

## Active Galactic Nuclei (AGN):

are extremely luminous extragalactic sources powered by supermassive black holes (SMBHs) at galactic centers.

### Observationally:

① Highly nonthermal spectra: Are bright from radio frequencies to  $\sim 10^{15}$  eV  $\gamma$  rays (as opposed to stars, which have  $\sim$ BB spectra and emit most of energy over 1-2 decades in  $\nu$ )  
 $\lesssim 100$  Mpc

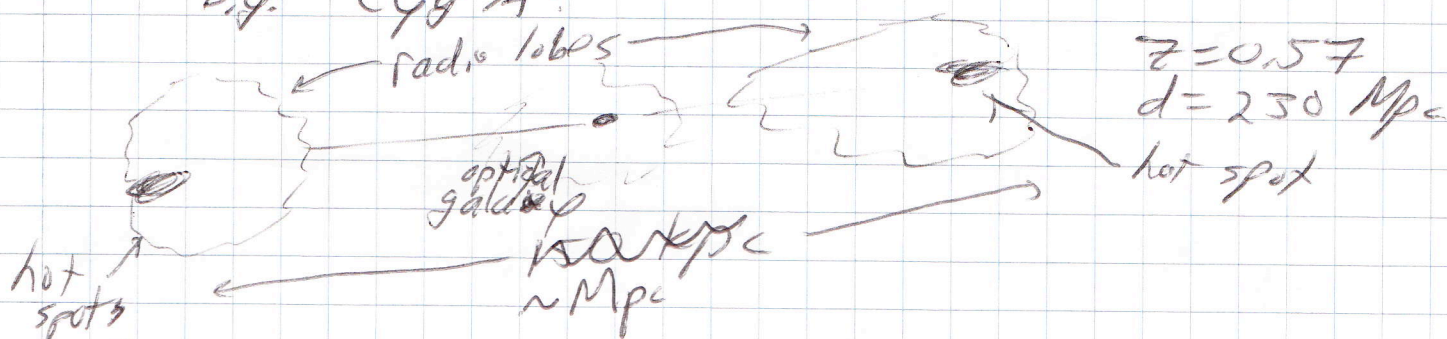
② Often have jets, expulsion of energy from in two opposite directions

③ Highly compact ( $\lesssim 3$  pc) luminous centers

④ Strong emission lines in spectra

⑤ Strong UV emission ( $\text{Ly-}\alpha$  + ...) from compact region near center

⑥ Jets may terminate in bright radio lobes;  
e.g. Cyg A:



⑦ Variability on short (as small as few mins) timescales; variability at all  $\nu$ .

⑧ Strong broad emission lines from central source.



## Taxonomy:

AGN < quasars, radio galaxies, Seyfert galaxies, blazars, QSOs, etc.  
classification historical ~ blind men with elephant

Quasars: luminous compact centers that outshine rest of galaxy  $L \sim 10^{45} - 10^{46} \text{ erg/s} \gg L_* \sim 10^{44} \text{ erg/s}$   
~10% have strong radio emission:  
radio loud quasars

Radio galaxies: look like typical ellipticals in optical but have  
 $L_{\text{radio}} \approx 3 \times 10^{41} \text{ erg/sec}$  from CR synchrotron  
 $\gg L_{\text{spiral}} \sim 10^{34} \text{ erg/sec}$  from SNRs

radio emission in radio galaxies comes from two radio lobes

FR I: brightest closest to source;  $L_{1.4 \text{ GHz}} \leq 10^{32} \text{ erg/s/Hz}$

FR II: brightest in hot spots at far ends;

$$L_{1.4 \text{ GHz}} \gtrsim 10^{32} \text{ erg/sec/Hz}$$

Seyfert galaxies: spiral galaxies w. very bright unresolved cores with strong emission lines from highly ionized states; e.g.,

C III]  $\lambda 1909$  Mg II  $\lambda 2800$  H $\gamma$  H $\beta$

$$L \sim 10^{43} - 10^{45} \text{ erg/sec}$$

usually radio quiet

Seyfert I: broad permitted H lines  
Seyfert 2: no broad permitted H lines  
are more likely than typical spiral to be merging



Blazars: polarized nonthermal emission  $\sim$  synchrotron  
large X-ray &  $\gamma$ -ray fluxes

Radio classification:

radio-loudness  $R_L = \log \left( \frac{F_{5\text{GHz}}}{F_{\text{VB}}} \right)$  B-band, 4400 Å

$R_L > 1$  radio loud  
10-15%

$R_L < 1$  radio quiet  
85-90%

Optical classification:

Type I AGN: strong continuum; broad + narrow emission lines

Type II AGN: weak continuum; only narrow em. lines

Example: 3C273 (optically brightest quasar)

$d \approx 680 \text{ Mpc}$   $z = 0.16$

spectrum  $\nu F_\nu \propto \nu^{1-\alpha}$   $\alpha \approx 1/3$  to  $\approx 1/0$

from  $\nu \sim 10^{12} \text{ Hz}$   $\nu \sim 10^{23} \text{ Hz}$   
IR  $\geq 100 \text{ MeV}$

to  $\sim$  facts

i.e. equal energy emitted per log  $\nu$  over 710 decades

Has big blue bump  $\sim 10^{15} \text{ Hz}$  (far UV)

another bump near  $10^{20} \text{ Hz}$  (MeV)

Radio emission (weaker): synchrotron from jets

Optical/UV: accretion disk and hot corona

IR: warm dusty torus heated by central source

X-ray/ $\gamma$ -ray: inverse-Compton scattering of optical/UV by relativistic  $e^-$ 's in hot gas surrounding accretion disk



characteristic emission lines of quasars include

Balmer series H $\alpha$  (6563 Å) H $\beta$  (4861 Å)

H $\gamma$  (4340 Å), Lyman- $\alpha$  (1216 Å)  
Mg II, C III, C IV

Variability:

lower-L sources tend to be more variable

timescales  $\sim$  min — years

$\Rightarrow$  source size  $l \leq c \Delta t \sim 2 \times 10^{12} \text{ cm} \left( \frac{\Delta t}{\text{min}} \right)$

cf.  $R_s = 3 \times 10^{12} \text{ cm} \left( \frac{M}{10^7 M_\odot} \right)$

Schwarzschild radius for BH of mass  $M$ .

Variability generally higher at larger  $\nu$ .

Often correlated over wide range of  $\nu$ .

Recombination times in broad-line regions  $\sim$  days

$\Rightarrow$  change in flux of ionizing radiation from central source may be followed some time later by change in BLR intensity. The observed time delay gives size of BLR: reverberation mapping

Narrow line regions are not variable; consistent with them being further away from central source.

Both variability timescales and luminosities suggest SMBHs of  $M \sim 10^6 - 10^9$  as sources:

$$L_{\text{edd}} = 6 \times 10^{46} \left( \frac{M_{\text{BH}}}{10^9 M_\odot} \right) \text{ erg/sec}$$



Assuming a radiative efficiency  $\xi = \frac{L}{\dot{M}c^2} \sim 0.1$ ,

$$\dot{M}_{\text{edd}} \sim 20 \left( \frac{M_{\text{BH}}}{10^9 M_{\odot}} \right) M_{\odot} \text{yr}$$

Characteristic growth time:  $t_{\text{grow}} = \frac{M_{\text{BH}}}{\dot{M}} \sim 5 \times 10^8 \xi \left( \frac{L}{L_{\text{edd}}} \right)^{-1} \text{yr}$

Unsolved mystery: SDSS 1148+3251 has  $z=6.4$ ,

when  $t_u \sim \text{Gyr}$  has  $M_{\text{BH}} \sim (2-6) \times 10^9 M_{\odot}$ .

If grew from  $\sim 10 M_{\odot}$  BH, would take time

$$t \sim \ln \left( \frac{10^9 M_{\odot}}{10 M_{\odot}} \right) t_{\text{grow}} \sim \text{Gyr to grow} \\ \approx t_u \quad ???$$

Typical quasar lifetime  $\sim 100 \text{ Myr} \sim \frac{t_u}{100}$  today.

$\Rightarrow$  expect quasars to be abundant, relative to galaxies, at  $z \sim 5-6$ , but less abundant today.

Dynamical "duty cycle"  $\sim 100 \text{ Myr}$

Measurement of BH masses:

① can use stellar dynamics within ~~radius~~ distance

radius of influence  $\rightarrow R_{\text{infl}} \sim \frac{GM_{\text{BH}}}{\sigma_*^2} \sim 16.2 \text{ pc} \left( \frac{M_{\text{BH}}}{8 M_{\odot}} \right) \left( \frac{\sigma_*}{200 \text{ km/s}} \right)^{-2}$

$\nearrow$   
stellar velocity distn

② Maser emission from disk measured w/ VLBI  
e.g. measure Keplerian rotation curve at  $\sim 0.2 \text{ pc}$   
e.g.,  $v \sim 1000 \text{ km/sec}$ . e.g., NGC 4258

③ Broadened Fe line in disk (maybe)

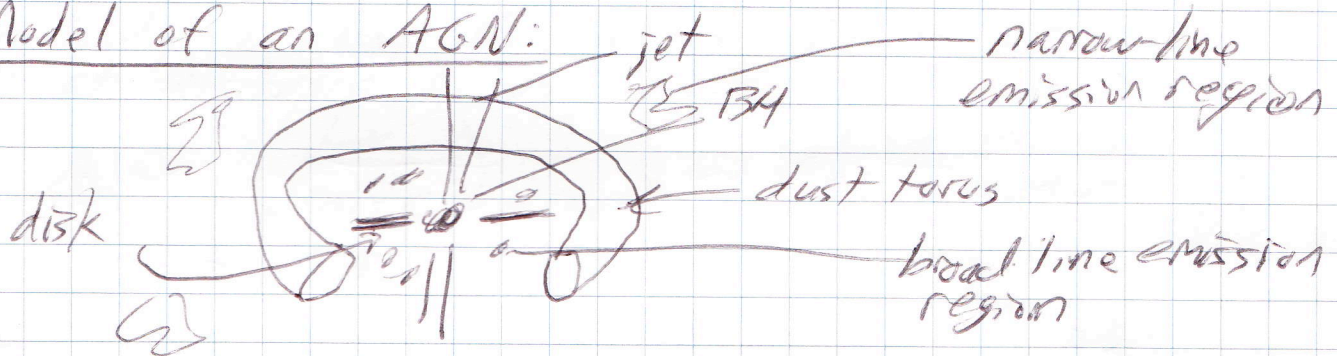


## Feeding the monster:

stellar clusters in galactic centers probably not dense enough to allow binary stellar encounters gravitational interaction to drive stars into BHs.

Are  $\therefore$  probably accreting gas; accretion may be triggered by gas inflow associated with galaxy mergers; evidence is that AGN activity seems correlated with mergers.

### Model of an AGN:



- ① BH masses seem to be correlated with B-Band luminosity and  $\sigma_*$  of bulges:

$$M_{BH} = 8 \times 10^7 M_\odot \left( \frac{L_{B, bulge}}{10^{10} L_{B, \odot}} \right)^{1.08}$$
$$= 1.66 \times 10^8 M_\odot \left( \frac{\sigma}{200 \text{ km/s}} \right)^{4.56}$$

but see wide variety of AGN behaviors for same  $M_{BH}$ .

- ② Disk: extend to  $\sim 100 - 1000 R_s$

SS disk:  $T(r) = 6.3 \times 10^5 \text{ K} \left( \frac{\dot{M}}{\dot{M}_{\text{edd}}} \right)^{1/4} \left( \frac{M_{BH}}{10^8 M_\odot} \right)^{-1/4}$

with  $\dot{M}_{\text{edd}} = 0.1 L_{\text{edd}} / (c^2)$   $\times \left( \frac{r}{R_s} \right)^{3/4}$

disk emission generally associated with big blue bump in UV.



Observationally, big blue bump obscured at  $\lambda < 912 \text{ \AA}$  because of Ly-break absorption by H in Milky Way

Higher-energy radiation from central source must be nonthermal; e.g., inverse-Compton scattering of UV photons by CR  $e^-$ 's that have been accelerated by shocks.

Observation of  $\sim \text{MeV}$  ( $\sim 2m_e c^2$ )  $\gamma$ 's implies that pair production may occur near BH. If  $\gamma$ -ray luminosity is  $L_\gamma$ , then number density of  $\gamma$ 's at distance  $r$  is

$$n_\gamma \sim \left( \frac{L_\gamma}{4\pi R^2 c} \right) \frac{1}{2m_e c^2} \quad \begin{array}{l} \text{above threshold for} \\ \gamma \rightarrow e^+ e^- \quad \text{Thomson} \\ \text{cross-section} \end{array}$$

Optical depth for  $e^+ e^-$  production is  $\tau \sim n_\gamma \sigma_T R$ ,  
so expect  $\tau \gtrsim 1$  when

$$\frac{L_\gamma \sigma_T}{8\pi R m_e c^3} \gtrsim 1$$

$$\text{or if } \frac{L_\gamma}{L_{\text{edd}}} \gtrsim \frac{4m_e}{m_p} \left( \frac{R}{R_s} \right) \sim 2.2 \times 10^{-3} \left( \frac{R}{R_s} \right)$$

In this case will get synchrotron radiation from central source.

Jets: collimated outflows from central source  
very radio bright; move at vnc with Lorentz factors  $\Gamma = (1-v^2)^{-1/2} \sim 30$ .

Superluminal motion:

Some jets have bright blobs or knots that are moving  $\perp$  to LOS, with apparent velocities

$$V = \frac{D \dot{\theta}}{D \dot{\theta}} \approx \sim 6c \quad !!$$

where  $D$  = distance



Such an apparent superluminal velocity arises because jet is moving toward us. In time interval  $\Delta t$ , the blob travels transverse distance  $\Delta y$ , so

$$\frac{\Delta y}{\Delta t} = v \sin \theta \quad \text{angle of motion wrt. to LOS}$$

In this case If the blob moves towards us, then we observe this time interval to be

$$\Delta t_{\text{obs}} = \Delta t - \frac{\Delta x}{c} = \Delta t(1 - \beta \cos \theta) \quad \beta = v/c,$$

so the apparent velocity is

$$v_{\text{app}} = \frac{\Delta y}{\Delta t_{\text{obs}}} = \frac{v \sin \theta}{1 - \beta \cos \theta}$$

which may be  $> c$ . the max  $v_{\text{app}}$  for given  $\beta$  is obtained by setting

$$\frac{dv_{\text{app}}}{d\theta} = 0 \Rightarrow \cos \theta_{\text{max}} = \beta \Rightarrow \sin \theta = \frac{1}{\Gamma}$$

$$\Rightarrow v_{\text{app, max}} = v\Gamma \quad \Gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

$\therefore$  Superluminal motion of  $v_{\text{app}} \approx 6c$  (e.g., in M87)  
 $\Rightarrow \Gamma \approx 6$ .

Doppler boosting:

Since  $I_\nu / \nu^3$  is a relativistic Lorentz invariant, and since the observed frequency is

$$\nu_{\text{obs}} = \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \theta} \nu_{\text{emitted}} \quad D$$

$$\text{We observe } I_\nu^{\text{obs}}(D\nu) = D^3 I_\nu^{\text{em}}(\nu).$$

So frequency is shifted by  $D$  and intensity by  $D^3$ .  
 E.g., if  $\Gamma = 4$  (and  $\cos \theta \sim 1$ ),

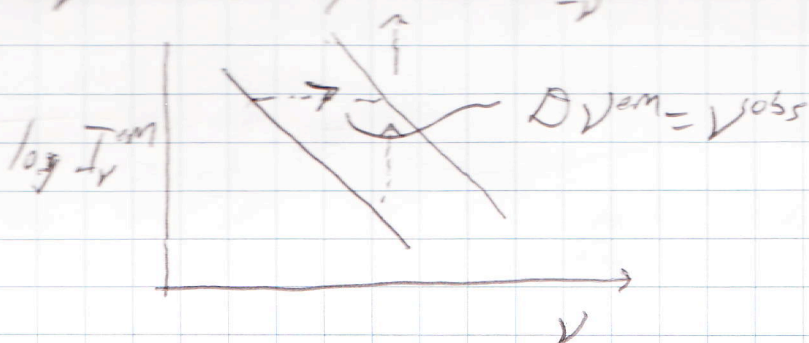
$$D \approx \sqrt{\frac{1 + \beta}{1 - \beta}} \sim \frac{1 + \beta}{(1 + \beta)\Gamma} \sim \frac{1 + \beta}{\Gamma} \sim \frac{10}{8} \text{ for } \Gamma \sim 5$$



So  $I_p$  may be boosted by  $\sim 1000$ !

If  $I_p^{em} \propto \gamma^2$ ,  $\Rightarrow I_p^{obs} = D^{3+2\alpha} I_p^{em}$

i.e.



### Collimation of jet:

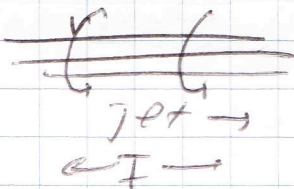
Jets stay collimated over huge distances. Why?

The turn-exhaust model (Blandford-Rees 1974):

supposes outflow of constant mass-injection rate into medium of ~~decrea~~ pressure  $p$  that decreases with distance  $r$  from source (as expected in galaxy). Can show that if gas flow in jet is adiabatic, the pressure can keep jet collimated.

Problem: pressure required near launch point is huge, far larger than observed.

Pinch effect: If there is current in jet along jet axis, it produced toroidal  $B$  that then confines jet.



Problems: jets suffer kink and Kelvin-Helmholtz instabilities

Simulations (relativistic/MHD) are being used to understand what's going. Show cocoons, shocked jet material that flows back to help further collimate jet.

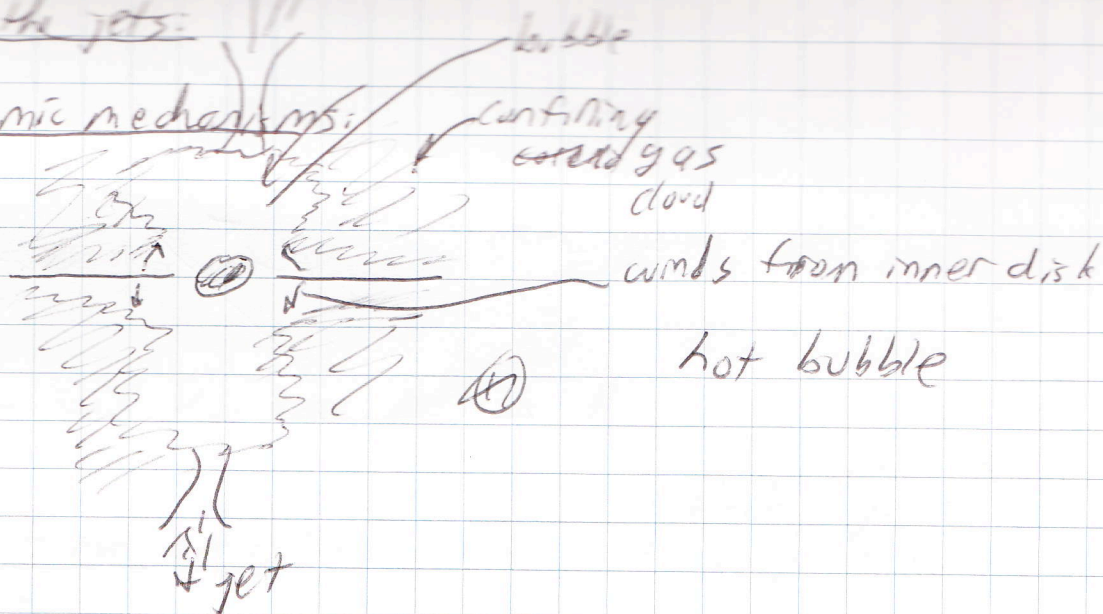




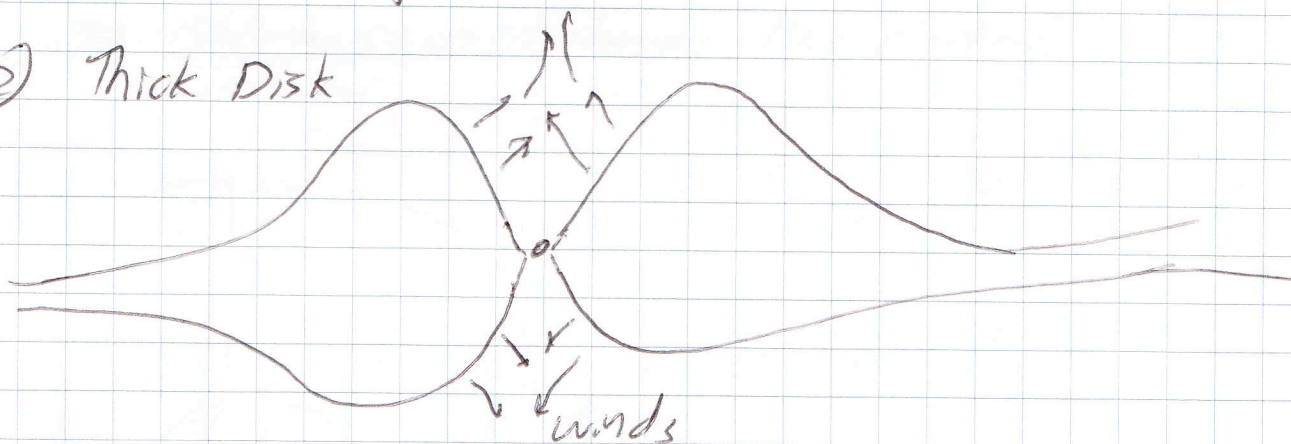
## Launching the jets:

### Hydrodynamic mechanisms:

①

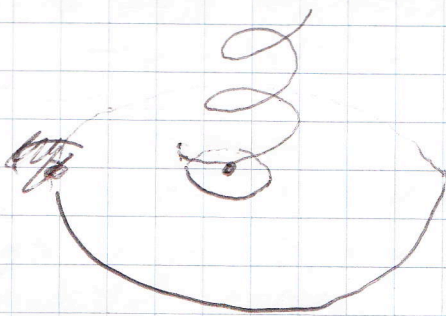


② Thick Disk



Neither of these seems to promising, as huge pressures are required. Moreover, expect strong B fields to play a role:

### Hydromagnetic Mechanisms:



Blanford-Payne:

B fields anchored to inner disk spiral around toward  $\hat{z}$  axis.

Plasma confined to move along field lines is flung away along jet axis.

May also be strong Poynting flux



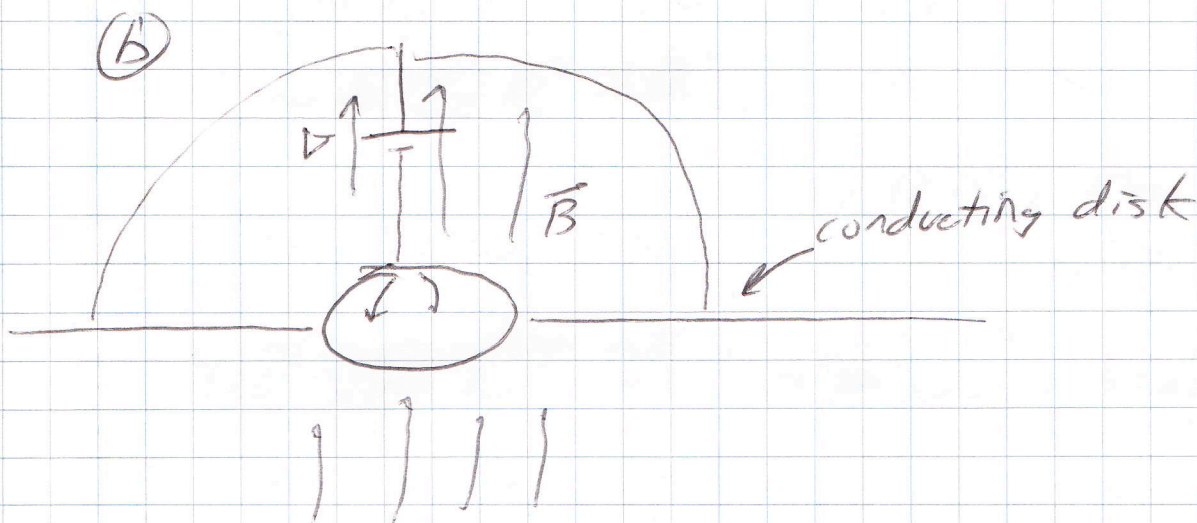
Blanford-Znajek: Is essentially same thing, but  $\vec{B}$ -field lines emerge from black hole (and are confined there by disk); rotation twirling of  $\vec{B}$ -field lines powered by spin of BH.

The reasoning (in brief):  $\leftarrow$  can all be backed up by complicated math

① BH no-hair theorems tell us that  $\vec{E}$  fields emerging from charged BH are radial; ~~just like~~ around i.e.  $\perp$  to ~~BH~~ BH horizon, just like those emerging from conducting sphere

~~$\Rightarrow$  BH~~

$\Rightarrow$  BH horizon behaves like electrical conductor



Suppose we put a spherical conductor, free to spin about its  $z$  axis surrounded by (and electrically connected to) a stationary conducting disk.

The circuit is completed by a wire that connects the north pole of the sphere to the disk.

The entire sphere is immersed in a uniform  $\vec{B}$  field

A voltage  $V$  is then applied. This drives a current  $I$  (from the NP to the equator)  $\perp$  through the sphere. There is then a nonzero torque,  $\propto \vec{J} \times \vec{B}$  that causes the conductor to spin.



Conversely, if there is no applied voltage, but the conductor is spinning, that spinning will drive a current through the circuit — a unipolar inductor

Likewise, in the BZ mechanism the spinning BH immersed in a  $\vec{B}$  field drives a current (and therefore does work with power  $RI^2$ ) through the circuit.

Let's do an OoM estimate:

If we drive a Poynting flux with  $\vec{E} \times \vec{B}$  over two cylinders of area  $\pi R_s^2$ , the Poynting luminosity will be

$$L \sim 2\pi R_s^2 \frac{c B^2}{4\pi} \sim \frac{1}{2} c B^2 R_s^2$$

$$\sim 1.5 \times 10^{47} \text{ erg/sec} \left( \frac{B}{10^4 \text{ G}} \right)^2 \left( \frac{M_{\text{BH}}}{10^6 M_\odot} \right)^2$$

The voltage drop ~~and~~ between BH NP and disk will be  $V \sim R_s B \sim 3 \times 10^{12} \text{ V} \left( \frac{M_{\text{BH}}}{10^6 M_\odot} \right) \left( \frac{B}{10^4 \text{ G}} \right)$

— In BH, the current carrying 'wires' are  $\vec{B}$ -field lines that thread the disk and BH.

### Radiation from Jets and Lobes:

Is presumably synchrotron radiation. Often linearly polarized, usually (but not always)  $\perp$  to jet axis. This is understood because

cross-sectional area of jet

$$B_{\parallel} \propto \frac{1}{A} \propto \frac{1}{(r\theta)^2} \quad \text{while} \quad B_{\perp} \propto \frac{1}{r} \quad \left( \text{like in radiation field} \right)$$

jet opening angle

so  $B_{\perp} \gg B_{\parallel}$  at sufficiently large  $r$ .



Eg. Cyg A:

$L \sim 10^4 L_\odot$  from lobes;  $n_e \sim 10^{-4} - 10^{-3} \text{ cm}^{-3}$   $B \sim 10 - 100 \mu\text{G}$

$$F_\nu \propto \nu^{-\alpha} \approx 0.6 \Rightarrow n_e(E) \propto E^{-3}$$

with  $S = 2\alpha + 1 \approx 2.2$

$\alpha$  ~~steepens~~ <sup>increases</sup> from hot spots to center of source

$\Rightarrow e^-$ 's accelerated in shock at hot spot and then lose energy (faster ones losing energy more rapidly) as they diffuse away from it

$\vec{B} \parallel$  jet in lobes, but chaotic near hot spots.

$e^-$ 's have synchrotron power,

$$\left(\frac{dE}{dt}\right)_{\text{synch}} = \frac{4}{3} \Gamma_T c \left(\frac{E}{m_e c^2}\right) \left(\frac{B^2}{8\pi}\right) = 1.1 \times 10^{-15} (\text{erg/s}) \gamma^2 \left(\frac{B}{G}\right)^2$$

with loss time

$$\tilde{t}_{\text{sync}} \approx \frac{E}{dE/dt} = \frac{6\pi m_e^2 c^3}{\Gamma_T B^2 E} = 655 \text{ sec} \left(\frac{B}{G}\right)^{-2} \left(\frac{E}{\text{erg}}\right)^{-1}$$

Using the characteristic synchrotron frequency,

$$\nu_c = \frac{\omega_c}{2\pi} = \frac{eB}{2\pi m_e c} \left(\frac{E}{m_e c^2}\right)^2$$

Then, the total energy in the lobes (in  $e^-$ 's) is

$$U_e = L \tilde{t}_{\text{sync}} = L \frac{(4\pi m_e c e)^{1/2}}{2^{1/2} \Gamma_T} B^{-3/2} \nu_c^{-1/2}$$

Assuming CR protons have energy  $U_p = k U_e$  (e.g.,  $k \approx 100$  in MW), the total energy is

$$U = (1+k)U_e + U_{\text{mag}}$$

Now  $U_e \propto B^{-3/2}$  and  $U_{\text{mag}} \propto B^2$



and  $U$  is minimized at  $U_{\min} = \frac{3}{2}(1+k)U_0$

when  $B = B_{\min} \sim 1300 \text{ G} \left( \frac{L}{\text{erg/sec}} \right)^{2/3} \left( \frac{v_{\text{rel}}}{10^4} \right)^{2/3} \left( \frac{\Delta}{\text{cm}^2} \right)^{-2/3} \times (1+k)^{2/3}$

e.g., in Cys A,  $U_{\min} \approx 5 \times 10^{-5} \text{ G}$   $U \sim 10^{59} \text{ erg}$

with  $L \approx 5 \times 10^{44} \text{ erg/sec}$ ,  $t_{\text{sync}} \sim 10^4 \text{ yr.}$

Find  $t_{\text{sync}} \ll \frac{50 \text{ kpc}}{c} \approx 1.6 \times 10^5 \text{ yr.}$  ← light travel time

so  $e^-$ 's must be re-accelerated within lobes, probably via Fermi acceleration inside hot spots.

Also see X-rays produced via synchrotron self-Comptonization (SSC) from jets. Here,  $\delta$  of frequency  $\nu$  is upscattered to frequency  $\nu' \sim \delta^2 \nu$  by  $e^-$  of  $\delta$ .

Broad-line regions: are regions near source from which broad-line emission comes from.

Strong emission lines due to decay of excited states produced by photoionizing radiation from source.

Line widths  $\Rightarrow$  bulk motions <sup>up to</sup>  $\sim 10^4 \text{ km/sec}$

(cannot be thermal because  $10^{12} \text{ K}$  gas would not be atomic).

$\frac{v}{c} \sim \frac{1}{30} \Rightarrow$  must be within  $\sim \frac{500}{30}$  Schwarzschild radii  $\sim 10 \text{ pc}$

In these clouds, an excited atom can decay radiatively or be collisionally de-excited.

By measuring relative strengths of lines w. different radiative-collisional ratios producing emission line

$\Rightarrow n_e \approx 10^9 - 10^{10} \text{ cm}^{-3}$  in BLR clouds



Total luminosity  $\Rightarrow$  total mass  $\Rightarrow$  Volume filling factor of BLR clouds is only  $\sim 10^{-6} - 10^{-5}$ , and have masses (in total) of few  $M_{\odot}$ .

Reverberation mapping gives  $\sim 20$  days for Seyfert 1 NGC 5548.

Covering fraction  $\sim 10\%$  (from continuum-line).

Narrow-line regions: are still large compared with typical galaxies

Have widths  $\sim 200 - 2000$  km/s; forbidden lines ( $t_{dec} \sim$  seconds), so are not collisionally de-excited.  
 $\Rightarrow n \sim 10^3 - 10^4 \text{ cm}^{-3}$ .

Spatially resolved in some Seyferts  $\sim 50 - 200 \text{ pc}$ .

Volume filling factor  $\sim 10^{-6}$   $M_{tot} \sim 10^6 M_{\odot}$

$T \sim 10,000 - 25,000 \text{ K}$ .

Seems to arise from cores  $\perp$  to disk.

Molecular torus:

IR bump in quasar spectra may be due to torus of dust or molecular gas which absorbs quasar radiation and re-radiates at  $T_{dust} \sim 20 - 80 \text{ K}$  at  $60 - 150 \mu\text{m}$ .

$$L_{IR} = 2\pi R_{dust}^2 \sigma T_{dust}^4$$

$$\Rightarrow R_{dust} = 0.4 \text{ pc} \left( \frac{L_{IR}}{10^{46} \text{ erg/sec}} \right)^{1/2} \left( \frac{T_{dust}}{2000 \text{ K}} \right)^{-2}$$

$\sim 50 - 100 \text{ pc}$



## Unified Model:

All AGN are the same; are just viewing along different directions;

e.g., blazar, looking right down jet

Seyfert looking from side; central source obscured by torus.