UNIVERSITY of GLASGOW

Astronomy A2Z Session 2004-05
Observational Astrophysics

10 Lectures, starting Autumn 2004

See also: **http://www.astro.gla.ac.uk/users/martin/teaching/a2obsast/index.html**

Summary of Course Aims:

Expanding on Astronomy 1, these 10 lectures will investigate quantitatively the observational tools and methods of data collection and reduction that underpin modern astrophysical observations. We will study how we detect celestial objects and the factors that limit what, and how well, we can observe. Topics covered:

- Ideas of radiant energy
- Detectors and Telescopes
- Examples of Optical Detectors
- Ideas of Sensitivity
- The Atmosphere
- Spectral Techniques
- Resolving Power and Interferometry
- Radio Interferometry (if time permits)

Learning Objectives:

On completion of the course students should understand and be able to explain or quantify

Section 1

- the concepts and units of: luminosity; radiant flux; flux density; solid angle; specific intensity; brightness temperature; apparent and absolute magnitude; bolometric and colour magnitudes; distance modulus; bolometric correction

Section 2

- simple telescope optics, including the concepts of image intensity and illumination and the basic principles of operation of telescopes at different wavelengths – from gamma rays to radio waves

Section 3

- the operation of photomultipliers, microchannel image intensifiers and charge-coupled devices

Section 4

- the concept of noise and bandwidth as the limits of sensitivity
- the statistical properties of Poisson noise and its relation to background and dark current noise in charge-coupled devices and the quantum efficiency of photon detectors
- the signal-to-noise ratio of astronomical observations

Section 5

- absorption and transmission windows in the electromagnetic spectrum
- optical depth and zenith extinction – Bouget's Law
- scattering, including Rayleigh scattering
- refraction and scintillation

Section 6

- the importance of spectroscopy in astrophysics; spectral resolving power
- prisms, Fraunhofer diffraction and diffraction gratings
- design of a slit spectrometer

Section 7

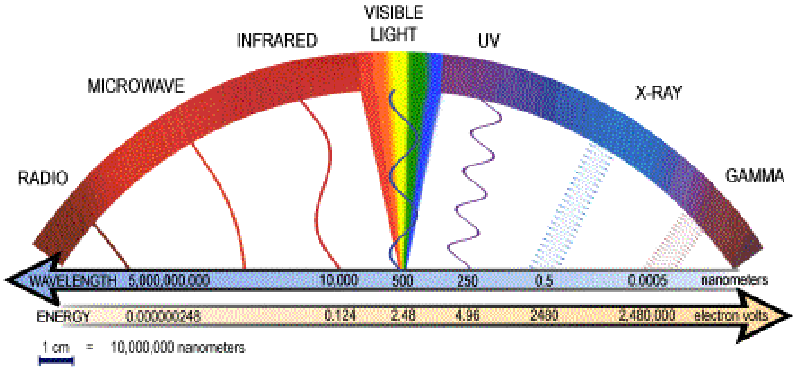
- diffraction and the λ/D relation
- 'seeing', speckle patterns and speckle interferometry
- the Michelson stellar interferometer and its foundations in optics theory
- interferometric measurements of stellar diameters and resolving of double stars

Section 8

- the method of Very Long Baseline Interferometry in radio astronomy and how it can be used to resolve structure in astronomical sources

1. Ideas of Radiant Energy

Astrophysical observations are almost always of **light**
(i.e. electromagnetic radiation)



There are some exceptions:-

- **Cosmic Rays**
- **Neutrinos**
- **Gravitational Waves**

But we won't consider them further in this course.

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

$$400\,\mathrm{nm} \;\leq\; \lambda \;\leq\; 700\,\mathrm{nm}$$

BLUE RED

$(1\,\mathrm{nm} = 10^{-9}\,\mathrm{m})$
$(1\,\text{Å} = 10^{-10}\,\mathrm{m})$

Nowadays observations are carried out from **gamma rays** $\lambda \leq 0.01\,\mathrm{nm}$
to **radio** $\lambda \geq 10\,\mathrm{cm}$

Remember

$$c = \lambda \nu \qquad (1.1)$$

Frequency (Hz)

Speed of light
$= 2.998 \times 10^{8}\ \mathrm{ms^{-1}}$

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

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

Planck's constant
$= 6.626 \times 10^{-34}\ \mathrm{Js}$

In A1 you met the concept of

Luminosity = energy radiated per unit time by a source
Unit = Watts (Joules per second)

In general, luminosity is dependent on wavelength or **frequency**.
i.e. astrophysical objects generally don't radiate the same amount of energy at all frequencies.

Hence we write $$L = L(\nu)$$ (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. $L = L(\lambda)$

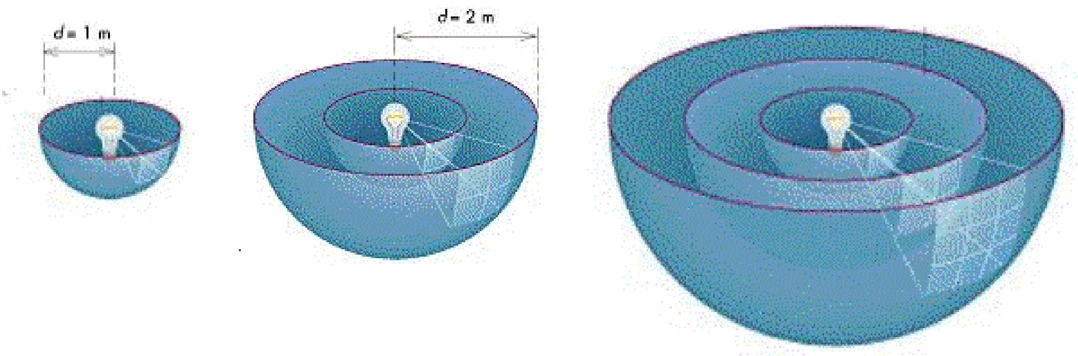
Relating $L(\nu)$ and $L(\lambda)$ is not trivial. See later in A2 Theoretical Astrophysics

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

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

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

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



Apparent brightness falls off with the square of the distance, because surface area of a sphere increases with the square of the radius

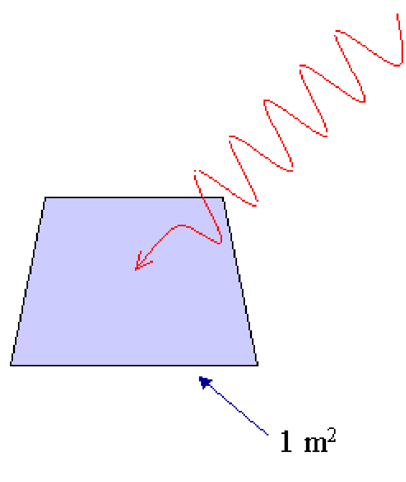
In A1 you also met the concept of

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

From inverse-square law,
for a source at distance D

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

Flux



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

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

Usually denoted by $F(\nu)$ or S_ν

Astronomers use a special unit for flux density

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

Jy 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. We will consider later some examples.

Suppose we observe in frequency interval $\nu_1 \leq \nu \leq \nu_2$

$$\textbf{Integrated Flux} \quad \mathbf{F} \quad = \quad \int_{\nu_1}^{\nu_2} S_\nu \, d\nu \qquad (1.7)$$

Define **bandwidth** (also known as bandpass, or passband)

$$\Delta\nu \quad = \quad \nu_2 - \nu_1 \qquad (1.8)$$

and $\bar{\nu} = \frac{1}{2}(\nu_1 + \nu_2)$

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

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

Integrated flux = flux density x bandwidth

Example

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

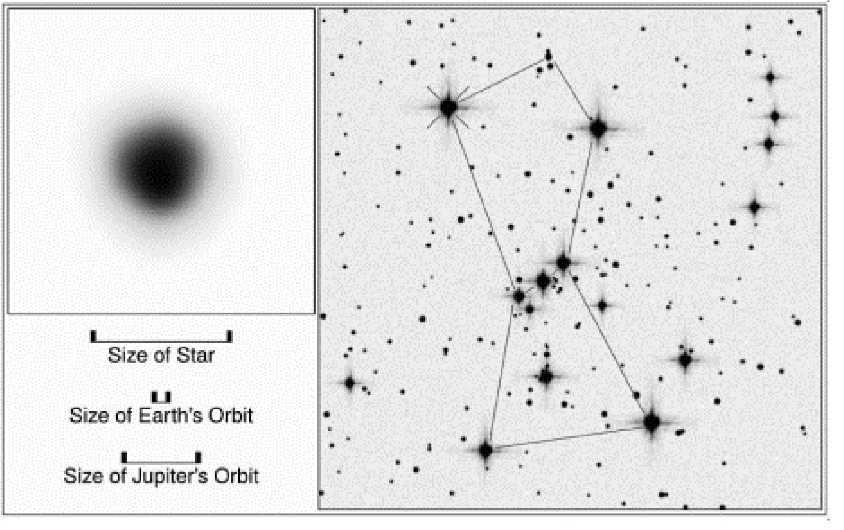
Solid Angle

Stars can be regarded as **point sources**

(barely) resolvable with HST

Angular diameter of the Sun = 0.533°

Angular diameter of Betelgeuse = 0.000014°

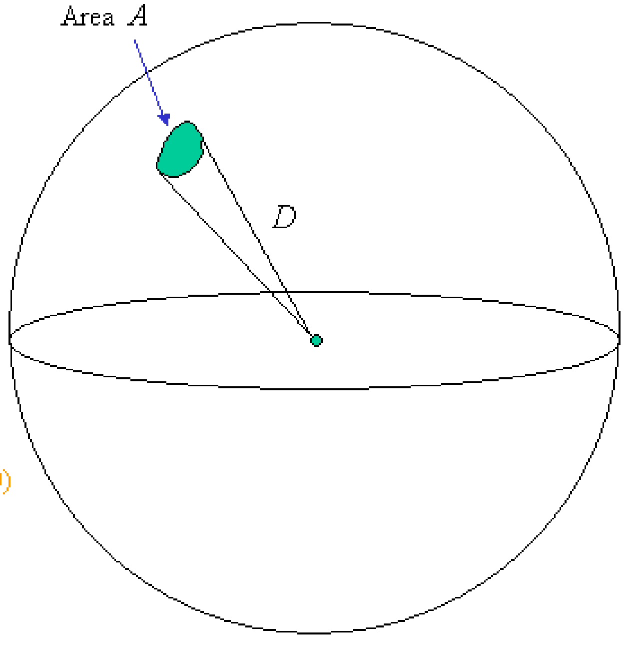


But many other objects (e.g. galaxies, nebulae) are **extended sources**.

We use **solid angle** as measure of the fraction of the sky covered (or subtended) by an extended source.

Unit of solid angle = **steradian** (sr)

Consider a source of projected area A at distance D



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

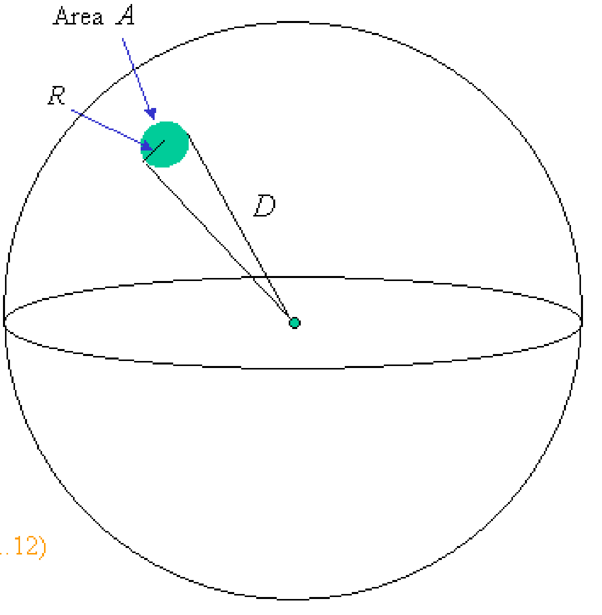
Whole sky = 4π sr

For a **spherical** source, of radius R

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

Thus

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



But

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

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

So

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

Need to be careful about units

In Eq. (1.12) angular diameter **must** be in radians, but is often measured in degrees (or arcminutes / arcseconds)

Examples

Calculate solid angle subtended by the Sun

ang. diam. = 0.533°

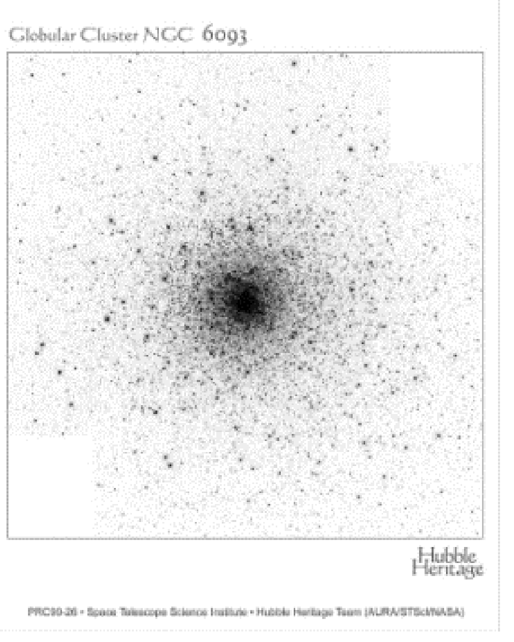
Calculate solid angle subtended by globular cluster NGC 6093

ang. diam. = 8.9 arcmin

Specific Intensity

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

Also, as can be seen clearly for NGC 6093, an extended source will not be equally bright across its entire projected area.

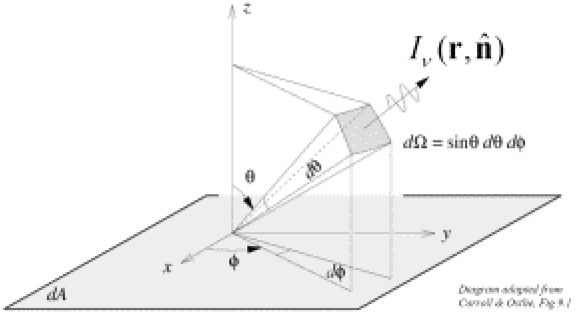


We need to introduce a new quantity to describe this variation in brightness. It is usually referred to as **specific intensity** or (particularly in the context of galaxies) as **surface brightness**

Consider a source emitting radiation.

dA = area element of the surface of the source.

dE_ν = energy emitted in the frequency range ν to $\nu + d\nu$, from surface element dA at position $\mathbf{r}$ on the surface of the source, into solid angle $d\Omega = \sin\theta \, d\theta \, d\phi$ around the direction with unit vector $\hat{\mathbf{n}}(\theta, \phi)$, in time interval t to $t + dt$



We define

$$dE_\nu = I_\nu(\mathbf{r}, \hat{\mathbf{n}}) \, dA \, dt \, d\nu \, d\Omega \tag{1.13}$$

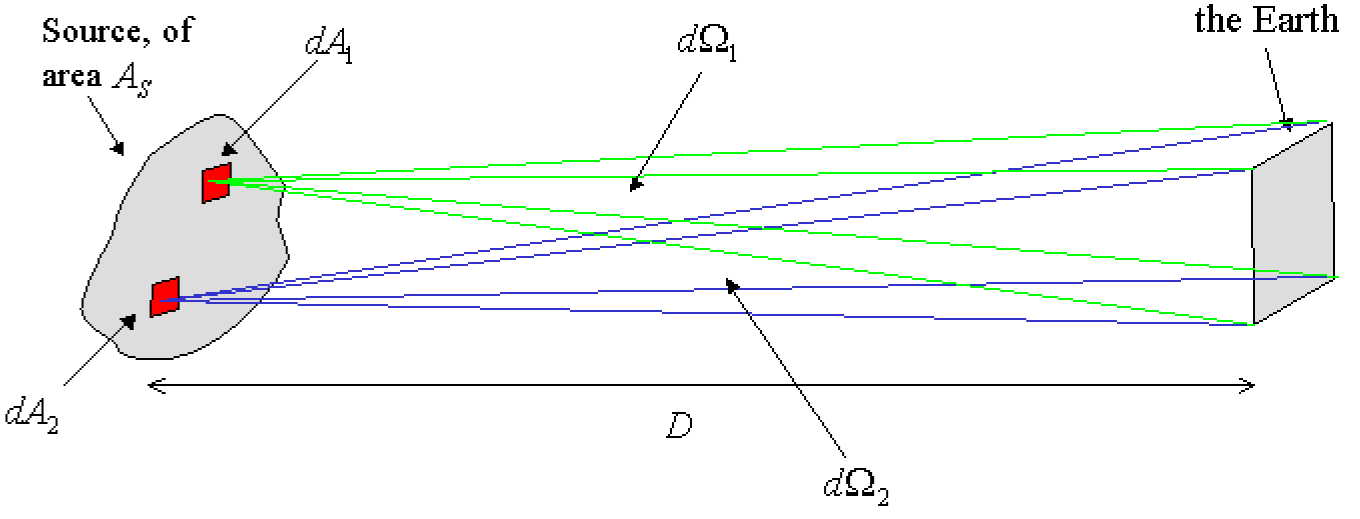
where $I_\nu(\mathbf{r}, \hat{\mathbf{n}})$ is known as the **Specific Intensity** of the radiation

The **Bolometric Luminosity** of the source is given by the integral of the Specific Intensity over frequency, solid angle and surface area of the source.

$$L_{\mathrm{bol}} = \iiint I_\nu(\mathbf{r}, \hat{\mathbf{n}}) dA \, d\nu \, d\Omega \tag{1.14}$$

Relating Specific Intensity and Flux Density

Consider an extended source of projected area A_S



Flux density from A_S = energy received per unit time, per unit frequency

$$= I_\nu(\mathbf{r}_1, \theta_1, \phi_1)\, dA_1\, d\Omega_1 \quad + \quad I_\nu(\mathbf{r}_2, \theta_2, \phi_2)\, dA_2\, d\Omega_2 \quad + \ \ldots \tag{1.15}$$

For a distant source we can assume that $d\Omega_1 = d\Omega_2 = \ldots = d\Omega$

Thus

$$S_\nu = \left[I_\nu(\mathbf{r}_1, \theta_1, \phi_1)\, dA_1 + I_\nu(\mathbf{r}_2, \theta_2, \phi_2)\, dA_2 + \ldots \right] d\Omega = \left[\int_{A_S} I_\nu \, dA \right] d\Omega \tag{1.16}$$

But, if D is measured in metres, then

$$d\Omega = \frac{1}{D^2} \tag{1.17}$$

So we can write

$$S_\nu = \left[\int_{A_S} I_\nu \, dA \right] \frac{1}{D^2} = \int_{A_S} I_\nu \frac{dA}{D^2} \tag{1.18}$$

Solid angle of area element dA on the **source** as seen from the **Earth**

Hence

$$S_\nu = \int_{\Omega_S} I_\nu \, d\Omega_S \qquad (1.19)$$

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

If I_ν is constant over the projected area of the source, then

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

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

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

Specific intensity is independent of distance ('constant along rays')

Example

For a **blackbody** of temperature, T

$$I_\nu = \frac{2h\nu^3}{c^2\left[\exp\left(\frac{h\nu}{kT}\right)-1\right]} \quad \mathrm{Wm^{-2}Hz^{-1}sr^{-1}} \qquad (1.21)$$

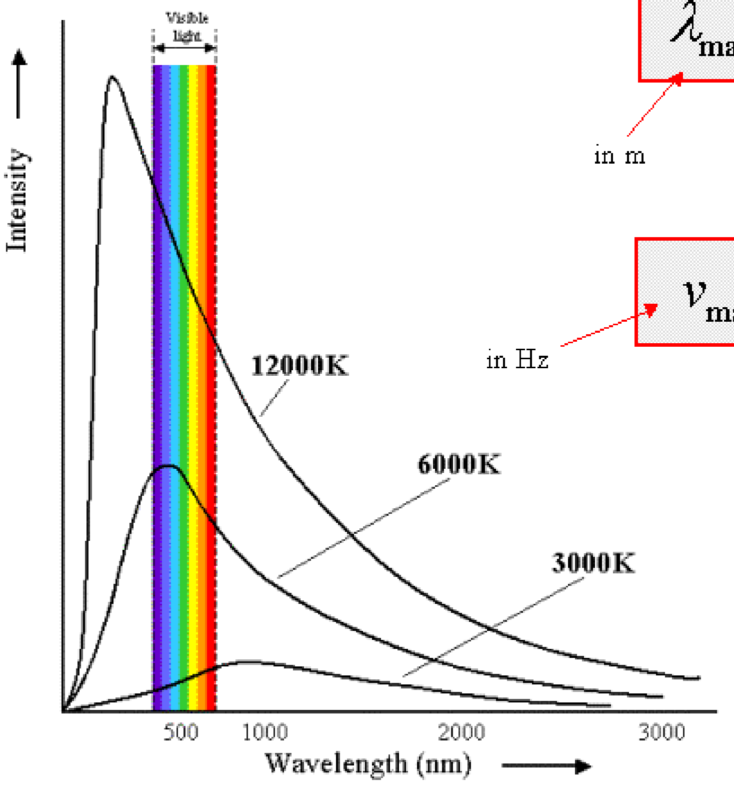
Blackbody radiation is **isotropic** (i.e. specific intensity doesn't depend on direction)

At a given frequency, I_ν depends only on T

$\Rightarrow$ We can use the measured I_ν to **define** a temperature

Recall **effective temperature** from A1Y Stellar course

Wien's Law



$$\lambda_{max} T = 2.9\times10^{-3} \quad (1.22)$$

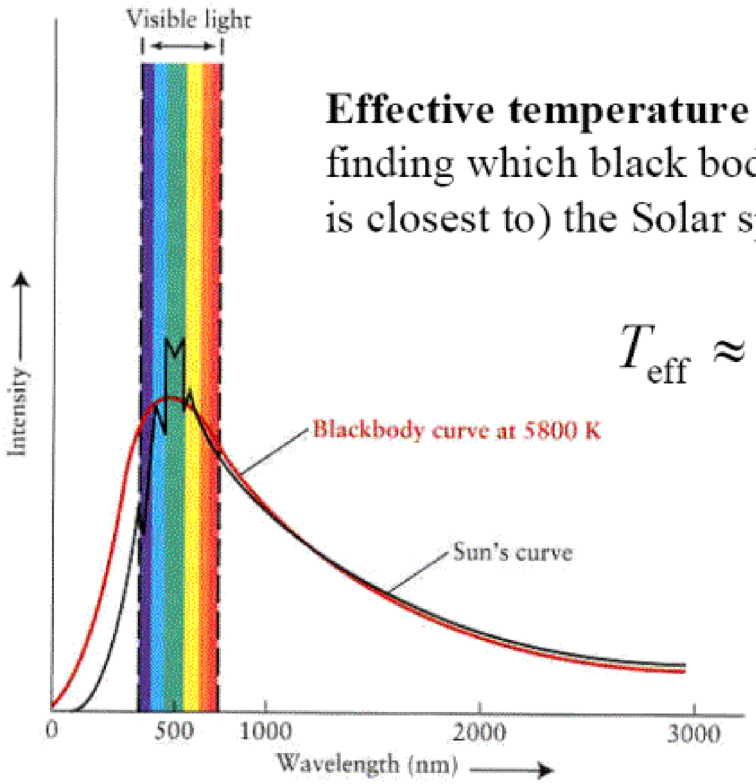
λ_{max} in m, T in K

$$\nu_{max} = 6\times10^{10}\, T \quad (1.23)$$

ν_{max} in Hz, T in K

Effective temperature determined by finding which black body curve 'best fits' (ie is closest to) the Solar spectrum

$$T_{eff} \approx 5800\,\mathrm{K}$$



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

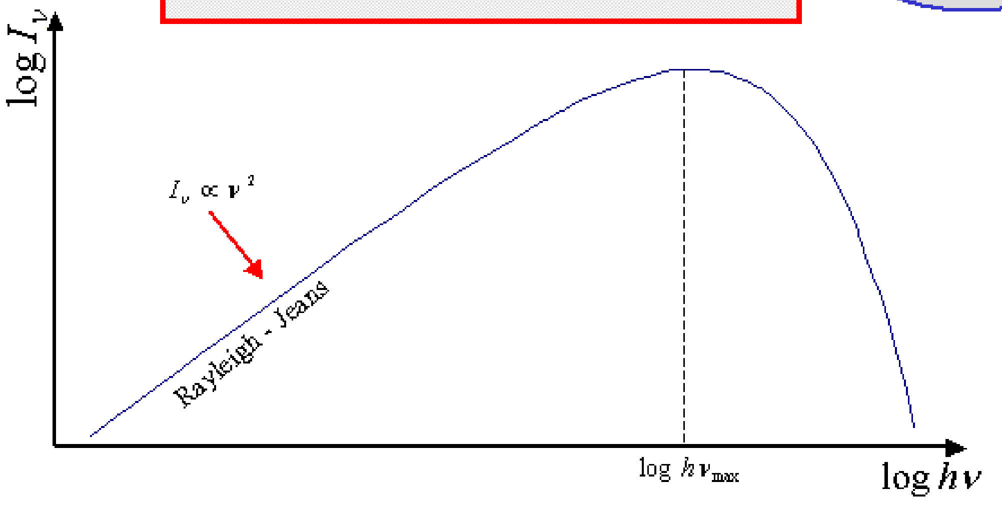
Brightness temperature

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

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



We define

$$T_b = \frac{c^2 I_\nu}{2\nu^2 k} \qquad (1.25)$$

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 handout).

Bolometric apparent magnitude

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

F: Radiant flux (over all frequencies)

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

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

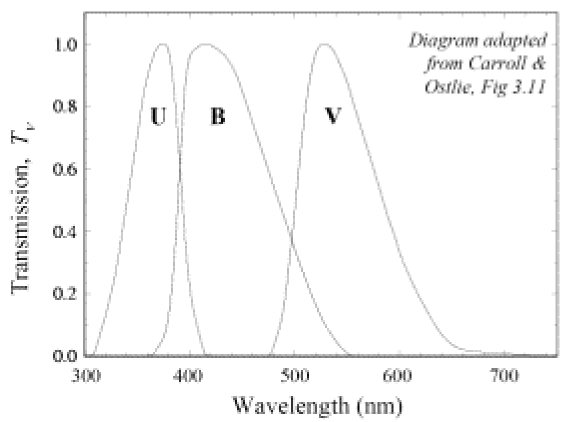
Colour Magnitudes

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

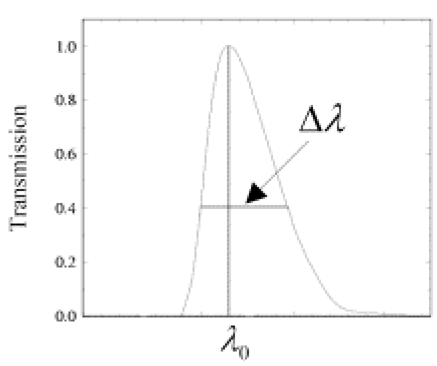
Increasing wavelength →



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 $\Delta\lambda$

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



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

$$m_U - m_B \equiv \mathbf{U-B} = -2.5\log_{10}\frac{\left(\int_0^\infty F_\nu T_U(\nu)\,d\nu\right)}{\left(\int_0^\infty F_\nu T_B(\nu)\,d\nu\right)} + C_{U-B}$$

$$m_B - m_V \equiv \mathbf{B-V} = -2.5\log_{10}\frac{\left(\int_0^\infty F_\nu T_B(\nu)\,d\nu\right)}{\left(\int_0^\infty F_\nu T_V(\nu)\,d\nu\right)} + C_{B-V}$$

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

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

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

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

Colour excess (E_{B-V}); Measured colour index ($\mathbf{B-V}$); True colour index ($(\mathbf{B-V})_0$)

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

$$A_V \approx 3.1 E_{B-V}$$

V-band extinction (A_V); Colour excess (E_{B-V})

$$A_B \approx 4.1 E_{B-V}$$

B-band extinction (A_B); Colour excess (E_{B-V})

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