SUPERMASSIVE BLACK HOLES IN AGN

PROBLEM SET #6 ON WEBWORK – DUE 11/6 AT MIDNIGHT

SUPERMASSIVE BLACK HOLES IN AGN

Active galaxies: quasars, radio galaxies, and their relatives

Why observations imply that AGN have supermassive black holes in their centers: accretion at the Eddington rate

Quasars and radio galaxies are the same thing viewed from a different angle

Accretion disks in AGN

Hubble-ACS image of quasar MC2 1635+119, showing that it lies at the center of an elliptical galaxy with peculiar shell-like collections of bright stars (Gabriela Canalizo, UCR)

DISTINCTIVE FEATURES THAT INDICATE THE PRESENCE OF A BLACK HOLE

Observe **two or more** of these features to "find" a black hole:

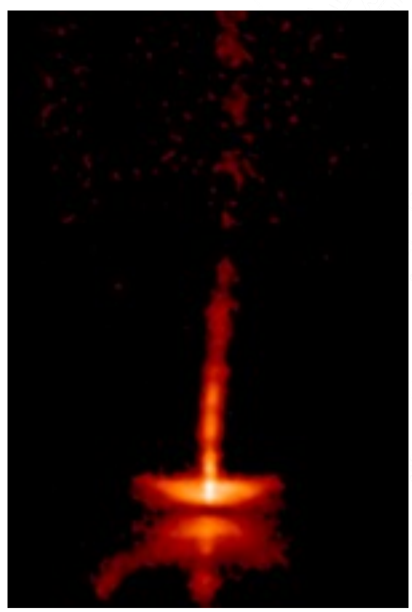
- **Gravitational deflection of light** by an amount requiring black hole masses and sizes
- **X-ray and/or γ-ray emission** from ionized gas falling into the black hole
- **Orbital motion of nearby stars or gas clouds** that can be used to infer the mass of (perhaps invisible) companions: a mass too large to be a white dwarf or neutron star might correspond to a black hole.
- **Motion close to the speed of light** or apparently greater than the speed of light ("superluminal motion")
- **Extremely large luminosity** that cannot be easily explained by normal stellar energy generation
- Direct observation of a large, massive **accretion disk**

IS THERE A BLACK HOLE THERE?

HH 30 (HST images by Alan Watson):

- Starlike object heavily obscured by dusty accretion disk
- Luminosity is $1{\times}10^{32}$ erg/s
- Shines mostly at infrared and radio wavelengths
- Twin jets, each several light years long, of material flowing out from the central object at 500 km/s

How many black hole characteristics does HH 30 have?

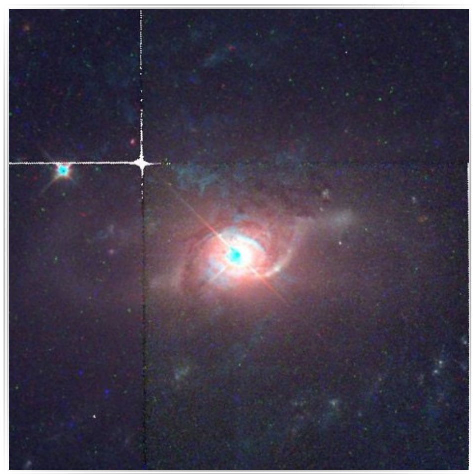


IS THERE A BLACK HOLE THERE?

3C 120 (Marscher et al. 2002):

- Spiral galaxy with extremely bright blue starlike nucleus
- Total luminosity $4{\times}10^{45}$ erg/s
- Powerful X-ray source
- Short (few light-year) jet visible near nucleus, showing motion at speeds up to $4.5{\times}10^{10}$ cm/s

How many black hole characteristics does 3C 120 have?



ACTIVE GALAXIES & ACTIVE GALACTIC NUCLEI (AGN)

These kinds of galaxies have **active nuclei**:

- **Quasars**
- **Radio galaxies**

Both originally discovered by radio astronomers.
Many hundreds of thousands of each are now known.

- **Seyfert galaxies**
- **Blazars**

Both originally discovered by visible-light astronomers.
Thousands of each are now known.

We know of millions of them, but active galaxies are quite rare, in the sense that they are vastly outnumbered by normal galaxies.

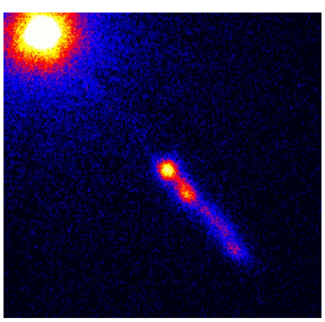
ACTIVE GALAXIES & ACTIVE GALACTIC NUCLEI (AGN)

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

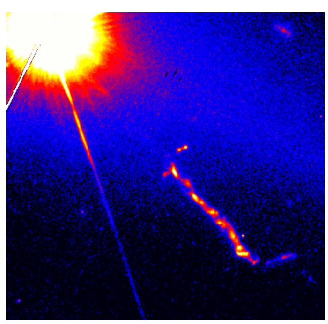
- All have some sort of “star-like” object at their centers that dominate the galaxies’ luminosities.
- They are all much more luminous than normal galaxies (by factors of 10-1000) and are therefore all thought to involve central, supermassive black holes.

We have briefly discussed quasars before. The distinguishing characteristics of a quasar:

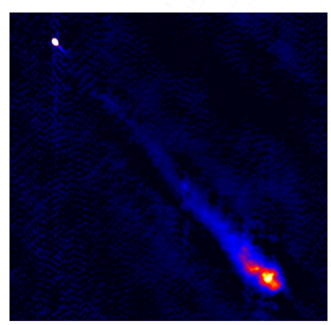
- Starlike galaxy nucleus with extremely large luminosity
- One-sided jet



In X-rays (*CXO*)



In visible light (*HST*)



In radio (*MERLIN*)

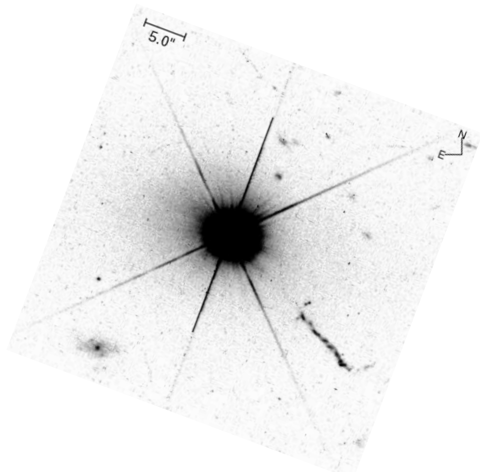
THE ARCHETYPAL QUASAR, 3C 273

In each case, the quasar (upper left) is starlike (despite the spreading glare in the visible and X-ray images) and is much brighter than anything else in the image. No “counterjet” is seen on the other side of the quasar from the jet in this image.

QUASARS ARE THE NUCLEI OF GALAXIES

Beyond the glare of the quasar can be seen starlight from the elliptical galaxy that plays host to the quasar.

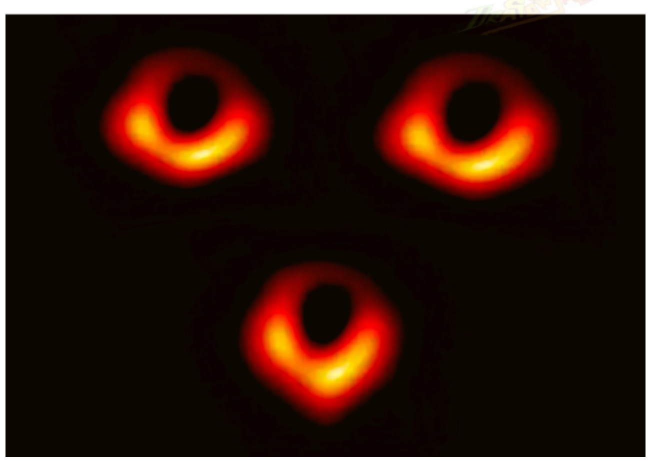
(HST-ACS photo-negative image of 3C 273 by John Bahcall, Princeton U.)



Black Hole : I don't give off visible light.. you literally can't take pictures of me

Some intelligent thing on a rock : *does it anyway*

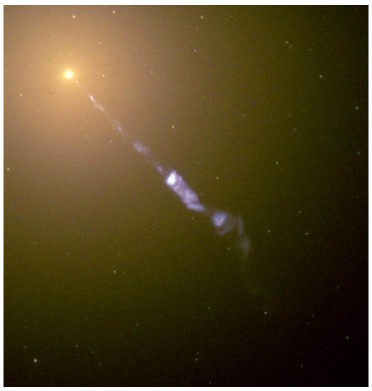
Black Hole :

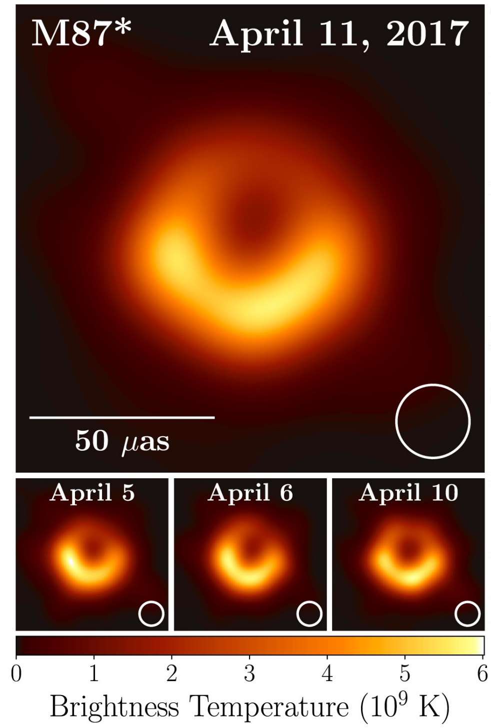


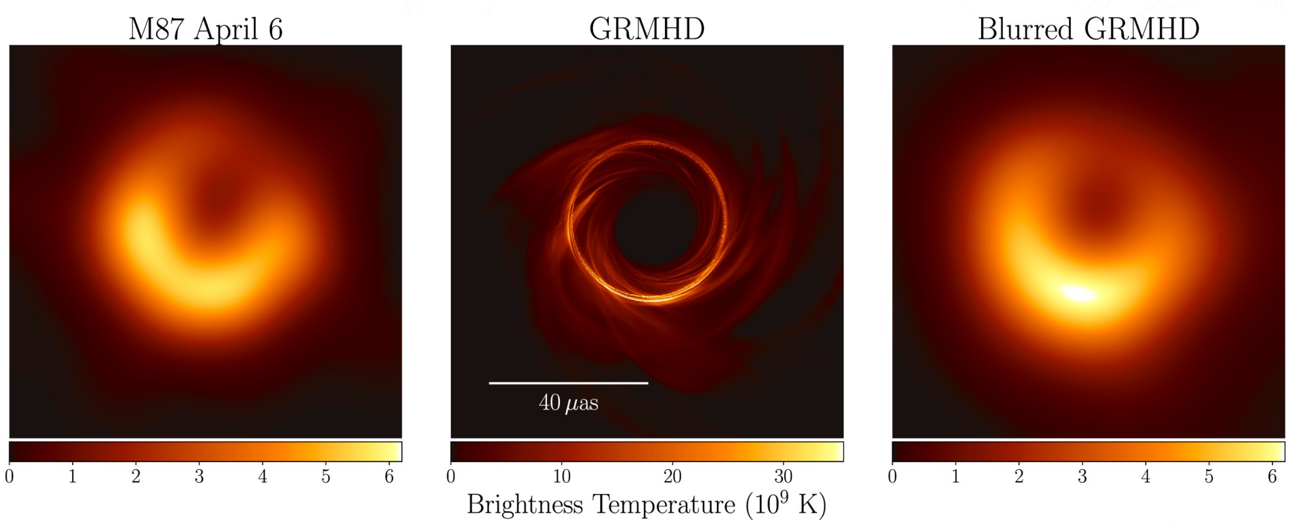
IMAGING THE ISCO OF A QUASAR

First image of the "shadow" of a black hole, and the light from its innermost stable circular orbit.

EHT collaboration (2019)





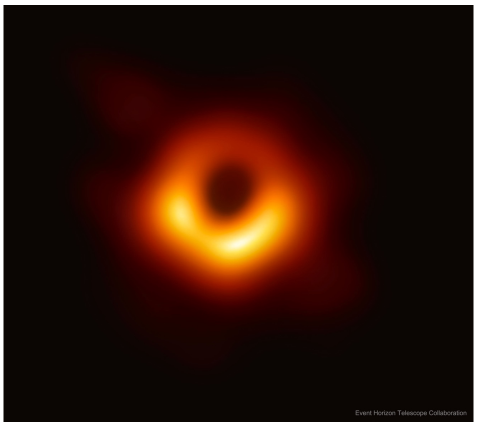


REALITY V. SIMULATIONS

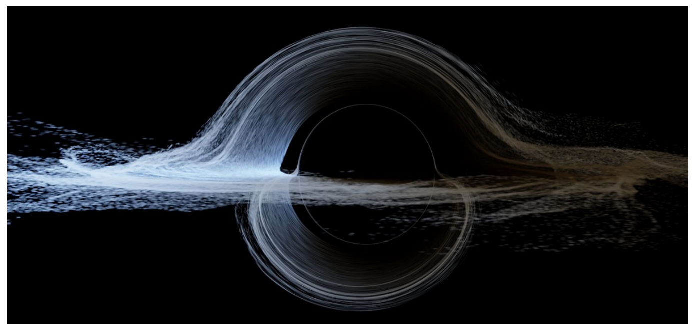
The image on the left is of the actual black hole. The center image is the result of a simulation (with "infinite" resolution), and the image on the right is the center simulation image blurred to match the telescope's systematics.

WHAT ARE WE SEEING?

Image of M87's black hole



Simulation of a BH

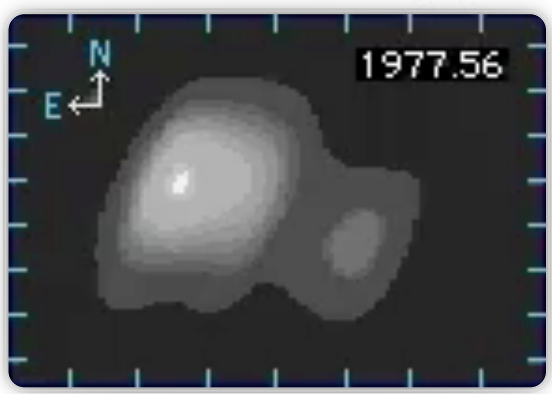


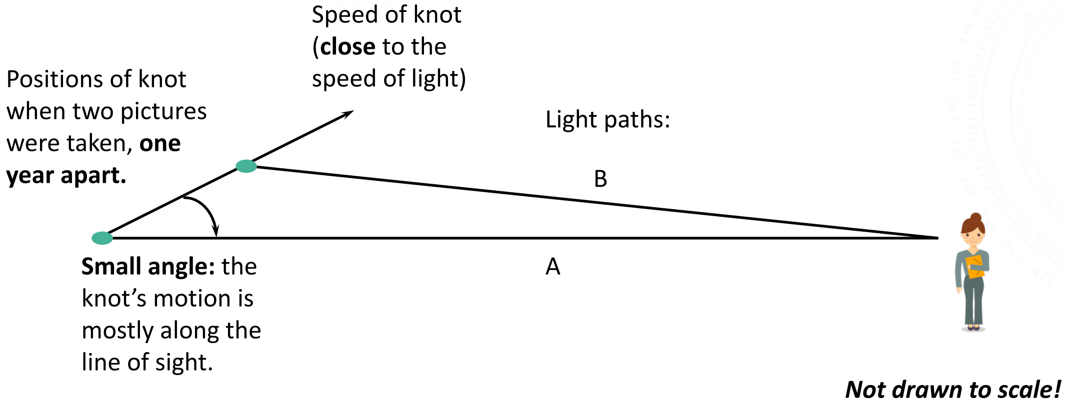
SUPERLUMINAL MOTION IN QUASAR JETS

- "Superluminal" → apparently faster than light

The innermost parts of the radio jet in 3C 273 consists mainly of small "knots" with separation that changes with time, as shown in these radio images taken over the course of three years (Pearson et al. 1981). The brightest (leftmost) one corresponds to the object at the center of the quasar.

One tick mark on the map border corresponds to 20.2 light years at the distance of 3C 273. Thus, the rightmost knot looks to have moved about 21 light years in only three years.





SUPERLUMINAL MOTION IN QUASAR JETS: AN OPTICAL ILLUSION

Light path B is shorter than path A. If the knot's speed is close to the speed of light, B is almost a light-year shorter than A. This "head start" makes the light arrive sooner than expected, giving the **appearance** that the knot is moving faster than light. (Nothing **actually** needs to move that fast for the knot to **appear** to move that fast.)

SUPERLUMINAL MOTION IN QUASAR JETS

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

Ejection speeds in astrophysics tend to be close to the **escape speed** of the object that did the ejecting. What has escape speeds near the speed of light?

- Neutron stars (but they cannot produce the quasar's luminosity)
- **Black holes** – like the ones that can produce the quasar's luminosity

MASS OF THE BLACK HOLE IN 3C 273

Quasars are too far away for us to see the details of the rotation of their accretion disks or the motions of nearby stars, so there have been no measurements of masses for quasar black holes, only rough limits like the following:

- **The biggest it can be**: "variability" circumference is 0.26 light years; if this is the same as the horizon circumference, the mass is

$$M = \frac{Cc^2}{4\pi G} = \frac{(0.26\ \mathrm{ly})(3\times10^{10}\ \mathrm{cm/s})^2}{4\pi(6.67\times10^{-8}\ \mathrm{cm^3/s^2g})} \times \frac{9.46\times10^{17}\ \mathrm{cm}}{1\ \mathrm{ly}}$$

$$M = 2.6\times10^{44}\ \mathrm{g} = 1.3\times10^{11} M_{\odot}$$

MASS OF THE BLACK HOLE IN 3C 273

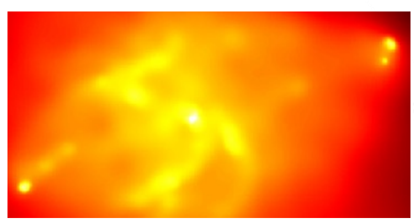
- **The smallest it can be**: small enough that **gravity just barely overcomes the outward pressure of X-rays**
  - This is called **accretion at the Eddington rate.**
  - Calculation of the mass by this means is not very complicated, but it is beyond the scope of this class, so we will skip to the answer: a $3\times10^7 M_{\odot}$ black hole accreting at the Eddington rate consumes $0.7M_{\odot}$ per year, and thus has the same luminosity as 3C 273 ($10^{12}L_{\odot}$).

Thus, the mass of the central black hole is probably in the range $10^8 - 10^{11} M_{\odot}$ – a very massive black hole no matter how you look at it (of order 100-100,000 times more massive than the black hole in Sgr A*).

- Most other quasar black holes are thought to be similar.

RADIO GALAXIES

- Discovered by radio astronomers in the 1950s: large, double-peaked, bright radio sources
- Identified with visible galaxies: a galaxy, *always* an elliptical one, is *always* seen to lie in between the two bright radio spots.
  - Radio galaxies are always ellipticals. Seyfert galaxies are always spirals.
- **Jets**: Detailed radio images revealed that all radio galaxies have jets, originating in the center of the galaxy and reaching out to the brighter radio spots. In contrast to quasars, most radio galaxies have two jets easily detectable, always oppositely-directed. One jet is usually brighter than the other by a large factor.



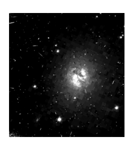
THE ARCHETYPAL RADIO GALAXY, CYGNUS A

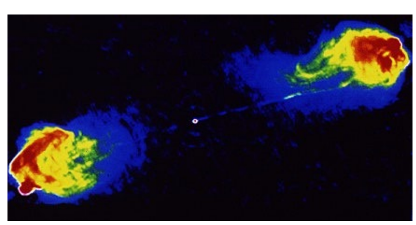
Not to be confused with Cygnus X-1.

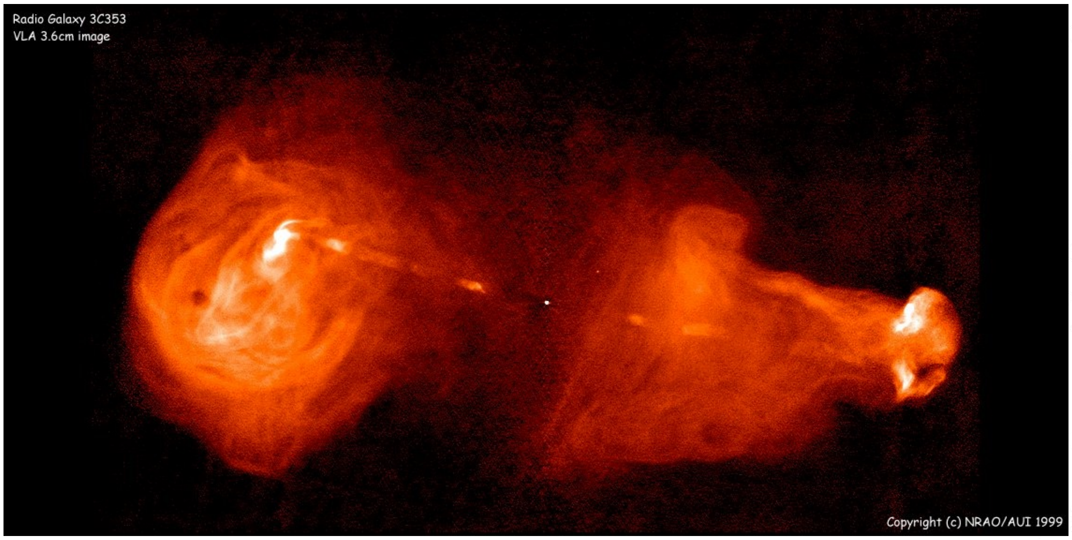
Top: X-ray image (*CXO* – Wilson et al. 2000)

Middle: Visible-light image (*HST-WFPC2 archives*)

Bottom: Radio image (*VLA* – Perley et al. 1984)







RADIO GALAXY 3C 353

Swain & Bridle (1997)

RADIO GALAXY BLACK-HOLE MASSES

With the Hubble Space Telescope, it has become possible to measure the masses of some radio-galaxy central black holes directly by observing the Doppler shifts of gas clouds nearby.

- M84, classic radio galaxy: Doppler shifts corresponding to the rotational speeds of 400 km/s, only 26 light years from the center of the galaxy.
- This indicates a central mass of $3{\times}10^{8} M_{\odot}$ – again, a supermassive black hole.
- This is thought to be typical of the masses of radio-galaxy black holes. Note that it is about what is obtained for quasar black holes.

BLAZARS

- Bright and starlike. It took a long time before very faint luminosities were detected around them to indicate that they are the nuclei of galaxies.
- Smooth spectrum: difficult to measure Doppler shift. Thus, it was not realized that these objects were far enough away to be galaxy nuclei at first.
- Many are strong point-like radio sources. (Stars are not; this was the first real indication that blazars are distant galaxies.)
- **Violently variable brightness**: large luminosity produced in a very small volume.
- No jets seen.

QUASARS, RADIO GALAXIES, AND BLAZARS ARE THE SAME THING (JUST SEEN FROM DIFFERENT ANGLES)

If the jets are relativistic (speeds close to c) then their brightness should increase the closer to "head on" they are viewed, and decrease if they recede from the observer.

- Quasars: radio galaxy jets viewed closer to head-on?

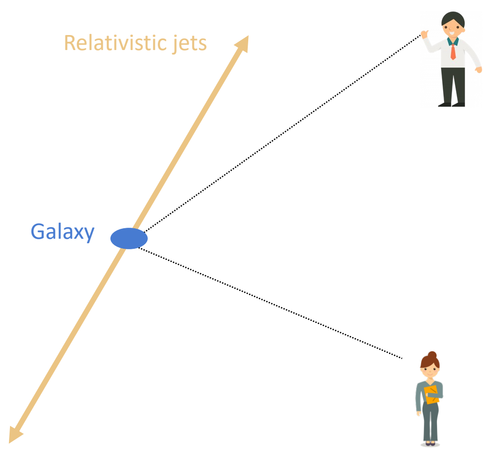
If viewed straight down the jet, the vicinity of the central "engine" as well as the amplified, approaching jet would not be obscured by the disk. The brightness may be highly variable as a result.

- Blazars: radio galaxy jets viewed very nearly head-on?

From these suggestions, it is possible to predict what the relative numbers of quasars, radio galaxies, and blazars should be.

- Observations confirm this prediction (e.g. Barthel 1989); the three are really the same kind of object.

QUASARS, RADIO GALAXIES, AND BLAZARS ARE THE SAME THING (JUST SEEN FROM DIFFERENT ANGLES)



An observer whose line of sight makes a small angle with the jet would see the object as a quasar. (For an extremely small angle, it appears as a blazar.)

An observer whose line of sight is closer to perpendicular to the jet would see the object as a radio galaxy.

TYPES OF AGN

Radio galaxy

- **Elliptical galaxy** with active nucleus at center
- Two jets, visible in the radio

Seyfert galaxy

- **Spiral galaxy** with active nucleus at center
- Zero, one, or two jets

Quasar

- Galaxy with active nucleus at center
- One jet, visible in the radio (line of sight is close to jet axis)

Blazar

- Galaxy with active nucleus at center
- Extremely bright, no jets (line of sight is along the jet axis)


A

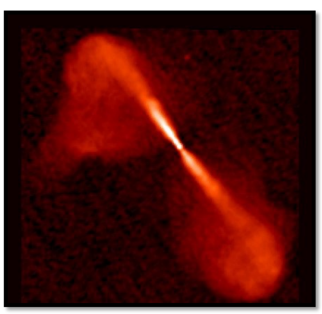

B

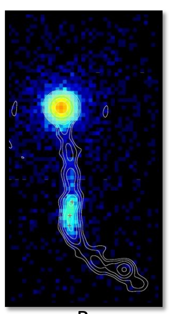

C


D

FIND THE ACTIVE GALAXY

Which of these is a visible-light picture of a radio galaxy?


A


B

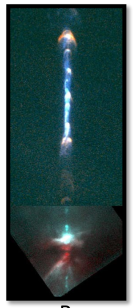

C


D

FIND THE ACTIVE GALAXY

Which of these is a radio image of a radio galaxy?

A



B

C

D

FIND THE ACTIVE GALAXY

Which of these is a visible-light picture of a Seyfert galaxy?

MATTER FALLING INTO AGN BLACK HOLES: LARGE ACCRETION DISKS

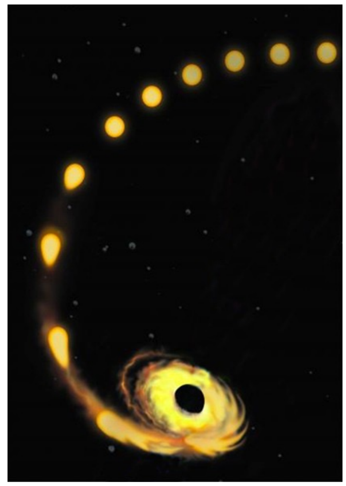
The disk-shaped collection of matter surrounding the black hole in an AGN arises rather naturally from the influence of the black hole on stars and other material in the galactic center.

- Stars in a galaxy perpetually interact with each other's gravity as well as the gravity of the galaxy at large.
- These interactions – long-range collisions – usually result in transfers of energy and momentum between stars. 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 the other going to a larger orbit.

MATTER FALLING INTO AGN BLACK HOLES: LARGE ACCRETION DISKS

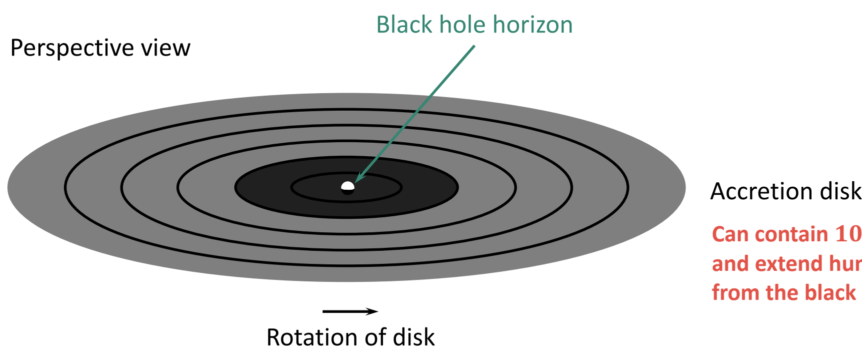
Thus, some stars are pushed to the very center of the galaxy after a number of these encounters. What happens if there is a black hole there?

- The star begins to fall in, but the **spin** of its orbital motion and the **tidal forces** that tend to rip the star apart keep this from happening all at once.
- Stellar material spreads out into a rotating, flat distribution around the black hole: the beginnings of an accretion disk.



AGN ACCRETION DISK FORMATION

Eventually, the tidally-disrupted material from many stellar encounters settles down into a flattened disk. Collisions among particles in the disk cause material to lose its spin and become **accreted** by the black hole. The disk is thus *gradually* consumed.



Can contain $10^3 - 10^6 M_\odot$ and extend hundreds of ly from the black hole

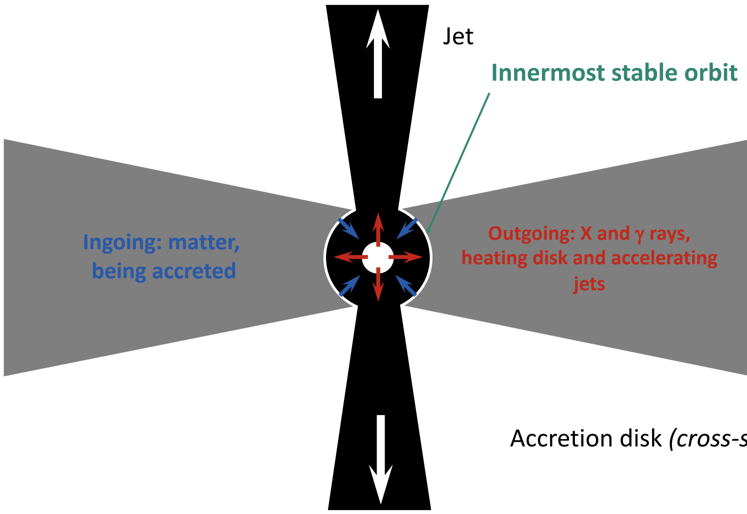
OPERATION OF AGN ACCRETION DISKS

- Recall that for non-spinning black holes, orbits with circumference less than $3C_S$ are unstable, and no orbits exist with circumference less than $1.5C_S$. Within this volume, the disk structure breaks down and material tends to stream in toward the horizon.
- A large amount of power, mostly in the form of X-rays and γ-rays, is emitted by the infalling material. Pressure exerted by this light 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.
  - Heated disk = **compact central object** seen in radio images of radio galaxies and quasars.

OPERATION OF AGN ACCRETION DISKS

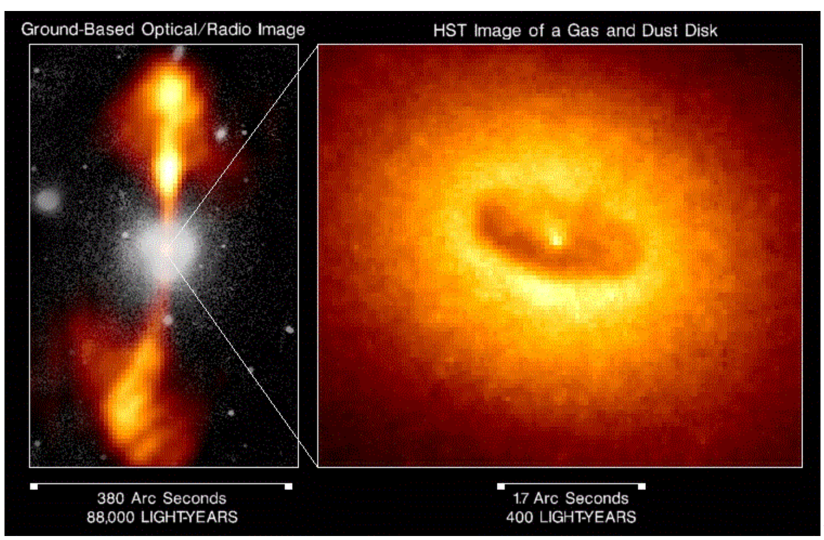
- Some of the particles absorbing the highest-energy light are accelerated to speeds approaching that of light. If their velocity takes them into the disk, they just collide with the disk material and lose their energy to heat. If their velocity takes them perpendicular to the disk, they may escape (Blandford & Rees 1975).
  - High-speed particles escaping perpendicular to the disk = **jets** seen in radio and visible images of radio galaxies and quasars. Their high speeds (approaching c) explain the one-sidedness and "faster than light" motion of quasar jets.
  - Several other possibilities exist for jet acceleration.

STRUCTURE OF AN AGN ACCRETION DISK



Accretion disk *(cross-section view)*

DISK AT THE CENTER OF RADIO GALAXY NGC 4261



Jaffe et al. (1996)