Galaxy Spectra

- Galaxy spectra
  - Continuum
  - Absorption Lines
  - Emission Lines
  - Typical Spectra
    - Elliptical
    - Spiral
    - Irregular

- Galaxy motion
  - Radial velocity
  - Redshift
  - Redshift \(\rightarrow\) distance
  - Peculiar velocities

- Galaxy inclination

- Gas, dust and stars
Continuum

- The combination of many Black-Body spectra spanning a range in temperatures
- This produces a fairly flat overall spectrum

- The main feature is the 4000Å-break
The 4000A-break

• Caused by:
  – blanket absorption of high energy radiation from metals in the stellar atmospheres
  – the lack of hot blue stars

• Hence:
  – Ellipticals => A strong 4000A-Break
  – Spirals    => A weak 4000A-Break
  – Irregulars => No 4000A-Break
Absorption Lines

• Mainly caused by Atoms/Molecules in a star’s atmosphere that absorb specific wavelengths

• Can also be due to COLD gas in the interstellar medium which can EXTRACT energy from the passing radiation
Emission Lines

- Caused by gas being ionized and heated and then re-radiating at specific allowed wavelengths

- Stars form from gas so are often embedded
- Young stars ionise gas which releases radiation at a specific wavelength as it recombines
M101

Emission nebulae (HII regions) in spiral arms
Absorption / Emission Lines

• Absorption Lines
  – Need metals in stellar atmospheres or cold gas in the interstellar medium

• Implies
  – Old stellar population = old galaxy

• From
  – Ellipticals
  – Spiral Bulges

• Emission Lines
  – Need very hot gas and O and B type stars

• Implies
  – Newly formed stars = star-forming/young galaxy

• From
  – Spiral Disks
  – Irregulars
Typical Spectral features

- **Absorption**
  - Ca(H) = 3933.7 Å
  - Ca(K) = 3968.5 Å
  - G-band = 4304.4 Å
  - Mg = 5175.3 Å
  - Na = 5894.0 Å

- **Emission**
  - [OII] = 3727.3 Å
  - Hδ = 4102.8 Å
  - Hγ = 4340.0 Å
  - Hβ = 4861.3 Å
  - [OIII] = 4959.0 Å
  - [OIII] = 5006.8 Å
  - Hα = 6562.8 Å
  - S₂ = 6716.0 Å
Example Spectrum: Elliptical

Strong absorption lines due to metals in the stellar atmospheres of a mostly low luminosity stellar population. No evidence of any emission lines and hence no young stars and no gas.
Some emission and some absorption indicating both a young and old stellar population.
A strong emission-line spectrum indicating many hot young stars heating the gas which is re-radiating at specific wavelengths which depend on the chemical composition of the gas.

Example Spectrum: Irregular

- [OII]
- Hβ
- [OIII]
- S2
- Hα

No 4000 Å-Break
Radial Velocities

• Most galaxy spectra are **REDSHIFTED**, which means their spectral features are offset compared to those measured for gasses in the lab
• i.e., characteristic combinations of lines are systematically offset to longer wavelengths
• This is interpreted as a DOPPLER shift and implies that galaxies are moving away
• Positive velocities: RECEEDING
• Negative velocities: APPROACHING

\[
\frac{\Delta \lambda}{\lambda} = \frac{\Delta v}{c}
\]
or

\[
\frac{\lambda_{\text{OBSERVED}}}{\lambda_{\text{CALIBRATION}}} = \frac{v + c}{c}
\]
Example Radial Velocity

OII is at 4000Å

$H\alpha$ is at 7030Å

$OII$ $H\alpha$ km/s $974, 21$

$c(v_{\text{CAL}} - v_{\text{OBS}}) = c\left(\frac{4000 - 3727}{3727}\right) = 21,974\text{km/s}$

$H\alpha$ $c\left(\frac{467}{6563}\right) = 21,500\text{km/s}$

GALAXY IS MOVING AWAY AT ABOUT 21,750 km/s
$d = \frac{v}{H_o}$
Reminder: Cepheid P-L relation

- Well studied stellar objects
- Very bright ($M_v \sim -2$)
- Pulsate regularly (~ few days)
- Pulsation period depends on luminosity
- P-L relation calibrated to 220 stars via Hipparcos parallax distances (1997)
- Measuring the pulsation and apparent magnitude for a distant Cepheid provides a direct distance measurement given a known P-L relation.
Redshift

• We now know the Universe is expanding (see later lectures)
• An expansion implies a stretching of space-time.
• The more space-time there is between you and an object the faster it will appear to be moving away.
• It is the expansion which causes a galaxy’s spectrum to be REDSHIFTED:

**STATIONARY:**

**DOPPLER SHIFT:**

**REDSHIFT:**

**REDSHIFT IS NOT THE SAME AS DOPPLER SHIFT**
Redshift

• A useful parameter for cosmology is the redshift:

\[ z = \frac{\lambda - \lambda_o}{\lambda_o} = \frac{\Delta \lambda}{\lambda_o} \]

• This is analogous to the definition of Doppler shift such that: from which follows:

\[ z \equiv \frac{V}{c} \]

\[ d = \frac{zc}{H_o} \]

• Although this is the wrong interpretation of redshift it is a good approximation for low-\( z \) \( (z < 0.1) \)

• Hubble constant = rate of expansion in units of \((\text{km/s})/\text{Mpc}\)
  — Current value \( \sim 75 \text{ km/s/Mpc} \)
Calculating distances

- Using Hubble’s Law (which we’ll discuss more later) we can easily estimate distances from a galaxy’s measured redshift.

  e.g., If $H_o = 75 \text{ km/s/Mpc}$ and the redshift is measured to be 0.1 what is its distance?

  $$d = \frac{zc}{H_o} = \frac{0.1 \times 3 \times 10^5}{75} = 400 \text{ Mpc}$$

  This implies that for example its [OII] line, normally at 3727A, occurred at 4100A.
Peculiar Velocities

- Gravitational attraction between galaxies and larger objects (clusters, groups, superclusters, filaments)
- Velocity we measure is not just the expansion of the universe

\[ V_{\text{RADIAL}} = V_{\text{RECESSIONAL}} \pm V_{\text{PECULIAR}} \]

- For example the MW is falling into Virgo which in turn is falling into The Great Attractor.
- *If we know a galaxy’s peculiar velocity we can correct for this additional velocity component.*
Peculiar Velocities

• What we measure from spectra:
  \( V_{RADIAL} \) or \( V_{LINE\ OF\ SIGHT} \)

• Objects velocity w.r.t. our surroundings:
  \( V_{PECULIAR} \) or \( V_{INFALL} \)

• Velocity due to expansion:
  \( V_{RECESSION} \) or \( V_{EXPANSION} \)

\[ V_{RADIAL} = V_{RECESSIONAL} \pm V_{PECULIAR} \]
Example

- The MW is falling \textit{towards} Coma at \( V_{\text{infall}} = 1000 \text{km/s} \).
- Distance is 50 Mpc (from Cepheids)
- If the redshift, \( z = 0.01 \), what is \( H_0 \) ?

\[
\begin{align*}
  z &= \frac{V_{\text{radial}}}{c} = \frac{V_{\text{recession}} - V_{\text{infall}}}{c} \\
  H_o &= \frac{V_{\text{recession}}}{d} = \frac{cz + V_{\text{infall}}}{d} = \frac{3000 + 1000}{50} \\
  H_o &= 80 \text{km/s/Mpc}
\end{align*}
\]

Note: Be very careful with the sign of \( V_{\text{infall}} \) & \( V_{\text{peculiar}} \), it is intuitive
Typically \( V_{\text{infall}} \) is subtracted but for \( V_{\text{peculiar}} \) it will depend on the
direction of the peculiar velocity (towards us= -ve, away= +ve)
Galaxy Inclination

FACE-ON
Inclination=0°

EDGE-ON
Inclination=90°

b=Minor Axis

a=Major Axis

Majority of galaxies are somewhere in between
Calculating the Inclination

- Assuming galaxies are circular:
- Inclination, $i$, is given by:
  \[
  \cos(i) = \frac{b}{a}
  \]

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

NB: $a$ is always measurable
Line of sight velocity

• When we measure the rotational velocity from a spectral line we need to correct for inclination.

\[
V_{\text{obs}} = V_{\text{rot}} \sin(i)
\]

Hence if,
- \(i=90\), \(V_{\text{obs}} = V_{\text{rot}}\)
- \(i=0\), \(V_{\text{obs}} = 0\)
Example

A long slit spectrum aligned along a galaxy’s major axis indicates a variation in the [OII] line of 5A. The midpoint of the [OII] line is observed to be at 3900Å and the major-to-minor axis ratio is 3. What is the rotational velocity of the outermost stars?

\[ i = \cos^{-1}(1/3) = 70.5^0 \]

Note: 5/2 Å

\[ V_{OBS} = \frac{\Delta \lambda}{\lambda} c = \frac{2.5}{3900} \times 3 \times 10^5 = 192 \text{ km / s} \]

Note: \( \lambda = 3900 \) and not 3727 (as reference is to the galaxy centre)

\[ V_{ROT} = \frac{V_{OBS}}{\sin(i)} = 204 \text{ km / s} \]
Stars, Dust and Gas in Galaxies

• Dust mass is negligible but can block up to 90% of the light and provides a good indication of where the fresh stars are
• Stars form from gas in galaxy
• In the high-density regions the gas is converted into Stars

- Elliptical: very little gas content
  - ~ all gas converted into stars

- Spiral: some gas content
  - most gas converted

- Irregular: lots of gas
  - little gas converted

\[
\frac{M_{HI}}{M_{STARS}} = 0.01 - 0.1
\]

\[
\frac{M_{HI}}{M_{STARS}} = 0.1 - 1.0
\]

\[
\frac{M_{HI}}{M_{STARS}} \geq 1.0
\]
Warm dust and starlight in Antennae galaxy
Optical and radio image of NGC891
Distribution of Gas and Stars

M82

M81

NGC 3077