Active Galactic Nuclei

Active galaxies Radio galaxies, QSOs, Blazars, Seyferts Accretion disks and jets

April 10, 2025

University of Rochester

Active Galactic Nuclei (AGN)

- The Eddington luminosity (or Eddington limits)
- The Galactic center (r < 3 pc): Keplerian motion around a black hole
- Radio galaxies, quasars, and blazars
- Relativistic and superluminal motion in quasar jets
- Seyferts: active spiral galaxies
- AGN accretion disks

Reading: Kutner Sec. 19.2–19.5; Ryden Sec. 21.1–21.3, & 21.Appendix

Composite image of Cen A in optical (ESO/WFI), radio (MPIfR/ESO/APEX), and X-ray (NASA/CXC).



Will any black hole do?

Not any black hole will be suitable. The large luminosity itself can stop the accretion due to the outward radiation pressure exerted on infalling material.

- Accretion will be able to take place steadily only if the force of gravity the black hole exerts on the infalling material exceeds the force from radiation pressure.
- Thus, the more massive the black hole, the larger the luminosity it can emit by accretion.
- The maximum luminosity possible via accretion is called the Eddington luminosity, and is defined by the point where gravity and radiation pressure are in balance.

イロン スポン イヨン イヨン 三日

Radiation & the motion of Solar-System bodies

Imagine a small spherical body of radius *R* a distance *r* from a star with luminosity *L*, such that $R \ll r$ and $R \gg \lambda$. The power it absorbs from starlight is

$$P_{\rm in} = \frac{dE_{\rm in}}{dt} = \frac{L}{4\pi r^2} \pi R^2$$

i.e., the input flux times the cross section. The rate at which it absorbs momentum is

$$\frac{dp_{\rm in}}{dt} = \frac{1}{c} \frac{dE_{\rm in}}{dt} = \frac{LR^2}{4cr^2}$$

Since it emits blackbody radiation equally in all directions, the total momentum from output radiation is zero and so there is a net force on the body from the input radiation:

$$\sum_{i} F_{i} = F_{\rm rad} = \frac{dp_{\rm in}}{dt} = \frac{LR^2}{4cr^2}$$

< □ > < @ > < E > < E > E のQC

The Eddington luminosity

To get the Eddington luminosity, we need to consider the radiation pressure on a gas rather than solid particles or bodies. We will start by considering the areas of the electron and proton shadows, $\pi R^2 = \sigma_e$ or σ_p .

"Classical radius:" assume rest energy comes from electrostatic potential energy:

$$mc^{2} = \frac{e^{2}}{r_{cl}}$$

$$R \approx r_{cl} = \frac{e^{2}}{mc^{2}} = \begin{cases} 2.8 \times 10^{-13} \text{ cm} & (e^{-}) \\ 1.5 \times 10^{-16} \text{ cm} & (p^{+}) \end{cases}$$

$$\sigma \approx \pi r_{cl}^{2} = \frac{\pi e^{4}}{m^{2}c^{4}}$$



The Eddington luminosity

Clearly most of the force is exerted on the electrons (bigger cross section). Done more carefully — accounting for quantum mechanics and for photon scattering rather than absorption — gives the **Thomson cross section**:

$$\sigma_e = \frac{8}{3}\pi r_{cl,e}^2 = \frac{8\pi e^4}{3m_e^2 c^4}$$
$$F_{rad,e} = \frac{dp_{in}}{dt} = \frac{L\sigma_e}{4\pi cr^2}$$
$$= \frac{2e^4L}{3m_e^2 c^5 r^2}$$

Each electron will drag a proton with it, regardless of whether the gas is neutral or ionized, because on macroscopic scales the gas has equal numbers of electrons and protons and the electrostatic attraction between them is strong.

・ロト ・四ト ・ヨト ・ヨト - ヨ

The Eddington luminosity

Similarly, each proton will drag an electron with it. The gravitational force exerted by the black hole on each proton is of course much larger than that on an electron.

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

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

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

where L_E is the Eddington luminosity.

◆□ ▶ ◆□ ▶ ◆三 ▶ ◆三 ▶ ● ● ● ●

QSO 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 $L = 10^{12}L_{\odot}$:

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

So a **supermassive black hole 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

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

・ロン ・四 と ・ 田 と ・ 田 と

QSO BHs have to be supermassive

Clearly, such a black hole must be quite different in origin from the stellar-mass black holes we considered earlier in the semester. Since stars do not form larger than about $100M_{\odot}$, they could not have arisen via a stellar collapse.

In fact, the origin of supermassive black holes is not well understood.

Leading models involve the interaction of galaxies and the transfer of interstellar matter between them during the interaction.

Supermassive BHs have observational consequences that we should see without much trouble.

- ▶ Ultra-high luminosities not possible via normal stellar processes.
- Material within a galaxy passing close to a BH like this should exhibit large (even relativistic) speeds, showing up in Doppler shifts and proper motions.

▲□▶ ▲□▶ ▲三▶ ▲三▶ - 三 - つへの

The Milky Way's central black hole

The dynamical center of the Galaxy is heavily extinguished. It cannot be seen at visible through longer X-ray wavelengths.

- It is bright in IR and radio and hard (short-wavelength) X-rays, which are transmitted through the dust.
- ▶ It was the first extraterrestrial object seen in radio by Karl Jansky in 1933.

Within the central 3 pc we find a dense cluster of stars, a bright compact radio source, and a swirl of gas clouds.

- Small bright radio source is called Sagittarius A*, or **Sgr A***.
- Sgr A* lies **precisely** at the center of the Galaxy (center of rotation): $(\alpha, \delta)_{J2000} = 17:45:40.0409, -29:00:28.118.$

◆□ ▶ ◆□ ▶ ◆三 ▶ ◆三 ▶ ● ● ● ●

Central 6pc of Sgr A West in X-rays

Sgr A* is the brightest starlike object in the center of this image taken with the Chandra X-ray observatory (CXC) (Wang et al. 2013).

Central 6pc of Sgr A West in Near Infrared

Sgr A* does not appear in this picture due to the fact that it is drowned out by light from all of the neighboring stars (NASA/STScI).



Orbital motion & the center of the Milky Way

Over the course of the past 40 years, astronomers have measured velocities related to orbital motion about the center for many objects that lie within 1 pc of the Galactic center:

- radial velocities of gas clouds
- radial velocities of stars
- proper motions of stars

The orbits do not lie in the plane of the rest of the Galaxy, but that does not matter; these are "test particles" we can use to determine the gravitational potential in the Galactic center.

イロト イポト イヨト イヨト 二日

Stellar motions near Sgr A*

Orbital solutions for stars next to Sgr A*, from the MPE Galactic Center group.



The black hole at the center of the Galaxy

- If the central stellar cluster were the only mass present (i.e. no central massive black hole) then the orbital velocities would decrease toward zero with *r* since *M*(*r*) would decrease to 0.
- If there is a massive black hole, the mass enclosed by the stellar orbits

$$M(r) = \frac{rv^2}{G}$$

should approach the mass of the black hole as $r \rightarrow 0$.

Results from stellar and gas-cloud Doppler shifts and proper motions (Schöedel et al. 2003).



enclosed mass (solar masses)

The black hole at the center of the Galaxy

Thus there is a black hole at the center of the Milky Way, and its mass is $(4.3 \pm 0.1) \times 10^6 M_{\odot}$ (GC 2022). It spins at 25% of its maximum rate.

- Presumably the radio and X-ray components of emission from Sgr A* are the outermost and innermost parts of the accretion disk around the black hole.
- It turns out that supermassive black holes are very common in galactic nuclei, but the prominent examples
 — those in active galactic nuclei are considerably more massive (10⁹M_☉).

The Event Horizon Telescope (a global long-baseline interferometric radio network) recently imaged the light orbiting around Sgr A*'s event horizon (EHT 2022).



What are we seeing?

Image of our black hole, Sgr A*

Simulation of a black hole



The Event Horizon Telescope

The global mm-wavelength network comprising the Event Horizon Telescope (Castelvecchi 2017).



April 10, 2025 (UR)

Astronomy 142 | Spring 2025

Active galaxies & AGN

Several types of galaxies are known to have active nuclei.

The following types were discovered by radio astronomers, and thousands are now known:

Quasars (a.k.a. QSOs) come in two varieties: radio-loud and radio-quiet.

Radio galaxies also come in two varieties: broad-line and narrow-line

These were discovered by visible-light astronomers, and hundreds are now known: Seyfert galaxies are all radio-quiet, in both broad-line and narrow-line types. Blazars a.k.a. BL Lacertae objects

Note that active galaxies are vastly outnumbered by normal galaxies.

▲□▶▲圖▶★≧▶★≧▶ ≧ のQの

Active galaxies & AGN

Different classes of active galaxies have a lot in common, despite their different appearances. The two most obvious common features:

- All have some sort of compact, "star-like," object at their very centers that dominate the galaxies' luminosities.
- They are more luminous by factors of 10 to 10³ than normal galaxies of the same Hubble type, and therefore all are thought to contain accreting, supermassive black holes.

We began discussing **quasars** last time. Their distinguishing characteristics are:

- Compact galaxy nucleus with extremely large luminosity
- One-sided jet

▲□▶▲圖▶★≧▶★≧▶ ≧ のQの

The archetypical quasar 3C 273



The luminosity of 3C 273, the first QSO discovered, is dominated by its starlike central core, visible in all three images above. It also has a jet but no "counterjet" visible on the other side of the quasar. The quasar is located inside an elliptical galaxy, $f_{\rm R}$, $f_$

April 10, 2025 (UR)

The "shadow" of a quasar's black hole

In 2019, the EHT collaboration took the world's first image of the light in orbit around a supermassive black hole.





April 10, 2025 (UR)

Reality v. simulation

The image on the left is of M87's supermassive black hole. The center image is the result of a simulation (with "infinite" resolution), and the image on the right is the center simulation image blurred to match the telescope's systematics. M87 April 6 GRMHD Blurred GRMHD







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?



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 $\theta \ll 45^{\circ}$ 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

$$egin{aligned} v_{\perp, ext{apparent}} &= rac{v\sin heta}{1 - rac{v}{c}\cos heta} = rac{v\sin heta}{1 - eta\cos heta} \ (v_{\perp, ext{apparent}})_{ ext{max}} &= vrac{1}{\sqrt{1 - eta^2}} = \gamma v \end{aligned}$$

(See this week's recitation for the derivation.) 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. Superluminal motion indicates that the real motion is relativistic.

イロン スポン イヨン イヨン 三日

Radio Galaxies

Radio galaxies were discovered in the 1950s at about the same time as quasars.

However, they are quite distinct from quasars. QSOs in the 1950s looked pointlike and were associated only with pointlike optical objects.

In contrast, radio galaxies appear to consist of a pair of extended radio lobes on either side of a visible, elliptical galaxy.

As radio interferometric measurements improved, radio galaxies were shown to also possess compact and pointlike central objects coincident with the galactic nuclei and connected to the lobes by narrow, usually straight jets.

The lobes themselves have fine filamentary structure. Many have hot spots as the ends of the jets.

▲□▶ ▲□▶ ▲ 三▶ ▲ 三▶ ● 三 のへで

The archetypical radio galaxy: 3C 405 (Cygnus A)

X-ray/optical/radio overlay of Cygnus A, the first known radio galaxy (Baade & Minkowski 1954). Visible image from HST-WFPC2; X-ray from NASA/CXC (Wilson 2000); radio from NRAO/AUI (Perley 1984).



Blazars

Blazars are bright and starlike. Only a very faint luminosity has been detected around them to indicate that they are the nuclei of galaxies (e.g., Oke & Gunn 1974).

The spectra from blazars are smooth, making it hard to measure Doppler shifts.

Most blazars are strong pointlike radio sources with significant variability. Stars are not. This was the first real indication that blazars are distant galaxies.

In fact, the variability implies a huge luminosity produced in a very small volume, implying the presence of a supermassive black hole. Only very short (< mas) jets have been observed, as seen in BL Lac on the right.



polarized 86 GHz radio emission, from

the GMVA (BU/MPIfR)

Seyfert galaxies

Discovered in the 1940s by Carl Seyfert, these are **spiral galaxies** with starlike nuclei, often brighter than the rest of the galaxy, with ionized gas associated with these centers. Type 1 Seyferts Some Seyferts are found with very broad recombination lines $(\sim 10^3 \text{ km/s in width})$ associated with the nuclei. Example: NGC 4151.

Type 2 Seyferts Other Seyferts have only narrow-line spectra ($\lesssim 10^2$ km/s) at the nucleus. Example: NGC 1068.

There are intermediate types of Seyferts as well.

The rotational and random speeds inferred from spectral lines near the galactic centers indicate supermassive black holes are present in these galaxies, like the blazars and quasars (QSOs).

▲□▶▲圖▶★≧▶★≧▶ ≧ のQの

Seyfert galaxies

Since spirals have a lot more interstellar gas and dust than elliptical radio galaxies and QSOs, the jets do not make it out of the galaxy.

Example: M106 (NGC 4258)

- Very short jet, oriented roughly along the galaxy's axis, seen in nucleus.
- The rest of the jet is apparently entrained in the disk of the galaxy.

M106 in X-rays from jet-driven shocks (blue) and visible light from normal galactic processes (red). Second visible image from R. Gendler.



Seyfert galaxies

Since spirals have a lot more interstellar gas and dust than elliptical radio galaxies and QSOs, the jets do not make it out of the galaxy.

Example: M106 (NGC 4258)

- Very short jet, oriented roughly along the galaxy's axis, seen in nucleus.
- The rest of the jet is apparently entrained in the disk of the galaxy.

M106 in X-rays from jet-driven shocks (blue) and visible light from normal galactic processes (red). Second visible image from R. Gendler.



The unified AGN model

Quasars, radio galaxies, and blazars are all powered by black holes but present different observational characteristics. It turns out that they are **the same thing** but viewed from different angles.

Relativistic accelerating electric charges **beam** the light they emit in the direction that they are going (topic covered in PHYS 218).

Thus, the approaching jet along our line of sight at an angle θ should be much brighter than the receding one (counterjet). Under simple assumptions for steady jets, (Blandford & Königl 1979),

$$\frac{f_{\rm jet}}{f_{\rm counterjet}} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^3 \gg 1 \text{ if } \theta \to 0, \beta \to 1$$

- ► Radio galaxy jets appear bipolar $\leftrightarrow \theta$ closer to 90°
- Quasar jets appear one-sided \leftrightarrow jet viewed closer to $\theta = 0$, consistent with the observation of superluminal motion
- ▶ Blazars show no jets, or an extremely short one-sided jet \leftrightarrow viewed at $\theta \approx 0$

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



(日) (同) (日) (日) (日)