Astronomical units

Distance: an **astronomical unit** (AU or au) is the mean distance between the Earth and the Sun (technically the radius of a circular orbit with same period as the Earth).

\[ 1 \text{ au} = 1.496 \times 10^{13} \text{ cm} \]

Angles: a circle has 360 degrees or 2\(\pi\) radians

\[ 1^\circ = \frac{2\pi}{360} \text{ radians} = 0.01745\ldots \text{ radians} \]

\[ 1 \text{ arcminute} = \frac{1}{60} \text{ degrees} \]

\[ 1 \text{ arcsecond} = \frac{1}{60} \text{ arcminutes} = 4.85 \times 10^{-6} \text{ radians} \]

Best resolution of optical telescopes (HST) is about 0.1".
A *parsec* (pc) is defined as the distance at which a `ruler’ of length 1 au subtends an angle of 1 arcsecond.

\[ 1'' = \frac{1 \text{ au}}{1 \text{ pc}} \]

\[ 1 \text{ pc} = \frac{1.496 \times 10^{13} \text{ cm}}{4.85 \times 10^{16}} = 3.086 \times 10^{18} \text{ cm} \]

1 pc = 3.26 light years - roughly the distance to the nearest stars. Convenient unit for stellar astronomy.

Sizes of galaxies usually measured in kpc (galaxy scales are 10-100 kpc).

Cosmological distances are 100s of Mpc to Gpc. Observable Universe is a few Gpc across.
Other common units are the Solar mass, Solar radius, and Solar luminosity:

\[
M_{\text{sun}} = 1.99 \times 10^{33} \text{ g} \\
R_{\text{sun}} = 6.96 \times 10^{10} \text{ cm} \\
L_{\text{sun}} = 3.86 \times 10^{33} \text{ erg s}^{-1} = 3.86 \times 10^{26} \text{ W}
\]

Usually use nm as a measure of wavelength, but may show plots in Angstroms:

\[
1 \text{ Å} = 10^{10} \text{ m} = 0.1 \text{ nm}
\]
1. Radiation processes

a) How is radiation affected as it propagates to the observer?
   • In general
   • Use results to understand spectra of stars, nebulae.

b) Mechanisms that produce radiation:
   • Transitions within atoms (or molecules)
   • Acceleration of electrons in a plasma by electric or magnetic fields.
Basic properties of radiation

Electromagnetic radiation of frequency $\nu$, wavelength $\lambda$ in free space obeys:

$$\lambda \nu = c$$  \hspace{1cm} \text{speed of light}

Individual photons have energy:

$$E = h\nu$$  \hspace{1cm} h = Planck’s constant

Common to measure energies in electron volts, where:

$$1 \text{ eV} = 1.6 \times 10^{-12} \text{ erg} = 1.6 \times 10^{-19} \text{ J}$$

In c.g.s. units:

$$h = 6.626 \times 10^{-27} \text{ erg s}$$

$$c = 3.0 \times 10^{10} \text{ cm s}^{-1}$$
**Simplification:** astronomical objects are normally much larger than the wavelength of radiation they emit:
- Diffraction can be neglected
- Light rays travel to us along **straight lines**

**Complexity:** at one point, photons can be traveling in several different directions:

- e.g. center of a star, photons are moving equally in all directions.

- radiation from a star seen by a distant observer is moving almost exactly radially.

Full specification of radiation needs to say how much radiation is moving in each direction.
Flux

Consider a small area dA, exposed to radiation for a time dt. Energy passing through the area is $F \cdot dA \cdot dt$, where $F$ is the **energy flux** (units erg s$^{-1}$ cm$^{-2}$).

Unless the radiation is **isotropic** (same in all directions), $F$ will depend on orientation of dA.

Spherically symmetric steady source of luminosity $L$. Energy conservation:

$$L = 4\pi r^2 F(r)$$

$$F(r) = \frac{L}{4\pi r^2}$$

**Inverse square law.**
As defined:
- $L$ is the total luminosity emitted at all wavelengths
- $F$ is the energy flux likewise integrated over all wavelengths

Hence, $L$ is called the **bolometric luminosity** (because a bolometer is a device that measures energy from all wavelengths).

`Spider-web’ bolometer - mostly used to detect microwave radiation.
Real detectors are sensitive to a limited range of wavelengths. Need to consider how the incident radiation is distributed over frequency.

\[ F = \int F_{\nu} \, d\nu \]

Integral of \( F_{\nu} \) over all frequencies

Units erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\)

Radio astronomers use this (logical) way of measuring fluxes, though for convenience they define:

\[ 1 \text{ Jansky (Jy)} = 10^{23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \]

\( F_{\nu} \) is often called the `flux density’ - to get the power received one just multiplies by the area and by the bandwidth of the receiver (or integrates if \( F_{\nu} \) varies significantly in that range).
Apparent magnitudes

For historical reasons, fluxes in the optical and infra-red are instead measured in magnitudes:

\[ m = 2.5 \log_{10} F + \text{constant} \]

If \( F \) is the total flux (all wavelengths), then \( m \) is the bolometric magnitude. Usually instead consider a range of wavelengths.

For example, in the visible band (\( V \), centered around 550 nm):

\[ m_V = 2.5 \log_{10} F + \text{constant} \]

Flux integrated over the range of wavelengths for this band.
Basic properties of magnitudes:

Consider two stars, one of which is a hundred times fainter than the other in some waveband (say V).

\[ m_1 = 2.5 \log F_1 + \text{constant} \]

\[ m_2 = 2.5 \log(0.01F_1) + \text{constant} \]

\[ = 2.5 \log(0.01) + 2.5 \log F_1 + \text{constant} \]

\[ = 5 + 2.5 \log F_1 + \text{constant} \]

\[ = 5 + m_1 \]

Source that is 100 times fainter in flux is five magnitudes fainter (larger number).

Faintest objects detectable with HST have magnitudes of around 28 in red / near infrared bands.
Common wavebands:

<table>
<thead>
<tr>
<th>Waveband</th>
<th>Central Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>U (ultraviolet)</td>
<td>365nm</td>
</tr>
<tr>
<td>B (blue)</td>
<td>440nm</td>
</tr>
<tr>
<td>V (visible)</td>
<td>550nm</td>
</tr>
<tr>
<td>R (red)</td>
<td>641nm</td>
</tr>
<tr>
<td>K (infra-red)</td>
<td>2.2µm</td>
</tr>
</tbody>
</table>

These are the central wavelengths of each band, which extend ~10% in wavelength to either side.

Zero-points (i.e. the constants in the equation for $m_V$ etc) are defined such that the magnitude of a standard star (Vega) is zero in all wavebands.
Colors

The color of a star or other object is defined as the difference in the magnitude in each of two bandpasses:

e.g. the (B-V) color is: $B - V = m_B - m_V$

Stars radiate roughly as blackbodies, so the color reflects surface temperature.

Vega has $T = 9500 \text{ K}$, by definition color is zero.

Which sense for hotter / cooler stars?
Color does not reflect temperature for objects with spectra very different from that of a blackbody.
Still can be useful - e.g. basis of most successful method for finding very distant (high redshift) galaxies:

**Observed** galaxy spectrum shifts to the right for source at higher redshift. Because spectrum has a sharp `break`, flux in U band drops off sharply.
Absolute magnitude

The absolute magnitude is defined as the apparent magnitude a source would have if it were at a distance of 10 pc (1 pc = 3.086 x 10^{18} cm).

Measure of the luminosity in some waveband.

Difference between the apparent magnitude m and the absolute magnitude M (any band) is a measure of the distance to the source:

$$m - M = 5 \log_{10} \frac{d}{10 \text{ pc}}$$

Distance modulus