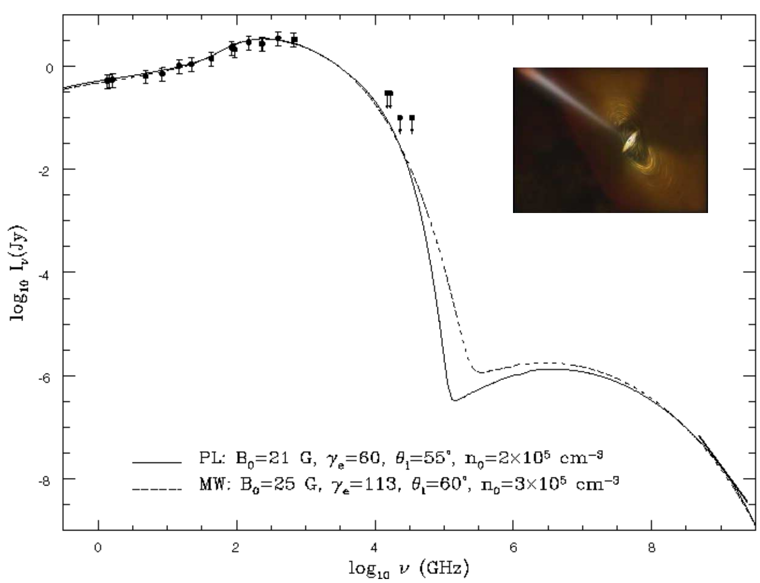
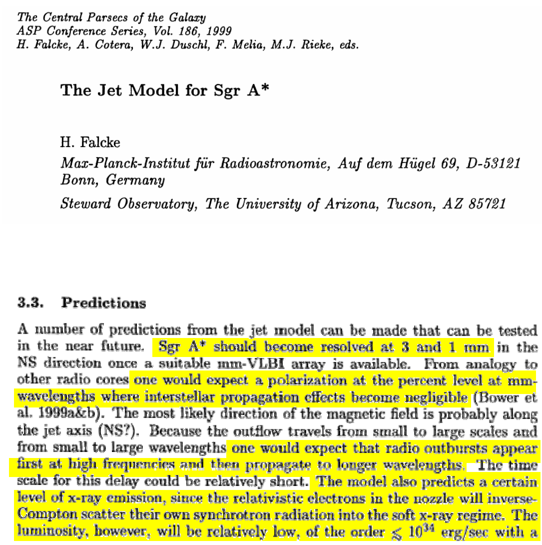
What is Sgr A?*
Emission Spectrum - Jet Model

- Sgr A* is a flat-spectrum, compact, variable radio core.
- The jet model has stood the test of time.
- Most of its prediction have been verified
- Jet power is 10^{38} erg/sec.
- Required accretion rate $\sim 10^{-8}$ $M_\odot$/yr.



Falcke, Mannheim, Biermann (1993); Falcke & Markoff (2000)

Theorists can make predictions



The Central Parsecs of the Galaxy
ASP Conference Series, Vol. 186, 1999
H. Falcke, A. Cotera, W.J. Duschl, F. Melia, M.J. Rieke, eds.

The Jet Model for Sgr A*

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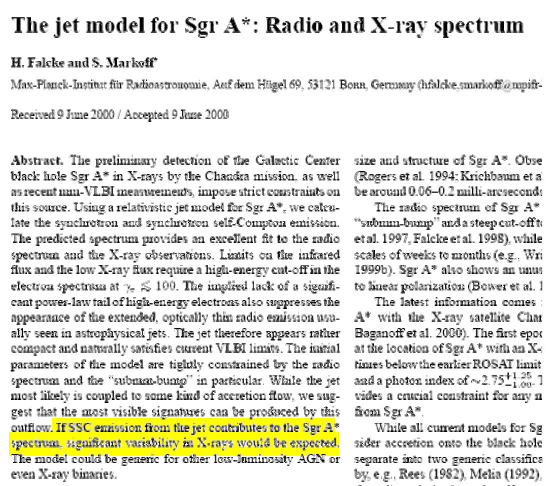
3.3. Predictions

A number of predictions from the jet model can be made that can be tested in the near future. Sgr A* should become resolved at 3 and 1 mm in the NS direction once a suitable mm-VLBI array is available. From analogy to other radio cores one would expect a polarization at the percent level at mm-wavelengths where interstellar propagation effects become negligible (Bower et al. 1999a&b). The most likely direction of the magnetic field is probably along the jet axis (NS?). Because the outflow travels from small to large scales and from small to large wavelengths one would expect that radio outbursts appear first at high frequencies and then propagate to longer wavelengths. The time scale for this delay could be relatively short. The model also predicts a certain level of x-ray emission, since the relativistic electrons in the nozzle will inverse-Compton scatter their own synchrotron radiation into the soft x-ray regime. The luminosity, however, will be relatively low, of the order $\lesssim 10^{34}$ erg/sec with a



The jet model for Sgr A*: Radio and X-ray spectrum

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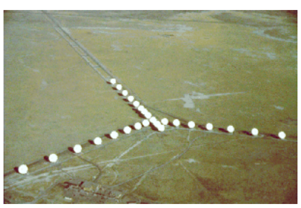
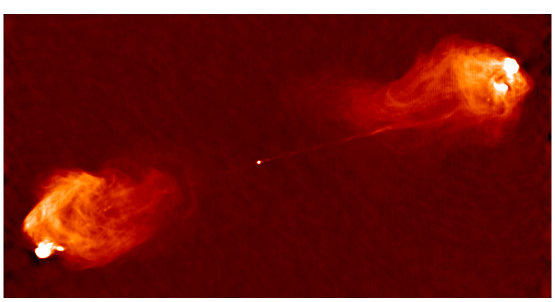
Abstract. The preliminary detection of the Galactic Center black hole Sgr A* in X-rays by the Chandra mission, as well as recent mm-VLBI measurements, impose strict constraints on this source. Using a relativistic jet model for Sgr A*, we calculate the synchrotron and synchrotron self-Compton emission. The predicted spectrum provides an excellent fit to the radio spectrum and the X-ray observations. Limits on the infrared flux and the low X-ray flux require a high-energy cut-off in the electron spectrum at $\gamma_e \lesssim 100$. The implied lack of a significant power-law tail of high-energy electrons also suppresses the appearance of the extended, optically thin radio emission usually seen in astrophysical jets. The jet therefore appears rather compact and naturally satisfies current VLBI limits. The initial parameters of the model are tightly constrained by the radio spectrum and the "submm-bump" in particular. While the jet most likely is coupled to some kind of accretion flow, we suggest that the most visible signatures can be produced by this outflow. If SSC emission from the jet contributes to the Sgr A* spectrum, significant variability in X-rays would be expected. The model could be generic for other low-luminosity AGN or even X-ray binaries.

size and structure of Sgr A*. Obse
(Rogers et al. 1994; Krichbaum et a
be around 0.06–0.2 milli-arcseconds
The radio spectrum of Sgr A*
"submm-bump" and a steep cut-off t
et al. 1997, Falcke et al. 1998), while
scales of weeks to months (e.g., Wr
1999b). Sgr A* also shows an unus
to linear polarization (Bower et al. 1
The latest information comes
A* with the X-ray satellite Cha
Baganoff et al. 2000). The first epo
at the location of Sgr A* with an X-
times below the earlier ROSAT limit
and a photon index of $\sim 2.75^{+1.25}_{-1.00}$. T
vides a crucial constraint for any m
from Sgr A*.
While all current models for Sg
sider accretion onto the black hole
separate into two generic classifica
by, e.g., Rees (1982), Melia (1992),



How does a proper jet look like

- This jet can be separated into three regimes:
  - Core (origin)
  - Jet (dissipationless energy transport)
  - Lobes (terminus)
- Radio cores are found in all accretion/jet sources:
  - Quasars
  - LLAGN
  - X-ray binaries

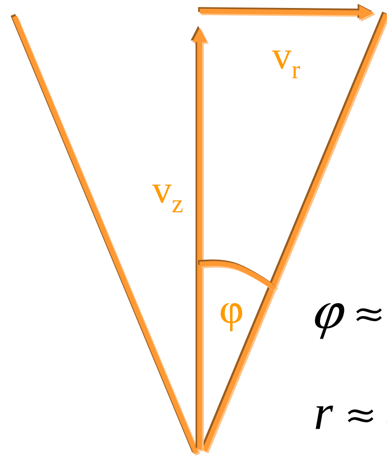


Perley/NRAO

□he Spectrum o□Jet-□ores□ □ree E□pansion Approach

- □lasma propagates at a constant proper speed ⇒ $v_{□}$□$\gamma_j\beta_j c$.
- The □isothermal□ plasma e□pands with sound speed ⇒ v_r□$\gamma_s\beta_s c$.
- The resulting shape is a cone with Mach number

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



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

$$r\approx\varphi z$$

□he Spectrum o□Jet-□ores□ □article and Energ□□ensit□Scaling

- □article conservation□

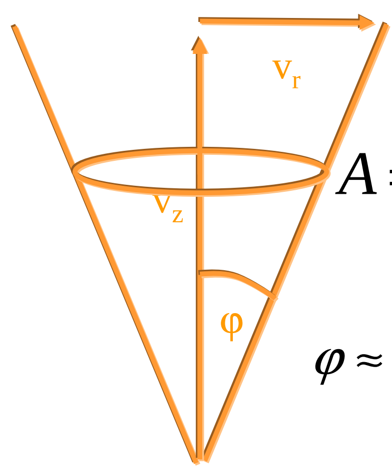
$$\dot{M}_j=\rho\cdot \mathrm{v}\cdot A=m_p n(r)\cdot\gamma\beta c\cdot\pi r^2$$

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

- □nergy conservation□

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

$$\Rightarrow B(r)=\sqrt{\frac{8L_{j,B}}{\gamma\beta c\cdot r^2}}\propto r^{-1}$$



$$A=\pi r^2$$

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

The Spectrum of Jet-Cores: Synchrotron Absorption

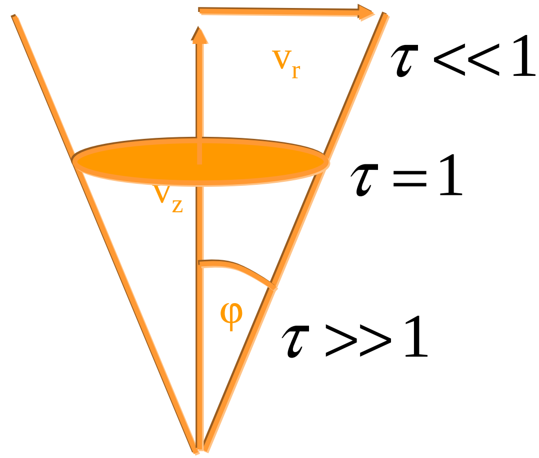
- Synchrotron Absorption:

$$\alpha_{sync} \propto B^4 \nu^{-3}$$

$$\tau \propto r\alpha_{sync}, \quad B \propto r^{-1}$$

$$\tau \propto r^{-3}\nu^{-3}$$

- At a specific observing frequency we see the τ=1 surface; the location is frequency dependent: $\Rightarrow r_{\tau=1} \propto \nu^{-1}$
- Basic prediction: size scales inversely with frequency.



The Spectrum of Jet-Cores: Synchrotron Emission

- Synchrotron Emission:

$$\varepsilon_{sync}(\nu) \propto B^{3.5}\nu^{-0.5}$$

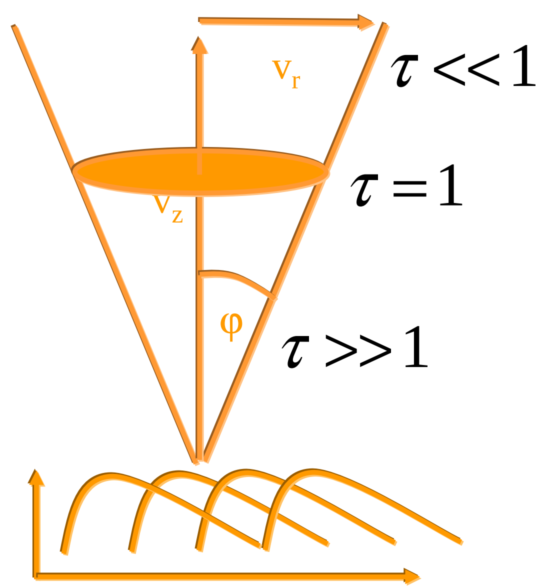
$$V \propto r^{-1}, \quad B \propto r^{-1}$$

$$S_\nu \propto V \cdot \varepsilon_{sync}$$

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

$$S_\nu \propto r^3 r^{-3.5} r^{0.5} = \text{const}$$

- For a conical jet the spectrum is flat!



Getting more Parameters: Standard Theory for Self-Absorbed Sources

Magnetic field, density, electron distribution

$$B \propto r^{-m} \quad \rho \propto r^{-n} \quad \frac{dN_e}{dE_e} \propto E^{-p}$$

$$\Rightarrow I_\nu \propto \nu^{\alpha} \quad R_{sync} \propto \nu^{\beta}$$

de Bruyn (1977)

Spectrum, size as function of frequency

$$\alpha = \frac{13-5n-3m-2mp+2p}{2-2n-2m-mp}$$

$$\beta = \frac{p+4}{2-2n-mp-2m}$$

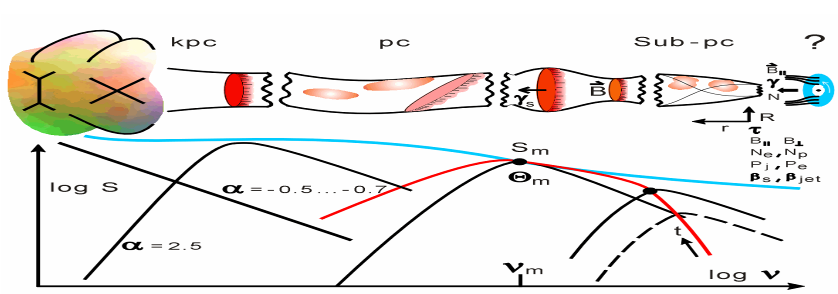
$$for\ n=2\ und\ m=1 \Rightarrow \alpha = 0\ \&\ \beta = -1$$

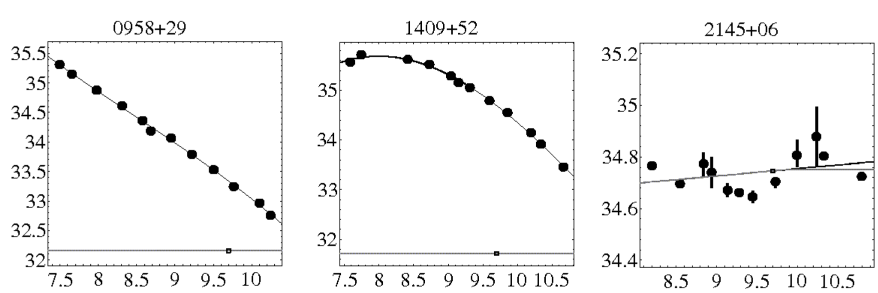
Natural solution for conical, freely expanding jets

$$\Rightarrow R_{sync} \propto \nu^{-1}\ \&\ S_\nu \propto \nu^{0}$$

Measuring size and spectrum of a source tells one the run of density and B-field with radius for a given particle distribution!

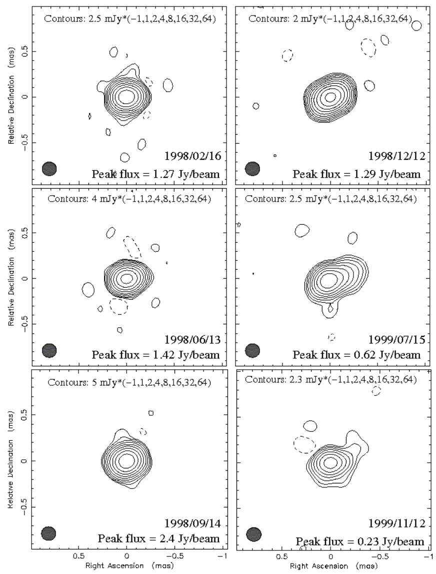
Radio Spectra of Quasars



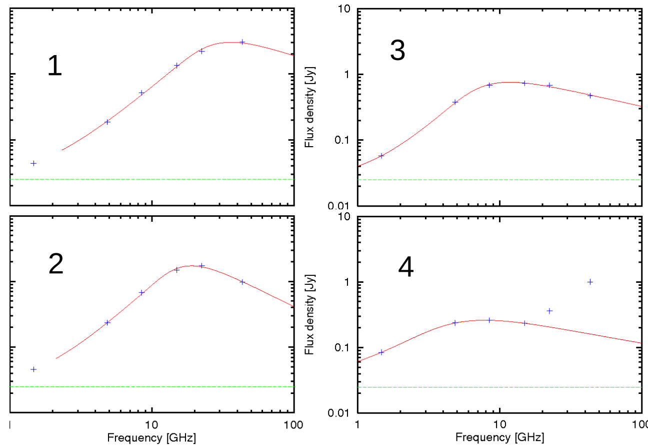


Falcke (1994)

The Outburst of the Jet-Less Quasar III Zw 2



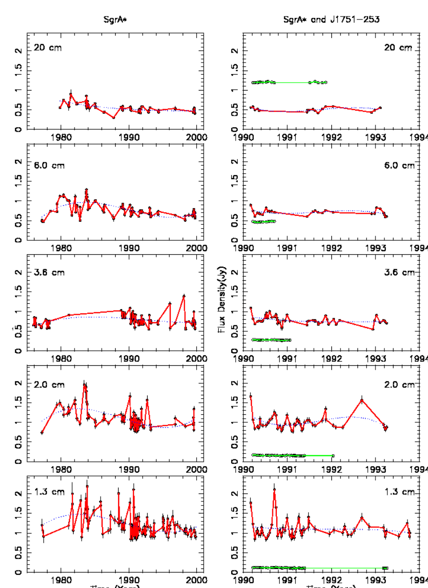
Time scale of III Zw 2 radio flare scales down to 20 min for Sgr A* …



Brunthaler, Falcke, Bower et al. (2005)

Sgr A* - Variability

- Sgr A* is strongly variable at all radio frequencies, up to a factor of two.
- The highest frequencies are more variable.
- One can identify individual bursts.
- This resembles the inside-out behaviour of III Zw 2 and other jets

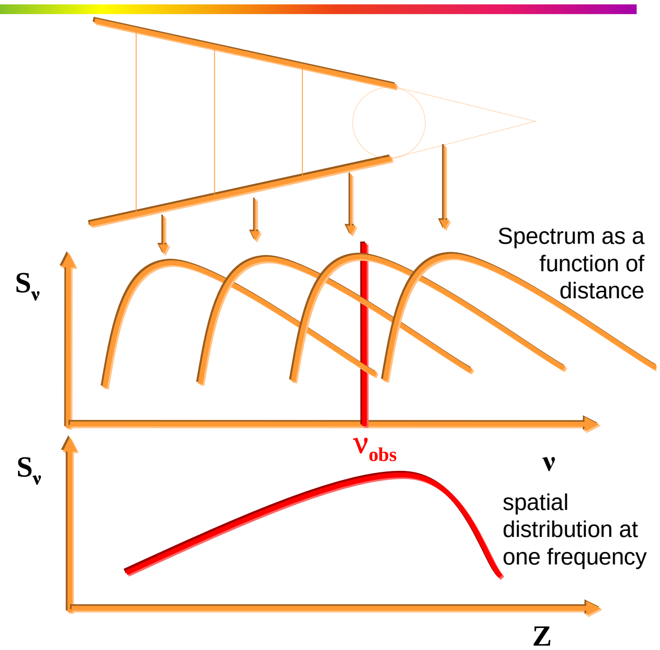


Zhao, Bower, Goss (2000)

□here is the □et□

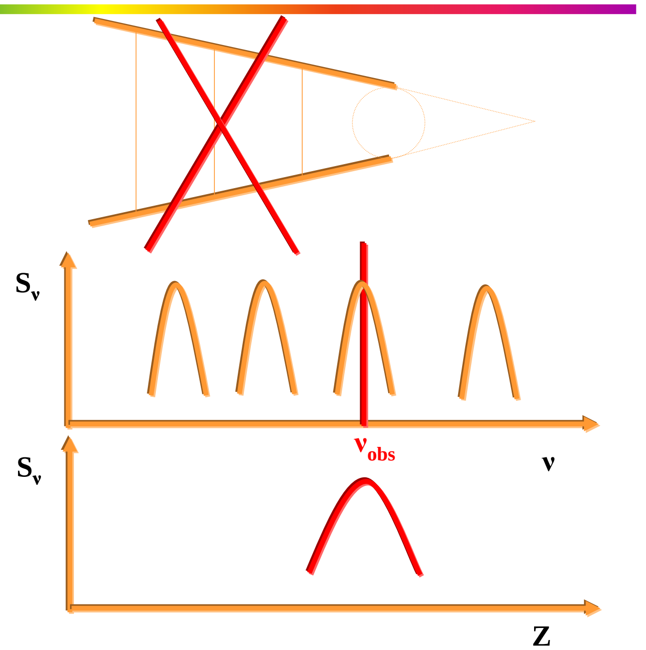
- □□an□onical jet with power law:
  - □B-field decreases
  - □Synchrotron pea□ frequency decreases
  - □But higher energy electrons ma□e up for this

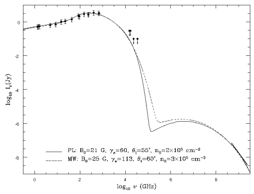
⇒□ore-jet structure is seen



Where is the jet?

- Jet without power law:
  - B-field decreases
  - Synchrotron peak frequency decreases
  - Only small range of jet can be seen at each frequency
  - Size is a function of frequency!
- Just the core is seen

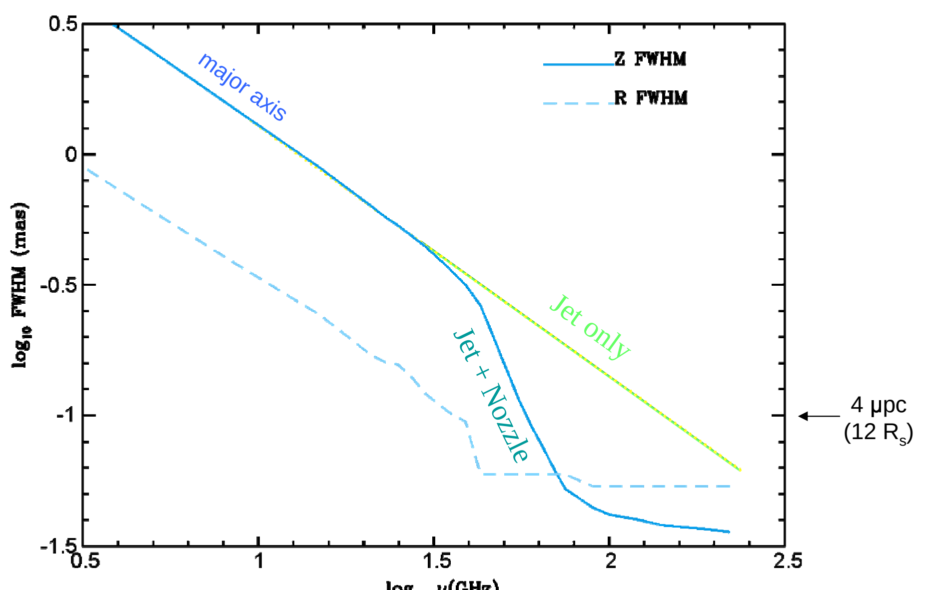




□□r □□ □□□□ □□□t□ess

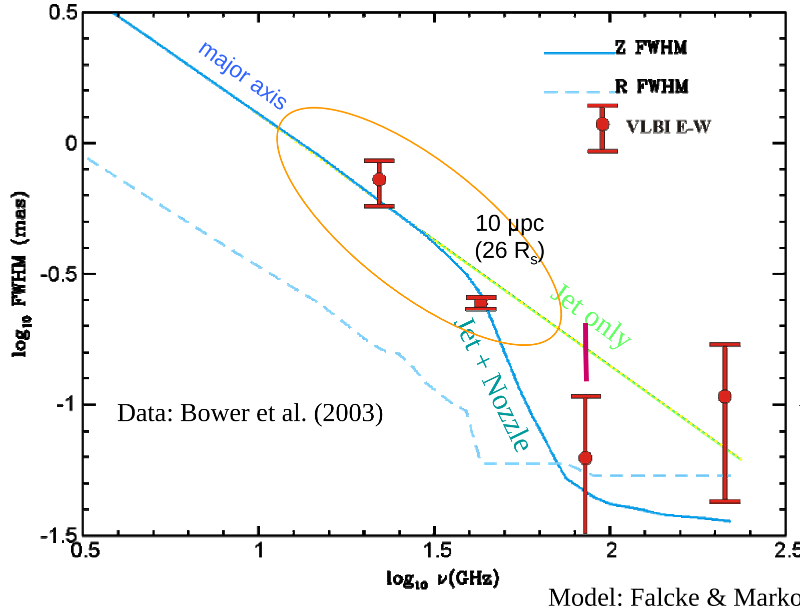
- The compactness of Sgr A* indicates a lack of a non-thermal power law (not the lack of a jet).
- The electron spectrum is “quasi-thermal”
- One has “thermal synchrotron” emission with B~10 G and E_e~30 MeV at the foot point.

□re□i□ti□□s □r□□ the □et □□□e□



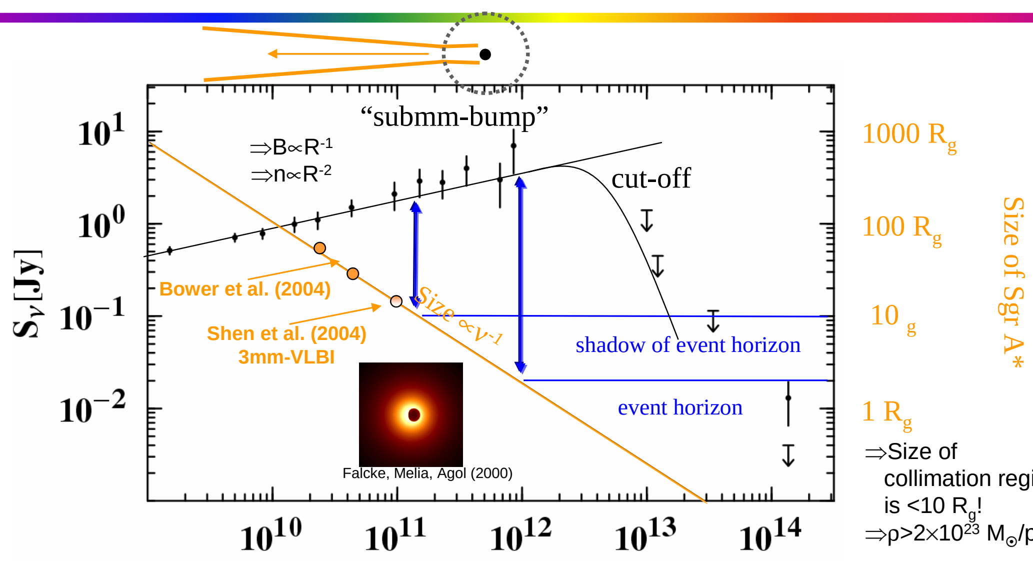
Model: Falcke & Markoff 2000, A&A

Comparison to Models



Model: Falcke & Markoff 2000, A&A

Correlation between Size and Spectrum of Sgr A*



⇒Size of collimation region is <10 R_g!

⇒$\rho > 2\times10^{23}\ M_\odot/pc^3$

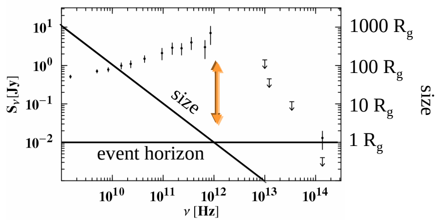
From $T_b \propto (\theta\nu)^{-2}$ & $\theta \propto \nu^{-1}$

⇒Tb~const, c_s ~ 0.1 c

⇒Sgr A* unbound

(at least ν<15 GHz)

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

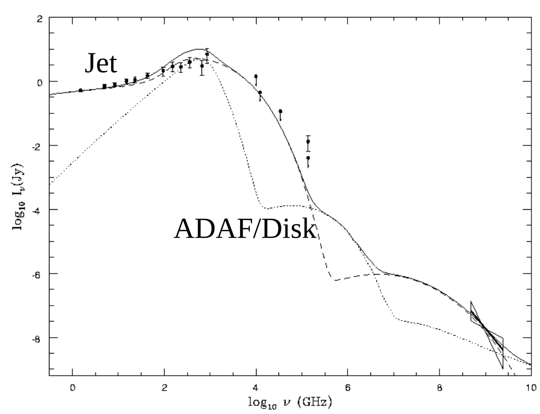


Size of Sgr A*: Some Implications

- We can determine scaling of B-field and particle density (de Bruyn 1977)
  - $B \propto 1/r$
  - $n \propto 1/r^{2}$.
- Spectrum indicates that size scaling continues at least
  - up until 220 GHz (5 R_s)
  - down to 300 MHz (Max size > 2.5×10^{15} cm)
  - High-frequency emission cuts off when the size scale reaches event horizon.
- The (brightness) temperature ($T_b \propto S_\nu \nu^{-2}\theta^{-2}$) is roughly constant:
  - $T_b \sim 1.5\times10^{10}$ K ($c_s \sim 0.1c$)
  - the plasma is unbound at least at R>70 R_s (15 GHz)
- 2 hr variability at 15 GHz:
  - sound speed $\geq$0.1c ($\sim10^{10}$K)

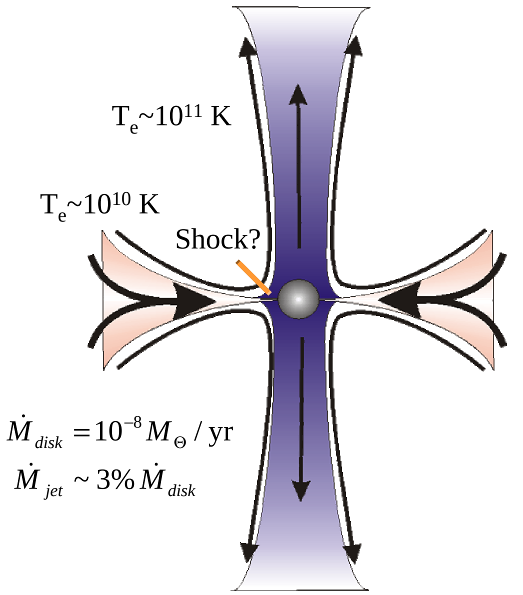
□□A□□o□el: □et □A□A□□S□oc□□eating

- □bservationally the □et dominates the spectrum at low frequencies – the dis□can only be significant at THz frequencies. □s it seen□
- Most matter has to go into the blac□hole□hence $n_{□et}$□□$n_{dis□}$
- □n order for the spectra to □oin smoothly to the dis□one needs $T_{e□dis□}$□□$T_{e□□et}$ – this requires a heating mechanism: shoc□or reconnection□
- There is no obvious reason why dis□and □et should have the same or even comparable levels – this does not come naturally.
- Warning: There is no guarantee that any of the THz□□R□□-ray emission is from the dis□

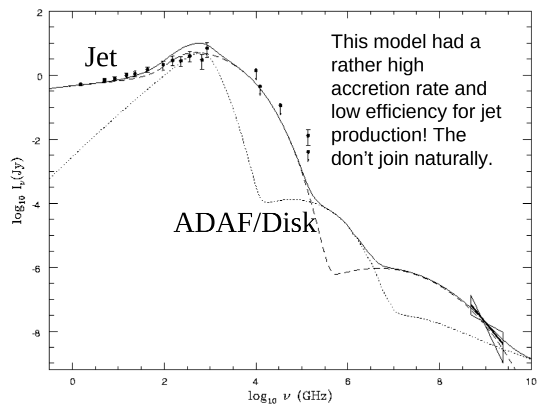


Yuan, Markoff, Falcke (2001)

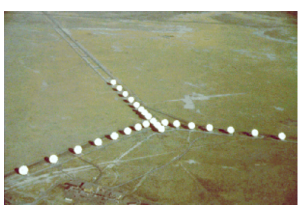
S□□mm□□□mp: A□A□or □et□



Why do jet and disk have similar emission levels at the foot point? Or is the entire spectrum jet emission?

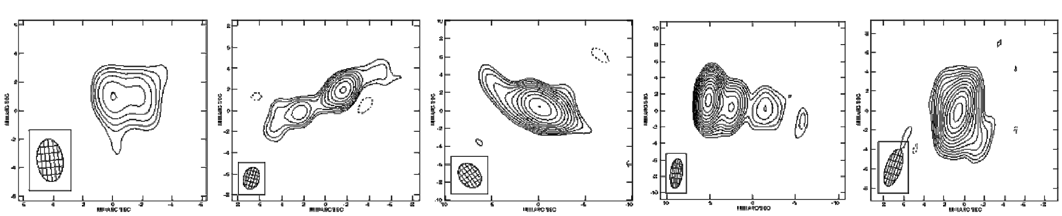


Yuan, Markoff, Falcke (2001)



Significant ot□ers: □□A S□r□e□of □□A□□

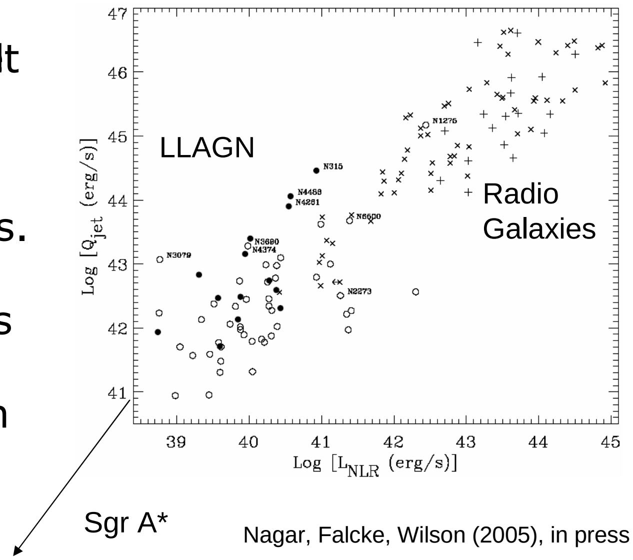
- □ompleted high resolution (100 – 1 mas) radio imaging survey of all (□200) low-luminosity active galactic nuclei (□□□G□s) and □G□s in the Ho□ □alomar Spectroscopic Sample of all (□ □□□) bright northern galaxies.
- We find:
  - High incidences of compact□variable flat-spectrum nuclei (~50□)
  - □ompact core spectral index: □□ □0.2 to 0.2
  - □et structures of the brightest ones



Nagar, Falcke, Wilson (2005), in press

□onnection to □a□io □ala□ies

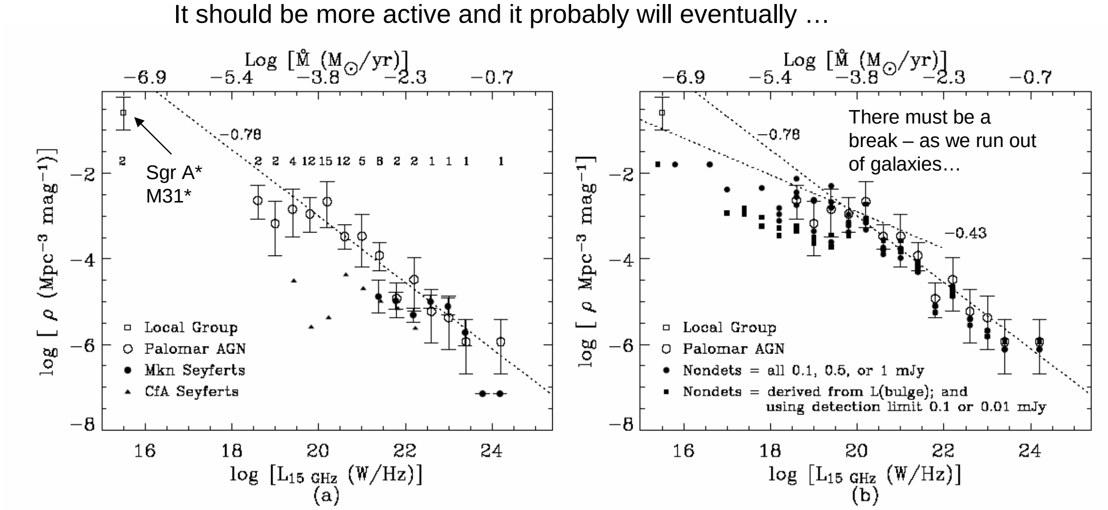
- Rawlings □Saunders (1991) showed a correlation between □et power and (optical) luminosity in the □arrow □ine Region (□□R) of radio galaxies.
- □□□G□ extend this correlation by □orders of magnitude.
- Most energy release in □□□G□ is in □inetic □et energy□



Nagar, Falcke, Wilson (2005), in press

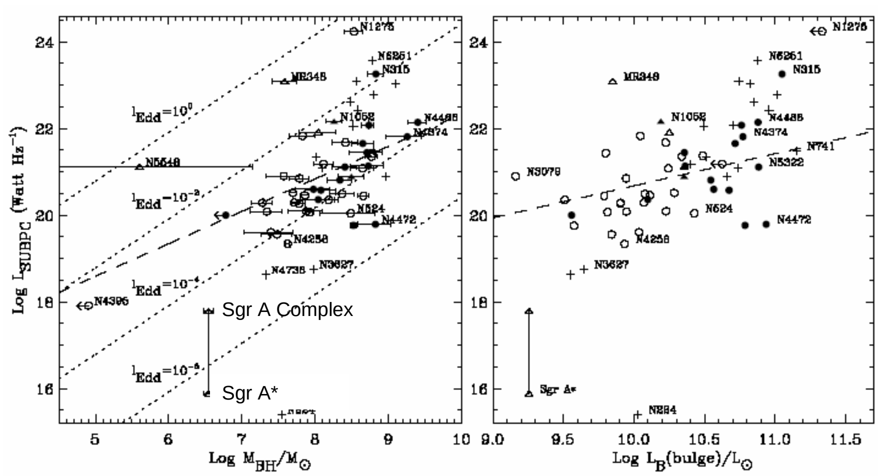
□a□io □ore □□minosit□ □□nction of all near□□ □□A□□

Sgr A* represents (almost) the bottom end of the radio core luminosity function!
It should be more active and it probably will eventually …



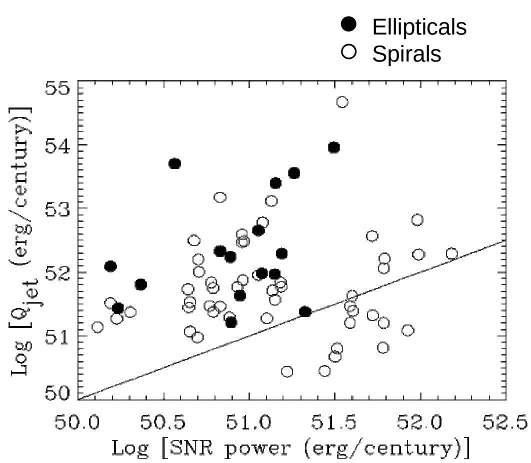
Nagar, Falcke, Wilson (2005)

Sgr A* □o□er in □□□ington □nits

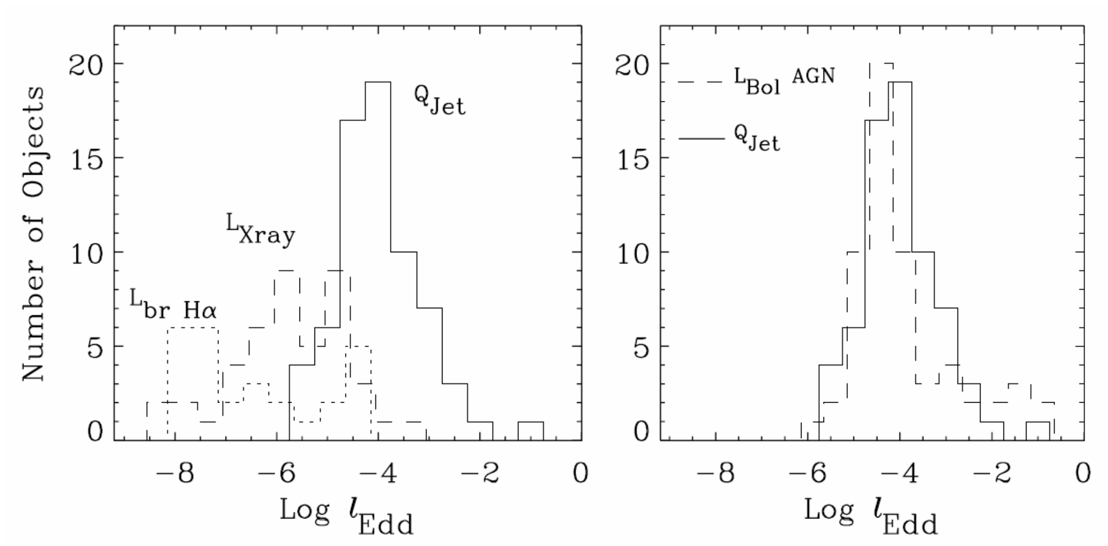


□herg□Inp□t into t□e IS□: □omparison □it□S□perno□ae

- □stimate Supernova rate as 1 S□/century/10^{10} □$_{B\odot}$ (van den Bergh □ Mc□lure 199□).
- □hergy per supernova ~ 10^{51} erg/sec.
- □hergy input from □ets dominates in most ellipticals and in many spirals.



Jet Power of Sgr A*



- Sgr A* (radio) has passed all predictions of the jet model and it can't be bound.
- There is no reason that submm-IR and X-ray emission should not also be jet-related.
  - But: NIR/X-ray is optically thin emission (∝T_e)
  - Radio/submm is optically thick emission (∝Mdot)
- A lot of parameters have been fixed recently:
  - size, accretion rate, B field, temperature, density
- Jet collimation happens within a few Schwarzschild radii. How can this work?
- Its properties are just like all the other cores and jets – Sgr A* is nothing special.
- Sgr A* and M31* are unusually faint for the size of their host galaxies.