $\alpha_{5/15}$ is
  - not larger than α~0.25
  - on average α~0.0

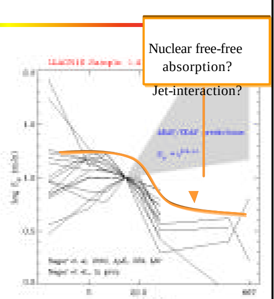
⇒Not a single highly inverted (ADAF) core

⇒no missing flux



Radio Observations of LLAGN

- Compile the spectra of LLAGN up to 660 GHz.
- Radio spectra are typically flat with a peak around 22 GHz (GPS-like).
- The ADAF model predicts strongly inverted radio spectra at higher frequencies.
- We find no evidence for this.
- ⇒ Morphological and spectral data suggest that the radio emission is dominated by jet-emission!

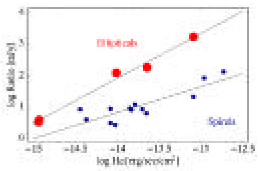


VLBA Sample: Radio-Loudness

Radio/Ha - ratio:

- Isolate core flux.
- Compare with nuclear Hα.
- Radio scales with Hα.
- There is trend for a larger Radio/Hα–ratio with larger bulge luminosity.

⇒ Larger black holes?
⇒ Lower radiative efficiency?
⇒ Lower Eddington Rate?
⇒ Larger obscuration?



VLBA Sample; Radio-Loudness

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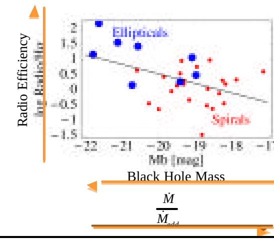
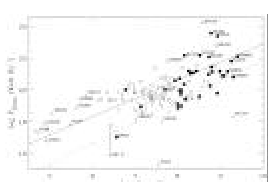


Black Hole Mass

- Consequently, there seems to be a correlation between black hole mass and radio flux.
- However, the main driver should be the accretion rate.

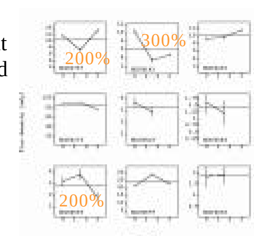
⇒ Larger black holes have more “headroom” (to the Eddington limit) and may accrete more
⇒ They are more jet-dominated (or selection was optical!).



Nagar, Falcke, Wilson (2002)

Multi-Epoch Observations of LLAGN

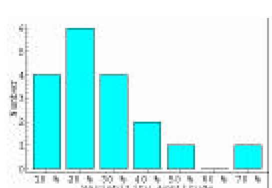
- Three different programs at the VLA in subsequent A-array seasons separated by 1.5 years.
- 2-3 epochs observations of brightest radio cores (>3 mJy)



Distribution of Variability Amplitudes

- Typical variability amplitude around 20%
- Tail up to 70%
- Variability comparable with blazars (lower power/smaller BHs?)

⇒ Many radio cores
⇒ Many are variable
⇒ More evidence for AGN



RMS/MEAN

„Pinpointing Black Holes“

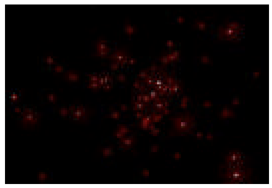
- We have identified the least-luminous black holes found in our cosmic neighborhood.
- What can we do with this?

⇒ VLBI also has extremely good astrometric capabilities.
⇒ Positions can be determined to sub-milliarcsecond precision!
⇒ We can locate the centers of nearby galaxies extremely precisely.

Dark Matter Search: Measuring Galaxy Motions

- Galaxies are not static.
- In a cluster relative galaxy motions of 200 km/sec are possible.
- This corresponds to 40 microarcseconds per year at one Mpc distance.
- This motion is sensitive to the dark matter distribution!
- So far we only have radial motions.
- Good mass models need proper motions!

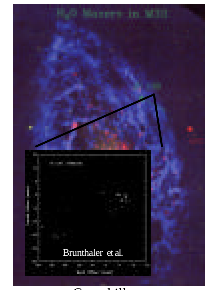
Simulation of 100 Galaxies over 16 Ga. (white=luminous matter, red=dark matter)



Berrington (1996-2000)

Dark Matter Search: H_2O Masers in M33 and IC10

- Water molecules are excited by X-rays or infrared radiation ⇒ population inversion
- A maser line (stimulated emission) is emitted around 21 GHz.
- The emission comes from a very compact region (long coherent path length!)
- Maser spots are ideal reference sources for VLBI.

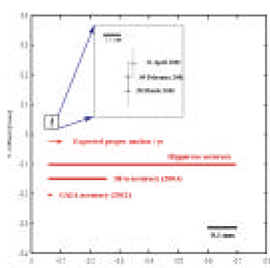


Greenhill, p.c.

Dark Matter Search: First Epoch Observations of IC10

- We have achieved a precision of 3-10 µas RMS.
- The expected components of motion are:
  - Milky Way rotation: 50µas/yr
  - IC10 motion : 25-50 µas/yr
  - IC10 rotation: 50 µas/yr
  - Maser motion: 10 µas/yr
- In one year we expect the discovery of extragalactic proper motion.

⇒ Precise mass model to get dark matter distribution.



Brunthaler, Falcke, Reid, in prep.

Conclusions and Future Directions

- At low accretion rates active black holes become increasingly jet- (and radio-) dominated.
- Radio (and possibly X-rays) maybe the only way to find the fossil black holes in the nearby universe.
- With EVLA & SKA we can hope to locate essentially all nearby supermassive black holes.
- This will provide us with the luminosity evolution of dead quasars.
- With VLBI the cores can be used to measure proper motion and study the 3D dynamics of galaxies out to Virgo within a decade (and locate dark matter).