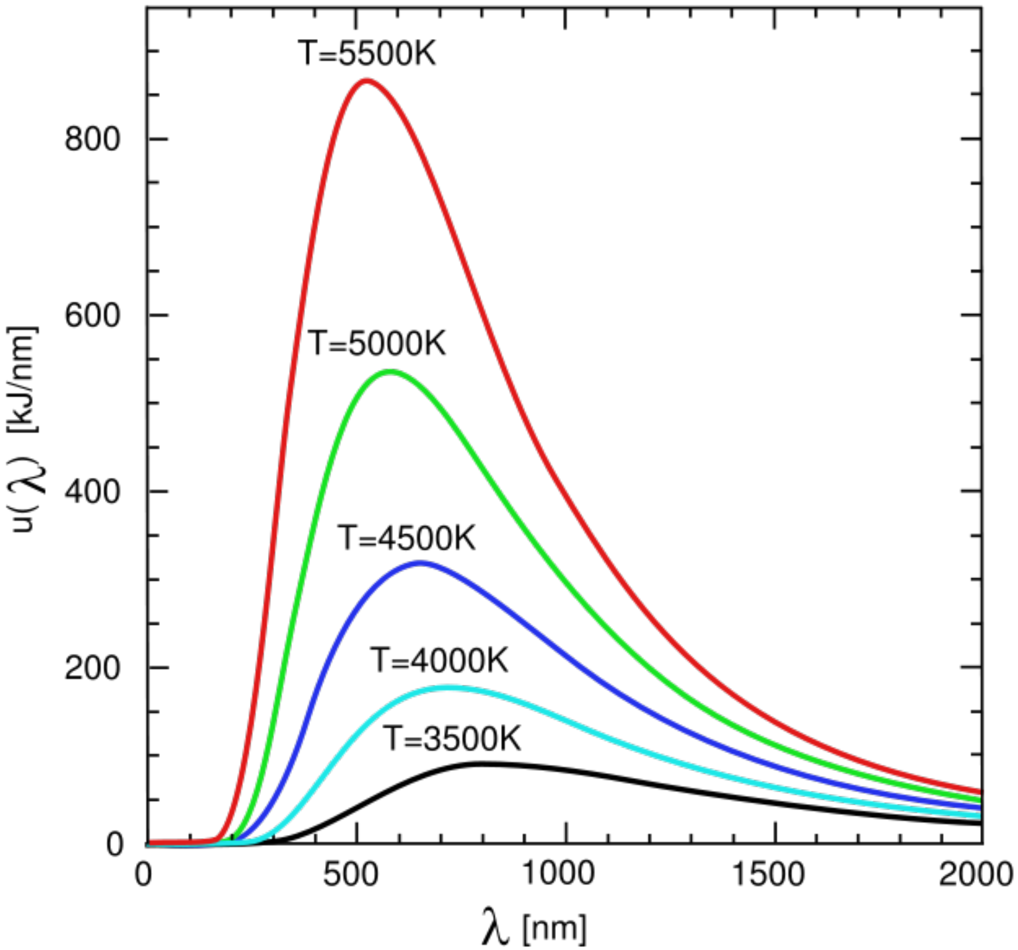
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

based on lectures by Bernhard Brandl



Lecture 1:

- Black body radiation
- Astronomical magnitudes
- Point ⇔ extended sources

Black Body

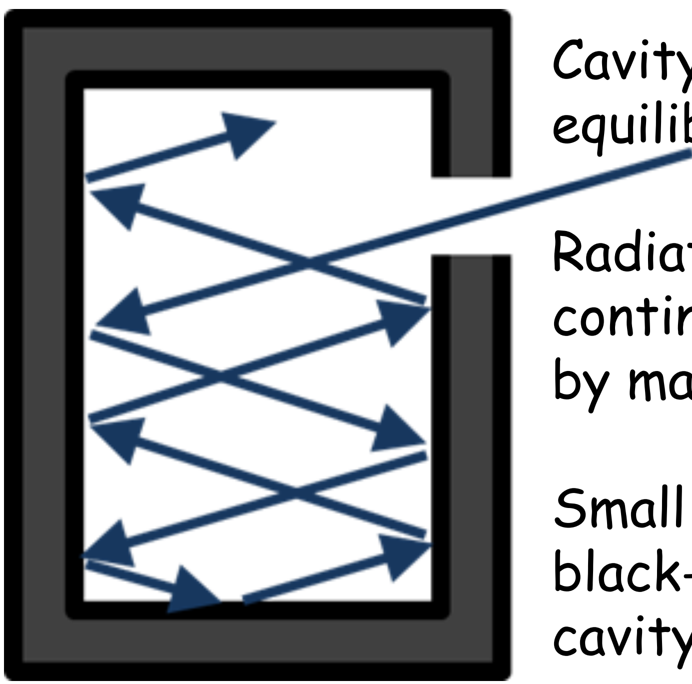
Radiation

Introduction

(from Wikipedia)

Kirchhoff (1860): "…imagine that bodies (…) completely absorb all incident rays, and neither reflect nor transmit any. I shall call such bodies perfectly black, or, more briefly, black bodies."

This shall be true of radiation for all wavelengths and for all angles of incidence.



Cavity at fixed temperature T in thermal equilibrium

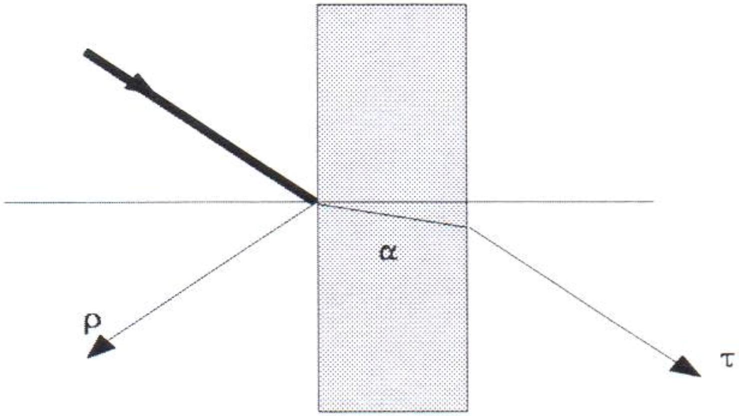
Radiation entering cavity will be "thermalized" by continuous absorption and re-emission of radiation by material in cavity or its walls.

Small hole → escaping radiation will approximate black-body radiation independent of properties of cavity or hole.

Kirchhoff's Law

Conservation of power requires:

$$\alpha + \rho + \tau = 1$$



with α = absorptivity, ρ = reflectivity, τ = transmissivity

cavity in thermal equilibrium with completely opaque sides:

$$\left.\begin{array}{c} \varepsilon = 1 - \rho \\ \alpha + \rho + \tau = 1 \\ \tau = 0 \end{array}\right\} \boxed{\alpha = \varepsilon}$$

ε = emissivity

Kirchhoff's law, applies to perfect black body

Radiator with ε = ε(λ) < 1 often called grey body

Definition of a Black Body

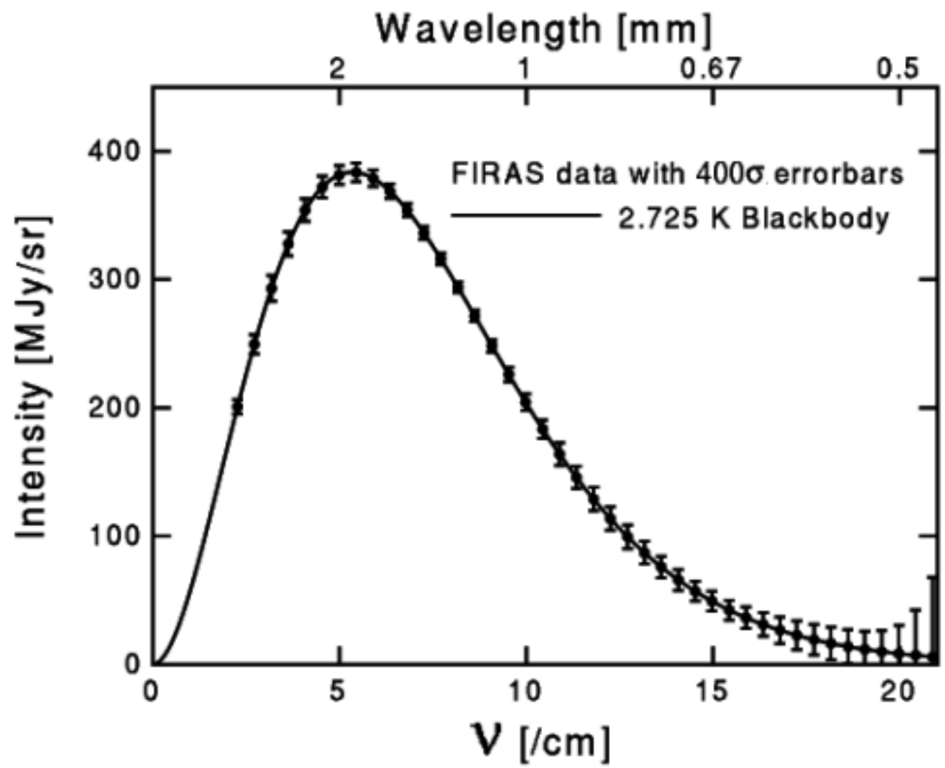
- Black body (BB) is idealized object that absorbs all EM radiation

- Cold (T~0K) BBs are black (no emitted or reflected light)

- At T > 0 K BBs absorb and re-emit characteristic EM spectrum

Many astronomical sources emit close to a black body.

Example: COBE measurement of the cosmic microwave background



Black Body Emission

Specific intensity I_ν of blackbody given by Planck's law:

$$I_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

in units of [W m^{-2} sr^{-1} Hz^{-1}]

(see course on Radiative Processes)

In wavelength units:

$$I_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

in units of [W m^{-3} sr^{-1}]

Conversion of frequency ⇔ wavelength units:

$$d\nu = \frac{c}{\lambda^2} d\lambda \quad \text{or} \quad d\lambda = \frac{c}{\nu^2} d\nu$$

Useful Approximations

$$I_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

High frequencies (hν >> kT) ➔ Wien's approximation:

$$I_\nu(T) = \frac{2h\nu^3}{c^2} \exp\left(-\frac{h\nu}{kT}\right)$$

Low frequencies (hv << kT) ➔ Rayleigh-Jeans' approximation:

$$I_\nu(T) \approx \frac{2\nu^2}{c^2} kT = \frac{2kT}{\lambda^2}$$

Emission ⇔ Power ⇔ Temperature

Total radiated power per unit surface (radiant exitance) is proportional to fourth power of temperature T:

$$\int_{\Omega}\int_{\nu} I_{\nu}(T)\, d\nu\, d\Omega = M = \sigma T^4$$

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

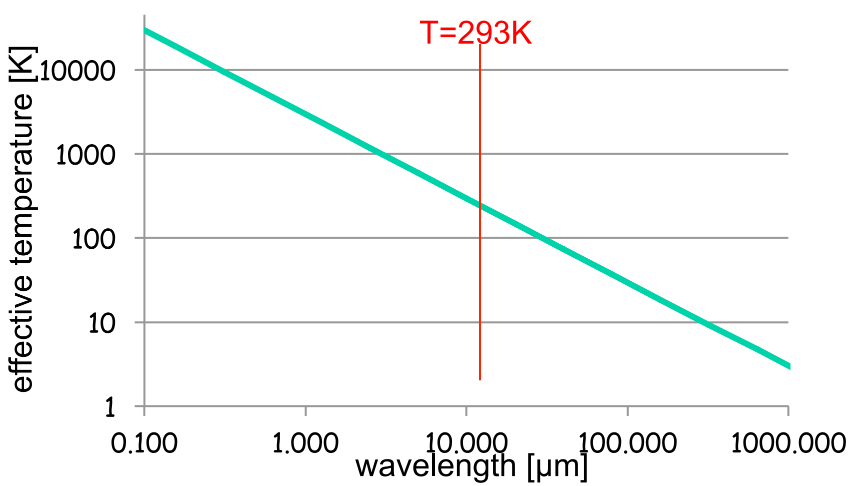
Assuming BB radiation, astronomers often specify the emission from objects via their effective temperature.

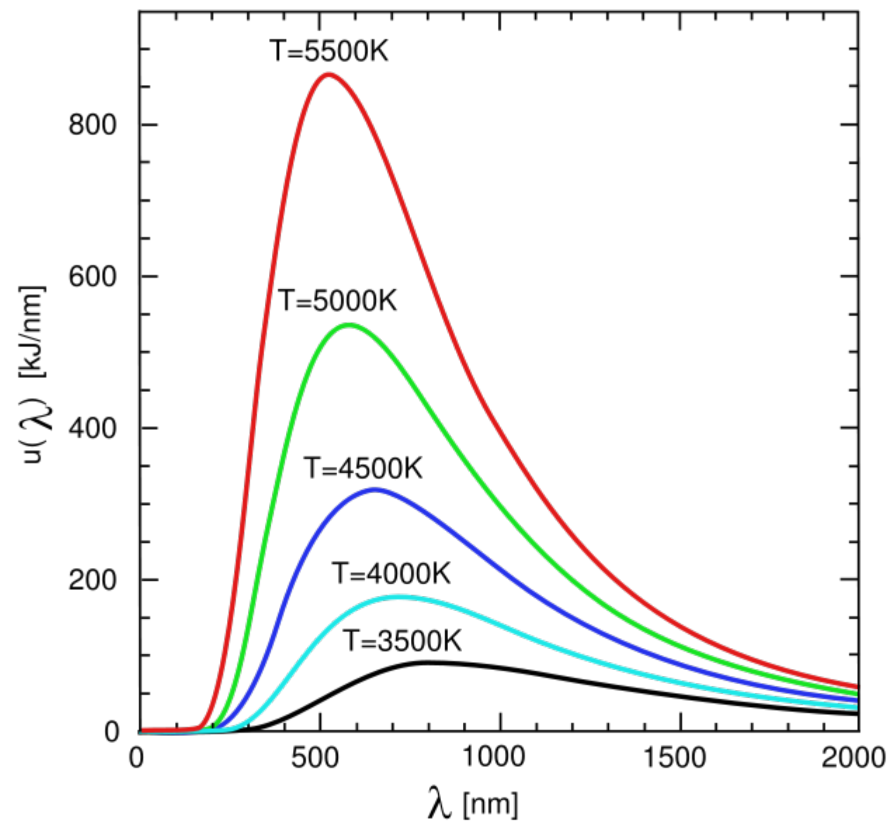
Effective Temperatures

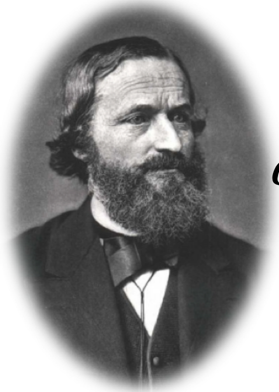
Temperature corresponding to maximum specific intensity given by Wien's displacement law:

$$\frac{c}{\nu_{\max}} T = 5.096 \cdot 10^{-3} \text{ mK} \quad \text{or} \quad \lambda_{\max} T = 2.98 \cdot 10^{-3} \text{ mK}$$

Cooler BBs have peak emission (effective temperatures) at longer wavelengths and at lower intensities:







$$\left.\begin{aligned} \varepsilon &= 1-\rho \\ \alpha+\rho+\tau &= 1 \\ \tau &= 0 \end{aligned}\right\} \quad \alpha = \varepsilon$$

Gustav Kirchhoff (1824 – 1887)

$$M = \sigma T^4$$

Josef Stefan (1835 – 1893)

Ludwig Eduard Boltzmann (1844 – 1906)

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right)-1}$$

Max Planck (1858 – 1947)

$$I_\nu(T) \approx \frac{2\nu^2}{c^2}kT$$

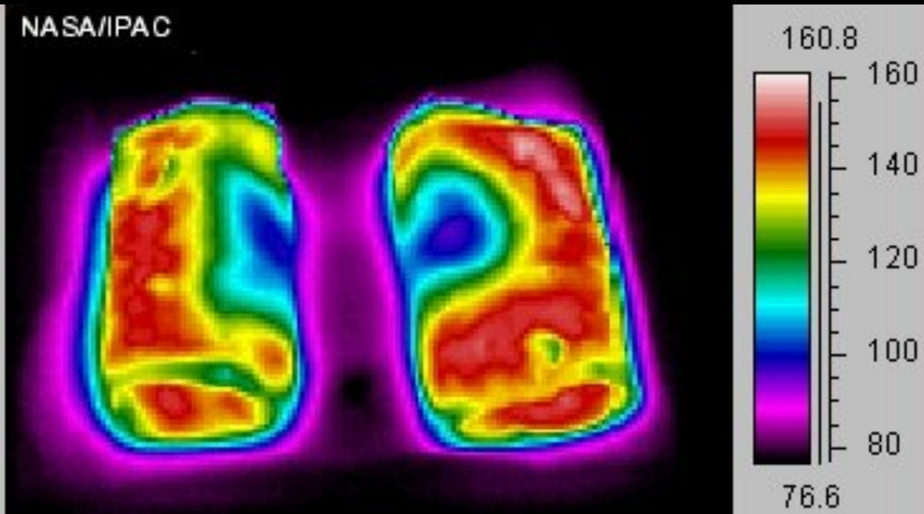
John William Strutt, 3rd Baron Rayleigh (1842 – 1919)

Sir James Hopwood Jeans (1877 – 1946)

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\exp\left(-\frac{h\nu}{kT}\right)$$

$$\lambda_{max} = \frac{2.98\cdot 10^{-3}\ \text{mK}}{T}$$

Wilhelm Wien(1864 – 1928)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160.8
160
140
120
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80
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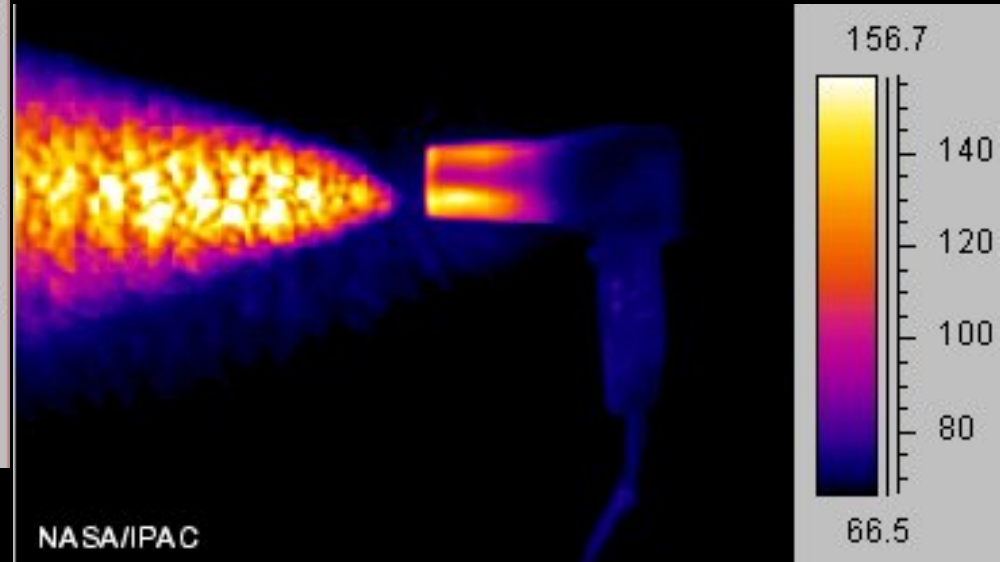
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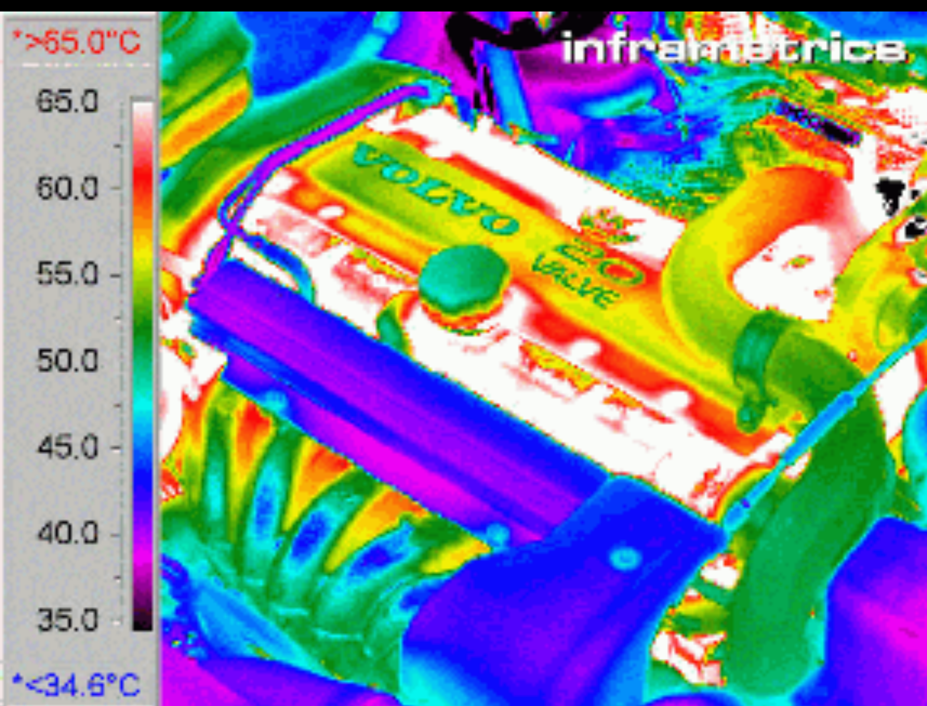
*>65.0°C
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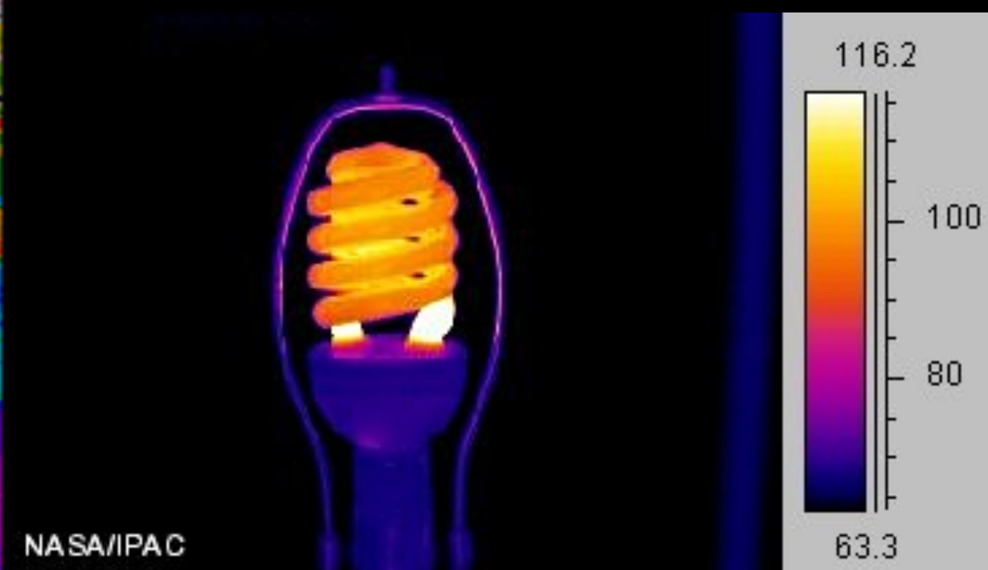
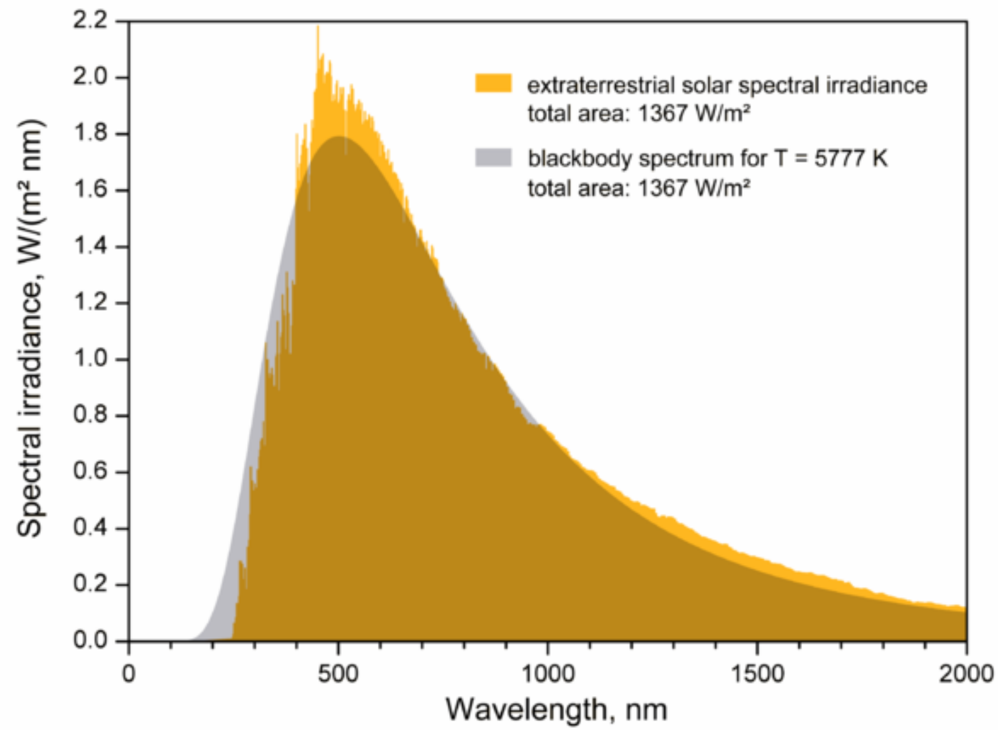

116.2
100
80
63.3
NASA/IPAC

Grey Bodies

Many emitters close to but not perfect black bodies.
With wavelength-dependent emissivity ε<1:

$$I_\lambda(T) = \varepsilon(\lambda) \cdot \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

Example: the Sun
(like many stars)



Brightness Temperature

Brightness temperature is temperature a perfect black body would have to be at to duplicate the observed intensity of grey body object at frequency *ν*.

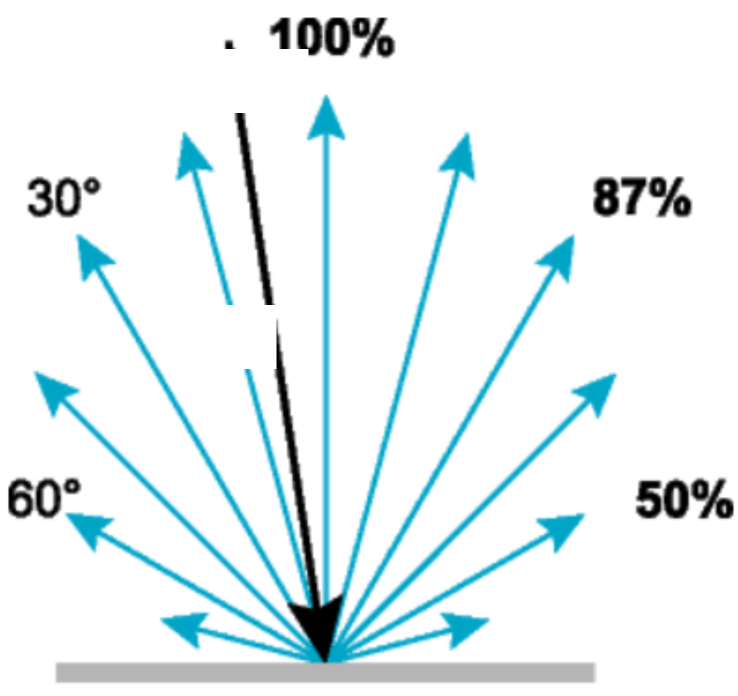
For low frequencies ($h\nu \ll kT$):

$$T_b = \varepsilon(\nu)\cdot T \overset{\text{Rayleigh-}}{\underset{\text{Jeans}}{=}} \varepsilon(\nu)\cdot \frac{c^2}{2k\nu^2} I_\nu$$

Only for perfect BBs is T_b the same for all frequencies.

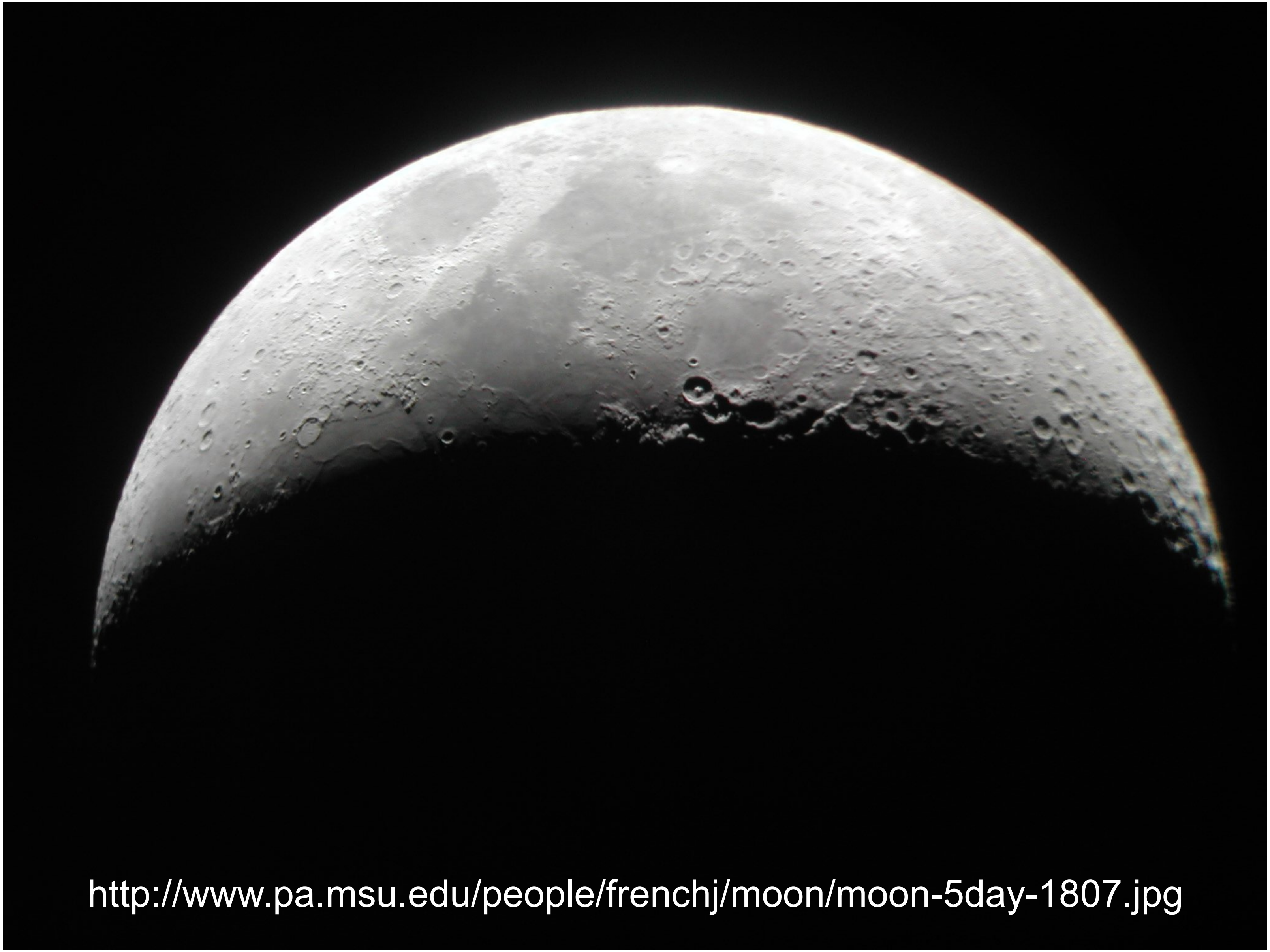
Lambert's Cosine Law

(Wikipedia:) Lambert's cosine law states that the radiant intensity from an ideal diffusively reflecting surface is directly proportional to the cosine of the angle θ between the surface normal and the observer.



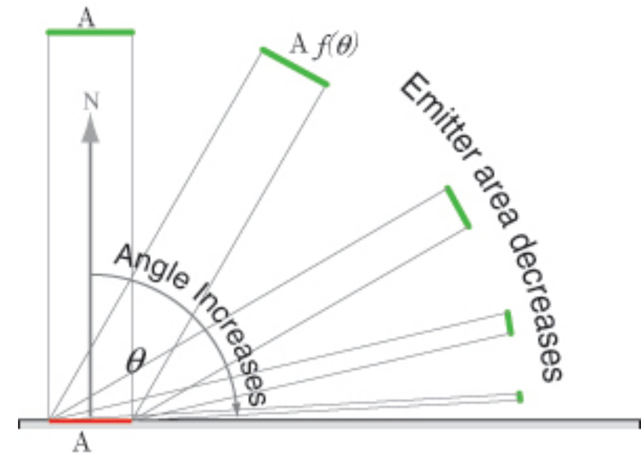
Johann Heinrich Lambert
(1728 – 1777)

The Moon: Lambertian Scatterer?



Lambertian Emitters

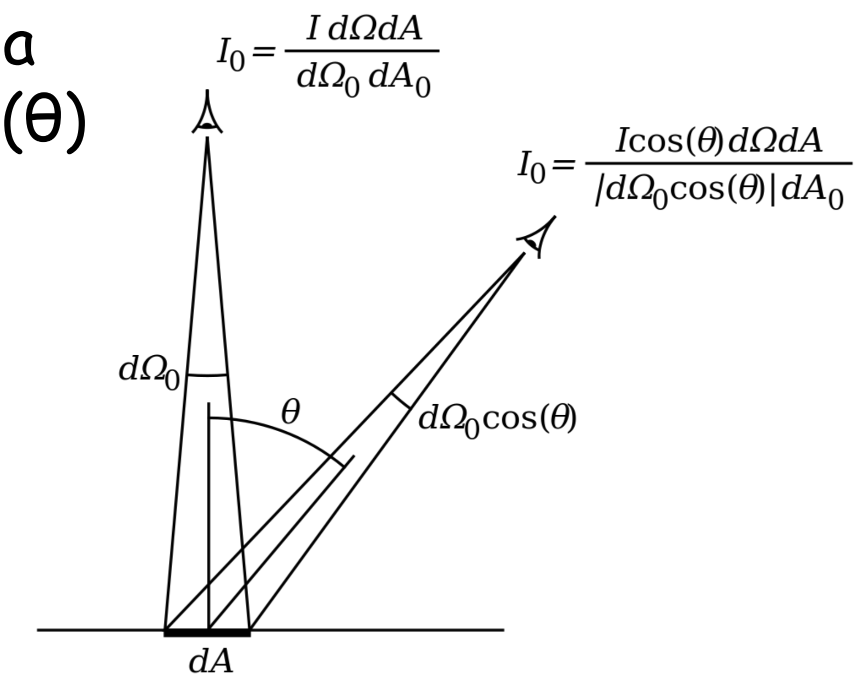
Radiance of Lambertian emitters is independent of direction θ of observation (i.e., isotropic).



Two effects:

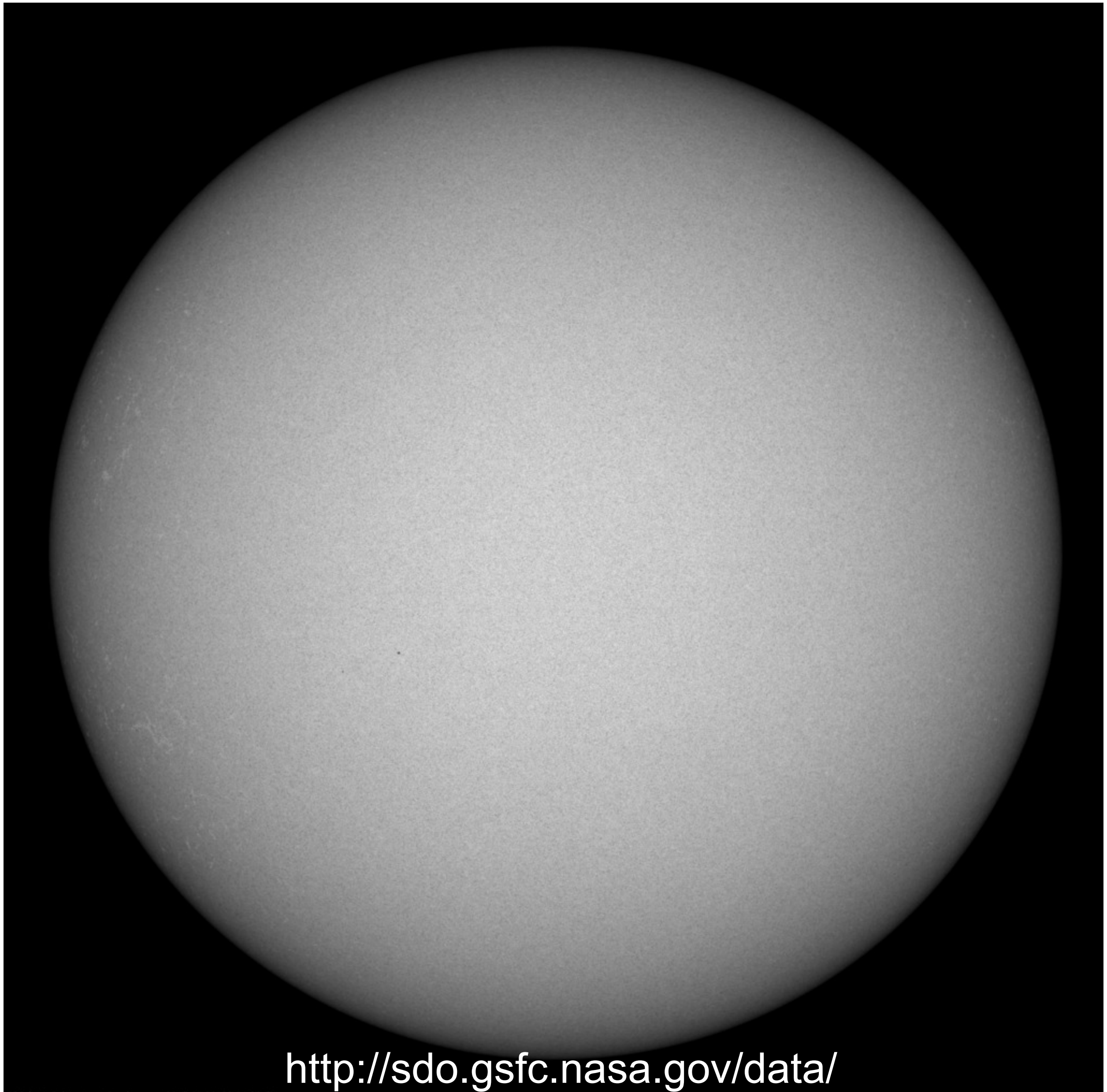
1. Lambert's cosine law → radiant intensity and *dΩ* are reduced by cos(θ)
2. Emitting surface area *dA* for a given *dΩ* is increased by $\cos^{-1}(\theta)$

→ Two effects cancel



Perfect black bodies are Lambertian emitters!

The Sun: Lambertian Emitter?



http://sdo.gsfc.nasa.gov/data/

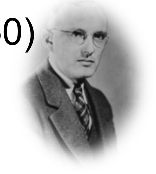
Astronomical Magnitudes

Summary of Radiometric Quantities

(see course on Radiative Processes!)

Name	Symbol	Unit	Definition	Equation
Spectral radiance *or* specific intensity	L_ν , I_ν	$W\ m^{-2}\ Hz^{-1}\ sr^{-1}$	Power leaving unit projected surface area into unit solid angle and unit $\Delta\nu$	
Spectral radiance *or* specific intensity	L_λ , I_λ	$W\ m^{-3}\ sr^{-1}$	Power leaving unit projected surface area into unit solid angle and unit $\Delta\lambda$	
Radiance *or* Intensity	L , I	$W\ m^{-2}\ sr^{-1}$	Spectral radiance integrated over spectral bandwidth	$L = \int L_\nu\, d\nu$
Radiant exitance	M	$W\ m^{-2}$	Total power emitted per unit surface area	$M = \int L(\theta)\, d\Omega$
Flux *or* luminosity	Φ , L	W	Total power emitted by a source of surface area A	$\Phi = \int M\, dA$
Spectral irradiance *or* flux density	L_ν , F_ν , I_ν	$W\ m^{-2}\ Hz^{-1}$ *	Power received at a unit surface element per unit $\Delta\nu$	
Spectral irradiance *or* flux density	$L_\lambda , F_\lambda , I_\lambda$	$W\ m^{-3}$ *	Power received at a unit surface element per unit $\Delta\lambda$	
Irradiance	E	$W\ m^{-2}$	Power received at a unit surface element	$E = \frac{\int M\, dA}{4\pi r^2}$

Karl Guthe Jansky (1905 – 1950)



*$10^{-26}\ W\ m^{-2}\ Hz^{-1} = 10^{-23}\ erg\ s^{-1} cm^{-2}\ Hz^{-1}$ is called 1 Jansky

Optical Astronomers use 'Magnitudes'

Origins in Greek classification of stars according to their visual brightness. Brightest stars were m = 1, faintest detected with bare eye were m = 6.

Later formalized by Pogson (1856): 1^{st} mag ~ 100 × 6^{th} mag

Magnitude	Example	#stars brighter
-27	Sun	
-13	Full moon	
-5	Venus	
0	Vega	4
2	Polaris	48
3.4	Andromeda	250
6	Limit of naked eye	4800
10	Limit of good binoculars	
14	Pluto	
27	Visible light limit of 8m telescopes	

Apparent Magnitude

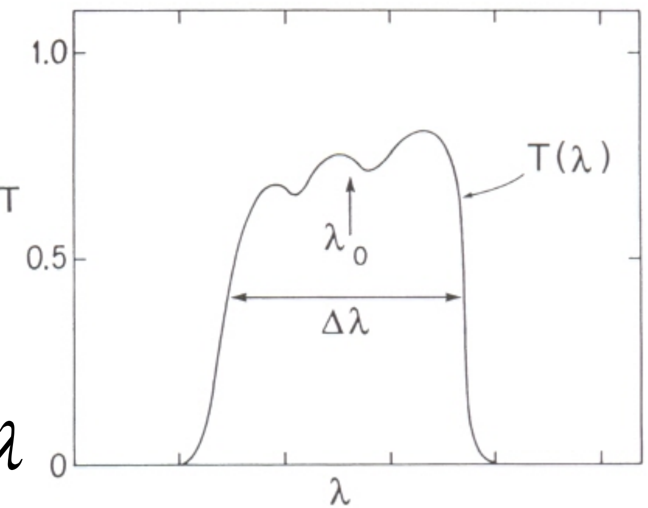
Apparent magnitude is *relative* measure of monochromatic flux density F_λ of a source:

$$m_\lambda - M_0 = -2.5 \cdot \log\left(\frac{F_\lambda}{F_0}\right)$$

M_0 defines reference point (usually magnitude zero).

In practice, measurements through transmission filter $T(\lambda)$ that defines bandwidth:

$$m_\lambda - M = -2.5\log\int_0^\infty T(\lambda)F_\lambda d\lambda + 2.5\log\int_0^\infty T(\lambda)d\lambda$$



Photometric Systems

Filters usually matched to atmospheric transmission
→ different observatories = different filters
→ many photometric systems:

- Johnson UBV system →
- Gunn griz
- USNO
- SDSS
- 2MASS JHK
- HST filter system (STMAG)
- AB magnitude system
- ...

Name	λ_0 [μm]	$\Delta\lambda_0$ [μm]
U	0.36	0.068
B	0.44	0.098
V	0.55	0.089
R	0.70	0.22
I	0.90	0.24
J	1.25	0.30
H	1.65	0.35
K	2.20	0.40
L	3.40	0.55
M	5.0	0.3
N	10.2	5
Q	21.0	8

http://en.wikipedia.org/wiki/Photometric_system

AB and STMAG Systems

For given flux density F_ν, AB magnitude defined as:

$$m(AB) = -2.5 \cdot \log F_\nu - 48.60$$

- object with constant flux per unit frequency interval has zero color.
- zero points defined to match zero points of Johnson V-band
- used by SDSS and GALEX
- F_ν in units of [erg s^{-1} cm^2 Hz^{-1}]

STMAG system defined such that object with constant flux per unit wavelength interval has zero color.

- STMAGs are used by the HST photometry packages.

Color Indices

Color index = difference of magnitudes at different wavebands = ratio of fluxes at different wavelengths.

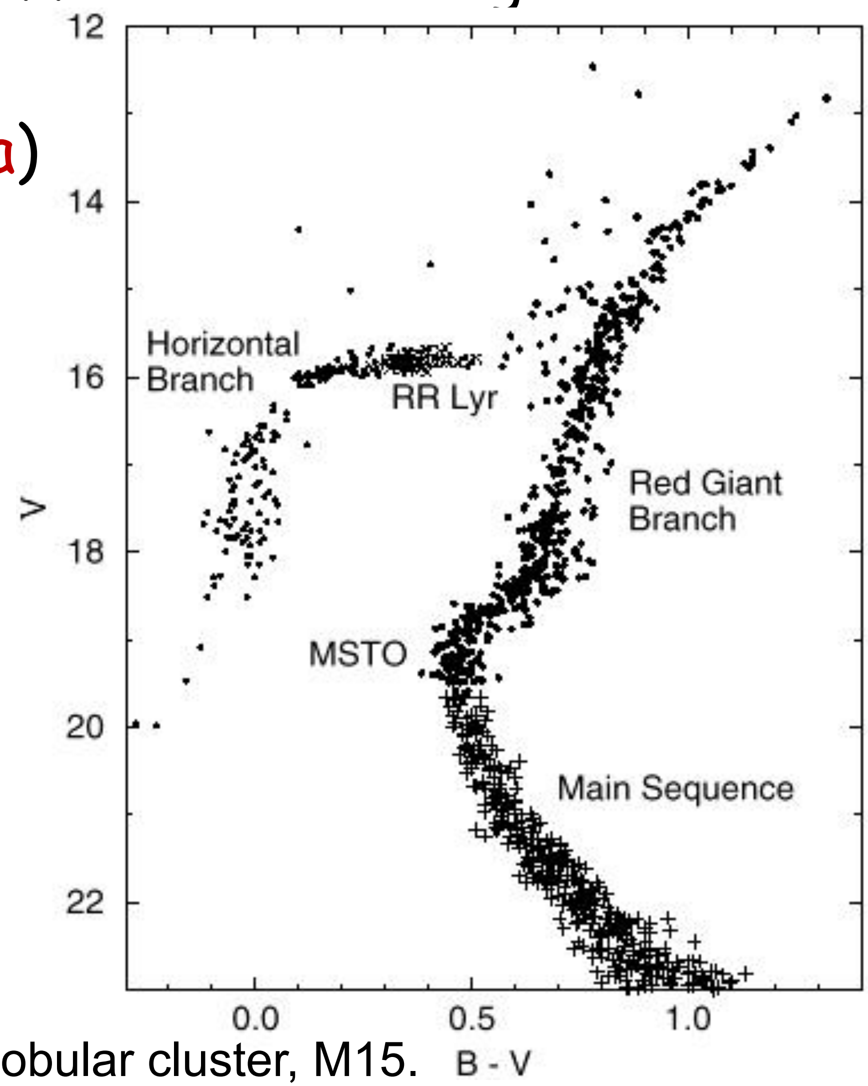
- Color indices of A0V star (Vega) about zero longward of V

- Color indices of blackbody in Rayleigh-Jeans tail are:

  B-V = -0.46

  U-B = -1.33

  V-R = V-I = ... = V-N = 0.0



Color-magnitude diagram for a typical globular cluster, M15.

Absolute Magnitude

Absolute magnitude = apparent magnitude of source if it were at distance D = 10 parsecs: $M = m + 5 - 5\log D$

M_{Sun} = 4.83 (V); $M_{Milky\ Way}$ = -20.5 → Δmag = 25.3 → Δlumi = 14 billion $L_{\odot}$

However, interstellar extinction *E* or absorption *A* affects the apparent magnitudes

$$E(B-V) = A(B) - A(V) = (B-V)_{\text{observed}} - (B-V)_{\text{intrinsic}}$$

Need to include absorption to obtain correct absolute magnitude:

$$M = m + 5 - 5\log D - A$$

Bolometric Magnitude

Bolometric magnitude is luminosity expressed in magnitude units = integral of monochromatic flux over all wavelengths:

$$M_{bol} = -2.5 \cdot \log \frac{\int_0^\infty F(\lambda) d\lambda}{F_{bol}} \quad ; F_{bol} = 2.52 \cdot 10^{-8} \frac{\mathrm{W}}{\mathrm{m}^2}$$

If source radiates isotropically:

$$M_{bol} = -0.25 + 5 \cdot \log D - 2.5 \cdot \log \frac{L}{L_\Theta} \quad ; L_\Theta = 3.827 \cdot 10^{26}\ \mathrm{W}$$

Bolometric magnitude can also be derived from visual magnitude plus a bolometric correction BC:

$$M_{bol} = M_V + BC$$

BC is large for stars that have a peak emission very different from the Sun's.

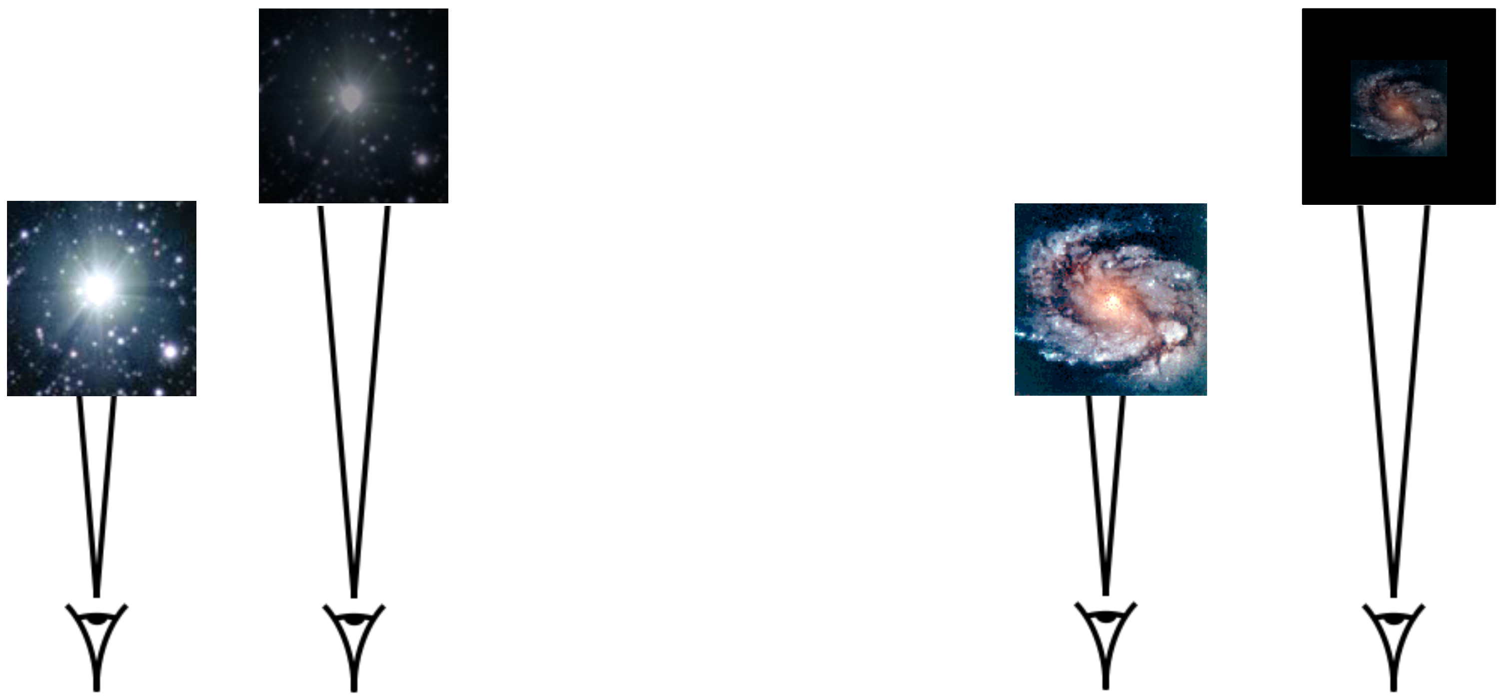
Photometric Systems and Conversions

Name	λ_0 [μm]	$\Delta\lambda_0$ [μm]	F_λ [$W\ m^{-2}\ \mu m^{-1}$]	F [Jy]	
U	0.36	0.068	4.35×10^{-8}	1 880	Ultraviolet
B	0.44	0.098	7.20×10^{-8}	4 650	Blue
V	0.55	0.089	3.92×10^{-8}	3 950	Visible
R	0.70	0.22	1.76×10^{-8}	2 870	Red
I	0.90	0.24	8.3×10^{-9}	2 240	Infrared
J	1.25	0.30	3.4×10^{-9}	1 770	Infrared
H	1.65	0.35	7×10^{-10}	636	Infrared
K	2.20	0.40	3.9×10^{-10}	629	Infrared
L	3.40	0.55	8.1×10^{-11}	312	Infrared
M	5.0	0.3	2.2×10^{-11}	183	Infrared
N	10.2	5	1.23×10^{-12}	43	Infrared
Q	21.0	8	6.8×10^{-14}	10	Infrared

$1\ \text{Jy} = 10^{-26}\ W\ m^{-2}\ Hz^{-1}$.

Point Sources and Surface Brightness

Point Sources and Extended Sources



Point sources = spatially unresolved

Brightness ~ 1 / distance^2

Size given by observation

Extended sources = well resolved

Surface brightness ~ const(distance)

Brightness ~ 1/d^2 and size ~ 1/d^2

Surface brightness [mag/arcsec^2] is constant with distance!

Calculating Surface Brightness

To describe the surface brightness of extended objects one uses units of mag/sr or mag/arcsec^2.

Magnitudes are logarithmic units; to get the surface brightness of an area *A*:

$$S = m + 2.5 \cdot \log_{10} A$$

The observed surface brightness [mag/arcsec^2] can be converted into physical surface brightness units via

$$S\left[\mathrm{mag/arcsec^2}\right] = M_\Theta + 21.572 - 2.5 \cdot \log_{10} S\left[L_\Theta/\mathrm{pc}^2\right]$$

with $L_\Theta = 3.839 \times 10^{26}\ \mathrm{W} = 3.839 \times 10^{33}\ \mathrm{erg\ s^{-1}}$