# **Active Galaxies**

The AGN population & Supermassive black holes

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### 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):

$$M > rac{2e^4L}{3Gm_pm_e^2c^5} = 3 imes 10^7 M_{\odot}$$

So a **supermassive black hole (SMBH) is required**, at least  $10 \times \text{larger than the central BH in the Milky Way.}$ 

There are QSOs with luminosities as large as  $10^{14}L_{\odot}$ , so we should expect to find central black holes in excess of  $10^9M_{\odot}$ , 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

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

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#### Accretion rate of a SMBH

The energy released as radiation from the accreted mass is

$$E = \varepsilon mc^2$$

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,

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

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#### 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

$$arepsilon \sim rac{R_S}{2(5R_S)} = 0.1$$

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

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

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# 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.

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#### 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  $(\frac{dm}{dt} = 2\pi \int \dot{\Sigma} r \, dr = \text{constant})$ ,  $\dot{\Sigma}(r, t)$  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

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

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

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

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# 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  $\gamma$  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.

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#### Structure of an AGN accretion disk (not to scale!)



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## AGN continuum emission



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### Source of emission is not thermal

Define the "brightness" temperature in terms of the specific intensity,

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

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<sub>B</sub>T<sub>b</sub>. 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)

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## Synchrotron radiation



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### Inverse Compton scattering

Relativistic electrons can produce photons with energies up through the X-ray via inverse Compton scattering, where low-energy photons are scattered by the relativistic electrons.

On average, each collision shifts the photon frequency

$$u_0 \to \langle \nu 
angle = rac{4}{3} \gamma^2 
u_0 \qquad (\gamma \gg 1)$$

If  $T_b > 10^{12}$  K, the photons produced by the inverse Compton scattering can themselves be scattered by the relativistic electrons, resulting in catastrophic cooling of the electrons.

This imposes a limit on the size of the region producing the radio emission, as  $T_b < 10^{12}$  K for relativistic electrons.

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# Emission lines: allowed v. forbidden transitions

In general, emission lines can be separated into two classes based on their spontaneous transition probability.

Permitted lines have high transition probabilities (corresponding to short lifetimes). These are the transitions allowed by the electric-dipole selection rules.

Forbidden lines have low transition probabilities (corresponding to long lifetimes) and are denoted by square brackets (e.g. [OIII]). These transitions have a zero dipole component, but non-zero higher-order components.

Semiforbidden lines have intermediate transition probabilities and are denoted by a single square bracket (e.g. CIII]).



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## Determining the source of ionization



Kewley et al. (2006)

# Emission line regions around the SMBH

Broad line regions are characterized by emission lines observed with  $\sigma_v > 1000$  km/s. If the motion is due to gravity, then the size of the region should be

$$R \sim \frac{GM}{\sigma_v^2}$$

which translates to a small ( $\lesssim 1$  ly) inner region surrounding the accretion disk.

Narrow line regions emit strong narrow lines with  $\sigma_v \sim 100$  km/s. If the motion is due to gravity, then these regions extend to  $\sim$ 50 pc around the central region.



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If the velocity of the relativistic charges takes them into the disk, then they just collide with disk material and lose their energy to heat. If their velocity takes them perpendicular to the disk, they may escape (Blandford & Rees 1975).

**Jets**: high-speed particles escaping perpendicular to the disk, observed in radio and visible images of radio galaxies and quasars.

Accelerated by gravity and by radiation pressure — and perhaps even magnetic effects — the escaping material is expected to be relativistic, just as we actually observe in jets.

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# Apparent superluminal motion in quasar jets

The innermost parts of the radio jet in 3C 273 consist mainly of small "knots" with separations that change measureably with time.

*Right*: Radio images taken over three years (1977-1980), plotted as temperature contours (Pearson et al. 1981). The dense region of lines on the left is the center of the quasar.

One tick on the map corresponds to 20.2 ly at the distance of 3C 273, so the knot on the right moved 21 ly in 3 yr.

I.e., v = 7c; the knot appears to be moving superluminally (faster than the speed of light), and not by a little bit.

How is this possible?

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## Apparent superluminal motion: An optical illusion

The apparent superluminal motion of the knot is a trick of perspective that occurs when the knot's true speed is relativistic ( $v \approx c$ ).



**Light path B is shorter than light path A** and, if  $\theta \ll 1$  and  $v \approx c$ , B is almost 1 ly shorter than A. This "head start" makes the light arrive sooner than expected, giving the **appearance** that the knot is moving faster than *c*.

# Apparent superluminal motion

The apparent speed perpendicular to the line of sight is

$$v_{\perp,\text{apparent}} = rac{v\sin\theta}{1 - rac{v}{c}\cos\theta} = rac{v\sin\theta}{1 - eta\cos\theta}$$
  
 $v_{\perp,\text{apparent}} \Big)_{\text{max}} = vrac{1}{\sqrt{1 - eta^2}} = \gamma v$ 

Thus, apparent speeds in excess of the speed of light can be obtained.

However, the apparent speeds only turn out to be much in excess of the speed of light if the actual speed of the radio-emitting knots is close to the speed of light.

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# Relativistic beaming



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#### Dusty torus

ALMA (ESO/NAOJ/NRAO), Imanishi et al., NASA/ESA HST, and A. van der Hoeven



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## Accretion disk in NGC 4261

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



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# 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

