AS1001: Extra-Galactic Astronomy

Lecture 6: Galaxy Orientation, Black Holes & Quasars

Galaxy Inclination

<table>
<thead>
<tr>
<th>FACE-ON</th>
<th>EDGE-ON</th>
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</thead>
<tbody>
<tr>
<td>Inclination $i = 0^\circ$</td>
<td>Inclination $i = 90^\circ$</td>
</tr>
<tr>
<td>$a =$ Major Axis</td>
<td>$b =$ Minor Axis</td>
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</tbody>
</table>

All galaxies are viewed with some inclination:

- $a = b$, $i = 0^\circ$
- $b = 0$, $i = 90^\circ$

NB: $a$ is always measurable

Calculating the Inclination

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

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

- $a = b$, $i = 0^\circ$
- $b = 0$, $i = 90^\circ$

Line-of-sight velocity

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

Need to correct for inclination.

Example: Inclination Corrections

A long-slit spectrum aligned with a galaxy’s major axis has an [OII] line at 3900Å that shifts by 5Å 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?

$$\cos i = \frac{b}{a} = \frac{1}{3} \quad i = \cos^{-1}(1/3) = 70.5^\circ$$

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

$$V_{\text{rot}} = \frac{\Delta \lambda}{\lambda} = \frac{2.5\text{Å}}{3900\text{Å}} \times (3 \times 10^5 \text{ km/s}) = 192 \text{ km/s}$$

$$V_{\text{rot}} = \frac{V_{\text{abs}}}{\sin i} = \frac{204 \text{ km/s}}{0.94}$$

Note: $\lambda = 3900$ 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

$$\frac{1}{2} m v^2 = \frac{G M m}{r}$$
$$v_{esc} = \left(\frac{2 GM}{r}\right)^{1/2}$$
$$c^2 = 3 \text{ km} \left(\frac{M}{M_{\odot}}\right)$$

Types of Black Hole
- Stellar-mass
  - Formed when a very massive star goes supernova
  $$M_{\text{BH}} \sim 10 M_{\odot}$$
- Super-massive
  - Formed in galaxy cores
  $$M_{\text{BH}} \sim 10^{4 - 5} M_{\odot}$$
- Most large galaxies have a super-massive black-hole (SMBH) in their core.

The SMBH in M31
- Star velocities $v > 110$ km/s for $r < 2.5$ pc

Use Virial Theorem to calculate the Mass

$$M_{\text{core}} = \frac{v^2 r}{G}$$
$$= \frac{(110 \times 10^3)^2 \times 2.5 \times (3 \times 10^{10})}{6.67 \times 10^{-11}}$$
$$= 1.4 \times 10^6 \text{ kg} = 6.8 \times 10^5 M_{\odot}$$

The SMBH in M31
- Star velocities $v > 1000$ km/s inside $r = 0.01$ pc!

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!
- $\sim 3 \times 10^5 M_{\odot}$ 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)

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

- Super-Massive Black Hole
- Relativistic Jet Particles Ejected Along Magnetic Field Lines
- Infalling Stars: Some to be shredded by Black Hole Tides
- Accretion Disk of Shredded Stars and Gas

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:
  $$ T(r) = \frac{3GMm}{8\pi r^2} = 10^4 \left( \frac{M}{M_{\odot}} \right) \left( \frac{r}{r_g} \right)^{-1/4} $$
- Accretion Luminosity:
  $$ L = \frac{GM}{r_g} = \eta M c^2 = 10^{41} \left( \frac{M}{M_{\odot}} \right) $$
- $\eta$ = 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:
- I see a BLAZAR
- I see a RADIO GALAXY
- I see a QUASAR

The Quasar Era
- Redshift surveys find highest density of quasars per unit volume around redshift $z \sim 2-3$
- Large redshifts $\Rightarrow$ large distances $\Rightarrow$ 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 hole mass decreases, event horizon shrinks.
- One escapes, removing $E = mc^2$.
- The other enters the hole, depositing negative energy.

Black Hole in front of Milky Way
Black hole Accretion disk
Virtual Pair
Borrow energy briefly from the quantum vacuum: $\Delta E \Delta t = h / 2 \pi$
Black Holes Evaporate

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

$$
T = \frac{k G M_{bh}}{4 \pi \hbar c^3} = \frac{\hbar c^3}{16 \pi^2 G M_{bh}}
$$

- Luminosity:

$$
L_{bh} = 4\pi c^3 \sigma T^4
$$

- Energy available:

$$
E_{bh} = M_{bh} c^2
$$

- Evaporation time:

$$
\tau_{bh} = \frac{E_{bh}}{L_{bh}}
$$

$M_{bh} = 10^{15}$ kg (Everest): $\tau_{bh} = 15$ billion years
$M_{bh} = 5 M_{\text{sun}}$: $\tau_{bh} = 10^{62}$ years