# 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

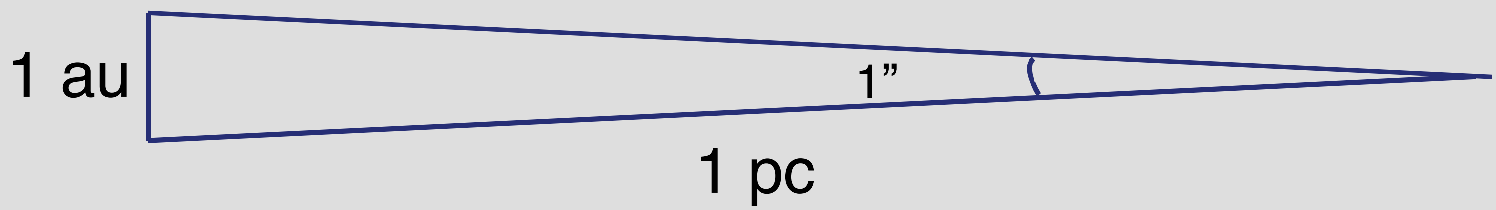
$$1^{\circ} = \frac{2\pi}{360} \text{ radians} = 0.01745\ldots \text{ radians}$$

$$1 \text{ arcminute} = \frac{1}{60} \text{ degrees}$$

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

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.




$$1'' = \frac{1 \text{ au}}{1 \text{ pc}} \Rightarrow 1 \text{ pc} = \frac{1.496 \times 10^{13} \text{ cm}}{4.85 \times 10^{-6}} = 3.086 \times 10^{18} \text{ cm}$$

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:

$$M_{sun} = 1.99 \times 10^{33} \text{ g}$$

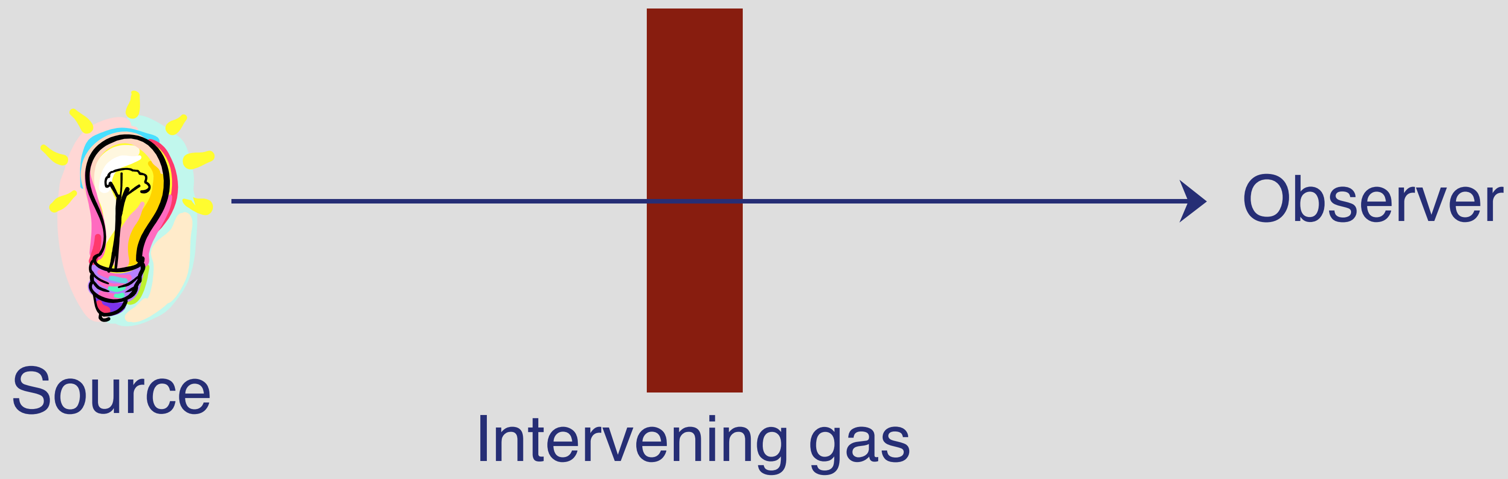
$$R_{sun} = 6.96 \times 10^{10} \text{ cm}$$

$$L_{sun} = 3.86 \times 10^{33} \text{ erg s}^{-1} = 3.86 \times 10^{26} \text{ W}$$

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:

$$\lambda\nu = c$$ ⟵ speed of light

Individual photons have energy:

$$E = h\nu$$ 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:

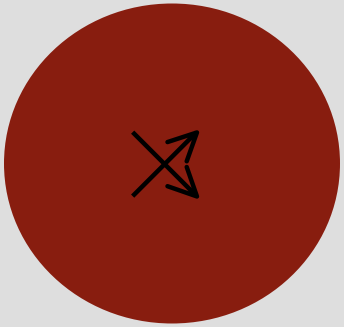
$$h = 6.626 \times 10^{-27} \text{ erg s}$$

$$c = 3.0 \times 10^{10} \text{ cm s}^{-1}$$

**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:



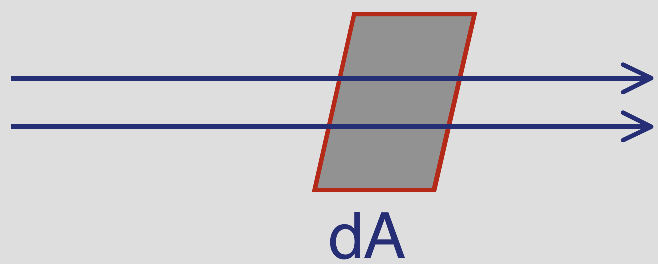
e.g. center of a star, photons are moving equally in all directions.

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

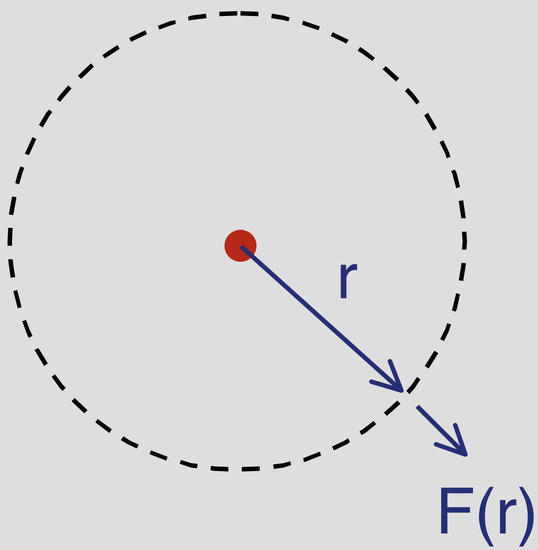
Full specification of radiation needs to say how much radiation is moving in each direction.

# Flux

Consider a small area dA, exposed to radiation for a time dt. Energy passing through the area is F.dA.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:

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

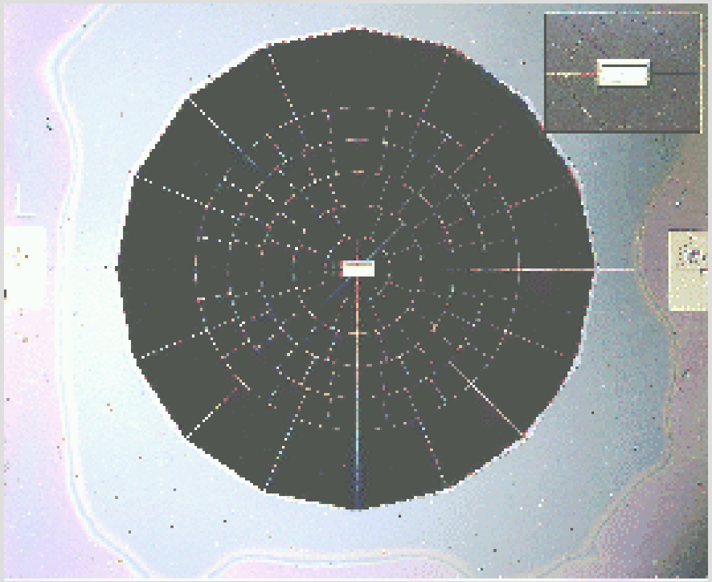
$$F(r) = \frac{L}{4\pi r^2}$$

**Inverse square law.**

As defined:

- L is the total luminosity emited 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.

Total energy flux

$$F = \int F_{\nu}(\nu) d\nu$$

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:

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

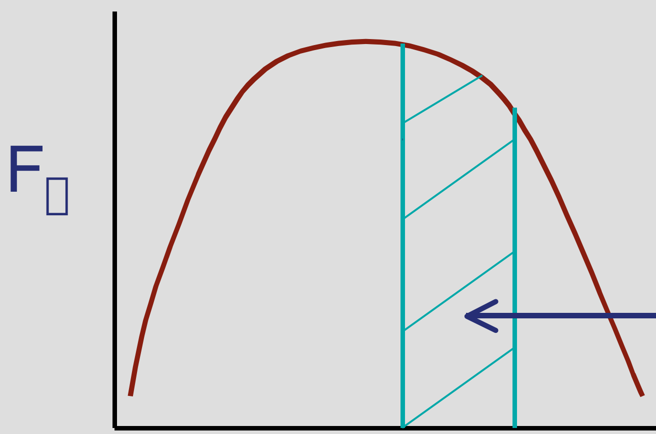
$F_{\nu}$ is often called the `flux density' - to get the power received one just multiplies by the area and by the bandwidth of the receiver (or integrates if $F_{\nu}$ varies significantly in that range).

## 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.




e.g. 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).

$$
\begin{aligned}
m_1 &= -2.5 \log F_1 + \text{constant} \\
m_2 &= -2.5 \log (0.01 F_1) + \text{constant} \\
&= -2.5 \log (0.01) - 2.5 \log F_1 + \text{constant} \\
&= 5 - 2.5 \log F_1 + \text{constant} \\
&= 5 + m_1
\end{aligned}
$$

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:

| | |
|---|---|
| **U** (ultraviolet) | 365nm |
| **B** (blue) | 440nm |
| **V** (visible) | 550nm |
| **R** (red) | 641nm |
| **K** (infra-red) | 2.2μm |

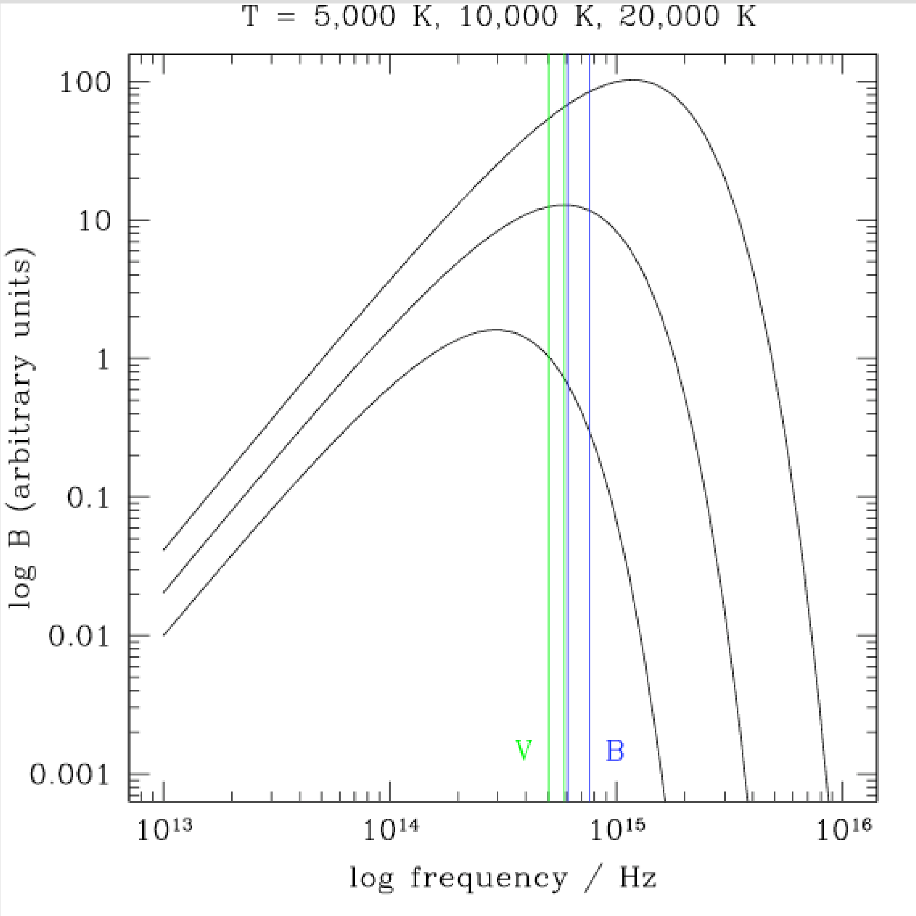
These are the central wavelengths of each band, which extend ~10% in wavelength to either side.

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 = $m_B$-$m_V$



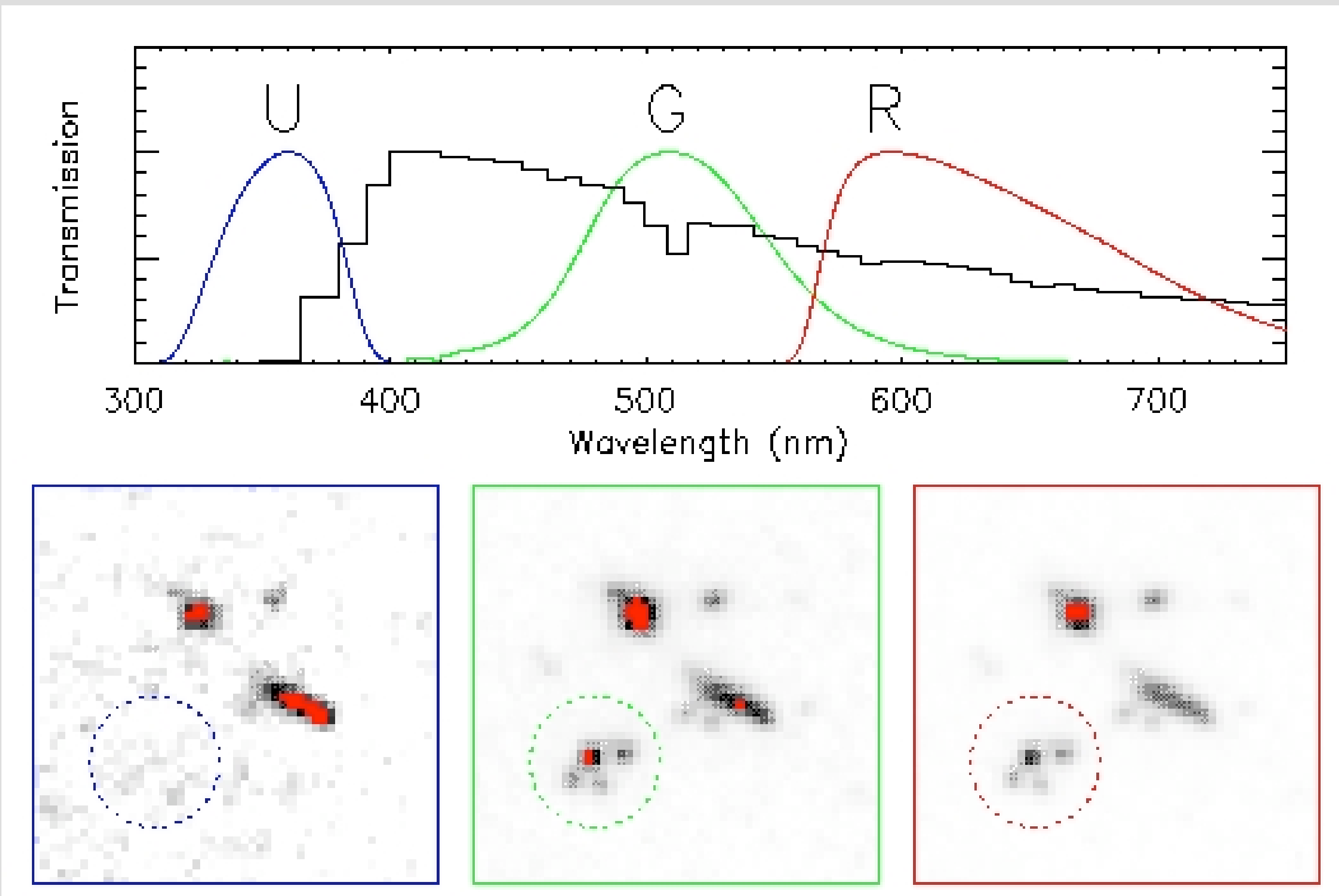

Stars radiate roughly as blackbodies, so the color reflects surface temperature.

Vega has T = 9500 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 = $3.086 \times 10^{18}$ 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:

$$\underbrace{m - M}_{\textbf{Distance modulus}} = 5\log_{10}\left(\frac{d}{10\ \text{pc}}\right)$$

**Distance modulus**