Active Galaxies

Supermassive black holes
The formation and evolution of AGN
AGN and galaxy formation

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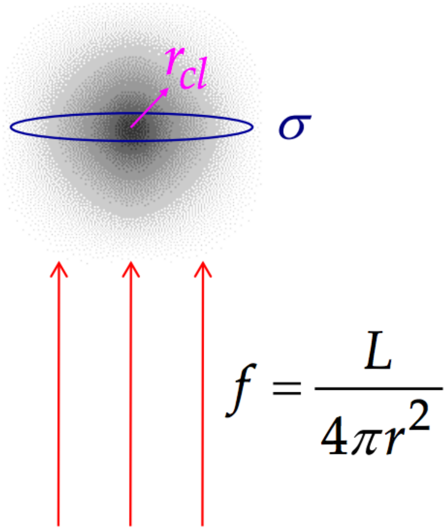
The Eddington luminosity

Around a black hole, most of the material is ionized gas, so an electron or proton is going to experience the gravitational force and radiation pressure.

The effective area of an electron or proton that is subject to radiation is its cross section. The cross section for an electron is the Thomson cross section,

$$\sigma_e = \sigma_T = \frac{8\pi e^4}{3m_e^2c^4}$$

The cross section is inversely proportional to the mass, so an electron has a larger cross section than a proton.



The Eddington luminosity

The net radiation force on the electron is

$$F_{\text{rad}} = \frac{dp_{\text{rad}}}{dt}$$

Recall that, for photons, $E = pc$, so

$$F_{\text{rad},e} = \frac{d}{dt}\left(\frac{E}{c}\right) = \frac{1}{c}\frac{dE}{dt}$$

dE/dt is the power absorbed by the electron from the luminosity, so

$$\begin{aligned} F_{\text{rad},e} &= \frac{1}{c} fA \\ &= \frac{L\sigma_e}{4\pi c r^2} \\ &= \frac{2e^4 L}{3m_e^2 c^5 r^2} \end{aligned}$$

The Eddington luminosity

Each electron will drag a proton with it, since the electromagnetic force dominates. The gravitational force exerted by the black hole on each proton is much larger than that on an electron.

Accretion takes place if $F_{\mathrm{grav},p} + F_{\mathrm{grav},e} > F_{\mathrm{rad},p} + F_{\mathrm{rad},e}$, or, to a good approximation, $F_{\mathrm{grav},p} > F_{\mathrm{rad},e}$.

Thus, in order to accrete while shining at luminosity L, the mass M of the black hole must be such that $\frac{GMm_p}{r^2} > \frac{2e^4 L}{3m_e^2 c^5 r^2}$:

$$L < \frac{3GMm_p m_e^2 c^5}{2e^4} \equiv L_E \qquad \text{given } M$$

$$M > \frac{2e^4 L}{3Gm_p m_e^2 c^5} \qquad \text{given } L$$

where L_E is the Eddington luminosity.

AGN BHs have to be supermassive

Now that we have an expression for the maximum luminosity that can be produced by accretion onto a body of mass M, we can estimate M given $L = 10^{12} L_\odot$ (the luminosity of 3C 273):

$$M > \frac{2e^4 L}{3 G m_p m_e^2 c^5} = 3 \times 10^7 M_\odot$$

So a **supermassive black hole (SMBH) is required**, at least 10× larger than the central BH in the Milky Way.

There are QSOs with luminosities as large as $10^{14} L_\odot$, so we should expect to find central black holes in excess of $10^9 M_\odot$, equivalent to the total mass of a good-sized galaxy.

The event horizon radius of the minimum-mass black hole that would power 3C 273 is

$$R_{\text{Sch}} = \frac{2GM}{c^2} = 0.6 \text{ AU}$$

Accretion rate of a SMBH

The energy released as radiation from the accreted mass is

$$E = \varepsilon m c^2$$

The corresponding luminosity is then

$$L = \frac{dE}{dt} = \varepsilon c^2 \frac{dm}{dt}$$

Assuming that this luminosity is powered by the gravitational potential of the SMBH, the accretion luminosity is

$$L = \frac{d}{dt}\left(\frac{GMm}{r^2}\right) = \frac{GM}{r}\frac{dm}{dt}$$

Rewriting this in terms of the Schwarzschild radius,

$$L = \frac{c^2}{2}\frac{R_S}{r}\frac{dm}{dt}$$

Accretion rate of a SMBH

The efficiency of the black hole is then

$$\varepsilon c^2 \frac{dm}{dt} = \frac{c^2}{2}\frac{R_S}{r}\frac{dm}{dt}$$
$$\varepsilon = \frac{R_S}{2r}$$

As we will see, most of the continuum radiation originates from $r \sim 5R_S$. The efficiency of a SMBH is then

$$\varepsilon \sim \frac{R_S}{2(5R_S)} = 0.1$$

This is a much higher efficiency than that of stellar nucleosynthesis (the p-p chain has an efficiency of $\sim$0.007).

For 3C 273, this translates to an accretion rate of

$$\frac{dm}{dt} = \frac{L}{\varepsilon c^2} \sim 0.68 M_\odot/\mathrm{yr}$$

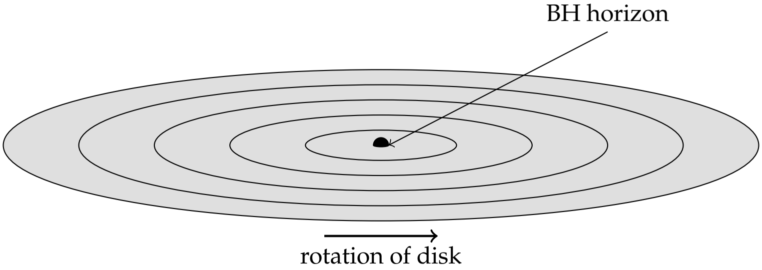
AGN accretion disks

A disk-shaped collection of matter surrounding the black hole in an AGN arises rather naturally, just as it does in galactic black holes and young stellar objects.

- Stars in a galaxy perpetually collide elastically, exchanging energy, momentum, and angular momentum.
- Two stars originally in similar orbits and undergoing such a collision will usually find themselves pushed to different orbits, one going to a smaller-circumference orbit and one going to a larger orbit.
- Thus some stars and gas clouds are pushed to the very center of the galaxy after a number of these encounters.
- There they are tidally sheared in the strong gravity near the black hole.

AGN accretion disks

Eventually the tidally-disrupted material from many stellar encounters settles down into a flattened disk.



The disk can contain $10^3 - 10^6 M_\odot$ and extend $\mathcal{O}(100\text{ ly})$ from the central black hole.

Accretion disks

The disk's surface mass density evolves with time, its behavior determined by the conservation of mass and angular momentum.

For a constant accretion rate ($\frac{dm}{dt} = 2\pi \int \dot{\Sigma} r \, dr =$ constant), $\dot{\Sigma}(r, t)$ depends on the disk's rotation speed and viscosity.

There is a transfer of angular momentum, and therefore energy, throughout the disk due to its viscosity and differential rotation.

In order to understand the disk's emission properties, we need to know its temperature profile.

The temperature profile of an accretion disk

Assuming that all of the dissipated energy is radiated away at the radius at which it is produced, and that the disk is optically thick so that the dissipated energy is thermalized, the temperature profile is

$$2\sigma_{\mathrm{SB}} T^4(r) = \frac{3GM}{4\pi r^3}\frac{dm}{dt}\left(1 - \sqrt{\frac{R_{\mathrm{in}}}{r}}\right)$$

- The temperature peaks at $r = \left(\frac{7}{6}\right)^2 R_{\mathrm{in}}$
- The energy emitted peaks at $r = \left(\frac{5}{4}\right)^2 R_{\mathrm{in}}$
- The total luminosity is $L = \frac{GM}{R_{\mathrm{in}}}\frac{dm}{dt}$
- Half of the total energy radiated away comes from within $r \sim 8R_{\mathrm{in}}$.

If $R_{\mathrm{in}} \sim R_S$, then $L \sim \frac{c^2}{4}\frac{dm}{dt}$.

Operation of AGN accretion disks

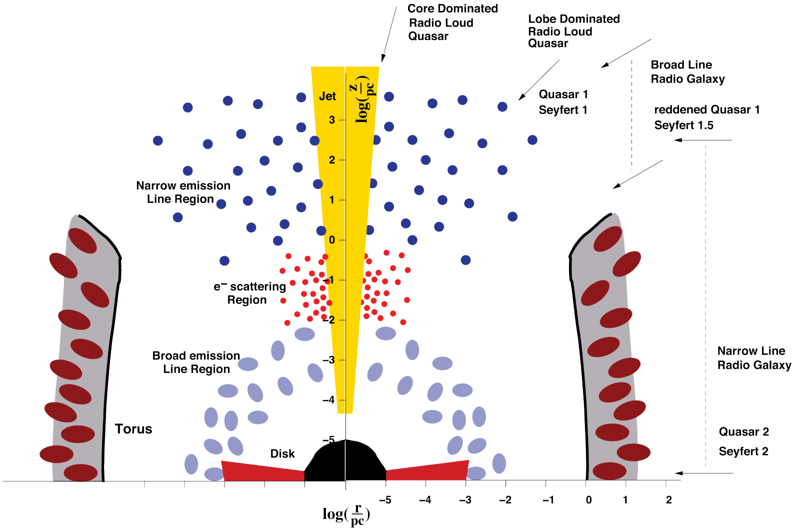
For non-spinning black holes, the innermost stable circular orbit (ISCO) is $3R_S$ and no orbits exist within $1.5R_S$. Within this volume the disk structure breaks down and material tends to stream towards the horizon.

A large amount of power, mostly in the form of X-rays and γ rays, is emitted by the infalling material. The pressure exerted by this radiation is what slows down the rate at which accretion takes place.

Much of this high-energy light is absorbed by the disk, which heats up and re-radiates the energy as longer wavelength light.

The heated disk is observed as a **compact central object** seen in radio images of radio galaxies and QSOs.

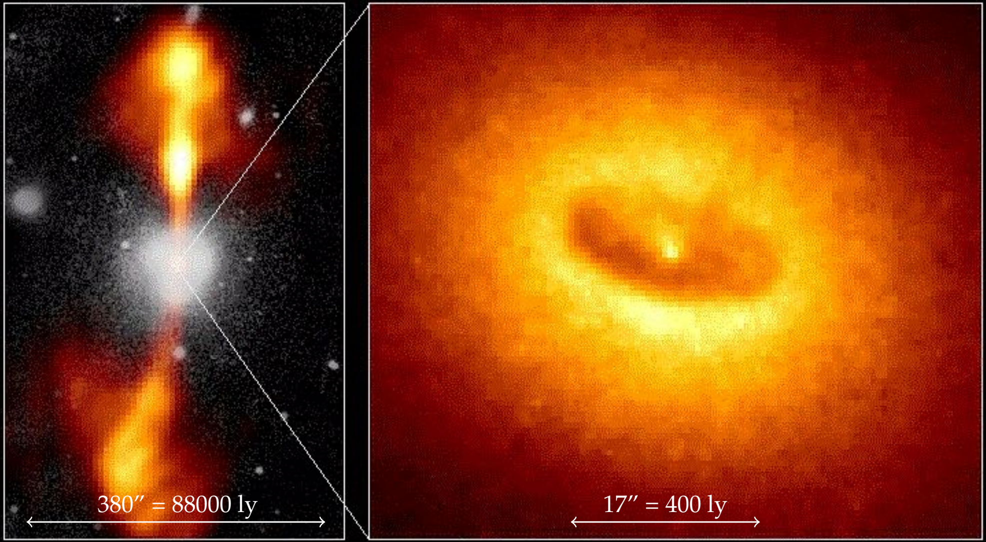
Structure of an AGN



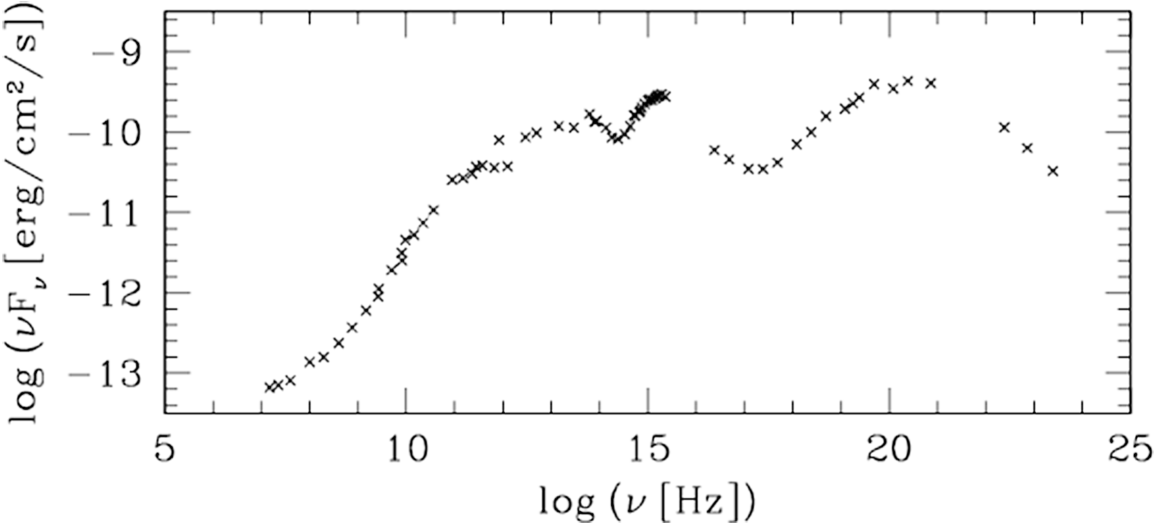
Zier & Biermann (2001)

Accretion disk in NGC 4261

Giant elliptical galaxy NGC 4261. Left: optical/radio overlay. Right: HST image of core. From NASA/STScI.



AGN continuum emission



Source of emission is not thermal

Define the “brightness” temperature in terms of the specific intensity,

$$T_b \equiv \frac{c^2 J_\nu}{2 k_B \nu^2}$$

For compact radio sources, $T_b \sim 10^{11}$ K.

- The amount of gamma radiation expected from an object with this temperature is much greater than that observed! So the **radio emission is not thermal.**
- In this radio region, the electrons must have an energy on the order of $k_B T_b$. This corresponds to an energy much larger than their rest energy, so the **electrons must be relativistic.**

Production mechanism of relativistic electrons

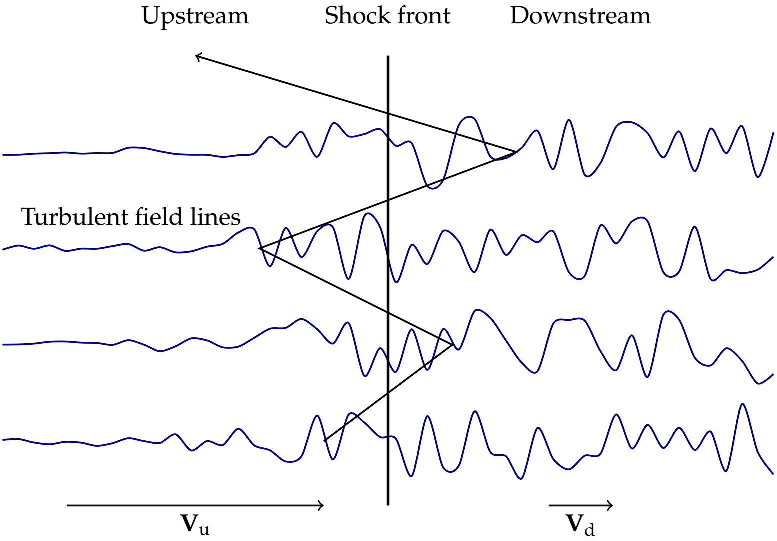
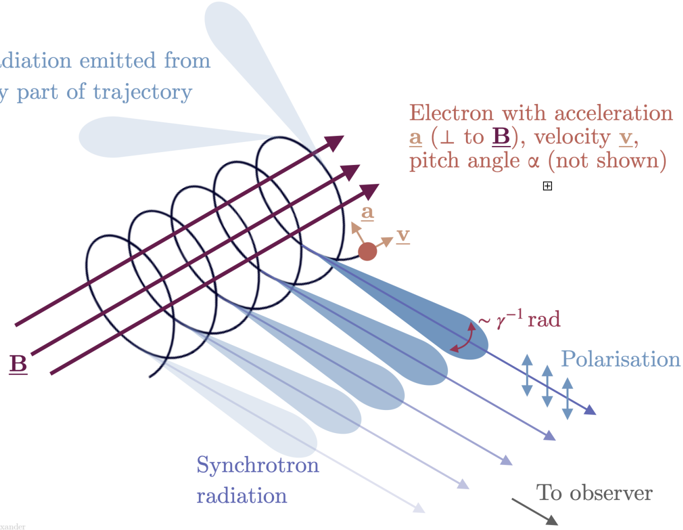


Figure based on Lee (2000)

Synchrotron radiation



Radiation emitted from any part of trajectory

Electron with acceleration $\underline{\mathbf{a}}$ (⊥ to $\underline{\mathbf{B}}$), velocity $\underline{\mathbf{v}}$, pitch angle α (not shown)

Polarisation

Synchrotron radiation

To observer

Emma Alexander

The unified AGN model

Schematic of the unified model of AGN. (See also Beckmann & Shrader (2012) and Netzer (2015).) The model indicates that observations depend only on:

1. Orientation w.r.t. the jet
2. Coverage of the nucleus by a torus of dust in the galactic plane
3. Luminosity of the central black hole