21 – AGN Part 2

"Facts"

L_{QSO}~10^{13} L_{Sun} ~ 10^{46} erg/s ~ 10^{39} W
R_{QSO}~10^{15} cm (~100 AU)

What powers the tremendous luminosities of the AGN?
How does the power source fit into such a "small" space?

Nucleosynthesis?

$$\frac{E}{mc^2} = \frac{\Delta mc^2}{mc^2} \sim 0.007$$
$$\frac{\Delta E}{\Delta t} = Power = L = 0.007\dot{m}c^2$$

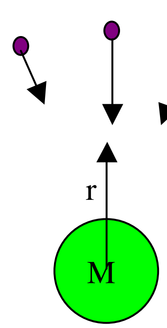
Suppose a galaxy converts 10% of all of its H during its 10^{10} year lifetime…..

$$\dot{m} = \frac{\frac{1}{10}10^{11}M_{sun}\left(2x10^{33}g\ /\ M_{sun}\right)}{10^{10}yr\left(3x10^{7}s\ /\ yr\right)} = \frac{2}{3}x10^{26}g\ /\ s$$
$$L = 0.007\left(\overbrace{\frac{2}{3}x10^{26}g\ /\ s}^{\dot{m}}\right)\left(\underbrace{9x10^{20}cm^2\ /\ s^2}_{c^2}\right)$$
$$= \underbrace{4x10^{44}erg\ /\ s}_{4x10^{37}W} \sim \frac{1}{25}L_{QSO}$$

NUCLEOSYNTHESIS WON'T WORK. TOO INEFFICIENT! What's left?

GRAVITATIONAL ENERGY (GPE⇒KE⇒ThE⇒RadE)

<u>Spherical Accretion</u>



$$L = \frac{\varepsilon GM}{r}\dot{m}$$

ε is the efficiency of converting mass into *radiant* energy. ε can be ~0.1 for accretion, as we will see later on.

What would happen if a galaxy of 10^{11} stars "drops" 10% of them onto a BIG MASS during its 10^{10} year lifetime?

$$L_{QSO} = \frac{\varepsilon GM}{r}\dot{m} = \frac{0.1\left(6.67x10^{-8}\right)M}{r}\frac{\frac{1}{10}10^{11}M_{sun}\left(2x10^{33}g / M_{sun}\right)}{10^{10}yr\left(3x10^{7}s / yr\right)}$$

$$10^{46}erg / s = 4x10^{17}\frac{M}{r}$$

This is possible IF $\frac{M}{r} \sim 2.5x10^{28}\ cgs$

This requires a very dense object:

White Dwarfs $\frac{M}{r} \sim \frac{M_{sun}}{R_{Earth}} \sim \frac{2x10^{33}}{6.4x10^{8}} \sim 3x10^{24}\ cgs$

Neutron Stars $\frac{M}{r} \sim \frac{M_{sun}}{10km} \sim \frac{2x10^{33}}{10^{6}} \sim 2x10^{27}\ cgs$

We need something denser than an atomic nucleus!!!!!

What about Black Holes? Here, the innermost distance that accreting matter can radiate its energy to the rest of the universe is the event horizon. For a nonrotating BH, this is located at the Schwarzschild Radius R_S:

$$R_S = \frac{2GM}{c^2}\ or\ \frac{M}{R_S} = \frac{c^2}{2G} \sim 7x10^{27}\ cgs$$

This certainly looks more promising, but we may still need a greater efficiency factor or higher accretion rate to make this work. Note: *Because the accretion rates need to be on the order of 1 M_{sun}/year, electron degenerate white dwarfs and neutron degenerate neutron stars must collapse into a black hole after a few years anyway, so all we are left with are black holes (or perhaps some other even more exotic object)!*

The Problem with Spherical Accretion:

It is very self-limiting. As the material falls down, it is running into photons radiating outward. These apply a force to the accreting matter. These will balance when the outward force due to radiation

$$F_{out} = \frac{\sigma_T}{c}\frac{L}{4\pi r^2}$$

equals the inward force due to gravity

$$F_{in} = \frac{GM\left(m_p + m_e\right)}{r^2} \approx \frac{GMm_p}{r^2}$$

The luminosity where this occurs is called the *Eddington Luminosity*

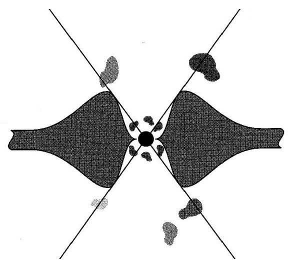
$$F_{out} = F_{in} \text{ when } L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T}$$

$$L_{Edd} \approx 1.3x10^{38}\left(\frac{M}{M_{sun}}\right) erg\ s^{-1}$$

We think that most "supermassive black holes" in the cores of galaxies (when they are there) are on the order of 10^8 M_{sun}. If so, the maximum luminosity a QSO or other AGN could have is 10^{46} erg/s. Many have L > L_{Edd}, and thus must be accreting in some sort of "super-Eddington" manner. How is this possible?

Accretion Disks?!

Here, much of the radiation may not even hit the accreting material! Detailed calculations suggest that L~20L_{Edd} can be achieved this way.



(ALSO: We use L here assuming that the radiation is emitted isotropically. This is obviously incorrect for "beamed" sources).

ACCRETION DISKS - GENERAL CHARACTERISTICS

Accretion disks generate their luminosity through viscous dissipation. The energy production rate per unit disk face area for a steady-state disk ($\dot{m}(R) = const.$) is

$$D(R) = \frac{3GM\dot{m}}{8\pi R^3}\phi(R)$$

For a star (an object with a real surface) $\phi(R) = 1 - \sqrt{\frac{R_*}{R}}$

For a Schwarzschild (non-rotating) black hole,

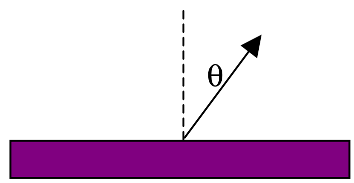
$$\phi(R) = 1 + \frac{1}{r/3 - 1} - \frac{2}{\sqrt{r/3 - 1}} \text{ for } r > 6$$

$$\text{where } r = \frac{Rc^2}{GM} = \frac{R}{R_G} \quad R_G \equiv \frac{R_S}{2} \text{ "gravitational radius"}$$

The innermost limit of r > 6 (i.e. R > $6R_G$ or R > $3R_S$) comes about because that is the closest marginally stable orbit possible for a SBH.

For a Kerr (maximally rotating) BH, $\phi(R)$ is more complicated. Here, the innermost value of R is at 1.23 R_G. This allows even higher disk temperatures to be achieved close in, but much of that energy is "lost" as the light must climb out of the gravitational potential well.

Emission at the Disk Surface



For a disk emitting at specific intensity I_ν erg cm^{-2} s^{-1} Hz^{-1} ster^{-1}, the net emission is

$$D(R) = \int_0^{2\pi}\int_0^{\pi} I_\nu(R)\cos\theta\sin\theta d\theta d\phi = \pi I_\nu(R)$$

for an isotropic radiator.

If the disk is optically thick, then $I_\nu = B_\nu$ (Planck function), and so

$$\pi\int_0^\infty B_\nu(R)d\nu = \sigma_{SB}T_{eff}^4(R)$$

$$\text{So}\ \ T(R) = \left[\frac{3GM\dot{m}}{8\pi R^3\sigma_{SB}}\phi(R)\right]^{1/4} \propto R^{-3/4}\phi^{1/4}$$

Scaling Parameters

Let $x = \dfrac{R}{R_G}$. Then (ignoring the ϕ term),

$$T_x \propto \left[\frac{M\dot{m}}{x^3 R_G^3}\right] = \left[\frac{M\dot{m}}{x^3\left(\frac{GM}{c^2}\right)^3}\right] \propto \dot{m}^{1/4}M^{-1/2}x^{-3/4}.$$

The total energy liberated over all frequencies $\propto T^4 \propto \dot{m}M^{-2}$ per unit surface area. The actual area $\propto R^2 \propto M^2$. $\therefore L \propto T^4 \propto \dot{m}$ as expected, and is independent of M: $L = \varepsilon\dot{m}c^2$.

Total Energy Liberated

Let L be the rate at which binding energy is released to universe by the accretion disk. It is possible, by integrating D(R) from infinity down to the innermost stable orbit R_{in}, that

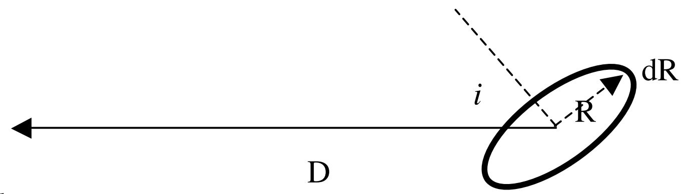
$$L \sim \frac{GM\dot{m}}{2R_{in}}$$

This is half of the total available gravitational energy that could be released for a mass that falls from infinity to R_{in}. In the case of stellar accretion disks, the other half must be released at a boundary shock front as the material hits the star. In the case of black holes, there is no "surface" to hit!

$$\varepsilon = \frac{L}{\dot{m}c^2} = \frac{GM}{2R_{in}c^2} = 3.7x10^{-29}\,\frac{M}{R_{in}}$$

	M	R_{in}	ε
White Dwarf	~0.8M_{sun}	~5000 km	~10^{-4}
Neutron Star	~1 M_{sun}	~20 km	~0.04
SBH		$\frac{6GM}{c^2}$	$\sim\frac{\varepsilon c^2}{6G}$~0.08
KBH		$\sim\frac{1.23GM}{c^2}$	$\sim\frac{\varepsilon c^2}{1.23G}$~0.4

Observed Spectrum



$$\Im_\nu = \oint I_\nu d\Omega = \oint I_\nu \frac{2\pi R dR \cos i}{D^2} \propto \int_{R_{in}}^{R_{out}} I_\nu(R) R dR$$

$IF \quad I_\nu = B_\nu$

$THEN$

$FOR \quad \nu << \dfrac{kT(R_{out})}{h} \quad B_\nu \to 2k\dfrac{T\nu^2}{c^2}$

$so \quad \Im_\nu \propto \nu^2$

$FOR \quad \nu >> \dfrac{kT(R_{in})}{h} \quad B_\nu \to 2h\nu^3 c^2 e^{-h\nu/kT}$

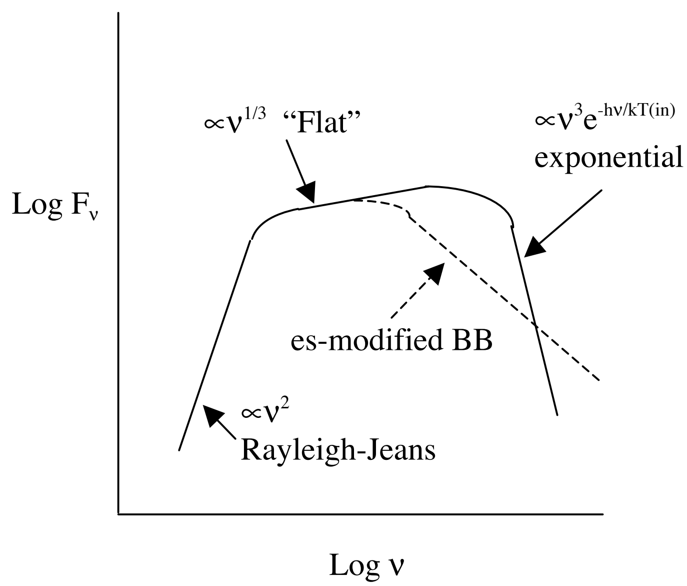
$so \quad \Im_\nu$ *dominated by* $e^{-h\nu/kT}$

BETWEEN THESE LIMITS :

letting $x = \dfrac{h\nu}{kT(R)}$

gives $\Im_\nu \propto \nu^{1/3} \displaystyle\int_0^\infty \frac{x^{5/3}}{e^x - 1} dx$

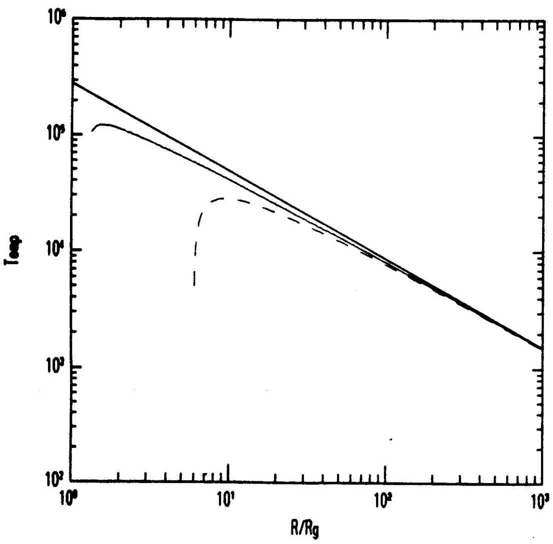
$\therefore \; \Im_\nu \propto \nu^{1/3} \quad or \quad \nu \Im_\nu \propto \nu^{4/3}$



The emitted spectrum of a geometrically thin optically thick disk is shown above right by the solid curve. Because each ring at distance R radiates like a blackbody, at the lowest frequencies the spectrum approaches the Rayleigh-Jeans tail of the coolest portion of the disk (at R_{out}). At the highest frequencies, the spectrum approaches the Wien tail of the hottest region of the disk (at R_{in}). Between those limits, the spectrum is the sum of blackbodies at intermediate temperatures, each weighted by the surface area of the ring at each temperature.

Under some conditions (discussed below), the disk may become *optically thin*, and the locally-emitted spectrum takes on a modified blackbody shape (dashed line in the figure).

In the figures below, I show the observed spectrum of a geometrically thin optically thick accretion disk surrounding a supermassive black hole, similar to those believed to power AGN. The temperature profiles for a SBH and KBH are shown on the left for the case of a BH mass of $10^9 M_\odot$. The spectra for a combination of parameters are on the right. Note the effects of changing the central mass or accretion rate.



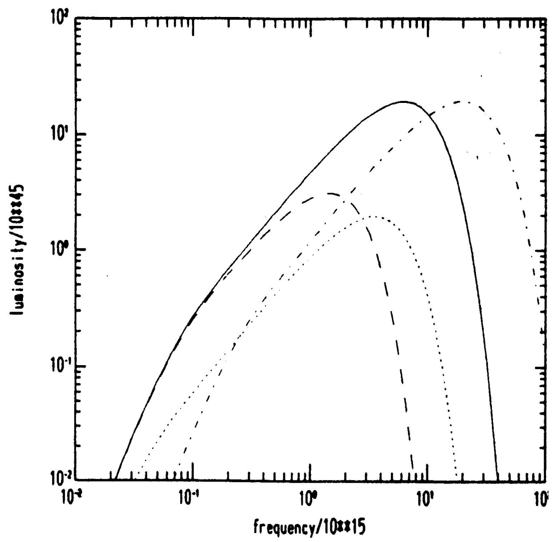


Fig. 3 - The temperature as a function of radial distance for a/M=0 (dashed line), a/M=0.9982 (thin solid line), and for $T \propto (R/Rg)^{-3/4}$ (thick solid line).

Fig. 4 - The emitted spectum of the accretion disk. In this and subsequent plots, the luminosity is that assigned to the disk if it were radiating isotropically. This plot is for a face-on disk. The solid line is for Rin=1.23, $M=10^9$, and $\dot{M}=1$. The other curves are similar except that Rin=6.0 (dashed curve), $\dot{M}=0.1$ (dotted curve), and $M=10^8$ (dot-dashed curve).

Optically Thin Disks

As in the case of hot luminous stars, it may be that the opacity is dominated by electron scattering, not thermal processes. If $\kappa_{es} >> \kappa_{abs}$ and $\tau < 1 \Rightarrow$ T must go up in order to carry the flux, and

$$I_\nu = \frac{2B_\nu\left(1 - e^{-\tau_*}\right)}{1 + \left(1 + \kappa_{es}/\kappa_{abs}\right)}$$

$$\begin{aligned} where\ \tau_* &= h\rho\sqrt{\left(\kappa_{es} + \kappa_{abs}\right)\kappa_{abs}} \qquad (h = disk\ thickness) \\ &\sim h\rho\sqrt{\kappa_{es}\kappa_{abs}} \quad when\ \kappa_{es} >> \kappa_{abs} \end{aligned}$$

and T is set by $\pi\int_0^\infty I_\nu(R)d\nu = D(R)$

Thin Disk Structure – viscosity-dependent "α-disks"

Viscosity ∝ total pressure = $P_{gas} + P_{rad}$

$$\text{3 regions} \left\{ \begin{array}{lll} P = P_{gas} & \kappa = \kappa_{abs} & \textit{outer regions} \\ P = P_{gas} & \kappa = \kappa_{es} & \textit{middle regions} \\ P = P_{rad} & \kappa = \kappa_{es} & \textit{inner regions} \end{array} \right\}$$

Yet other models have attempted to include pressure due to magnetic fields frozen into the ionized gas in the disk.

Thick Disks & Radiation Tori

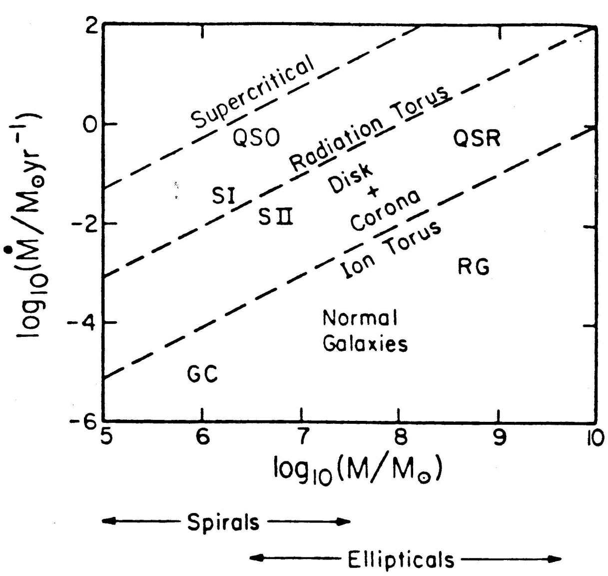
In the inner regions, R/h gets small and so the disk is effectively geometrically thick. Also, as P_{rad} becomes large, it can "puff up" the disk. The emitted spectrum behaves somewhat like a large stellar photosphere.

Ion Tori

For small values of $\dot{m}/M$, the electrons can decouple from protons, cool faster than the protons, and leave a hot ion cloud. To the best of my knowledge, no detailed spectral calculations have been done for this scenario.

Supercritical Accretion

Here, big optically thick clouds (not effectively stopped by radiation pressure) accrete at a rate much higher than the Eddington limit. Again, no detailed calculations of the spectrum, as far as I know.



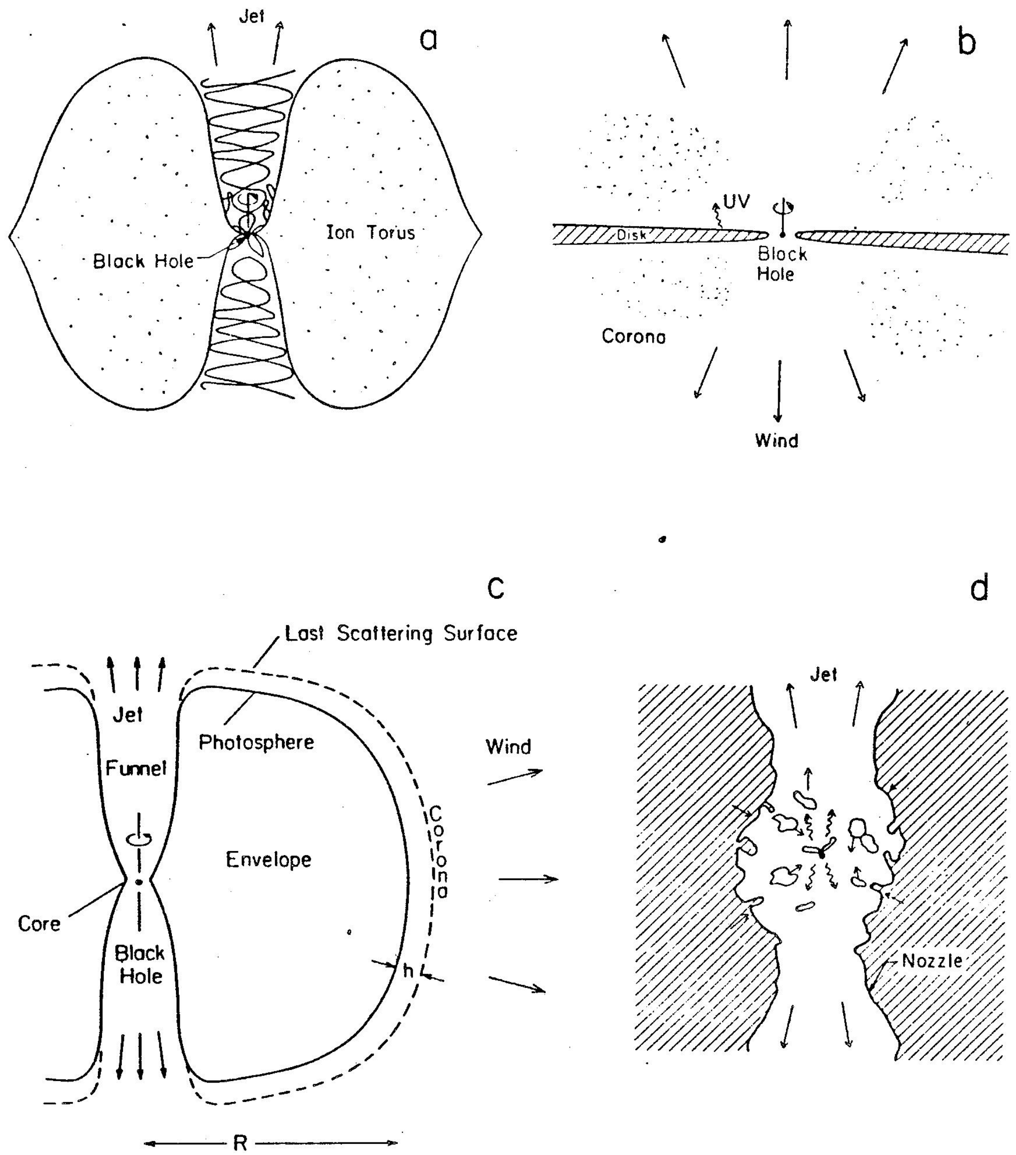


FIG. 2. Four modes of disk accretion: (a) Ion torus, (b) Disk and corona, (c) Radiation torus, and (d) Super-critical accretion.

acquire a temperature comparable with the virial temperature (∿100 MeV) and form a thick ring in orbit around the hole. If the electrons were to be maintained at the same temperature they would be ultrarelativistic and the torus would cool and deflate very rapidly. It is therefore necessary that the electrons be substantially cooler than the

It is generally though that a thin disk that puffs up in the innermost zone is the most likely structure of the accretion disk and that the disk is responsible for the “Big Blue Bump” on the visible-UV portion of the SED of AGN. Comptonized photons from the disk may be responsible for the X-ray emission in radio-quiet objects, while comptonized jet photons may be responsible for the X-rays in radio-loud object (more on this later).

For a standard "α-disk" models, there are a number of timescales for possible variability that could, in principle, be tested against observations of the BBB.

t_ϕ	the timescale for variability due to a gas blob's orbital motion
t_z	the timescale for hydrostatic equilibrium to be established vertically
t_{th}	the timescale for the disk to dump a large fraction of its energy
t_v	the timescale for changes in the surface density due to viscosity
$\Delta t(R)$	the time it takes a particle to spiral in from the outer radius
$\Delta t_s(R)$	the sound travel time from the outer radius

For example, with $\dot{m} = 0.13 M_{sun} / yr \quad M = 7x10^8 M_{sun}$:

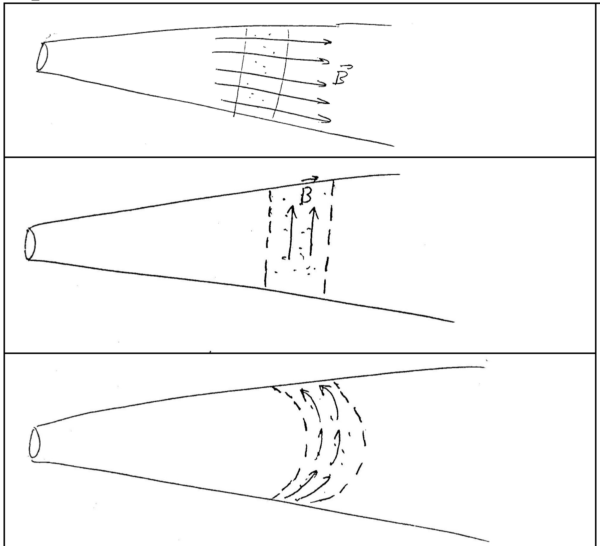
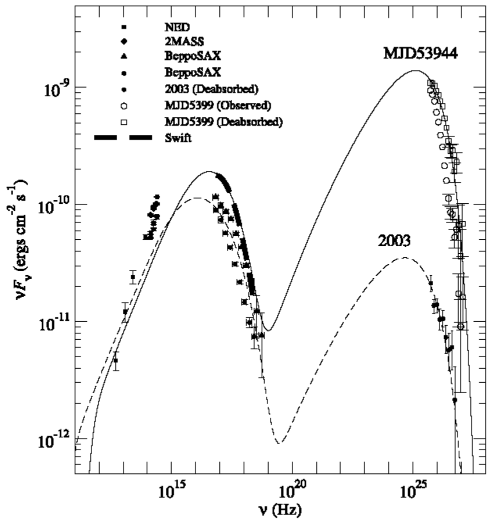
R/R_G	1.23	10	100	1000
t_ϕ	1 hr	1 d	1 mo	3 yr
t_z	1-5 hr	1-3 d	30-100 d	3-9 yr
t_{th}	1 d – 1 mo	10 d – 3 yr	1-100 yr	30-3000 yr
$t_{v\Sigma}$ a	50 d	3 yr	10^2 yr	10^3yr
b	14 y	300 yr	10^4 yr	10^5yr
c	200 d	10 yr	$3x10^3$ yr	10^4 yr
d	50 yr	10^3 yr	$3x10^4$ yr	10^6 yr
$\Delta t(R)$		10^6-10^8 yr		
$\Delta t_s(R)$		10^4 yr		

$$\left\{\begin{matrix} t_z \\ t_{th} \\ \Delta t(R) \end{matrix}\right\} \Rightarrow \textit{for } \alpha = 0.1 \textit{ and } 0.001$$

$$t_v \sim \left(\frac{R}{h}\right)^2 \frac{t_z}{\alpha} \left\{ \begin{matrix} \left\{\begin{matrix} a & \alpha = 0.1 \\ b & \alpha = 0.001 \end{matrix}\right\} \textit{and } t_z = t_\phi \\ \left\{\begin{matrix} c & \alpha = 0.1 \\ d & \alpha = 0.001 \end{matrix}\right\} \textit{and } t_z = \dfrac{h}{c_s} = \dfrac{8000 M^{3/4} \dot{m}^{3/20} \alpha^{-1/10}}{c_s} \left(\dfrac{R}{R_G}\right)^{9/8} \end{matrix} \right\}$$

What About the Jets?

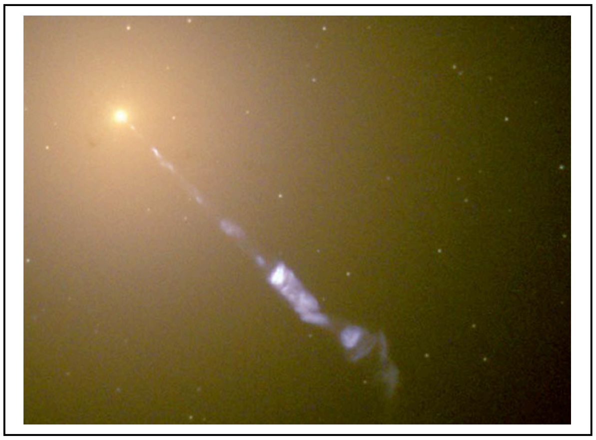
The jets exhibit power-law spectra and significant polarization, indicating that they are emitting synchrotron radiation. The magnetic field can take on a variety of different spatial distributions:

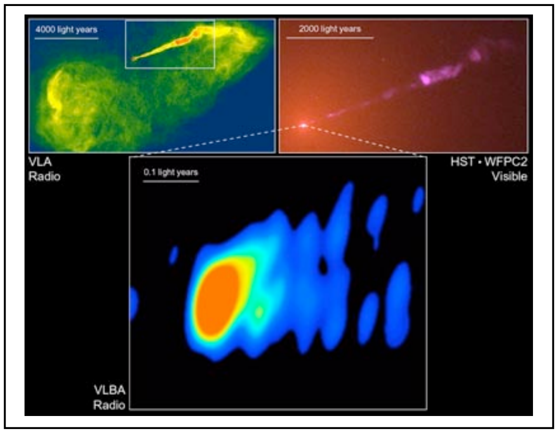
	
Outward flows can affect the magnetic field geometry.	PKS 2155-304 exhibits a double-peaked spectral energy distribution due to synchrotron and self-Compton scattering. From Kusunose & Takahara 2008, ApJ, 682,7 84

$$\nu_{scatt} \approx \gamma^2 \nu_0$$

Many blazers are now known to be strong sources of TeV γ-rays. Correlated observations of γ-ray "flares" with X-rays and VLBI radio structures suggest that the γ-rays are produced by inverse-Compton scattering in the jets, and that the Doppler boost Lorentz factors may be as high as 50!

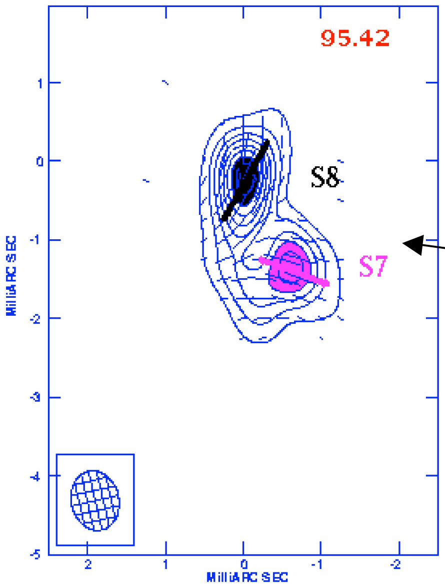
Sometimes the jets in AGN can be seen in visible light, as in M 87 and 3C 273. Bright "knots" in the jet are probably where a major shock is present:





The jet in M 87 (Virgo A) image by the Hubble Space Telescope, along with radio images.

Due to the compression at the shock front, the magnetic fields can get aligned and the particle energies increased. Both help produce large amounts of polarized flux.



The "cores" of these jets, which are stationary (no superluminal motion) are probably the "base" of the jet – actually the place where the source is becoming optically thick.

High spatial resolution (Very Long Baseline Interferometry – VLBI) polarization & flux map of BL Lac.

Simultaneous VLBI and visible-wavelength polarization measurements suggest that the polarized visible light originates at the base of the radio jet.

Note that what we see is actually the *projection* of the magnetic field direction on the sky. The direction of this projection will undergo rotation if the material is moving relativistically (due to the aberration).