Lectures

- Tuesdays:
  - 10-11am in Strathcona Lecture Theatre 7
  - Start Jan 10; end Mar 20
- Thursdays:
  - 12-1pm in Physics West 117
  - Start Jan 12; end Mar 22
  - **Note: no lecture on Thurs Feb 2nd**

- Lecture notes will be available through WebCT

Books

- Astrophysical Techniques
  - C. R. Kitchin, 5th Edition, CRC Press
- Observational Astronomy
  - D. Scott Birney et al., 2nd Edition, CUP
- Observational Astrophysics
  - Robert C. Smith, CUP
- Detection of Light
  - George Rieke, 2nd Edition, CUP
- Handbook of Infrared Astronomy
  - I. S. Glass, 1st Edition, CUP
- Handbook of X-ray Astronomy
  - Keith Arnaud et al., 1st Edition, CUP
- An Introduction to Radio Astronomy
  - Bernard Burke and Franci Graham-Smith, 3rd Edition, CUP
- [Universe
  - Freedman & Kaufmann, 8th Edition, Freeman]

Assessment

- Exam, Part 1:
  - Answer 4 out of 6 short questions
  - 40% of the exam mark
  - Approx 7.5min per question
- Exam, Part 2:
  - Answer 2 out of 3 long questions
  - 60% of the exam mark
  - Approx 30min per question

- Assessed problems:
  - Included in the Year 2 lecture problem sheets
  - Weeks 2, 3, 4, 6, 7, 8, 9, 11

Problems and Past Exams

- In addition to assessed problems:
  - Small numerical examples in lectures
  - Un-assessed problem sheets / past exam questions
- Relevant past exam papers:
  - 2004 – 2007: Astronomical and Space Instrumentation
  - 2008 – 2011: Observing the Universe

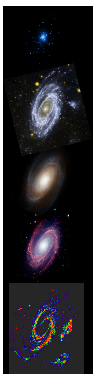
Revision / catch up

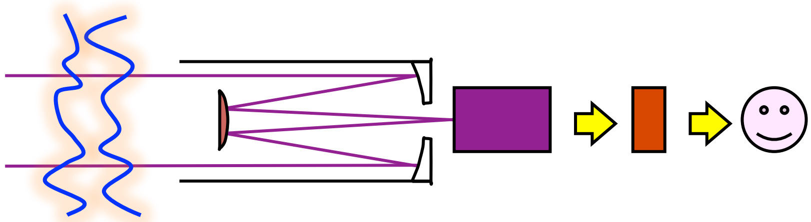
- Either:
  - Review your notes from “Introduction to Astrophysics”
  - Read Universe …
- Universe; Freedman & Kaufmann:
  - Chapter 2; Knowing the Heavens
  - Chapter 5; The Nature of Light
  - Chapter 17; The Nature of Stars
    - 17.1, 17.2, 17.3, 17.4
  - Chapter 26; Cosmology
    - 26.1, 26.2, 26.3, 26.4

Course Objectives

- Teach you about the physics of the detection of electromagnetic radiation from stars, and galaxies:
  - Interaction of radiation with the Earth's atmosphere
  - Collection of radiation with a telescope
  - Detection of radiation with instruments/detectors
- Concentrate on optical/infrared radiation to teach you the basic physics/principles
- Explain how the physics of higher/lower energy radiation forces collection/detection methods to change
- Teach you how to do realistic signal-to-noise ratio calculations for common astronomical observations
- Introduce you to advanced observing methods and describe future observing opportunities

Overview

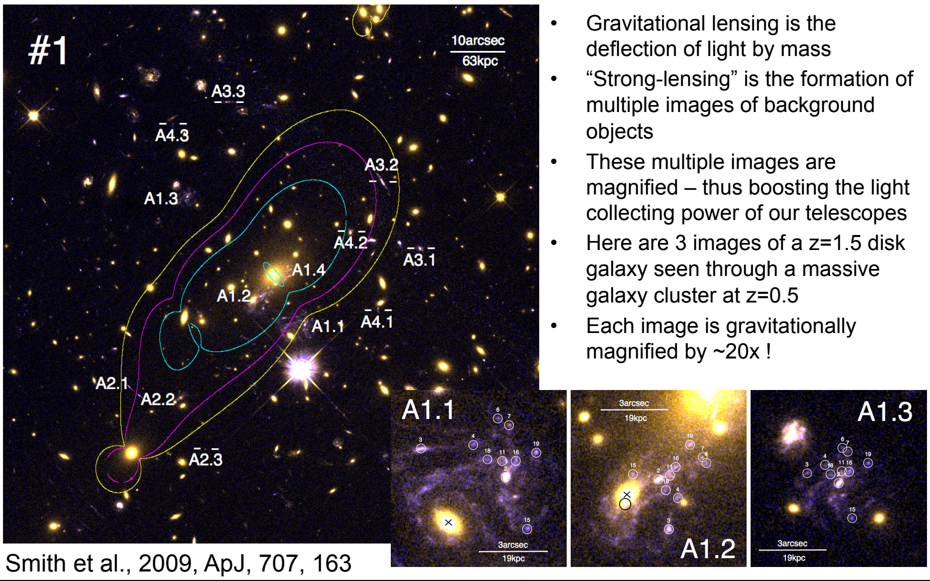




Atmosphere:	Telescopes:	Instruments:	Detectors:
• Transmission	• Optics	• Imagers	• Human eye
• Extinction	• Design options	• Spectrographs	• Photography
• Optical depth	• Aberrations	• [Polarimeter]	• Photomultipliers
• Turbulence	• Performance	• [Photometer]	• Charge-coupled devices (CCDs)
• Refraction	• Location		
• Emission	• Satellites		

Examples of advanced methods: adaptive optics, OH suppression, gravitational lensing

Cosmic Zoom Lenses



- Gravitational lensing is the deflection of light by mass
- "Strong-lensing" is the formation of multiple images of background objects
- These multiple images are magnified – thus boosting the light collecting power of our telescopes
- Here are 3 images of a z=1.5 disk galaxy seen through a massive galaxy cluster at z=0.5
- Each image is gravitationally magnified by ~20x !

Smith et al., 2009, ApJ, 707, 163

A Broad Range of Physics

- Compton scattering
- Rayleigh scattering
- Pair production
- Photoelectric effect
- Band theory of solids
- Solid-state physics
- Black body radiation
- Refraction by an ionized medium
- Bragg diffraction
- Geometrical optics
- Wave optics
- Interferometry
- Gravitational lensing
- Turbulence
- Poisson statistics
- Fermi-Dirac statistics

Syllabus

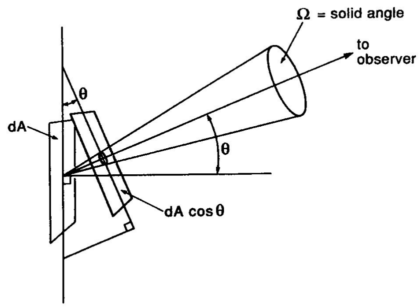
- Preliminaries (developing basic ideas from Intro to Astrophysics)
- Earth's atmosphere
- Collection of light with telescopes
- Detection of light – from photography to CCDs
- Signal and noise
- Photometry and spectroscopy
- Near-infrared observations
- Radio observations
- Observing from space
- X-ray observations
- Far-infrared observations
- Advanced techniques
- Future observing facilities

Preliminaries

Solid angle
Luminosity, flux, intensity
Black body radiation
The human eye
Magnitudes

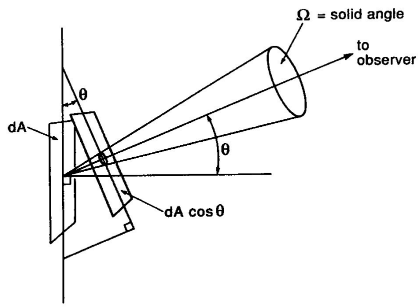
Solid Angle

- An object is a distance r away from an observer
- It has an area perpendicular to the observer's line of sight of:
  $ds = dA \cos\vartheta$
- And subtends a solid angle at the observer of:
  $d\Omega = ds/r^2$
- Solid angle is dimensionless with units of steradians (sr)
  $1sr = 1rad^2 = (180/\pi)^2 \deg^2$
- The whole sky subtends a solid angle of 4π sr:
  $d\Omega = 4\pi r^2/r^2 = 4\pi$ sr $= 4\pi\ (180/\pi)^2 \deg^2 = 41{,}253 \deg^2$



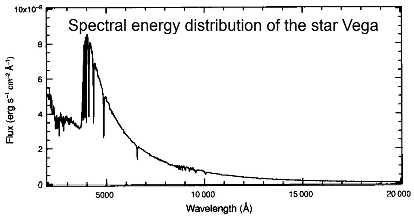
Luminosity, Flux, and Intensity

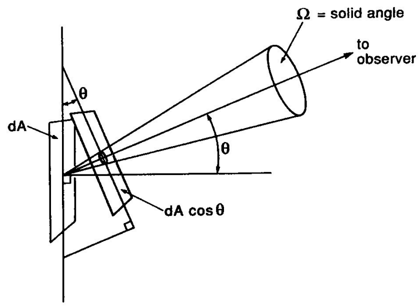
- The luminosity, L, of an object is the total power radiated by it
- Common units of luminosity are:
  - Watts (SI): $1\ W = 1\ J\ s^{-1}$
  - Ergs (cgs): $1\ erg\ s^{-1} = 10^{-7}\ W$
  - Solar: $1\ L_{\odot} = 3.9\times10^{26}\ W$
- The flux, F, is the power per unit area flowing through a surface
- The flux through a sphere a distance d from a source of luminosity L:
  $F = L / 4\pi d^2$ ($W\ m^{-2}$)
- Intensity, I, is the flux per unit solid angle in the direction ϑ:
  $L = \int I \cos\vartheta\, dA\, d\Omega$



Monochromatic Flux

- Flux is generally a function of wavelength
- Monochromatic flux is the flux per unit wavelength:
  $F_\lambda = E_\lambda$ / (dA cosϑ dt dλ)
- where E_λ is the energy detected from a source of area dA cosϑ, in time dt, in a wavelength range dλ:
  $E_\lambda = \int E(\lambda)\, d\lambda$
- Or per unit frequency:
  $F_\nu = E_\nu$ / (dA cosϑ dt dν)
- Conversion is easy:
  $\nu F_\nu = \lambda F_\lambda$
- Units (e.g.):
  W m^{-2} Hz^{-1}; erg s^{-1} cm^{-2} um^{-1}





Specific Intensity

- Similarly, specific intensity is also a function of wavelength
- It is defined as the monochromatic flux per unit solid angle:

$I_\nu = F_\nu / d\Omega$ units: erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}
$I_\lambda = F_\lambda / d\Omega$ erg s^{-1} cm^{-2} um^{-1} sr^{-1}

Black bodies

- Black bodies …
  - are a useful idealized objects
  - they can be used as an approximation to real stars and galaxies
  - are in thermal equilibrium with their surroundings
  - are perfect absorbers and emitters of radiation at all wavelengths
- Radiation from a black body therefore …
  - is independent of its composition, size and shape
  - depends only on its temperature
- Flux (formally specific intensity) from a black body of temperature T is described by the Planck functions:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/(kT)} - 1}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/(\lambda kT)} - 1}$$

Black bodies

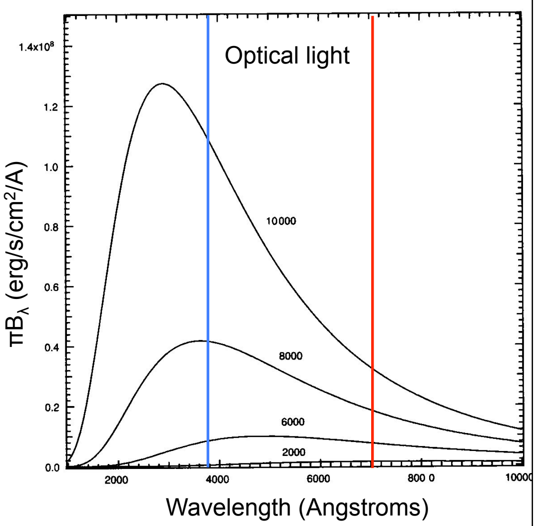
- Hotter black bodies emit more energy
- For a spherical blackbody of temperature T and radius R:

$$L = \int_{\pi} d\Omega \int_{4\pi R^2} dA \int_0^\infty B_\lambda(T) d\lambda = 4\pi R^2 \sigma T^4$$

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
(Stefan-Boltzmann constant)

- Radiation from hotter black bodies peaks at shorter wavelengths

$\lambda_{max}(m) = 2.8983 \times 10^{-3} / T(K)$
(Wien displacement law)

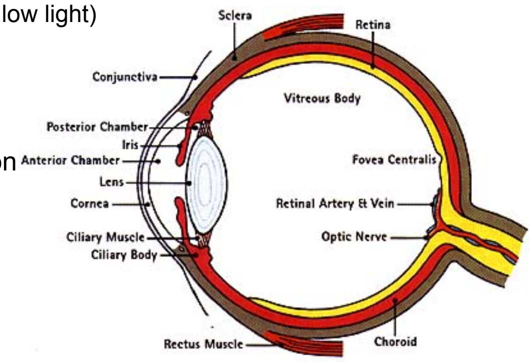


A Simple Calculation

- The temperature and radius of the Sun, and distance from Earth are:
  - $T_\odot$ = 6000K
  - $R_\odot$ = 6.96x10^8m
  - d = 1AU = 1.496x10^{11}m
- What is the luminosity of the sun?
- $L = 4\pi R^2 \sigma T^4 = 4 \times 10^{26}$ W
- What flux of solar radiation does this imply on Earth?
- $F = L / 4\pi d^2 = 1.4 \times 10^3$ W m^{-2}
- What assumptions have you made in this calculation?
- That the Sun is a black body

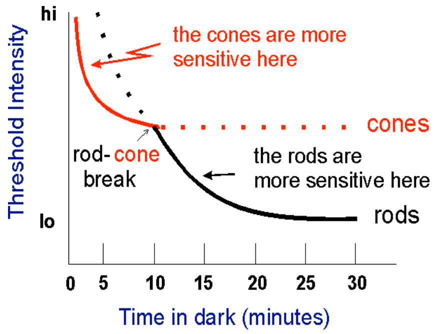
Human Eye

- The eye was the first device used by humans to “observe the universe”
- Focus of the lens can be altered by muscles that change its shape
- Retina contains two kinds of detector cells:
  - rod (b&w, sensitive to low light)
  - cone (colour vision)
- Integrates for 0.1s
- Efficiency ≈ 10%
- Aberrations are common
  - e.g. astigmatism

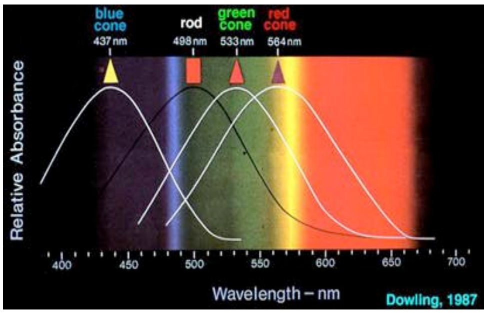


Human Eye – rods and cones

Rods and cones have different sensitivities to varying light levels:



Three types of cones have different spectral responses:



Apparent Magnitudes

- Apparent magnitude is a measure of how bright an object appears to be in the sky – i.e. it ignores how far away the object is
- Magnitude scale introduced by Greek astronomer Hipparchus:
  - 1^{st} magnitude: the brightest stars he could see
  - 2^{nd} magnitude: stars approx half as bright as the brightest
  - 3^{rd} magnitude: …
  - 6^{th} magnitude: the faintest stars he could see
- 6^{th} magnitude star is roughly 100x fainter than a 1^{st} magnitude star:
  - $(2.512)^{(6-1)} = 2.512^5 = 100$
- Magnitude scale is therefore logarithmic, with brighter objects having smaller magnitudes
- The difference between the apparent magnitudes of two objects of measured fluxes F_1 and F_2 is: $m_1 - m_2 = -2.5 \log (F_1 / F_2)$

Worked Example

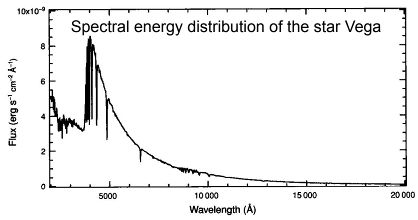
On Feb 1, 2008, Venus was observed at m_V=-4 and Jupiter was observed at m_V=-1.9, both in the V-band (i.e. 550nm).

Which planet was the brightest, and by what factor in flux?

$$\begin{aligned} m_1 - m_2 &= -2.5\log_{10}\frac{f_1}{f_2} \\ -4 + 1.9 &= -2.5\log_{10}\frac{f_1}{f_2} \\ 2.1 &= -2.5\log_{10}\frac{f_1}{f_2} \\ 6.9 &= \frac{f_1}{f_2} \end{aligned}$$

Calibration of Magnitudes

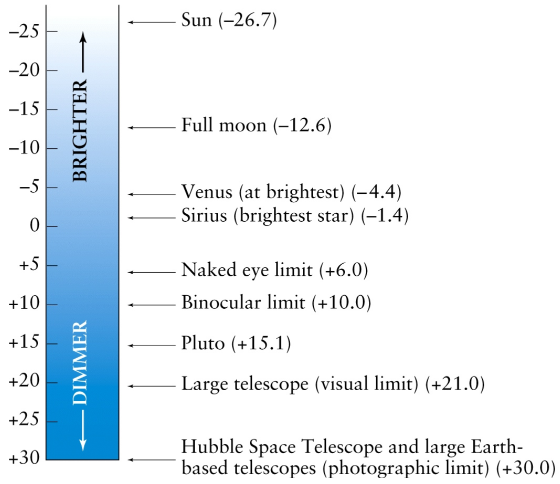
- In general the apparent magnitude of an object is defined thus: $m = m_0 - 2.5\log(F)$
- m_0 is the "zero-point", which doesn't appear in the formula for magnitude difference: $m_1 - m_2 = [m_0 - 2.5\log(F_1)] - [m_0 - 2.5\log(F_2)] = -2.5\log(F_1/F_2)$
- Zero-points are traditionally calibrated relative to Vega:
  - 0^{th} magnitude star in the northern sky
  - Bright across whole visible window
  - Neither variable, nor double
- At 550nm Vega has a monochromatic flux of $F_\lambda = 3.6\times10^{-9}$erg s^{-1} cm^{-2} A^{-1}
- This implies a zero-point of: $m_0 = 2.5\log(3.6\times10^{-9}) = -21.1$



The Apparent Magnitude Scale

Negative magnitudes indicate very bright objects

Large positive magnitudes indicate very faint objects



Taking account of distance

- So far we have defined magnitude in terms of flux:
  $m_1 – m_2 = –2.5\log(F_1/F_2)$
- The flux from an object of luminosity L, a distance d away is:
  $F = L / (4\pi d^2)$
- So the flux ratio of two objects of the same L, at distances of d1 and d2 respectively is:
  $F_1/F_2 = (d_2/d_1)^2$
- And the difference between the apparent magnitudes of these two objects is:
  $m_1 – m_2 = 5\log(d_1/d_2)$

Absolute Magnitudes

- Absolute magnitude is defined as the magnitude an object would have if it were placed a distance of 10 parsecs away
- It is conventionally denoted by "M", with "m" reserved for apparent magnitudes
- With magnitude defined in terms of flux, F, thus: $m = m_0 - 2.5\log(F)$ and $F = L/(4\pi d^2)$, if we observe an object of luminosity L, at a distance of d, to have an apparent magnitude of m, we can write:

  $m - M = 2.5\log(d^2) - 2.5\log(10^2) = 5\log(d/10)$

  where d is measured in parsecs
- The quantity "m – M" is called the distance modulus

Calculation

- The apparent V-band magnitude of the Sun is: $m = -26.74$
- The sun is 1AU away: $1\text{AU} = 1.496\times10^{11}\text{m} = 4.83\times10^{-6}\text{pc}$
- What is the absolute V-band magnitude of the Sun?
- $m - M = 5\log(d/10)$
- $M = m - 5\log(d/10) = -26.74 - 5\log(4.83\times10^{-7}) = 4.84$

Eye: Efficiency

- Average quantum efficiency of eye ≈ 10%
- Star of zeroth magnitude, m_V=0, yields 10^4 photons s^{-1} cm^{-2} nm^{-1}
- Fully dilated pupil has area 0.5 cm^2
  - Bandpass 200 nm
  - So 10^6 photons reach the eye per sec from a mV=0 star
  - Eye stores information for only 0.1 second, so 10^5 photons reaches retina from such a star
  - Since efficiency is 10%, the eye registers 10^4 photons
- To "see" a star, the eye requires at least 30 photons
- So what is the faintest star the eye can "see"?
- Has to be 300 times fainter, i.e., 2.5 log(300) = 6.2 magnitudes fainter: m_V = 6.2