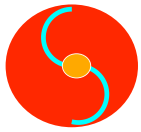
AS1001:Extra-Galactic Astronomy

Lecture 6: Galaxy Orientation,
Black Holes & Quasars

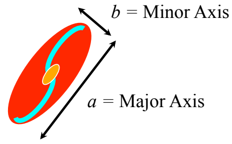
Galaxy Inclination



FACE-ON — Inclination i = 0º

EDGE-ON — Inclination i = 90º

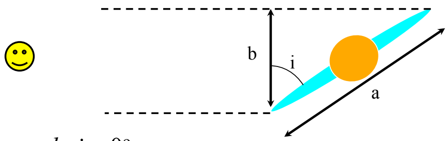
All galaxies are viewed with some inclination:



Calculating the Inclination

- Assuming a thin circular disc:
- Inclination, i, given by:

$$\cos(i) = \frac{b}{a}$$



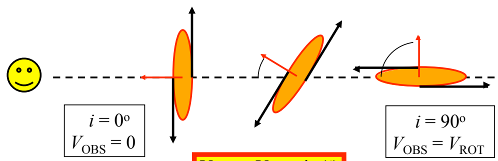
- $a = b$, $i = 0º$
- $b = 0$, $i = 90º$

NB: a is always measurable

Line-of-sight velocity

The **Doppler Shift** measures the component of velocity **along the line of sight**.

Need to correct for inclination.



$$V_{OBS} = V_{ROT}\sin(i)$$

Example: Inclination Corrections

A long-slit spectrum aligned with a galaxy's major axis has an [OII] line at 3900A that shifts by 5A from one side to the other side of the galaxy. The major-to-minor axis ratio is 3. What is the rotational velocity of the outermost stars ?

$$\cos i = b/a = 1/3 \qquad i = \cos^{-1}(1/3) = 70.5^0$$

$$\sin i = \sqrt{1-\cos^2 i} = \sqrt{1-(1/9)} = \sqrt{8/9} = 0.94$$

Note: (5 A)/2

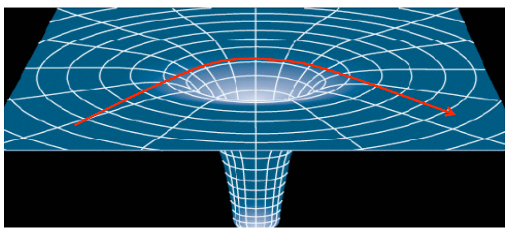
$$V_{OBS} = \frac{\Delta\lambda}{\lambda}c = \frac{2.5\text{A}}{3900\text{A}} \times \left(3\times10^5 \text{ km/s}\right) = 192 \text{ km/s}$$

$$V_{ROT} = \frac{V_{OBS}}{\sin(i)} = 204 \text{ km/s}$$

Note: λ=3900 and not 3727

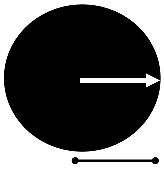
Black Holes

Gravity = curvature of space-time by matter/energy. Pack mass into a small enough volume, and the space-time can be so distorted that nothing, not even light, cannot escape.



The Schwarzschild Radius

- Where the escape velocity equals the speed of light.
- Nothing, not even light, can escape from inside the Event Horizon, at the Schwarzschild Radius r_S.
- Escape velocity: set Kinetic Energy = Gravitational Energy



r_S

$$\frac{1}{2} m v^2 = \frac{G M m}{r}$$

$$v_{esc} = \left(\frac{2 G M}{r}\right)^{1/2}$$

$$r_S = \frac{2 G M}{c^2} = 3\,\text{km}\left(\frac{M}{M_{sun}}\right)$$

Types of Black Hole

- Stellar-mass
  - Formed when a very massive star goes supernova

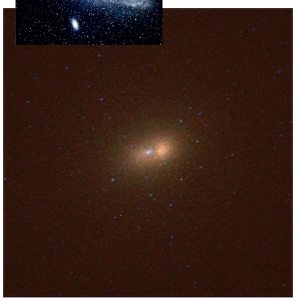
$$\mathbf{M_{BH} \sim 10\, M_\otimes}$$

- Super-massive
  - Formed in galaxy cores

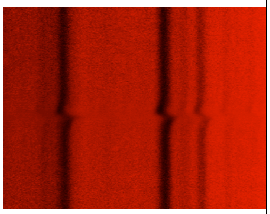
$$\mathbf{M_{BH} \sim 10^{7-9} M_\otimes}$$

- Most large galaxies have a super-massive black-hole (SMBH) in their core.

The SMBH in M31



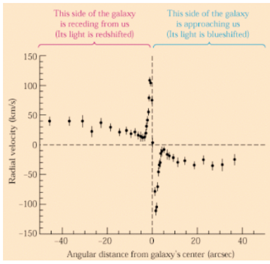
Stars orbiting near the core



Spectra showing velocities of stars on either side of the core

The SMBH in M31

- Star velocities v > 110 km/s for r < 2.5 pc

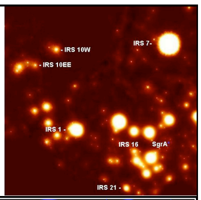


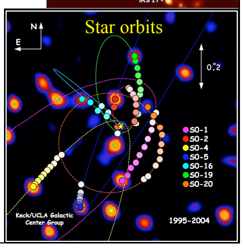
Use Virial Theorem to calculate the Mass

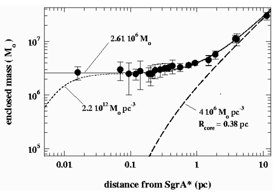
$$\mathbf{M}_{CORE} = \frac{v^2 r}{G} = \frac{(110\times10^3)^2 \times 2.5 \times (3\times10^{16})}{6.67\times10^{-11}} = 1.4\times10^{37}\text{kg} = 6.8\times10^{6}\mathbf{M}_\otimes$$

Milky Way's SMBH

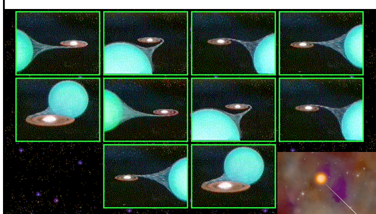
- Infrared images (to see thru dust) show a compact star cluster.
- Star velocities v > 1000 km/s inside r = 0.01 pc!
- => 3 x 10^6 M_{sun} Black Hole in the Milky Way's core







Stars orbiting a Black Hole



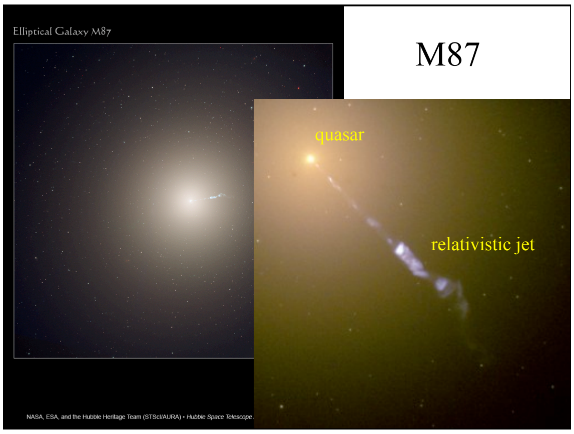
Circular orbit: Stars can orbit safely. If star close enough to fill its "Roche lobe", mass transfer forms an Accretion Disk.

Highly elliptical orbit: Black hole tides can shred a star that comes too close. Debris forms an Accretion Disk, eventually swallowed by hole.

Discovery of Quasars

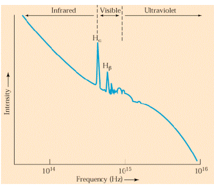
- Quasars are Super-Massive Black Holes "feeding".
- Originally known as Quasi-Stellar Objects (QSOs).
- For many years "stars" with unknown spectral features were found but their nature unknown !
- 1963: Martin Schmidt recognised that QSOs have known emission lines with large redshifts
  (hence QSO luminosities >> galaxies)
- Hence QSOs are extra-galactic objects but:
  - Appear star-like (i.e., not extended but point-like)
  - Outshine galaxies (by up to 10^5 times)
  - Very broad emission lines ($\Delta v \sim 10^4$ km/s)
  - X-ray and radio emission (from relativistic jets)

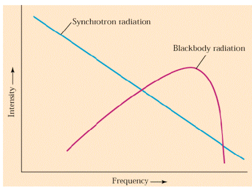
M87



Quasar Spectra

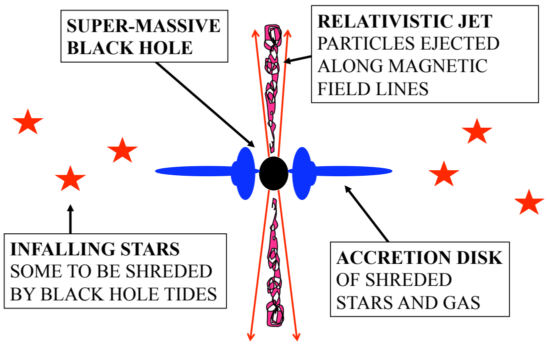
- QSO spectra show both thermal (Blackbody) and non-thermal (Synchrotron) emission.





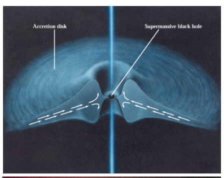
- Blackbody from multi-temperature Accretion Disk.
- Synchrotron from Relativistic Jets: relativistic charged particles electrons spiraling around magnetic field lines.

Simplified Quasar Model

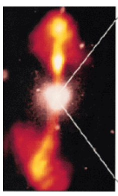


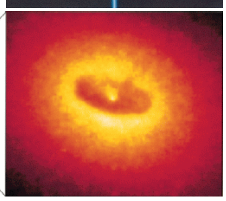
SMBH Model/Observations

MODEL



OBSERVATIONS
(NGC 4261)





Quasars: Powered by Accretion

- Gravitational energy is released as mass accretes.
- Friction in the accretion disk moves angular momentum outward as the gas spirals in. Friction also heats the gas.
- Accretion Disk Temperature Profile:

$$T(r) \sim \left(\frac{3 G M \dot{M}}{8 \pi \sigma r^3} \right)^{1/4} = 10^6 K \left(\frac{\dot{M}}{M_{SUN} / yr} \right)^{1/4} \left(\frac{M}{10^8 M_{SUN}} \right)^{-1/2} \left(\frac{r}{r_S} \right)^{-3/4}$$

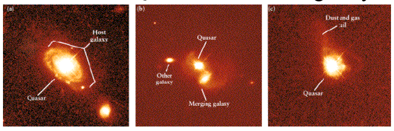
- Accretion Luminosity:

$$L \sim \frac{G M \dot{M}}{r_S} = \eta \dot{M} c^2 \sim 10^{11} L_{SUN} \left(\frac{\dot{M}}{M_{SUN} / yr} \right)$$

- η = Efficiency of converting rest mass energy into light:
  - Up to 15% for accretion onto a black hole
  - Much smaller for nuclear fusion

Types of Active Galactic Nuclei

- 1993: HST reveals "Quasar fuzz" = host galaxy.

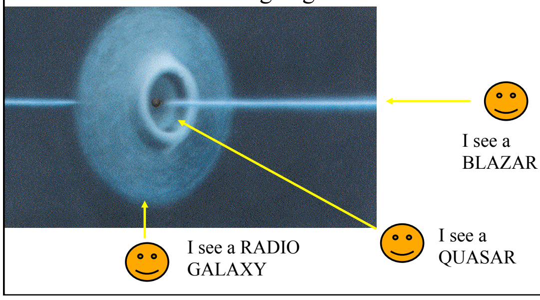


- Active Galactic Nuclei (AGN) in the cores of galaxies.
  - Quasar = Bright AGN outshining the host galaxy
  - Seyfert = Fainter AGN luminosity equals host galaxy
  - Radio Galaxy = AGN with radio lobes
  - Blazar = AGN with no lines and rapid variability

WHY SO MANY DIFFERENT TYPES ?

AGN Unification

Different AGN types are now understood to be due to different viewing angles:



The Quasar Era

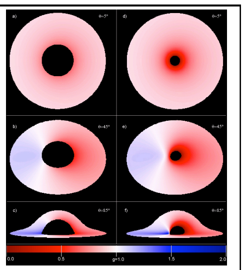
- Redshift surveys find highest density of quasars per unit volume around redshift $z \sim 2\text{-}3$
- Large redshifts => large distances => large "lookback times" i.e., we see quasars as they were in the past, when the Universe was young.
- Nearest quasar: 3c273 at 250 Mpc
  vs 5 Mpc typical galaxy-galaxy distance.
- Thus, very low density of quasars today.
- Quasars were once common, but then died out.

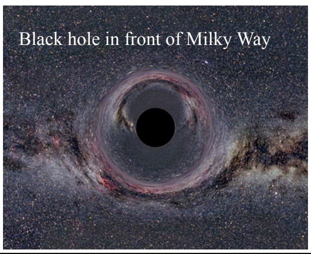
Quasars and Galaxy Formation

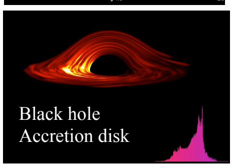
- All large nearby galaxies harbour a SMBH. When swallowing stars/gas, this becomes an AGN.
- During a mad feeding frenzy (e.g. triggered by merger with another galaxy) the SMBH may eat 1000 Msun/year. The galaxy temporarily becomes a Quasar, with an AGN 1000 times brighter than the starlight from the galaxy.
- SMBH, AGN activity, and Quasars are important for galaxy formation (e.g. SMBH mass is always a few % of the stellar bulge mass) but full story still being worked out.

Black Hole Lensing Effects

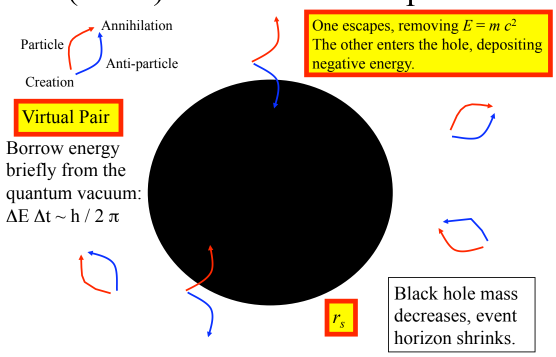
*Light rays bend toward the mass.
*Emerging photons are redshifted.
*Light is beamed and boosted in the direction of relativistic motion.







(small) Black Holes Evaporate



Black Holes Evaporate

- ***Hawking Radiation**:* involves gravity (G), relativity (c), thermodynamics (k) and quantum mechanics (h).
- Black holes emit Blackbody radiation with a temperature

$$kT = \frac{hGM_{bh}}{4\pi^2 c\, r_s^2} = \frac{hc^3}{16\pi^2 G M_{bh}}$$

- Luminosity: $L_{bh} = 4\pi r_s^2 \sigma T^4$
- Energy available: $E_{bh} = M_{bh} c^2$
- Evaporation time: $t_{bh} = E_{bh} / L_{bh}$
- $M_{bh} = 10^{15}$ kg (Everest) : $t_{bh} = 15$ billion years
- $M_{bh} = 5\ M_{sun}$: $t_{bh} = 10^{62}$ years