Astronomy A2Z Session 2008-09

Observational Astrophysics

10 Lectures, starting January 2009

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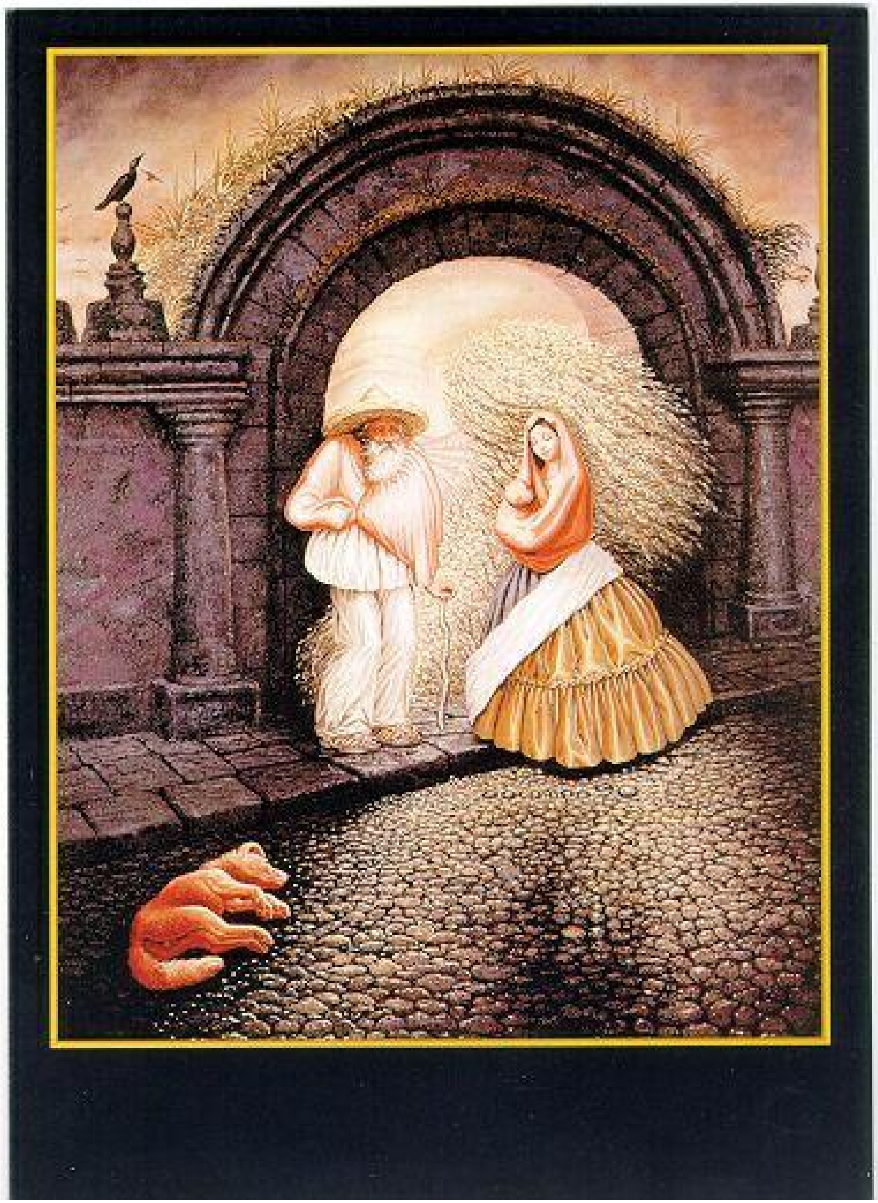
Course aims

(these are not always obvious!)

Observational Astrophysics 2 forms a bridge between Levels 1 and 3, consolidating the elementary material covered in Astronomy 1 and introducing more advanced concepts in preparation for Honours.



Good books to read

•An introduction to Modern Astrophysics, Carroll & Ostlie – the A2 recommended textbook!

•Astronomy Principles and Practice, Roy & Clarke – much good material, based on the Glasgow courses.

•Astronomical Observations, Walker – rather simple overview of modern instrumentation, biased to the optical.

•Observational Astrophysics, Smith – Instrumentation and descriptions of stars and galaxies etc.

•High Energy Astrophysics vol. 1, Longair Useful for Detectors and A3/4.

Topics

- Section 1 Ideas of astrophysical measurements: astrophysical observations, units, luminosity, flux, intensity

- Section 2 Detectors and telescopes: optical, X-ray and gamma-ray detectors, radio telescopes

- Section 3 Optical detectors: photographic plates, photomultipliers, image intensifies, charge coupled devices (CCDs)

- Section 4 Sensitivity, uncertainties and noise: poisson statistics, standard deviation, background, telescope design

- Section 5 Observations through the atmosphere: absorption, refraction and scattering

- Section 6 Spectral techniques: diffraction gratings, spectral resolution, slit spectrometers, spectroscopy: spectra and spectral resolving power

- Section 7 Angular resolution: aperture diffraction, the Airy disk, interferometry.

Ideas of astrophysical measurement

What we can observe?

Particles:

- cosmic rays
- neutrinos
- neutrons
- solar particles

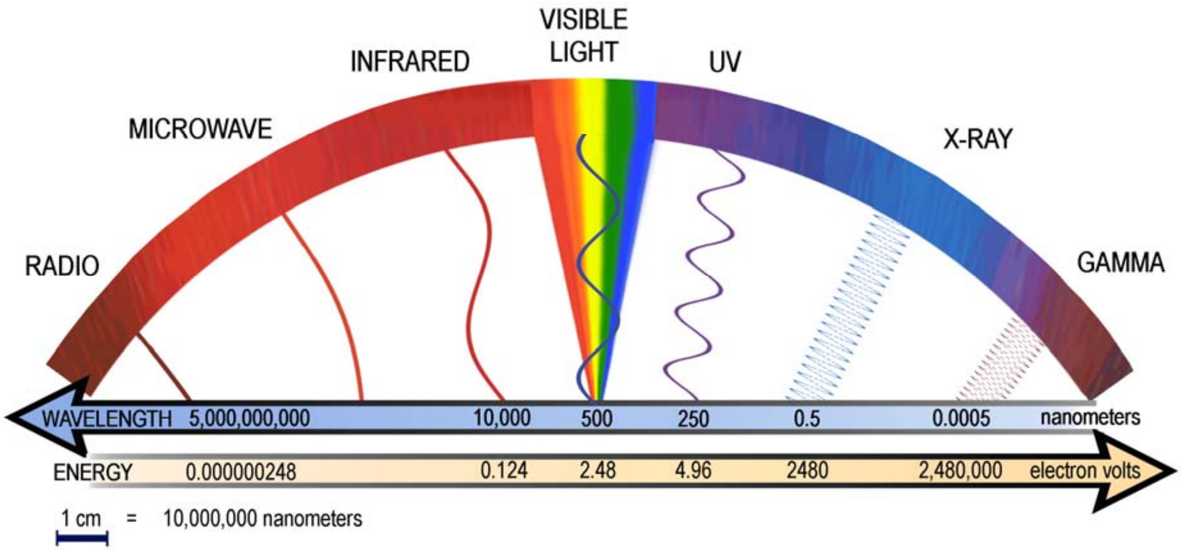
Electromagnetic emission

- optical range
- radio waves
- X-rays and gamma-rays

- In-situ measurements of electric/magnetic fields
- Gravitational waves??

Ideas of Radiant Energy

Astrophysical observations are almost always of electromagnetic radiation



Historically, it was mainly the visible part of the E-M spectrum that was used:

$$\boxed{400\,\text{nm} \le \lambda \le 700\,\text{nm}} \qquad \left(1\,\text{nm} = 10^{-9}\,\text{m}\right)$$

BLUE RED

Nowadays observations are carried out from gamma rays $\lambda < 0.01\,\mathrm{nm}$ to long-wavelength radio waves $\lambda > 1\,\mathrm{km}$

Remember

$$\boxed{c = \lambda \nu} \qquad (1.1)$$

Frequency (Hz)

Speed of light

$(= 2.998 \times 10^{8}\ \mathrm{ms^{-1}})$

$$\boxed{E = h\nu = \frac{hc}{\lambda}} \qquad (1.2)$$

Energy (joules, electronvolts, ...)

$(1\,\mathrm{eV} = 1.602 \times 10^{-19}\,\mathrm{J})$

Planck constant $(= 6.626 \times 10^{-34}\ \mathrm{Js})$

- In A1 you met the concept of

Luminosity = energy radiated per unit time by a source

SI unit = watt (joules per second)

In general, luminosity is dependent on frequency (or wavelength).

i.e. astrophysical objects are generally 'coloured' – they don't radiate the same amount of power in all frequency bands.

Hence we write $$\boxed{L = L(\nu)} \qquad (1.3)$$

Sometimes referred to as *monochromatic luminosity*

and $L(\nu_0)\,\Delta\nu$ = energy radiated per unit time by a source in the frequency interval $\Delta\nu$ centred on ν_0

- Strictly speaking we should write the luminosity as the integral

$\int_{\nu_0 - \frac{1}{2}\Delta\nu}^{\nu_0 + \frac{1}{2}\Delta\nu} L(\nu)\, d\nu$ but provided $\Delta\nu$ is small we can approximate by $L(\nu_0)\,\Delta\nu$

- Sometimes we consider instead luminosity as a function of wavelength, i.e.

$$L = L(\lambda)$$

- Relating $L(\nu)$ and $L(\lambda)$ is straightforward, but needs care.

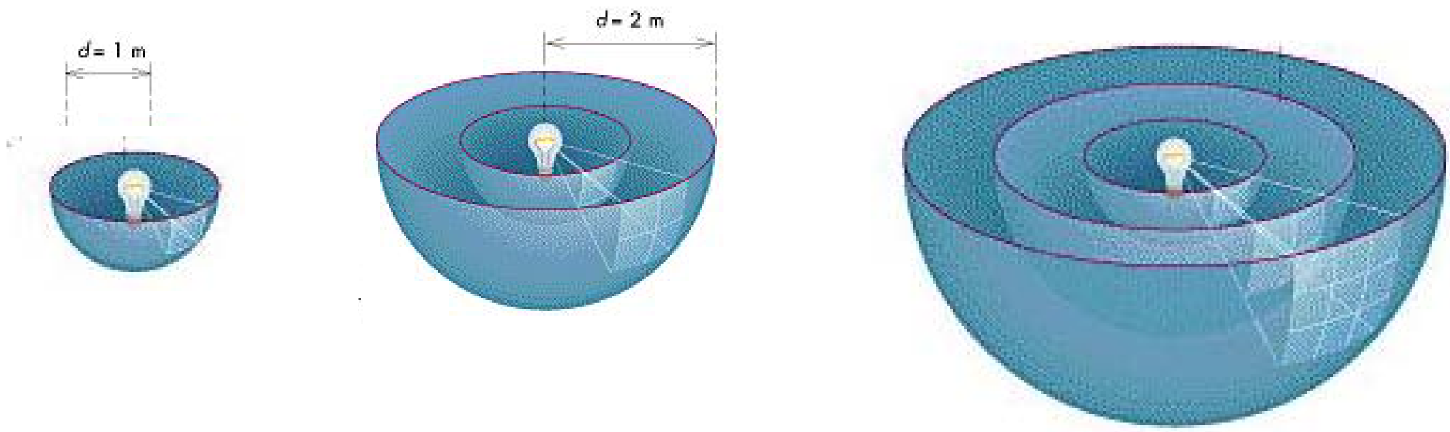
(See A2 Theoretical Astrophysics notes!)

Bolometric Luminosity = energy per unit time radiated at *all* frequencies or wavelengths

(1.4) $$L_{\mathrm{bol}} = \int_0^{\infty} L(\nu)\, d\nu = \int_0^{\infty} L(\lambda)\, d\lambda$$

Note: Luminosity is an **intrinsic** property of a source

Usually we assume that astrophysical point sources radiate isotropically (i.e., uniformly in all directions). This allows us to relate their luminosity to their **apparent brightness, or flux,** which decreases with distance, according to an inverse-square law.



Apparent brightness, or flux, falls off with the square of the distance, because the surface area of a sphere increases with the square of its radius. (Note this is clearly true for point sources, where all the radiation in travelling radially outwards, but also true for extended uniform spherical sources is you define the flux from an extended source in the right way).

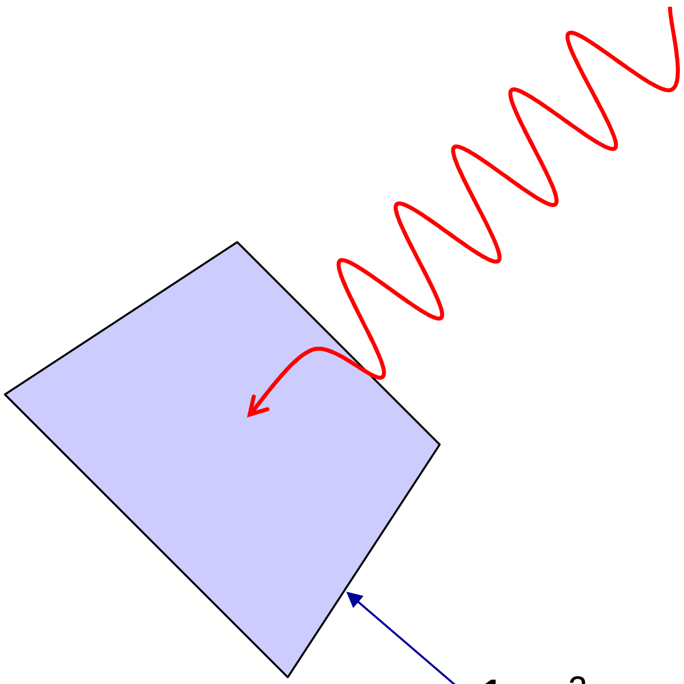
Radiant Flux = energy per unit time crossing a unit area perpendicular to the direction of light propagation

SI unit: watts per square metre (Wm^{-2})

From this definition, for an isotropic point source of luminosity L at distance D :

$$\boxed{F = \frac{L}{4\pi D^2}} \qquad (1.5)$$

Flux Area of a sphere



1 m^2

- As with luminosity, in general we need to work with a measure of flux which is frequency dependent. We therefore define

flux density = energy per unit time, *per unit frequency interval*, crossing a unit area perpendicular to the direction of propagation

Usually denoted by $F(\nu), S(\nu), F_\nu$ or S_ν

- Astronomers use a special small unit for flux density

$$10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}} = 1\ \text{jansky (Jy)} \qquad (1.6)$$

The jansky is a common unit of measurement in radio, microwave and infra-red astronomy. It is less common in optical astronomy, although it has become more widely used in recent years.

- Suppose we observe in frequency interval $\nu_1 \le \nu \le \nu_2$

$$\boxed{\text{Flux in this interval, } F = \int_{\nu_1}^{\nu_2} S_\nu \, \mathrm{d}\nu} \qquad (1.7)$$

We define the **bandwidth** of this interval as

$$\boxed{\Delta\nu = \nu_2 - \nu_1} \qquad (1.8)$$

and the mean frequency as $\quad \bar{\nu} = \tfrac{1}{2}\left(\nu_1 + \nu_2\right)$

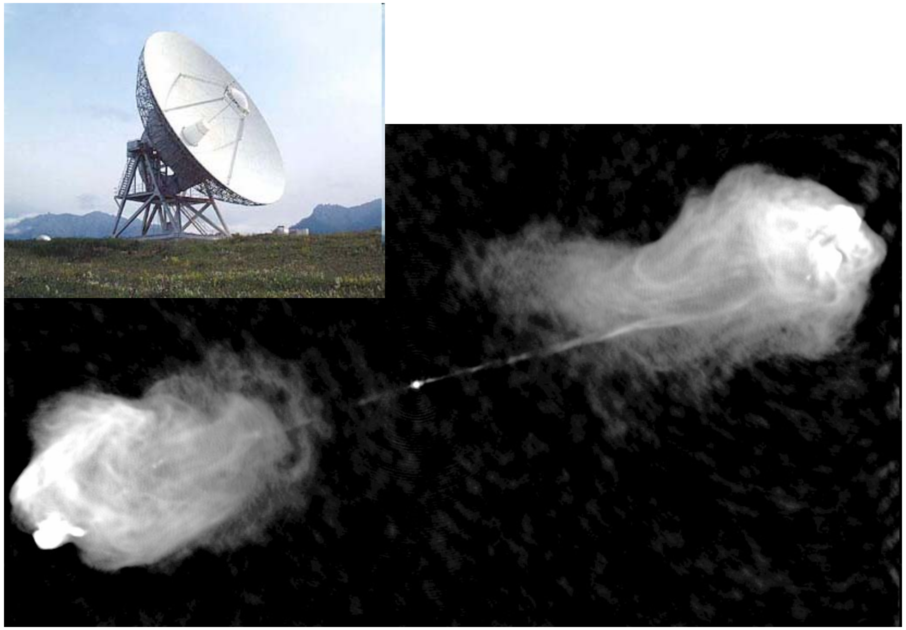
If $\Delta\nu$ is small **or** S_ν is either flat
or varies linearly with frequency, then

$$\boxed{F = S_{\bar{\nu}} \, \Delta\nu} \qquad (1.9)$$

Integrated flux = flux density x bandwidth

Example

The radio source Cygnus A has a flux density of 4500 Jy at a frequency of 450 MHz. How much energy is incident on a radio telescope, of diameter 25 m, which observes Cygnus A for 5 minutes over a bandwidth of 5 MHz around this frequency?



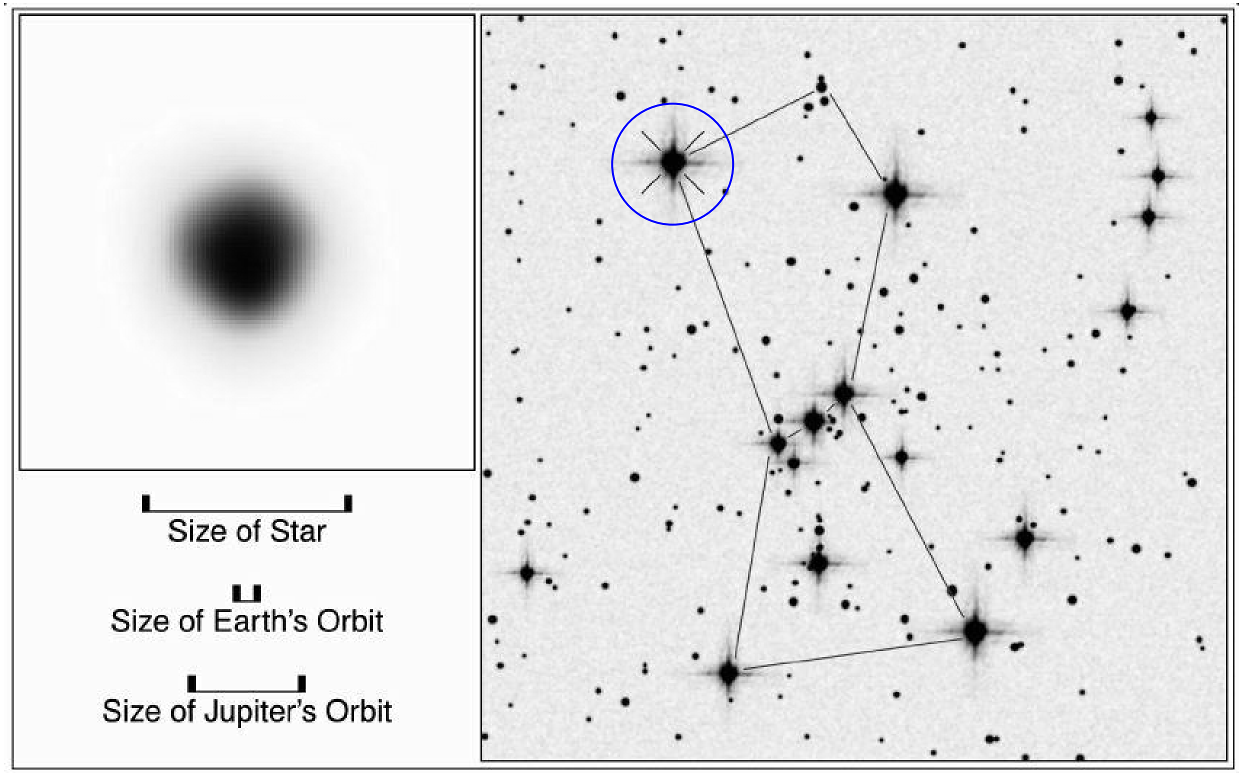
Solid Angle

Most stars can be regarded as point sources, with no appreciable angular width

angular diameter of the Sun = 0.533 degrees

angular diameter of Betelgeuse = 0.000 014 degrees

(barely) resolvable with HST



We use solid angle as measure of the fraction of the sky covered by an extended source.

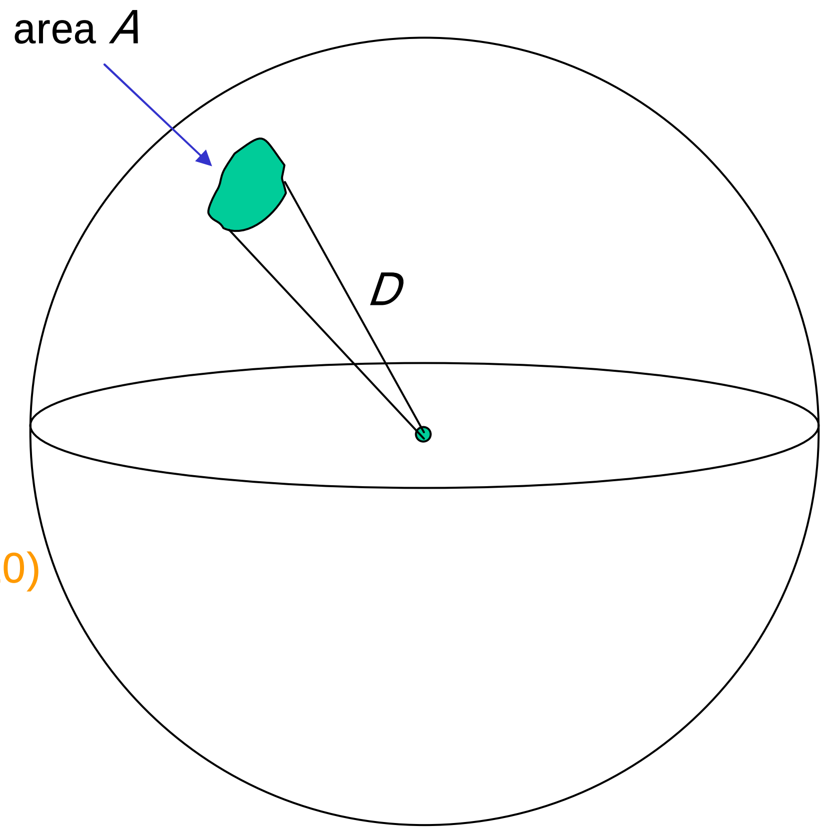
SI unit of solid angle

= **steradian** (sr)

Consider a source of projected area A at a distance D

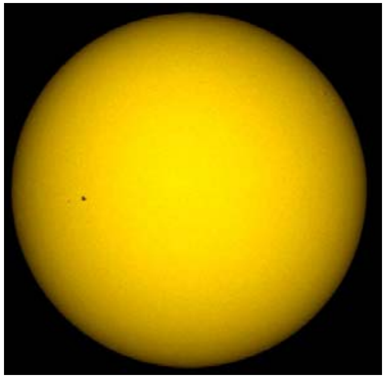
solid angle $$\Omega = \frac{A}{D^2} \quad (1.10)$$

Whole sky = $\frac{4\pi D^2}{D^2} = 4\pi$ sr



For a spherical source, of radius R

Projected area, $A = \pi R^2$



so

$$\boxed{\Omega = \pi \left(\frac{R}{D}\right)^2} \quad (1.11)$$

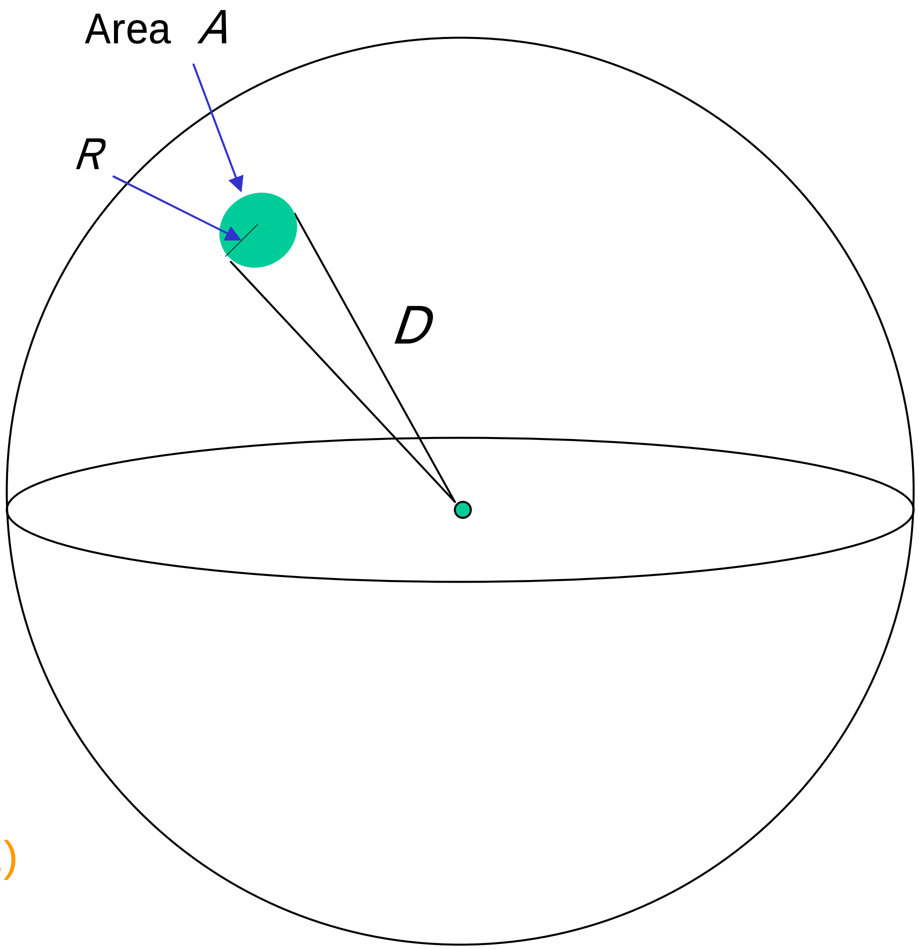
but

$$\theta = \frac{2R}{D}$$

Angular diameter of source, in radians (using $\tan\theta \cong \theta$)

so

$$\boxed{\Omega = \pi \left(\frac{\theta}{2}\right)^2} \quad (1.12)$$



You need to be careful about units

In Eq. (1.12) angular diameter **must** be in radians to get a solid angle in steradians, but it is often given in degrees (or arcminutes / arcseconds)

Examples

Calculate solid angle subtended by the Sun,

ang. diam. = 0.533 degrees

Calculate solid angle subtended by globular cluster NGC 6093,

ang. diam. = 8.9 arcmin

But many other objects (e.g. galaxies, nebulae) are **extended**

Specific Intensity

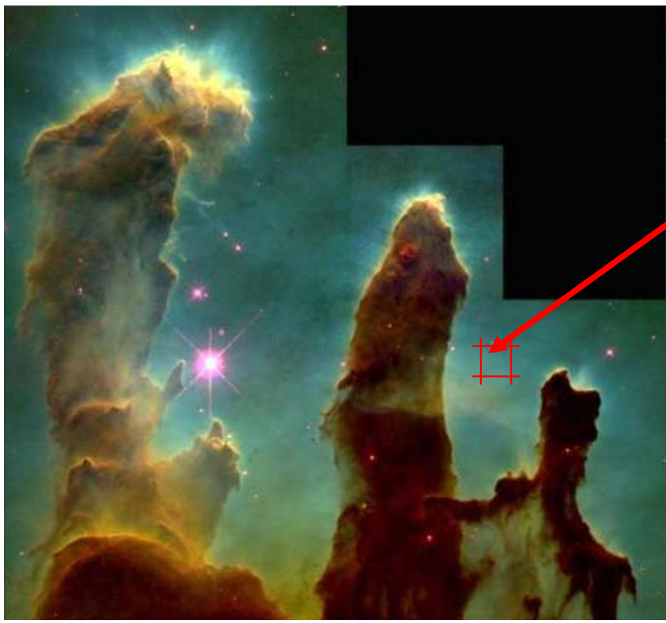
An **extended source** (e.g. a galaxy) may deliver the same flux density as a **point source** (e.g. a star) but it is spread over a small area of the sky.

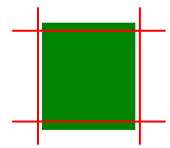
Also, as can be seen clearly for this planetary nebula, an extended source will not be equally bright across its entire projected area.

We need to introduce a new quantity to describe this variation in brightness. It is usually referred to as **specific intensity** or (particularly in the context of galaxies) as **surface brightness.**

Specific intensity

- We define specific intensity to be the flux density of the source (through a plane perpendicular to the direction of the source) per unit solid angle. Generally, this varies over the source:

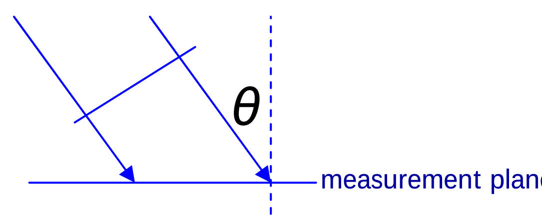




small square
(image pixel)

Pixel has solid angle $\mathrm{d}\Omega$
generates flux density $\mathrm{d}S_\nu$

If the rays arrive at an angle, the flux is reduced by $\cos\theta$:



so $$I_\nu \cos\theta = \frac{\mathrm{d}S_\nu}{\mathrm{d}\Omega}$$

For an astronomical source, θ is usually very small, so $$I_\nu \approx \frac{\mathrm{d}S_\nu}{\mathrm{d}\Omega}$$

Hence

$$\boxed{S_\nu = \int_{\Omega_S} I_\nu \cos\theta \, d\Omega \approx \int_{\Omega_S} I_\nu \, d\Omega} \qquad (1.19)$$

For astronomical sources

Flux density = integral of the specific intensity over the solid angle of the source

If I_ν is constant over the source on the sky, then

$$\boxed{S_\nu = I_\nu \, \Omega_S} \qquad (1.20)$$

Specific intensity is independent of the distance to the source!

$S_\nu \propto D^{-2}$ from Eq. (1.5)

$\Omega_S \propto D^{-2}$ from Eq. (1.10)

Example

For a **blackbody** of temperature T

$$\boxed{I_\nu = \frac{2h\nu^3}{c^2\left[\exp\left(\frac{h\nu}{kT}\right)-1\right]} \quad \text{W m}^{-2}\text{ Hz}^{-1}\text{ sr}^{-1}} \tag{1.21}$$

Blackbody radiation is **isotropic** (i.e. specific intensity doesn't depend on direction).

At a given frequency, I_ν depends only on T
$\Rightarrow$ We can use the measured I_ν to **define** an **effective temperature** for that part of the source (recall effective temperature from A1Y stellar course).

We can make a similar definition, common in **radio astronomy**:

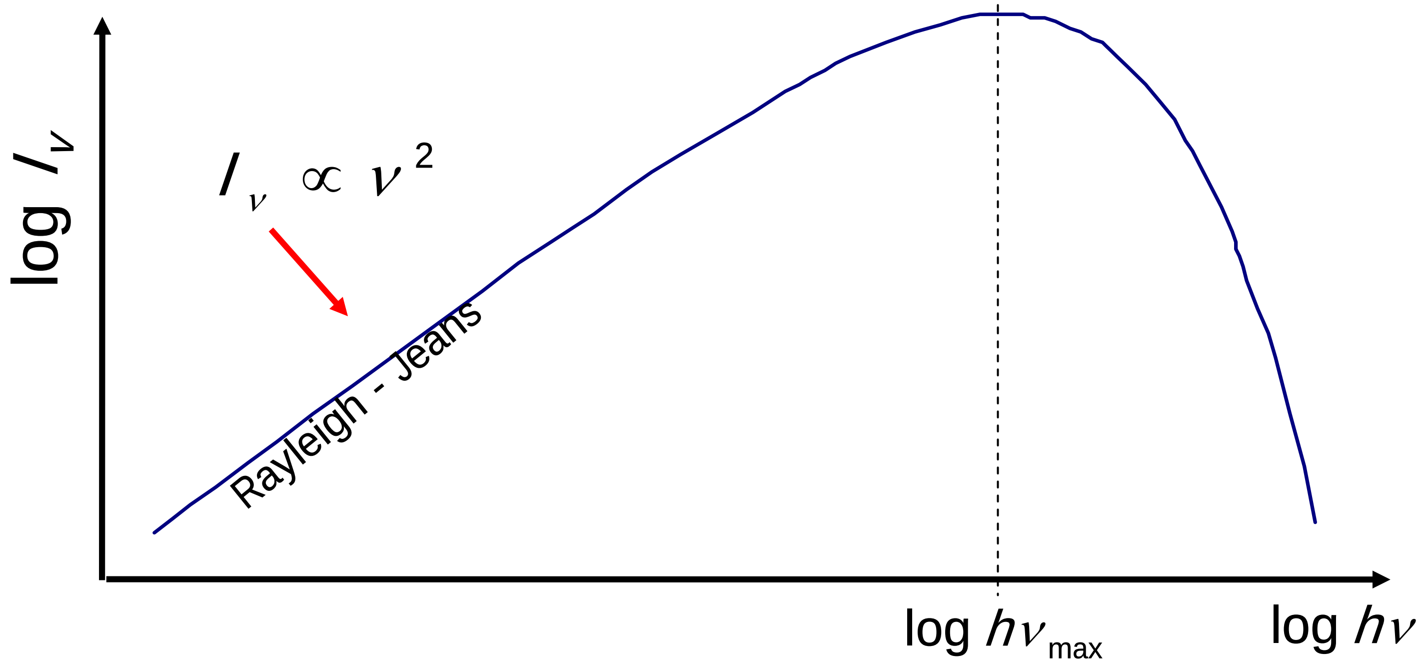
Brightness temperature

At typical radio frequencies and temperatures $h\nu << kT \quad \Rightarrow \quad \exp\left(\frac{h\nu}{kT}\right) - 1 \approx \frac{h\nu}{kT}$

Hence

$$I_\nu = \frac{2h\nu^3}{c^2\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]} \cong \frac{2\nu^2 kT}{c^2} \qquad (1.24)$$

Rayleigh – Jeans approximation



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Rayleigh – Jeans approximation

(1.24)

We define

$$T_b = \frac{c^2 I_\nu}{2k\nu^2}$$

(1.25)

Brightness temperature

Measured intensity

Note that we can **always** define a brightness temperature, but it will only correspond to the actual temperature if the source is approximately a black body and $h\nu << kT$

Example

The quasar 3C123 has an angular diameter of 20 arcsec, and emits a flux density of 49 Jy at a frequency of 1.4 GHz.

Calculate the brightness temperature of the quasar.

The Magnitude System

While many modern astrophysical observations are made in terms of flux density, **optical astronomy** has mainly retained the **magnitude system**, which is based on a logarithmic scale (See A1 and handout).

Bolometric apparent magnitude

$$\boxed{m_{\mathrm{bol}} = -2.5\log_{10} \mathrm{F} + \mathrm{const.}}$$

Radiant flux (over all frequencies)

Need to calibrate via standard stars. e.g. **Vega** defined to have bolometric apparent magnitude zero

$$\boxed{m_{\mathrm{bol}} = -2.5\log_{10} \frac{\mathrm{F}}{\mathrm{F_{Vega}}}} \qquad (1.26)$$

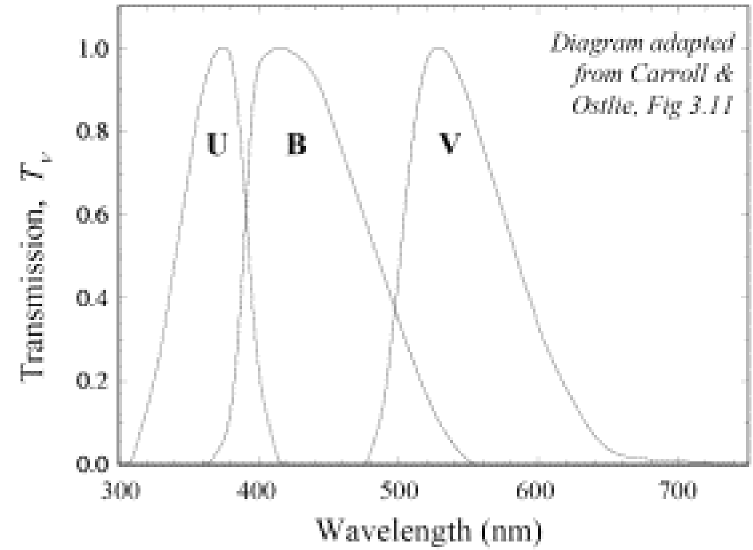
Colour Magnitudes

Usually we measure magnitudes through a **filter**, which transmits only over a small range of frequencies

The **Johnson System** is a set of standard filters, from the near ultraviolet to the infrared:

U	B	V	R	I	J	H	K	L	M	N

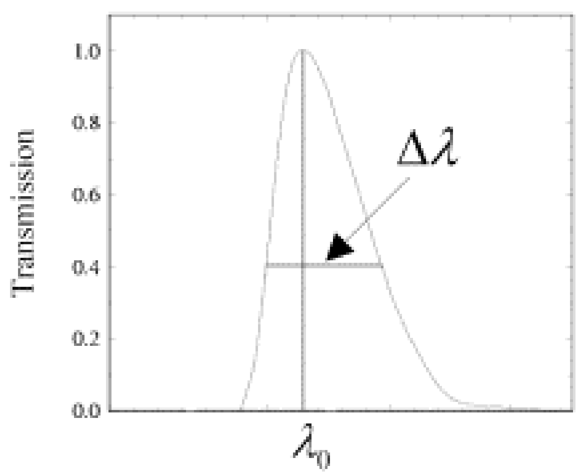
Increasing wavelength



The **transmission function**, T, defines the fraction of light transmitted by the filter as a function of frequency (or wavelength)

For each Johnson filter, T peaks at some wavelength λ_0, and has a characteristic width $\Delta\lambda$

$$m_{\mathbf{FILTER}} = -2.5\log_{10}\left(\int_0^\infty F_\nu\, T_{\mathbf{FILTER}}(\nu)\,d\nu\right) + C_{\mathbf{FILTER}}$$



bolometric apparent magnitude : $T(\nu) = 1$ at **all** frequencies

Example: **UBV** magnitudes		
Filter	λ_0 (nm)	$\Delta\lambda$ (nm)
$m_U \equiv \mathbf{U}$	365	68
$m_B \equiv \mathbf{B}$	440	98
$m_V \equiv \mathbf{V}$	550	89

Colour Indices

The *difference* between certain Johnson magnitudes defines a **Colour Index**, which gives information on the **temperature** of a star (recall A1Y).

e.g. we define

$$m_{\mathbf{U}} - m_{\mathbf{B}} \equiv \mathbf{U - B} = -2.5\log_{10}\frac{\left(\int_0^\infty F_\nu T_{\mathbf{U}}(\nu)\,d\nu\right)}{\left(\int_0^\infty F_\nu T_{\mathbf{B}}(\nu)\,d\nu\right)} + C_{\mathbf{U\text{-}B}} \qquad m_{\mathbf{B}} - m_{\mathbf{V}} \equiv \mathbf{B - V} = -2.5\log_{10}\frac{\left(\int_0^\infty F_\nu T_{\mathbf{B}}(\nu)\,d\nu\right)}{\left(\int_0^\infty F_\nu T_{\mathbf{V}}(\nu)\,d\nu\right)} + C_{\mathbf{B\text{-}V}}$$

The difference between the bolometric magnitude and the Johnson **V** band magnitude is called the **bolometric correction**

$$\boxed{BC = m_{\mathrm{BOL}} - \mathbf{V}}$$

It measures what fraction of the light from a source is observed visually

Generally, some of the light from a star is **absorbed** on the way to us. We call this effect **extinction**; it causes the measured colour index to be **reddened**. We define the **colour excess**, or **reddening** as

$$\boxed{E_{\mathbf{B\text{-}V}} = (\mathbf{B - V}) - (\mathbf{B - V})_0}$$

Colour excess

Measured colour index

True colour index

We can estimate $E_{\mathbf{B\text{-}V}}$ from a **colour-colour diagram** (See 'Stars and Their Spectra' and A2 labs). This can let us determine the amount of extinction.

Example

The star Merope in the Pleiades is observed to have apparent magnitudes $B = 4.40$ and $V = 4.26$. The V band extinction affecting this observation is estimated to be 0.2 magnitudes.

Estimate the true colour index of Merope.