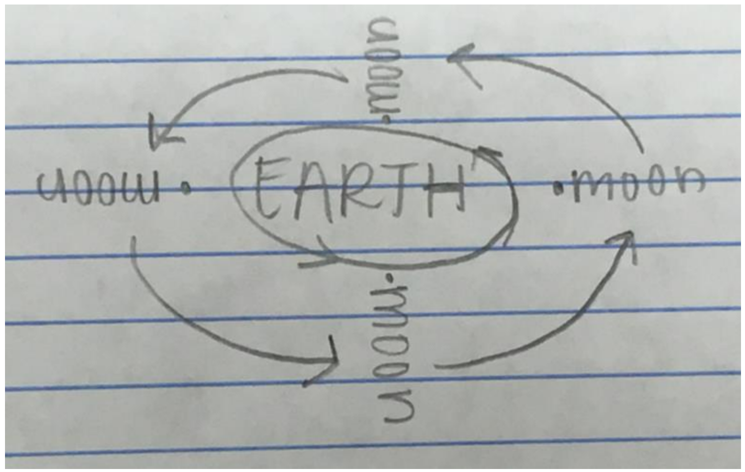
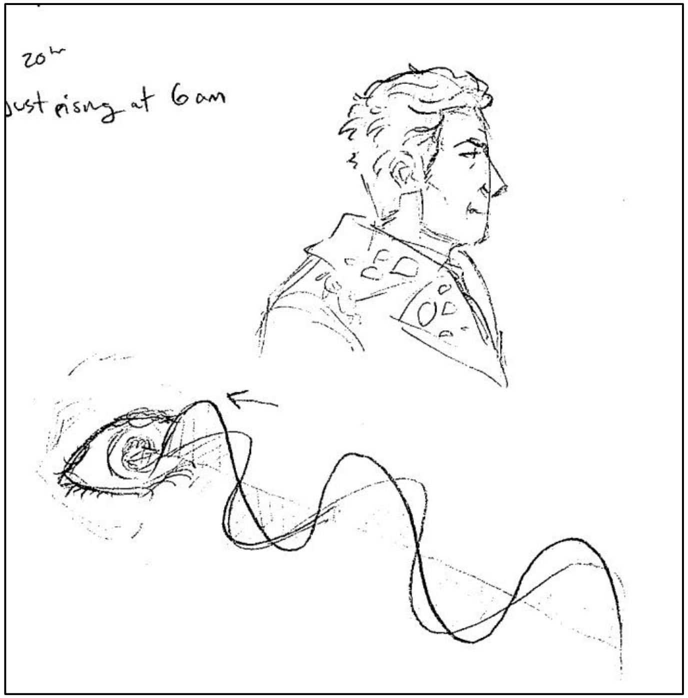
What phenomenon is illustrated by this student's Doodle?

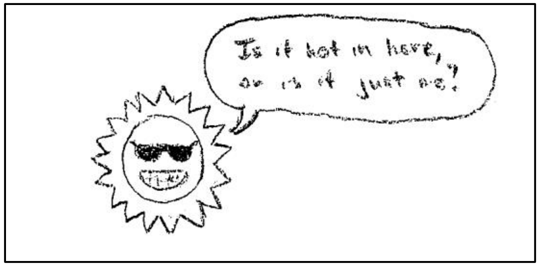


Work together!

- **A. The ecliptic**
- **B. The celestial equator**
- **C. Synchronous rotation**
- **D. Moon phases**

Your Doodles about Light





YES!
The human eye can detect a single photon of light.

Highest-Energy Photons Ever Recorded Blasted to Earth from the Crab Nebula

Energetic gamma rays thousands of light years away have been recorded by scientists, and it's the highest energy light ever measured.

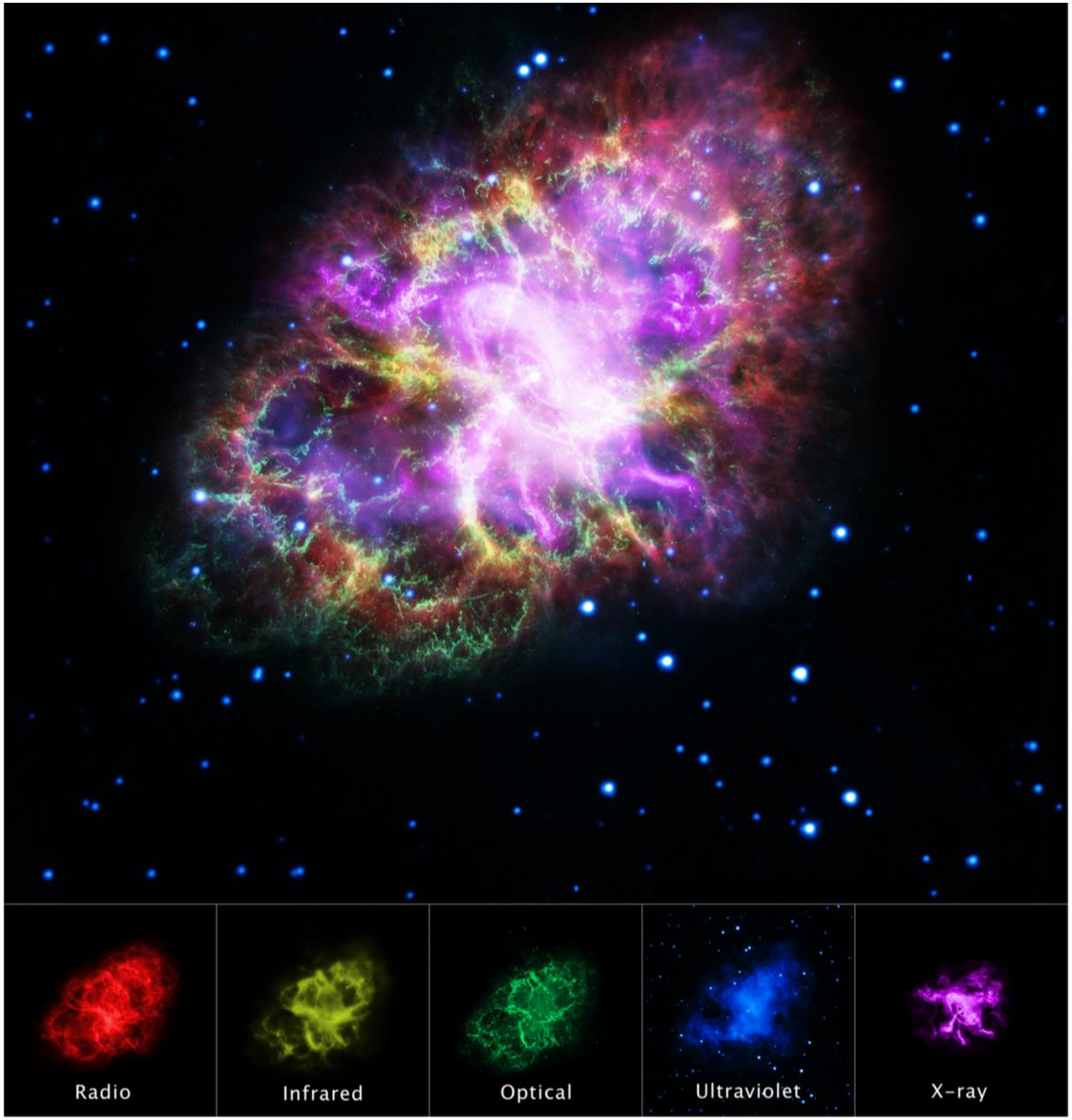
By Fabienne Lang

August 01, 2019

Energy = 450 Tev

Roughly equivalent to a flying mosquito

What does that number mean? Well, electronvolts are a measure of energy. A flying mosquito has about 1 TeV of kinetic energy, whereas something like the Large Hadron Collider, which accelerates particles and then smashes them together, operates at about 14 TeV.

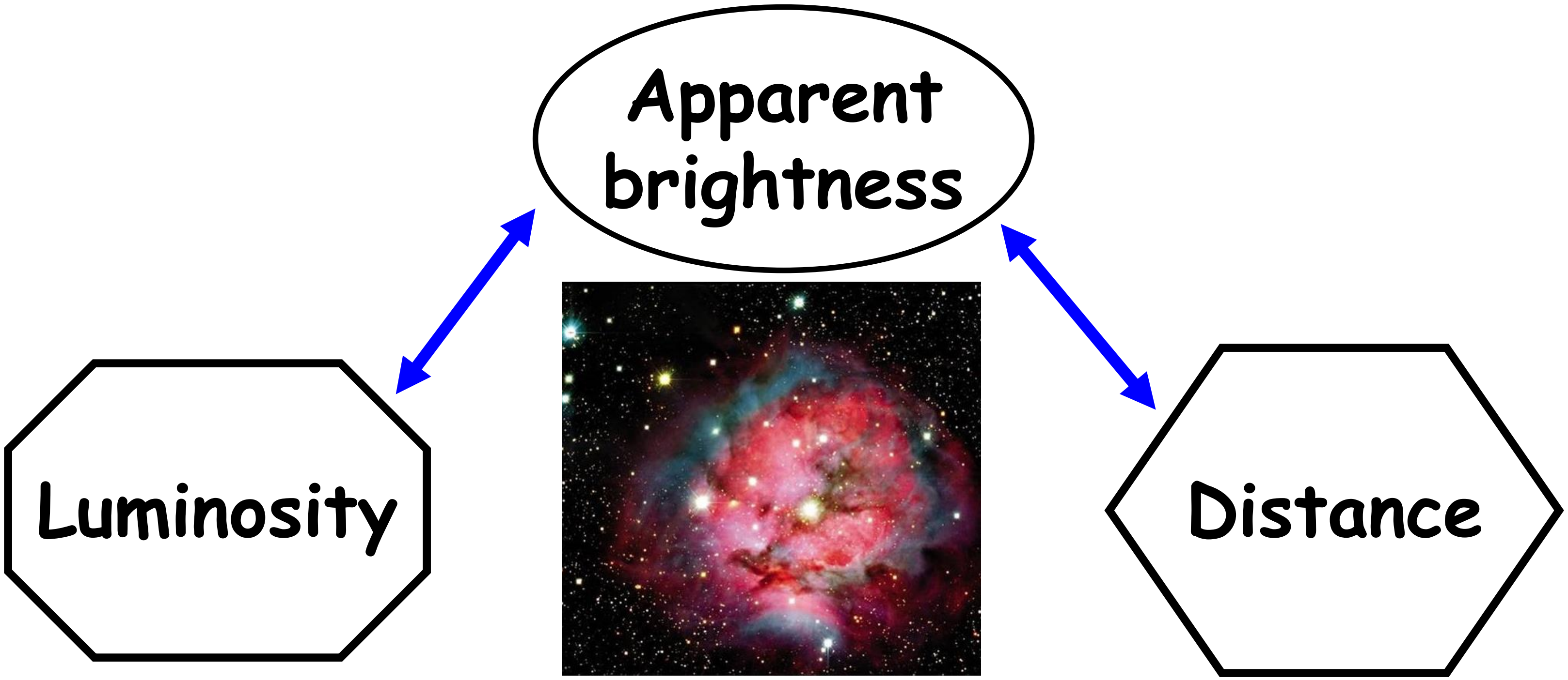


Crab Nebula

Observation data: J2000.0 epoch	
Right ascension	05h 34m 31.94s[1]
Declination	+22° 00′ 52.2″[1]
Distance	6500 ± 1600 ly (2000 ± 500[2] pc)
Apparent magnitude (V)	+8.4
Apparent dimensions (V)	420″ × 290″[3][b]
Constellation	Taurus
Physical characteristics	
Radius	~5.5 ly (~1.7[4] pc)
Absolute magnitude (V)	−3.1 ± 0.5[c]
Notable features	Optical pulsar
Designations	Messier 1, NGC 1952, Taurus A, Sh2-244[1]

"Standard Candles"

An object's brightness depends on its distance and how bright it really is.

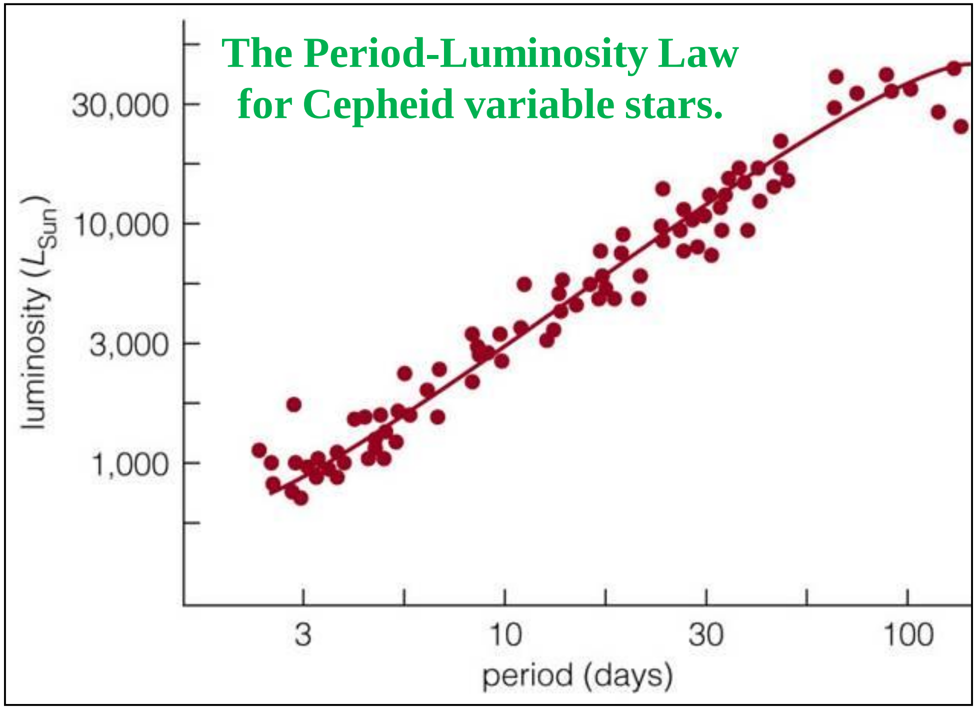


If we know two of these characteristics, we can determine the third.

More Interactive Problems

The Sun-like star α Cen has ~1 L_{Sun}.

If a Cepheid star of ~30 day period has the same brightness as α Cen, how far away is the Cepheid star?



"Monochromatic Flux"

"Flux Density"

The flux in a particular bandwidth of wavelength or frequency

$$\mathbf{F_\lambda} = dE / (dA\ dt\ d\lambda)$$

$$\mathbf{F_\nu} = dE / (dA\ dt\ d\nu)$$

What are the units of Flux Density?

<u>units</u>: ergs cm^{-2} sec^{-1} cm^{-1}

ergs cm^{-2} sec^{-1} Hz^{-1}

Total Flux Emitted by an Object

Integrate over all wavelengths or frequencies

$$\mathbf{F} = \int_0^{\infty} F_\nu \, d\nu = \int_0^{\infty} F_\lambda \, d\lambda$$

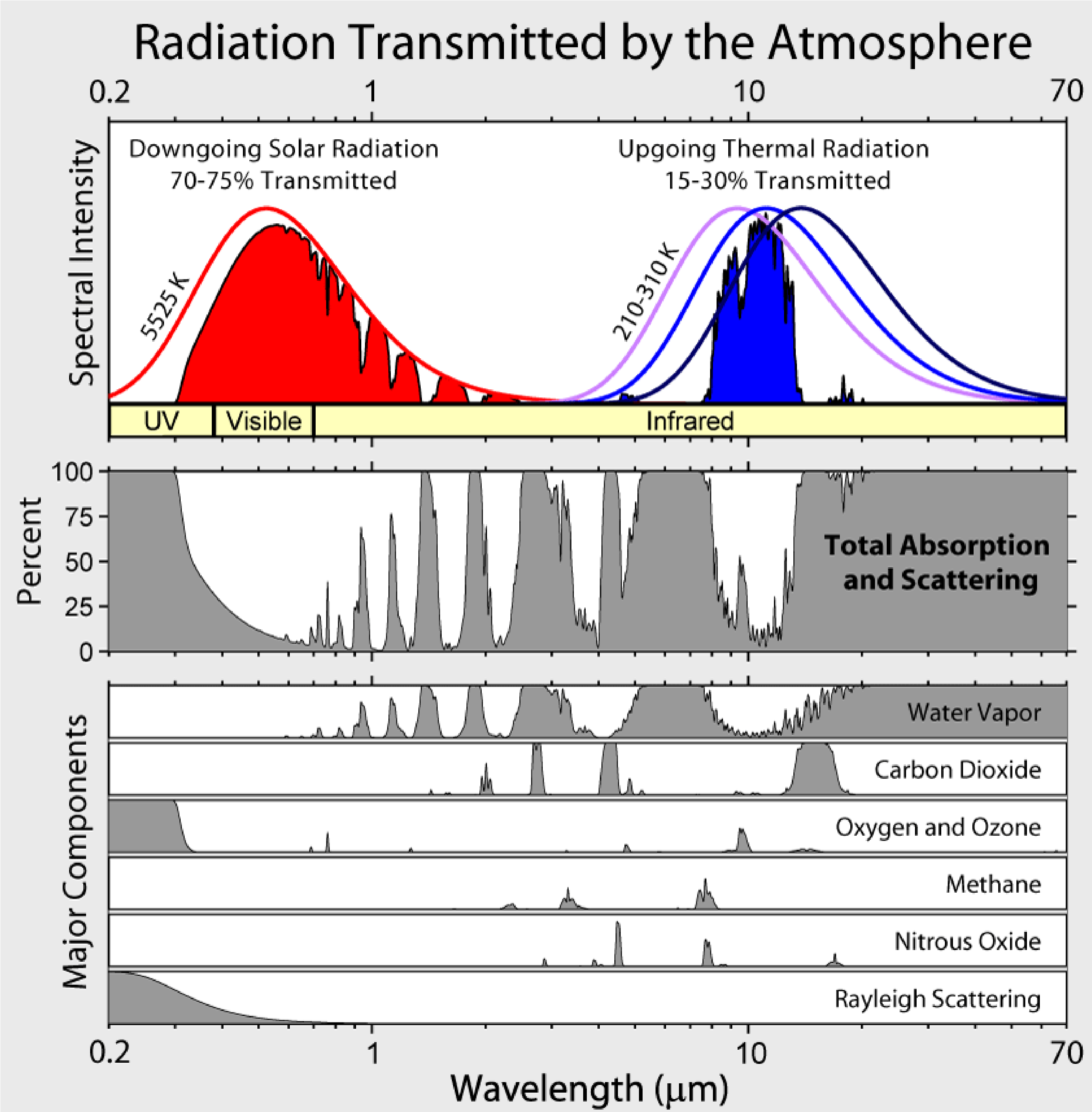
<u>units: </u>ergs cm^{-2} sec^{-1}

<u>Note</u>:

$d\lambda \neq d\nu$

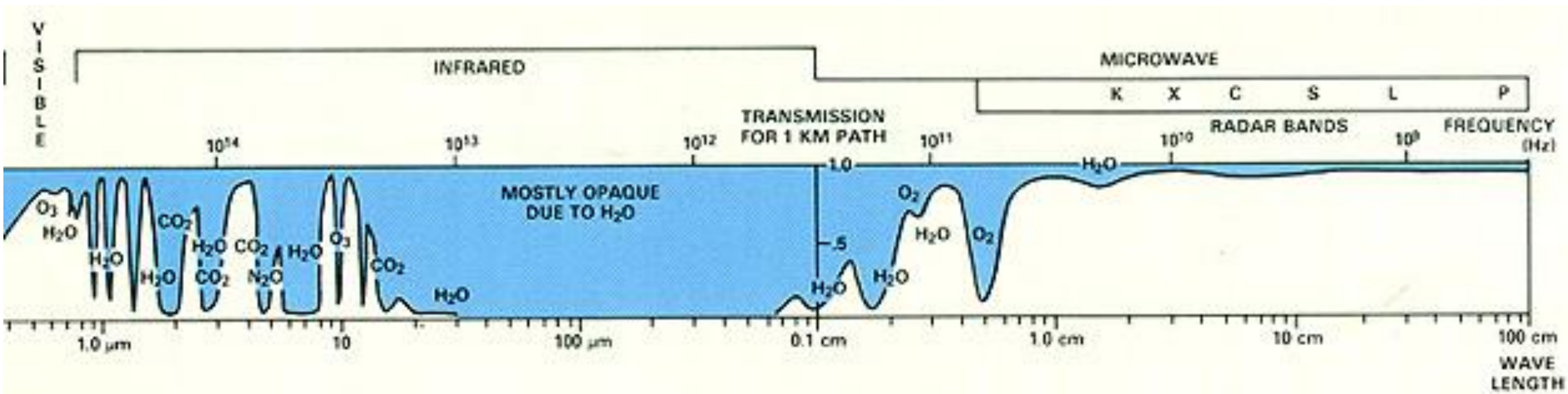
$F_\lambda \neq F_\nu$

[Solve problem #2 in Homework #5 to find the conversion.]

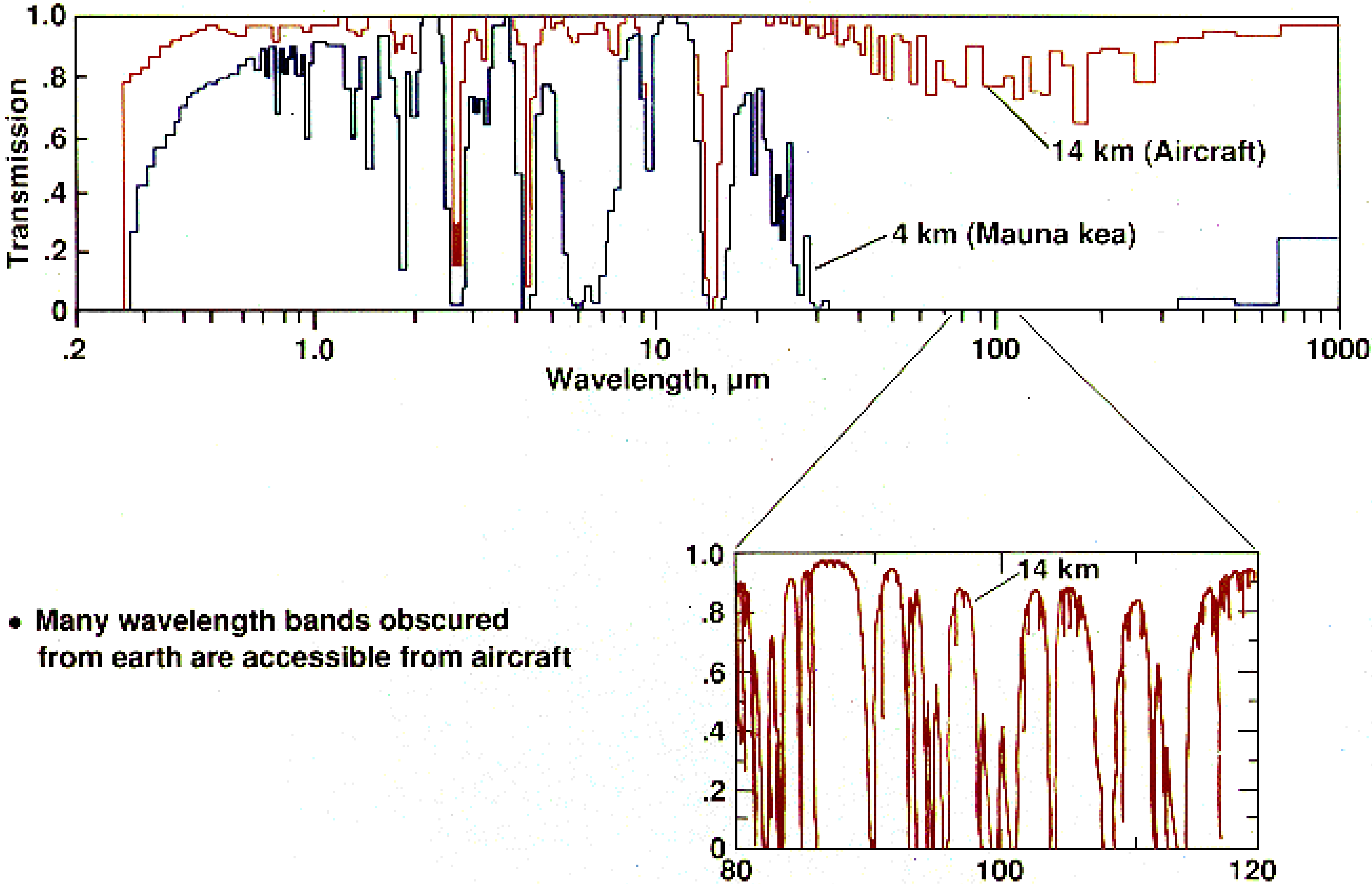


photometric
“windows”

Atmospheric Transmission
“windows” of transparency

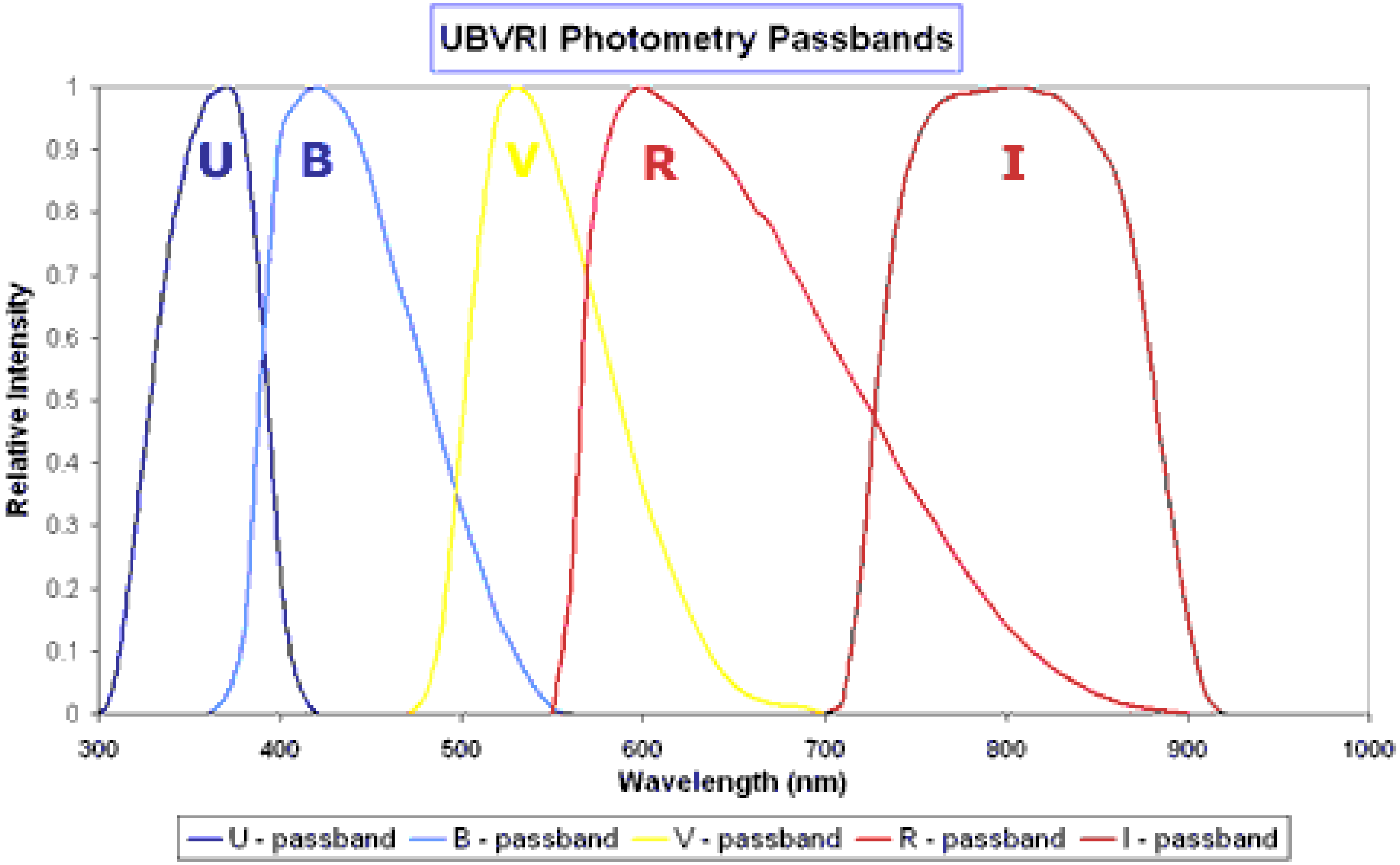


ATMOSPHERIC TRANSMISSION VERSUS WAVELENGTH

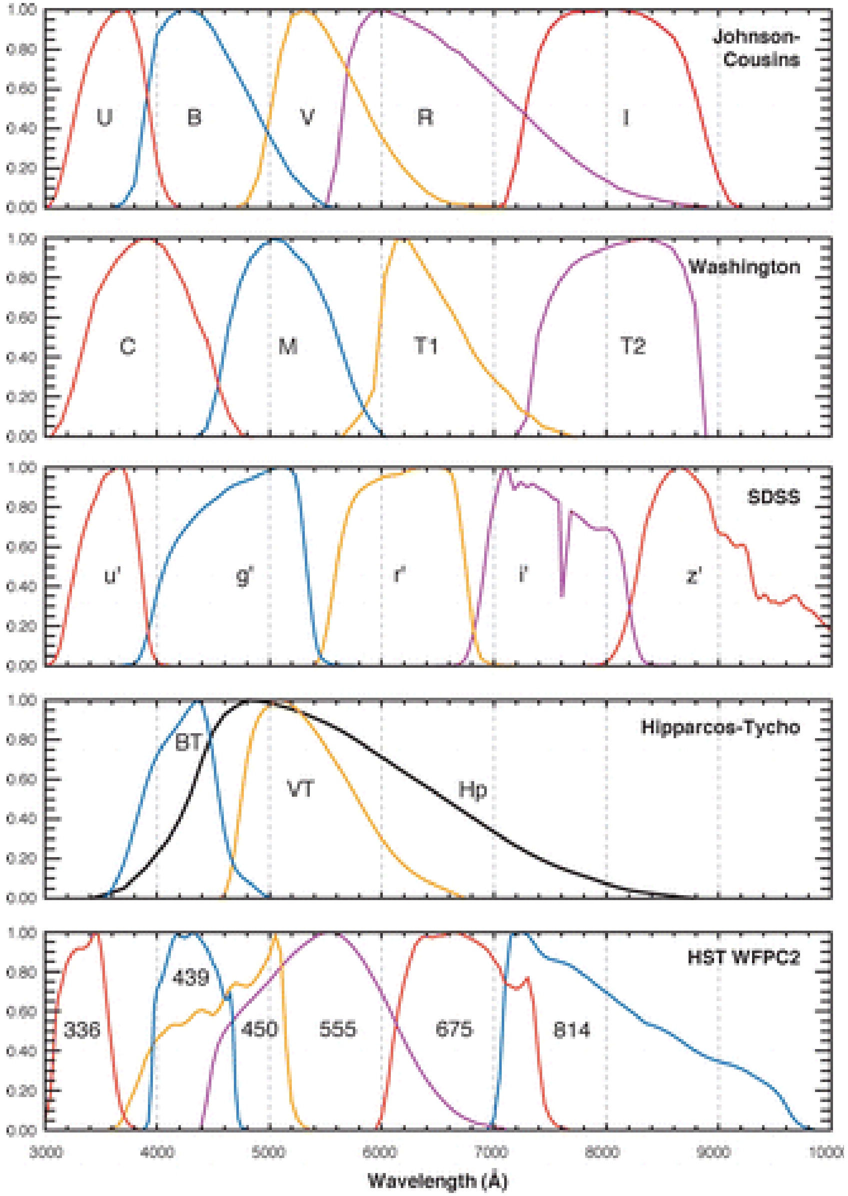


- Many wavelength bands obscured from earth are accessible from aircraft

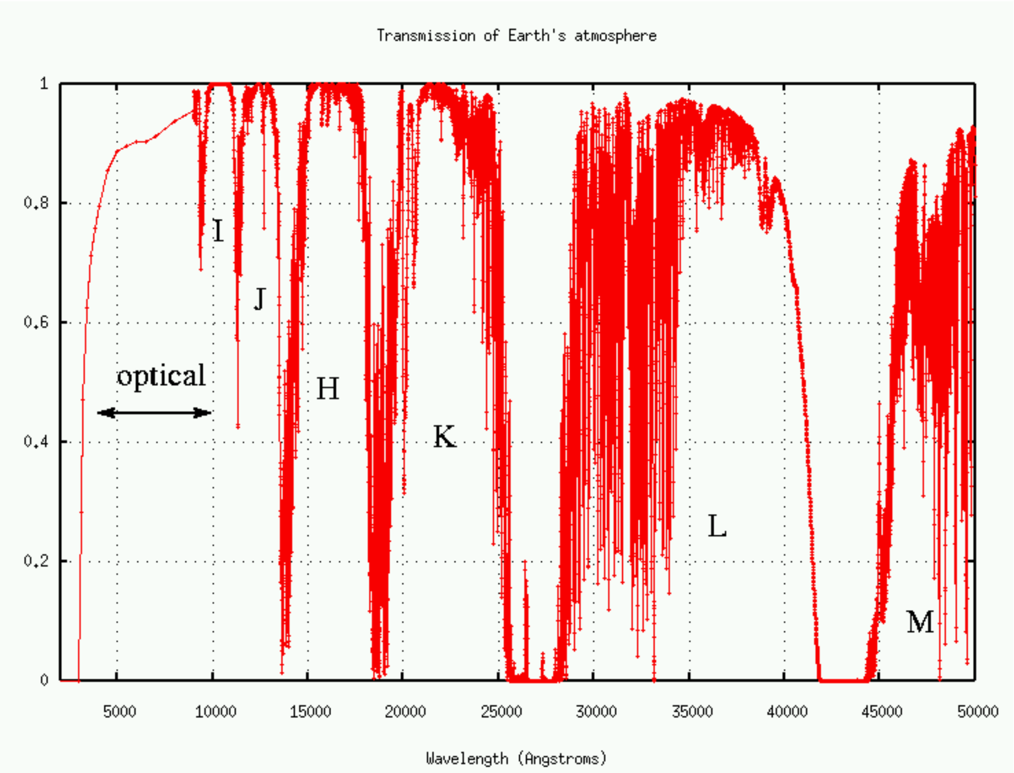
“Photometric” Filters



Photometric Systems



Bessell, MS. 2005
Annu. Rev. Astron. Astrophys. 43: 293–336



“Magnitudes”

- **Hipparchos (~150 BC):**
  - **Labelled stars according to “size” (i.e., apparent brightness = flux)**
  - **Twice as bright => mag. 5**
- **Our senses are logarithmic, i.e., powers of ten.**
- **From modern electronic measurements:**
  - **A difference of one magnitude equals a flux ratio of**
    - $100^{1/5} = 2.5119$
    - **so 5 magnitudes =** $[100^{1/5}]^5$ **= 100x in flux (brightness)**
  - **F (mag = 2) / F (mag= 1) = 2.5119**
  - $F_2/F_1 = 2.5119^{(m1-m2)}$

Consider two stars of flux F_1 and F_2

$2.5119^{(m1-m2)} = F_2/F_1$

$(m_1-m_2) \log (2.5119) = \log (F_2/F_1)$

$\log (2.5119) = \log (100^{1/5}) = 1/5 * \log 100 = 0.4$

$0.4\ (m_1-m_2) = \log (F_2/F_1)$

$\Delta m = (m_1-m_2) = 2.5 \log (F_2/F_1)$

CHECK: What if $m_1-m_2 = 5$. Then F_2/F_1 = ____?

Let one star have "zero magnitude"

magnitude difference = $\Delta m = (m_1 - m_2) = 2.5 \log (F_2/F_1)$

Let $m_1 \equiv 0$,
so $F_{m=0}$ is the flux from a zero-magnitude star
The star Vega is defined as zero-magnitude.

Then $m_2 = -2.5 \log (F_2/F_{m=0})$

So, in general:
$m = -2.5 \log (F/F_{m=0})$

$m=m_v$ and $F=F_v$ are defined for some bandwidth, like visual ("v")

Absolute Magnitude

magnitude difference = $\Delta m = (m_1 - m_2) = 2.5 \log (F_2/F_1)$

$F = L/4\pi d^2$

$(m_1 - m_2) = 2.5 \log (L_2/d^2{}_2 \div L_1/d^2{}_1)$

Imagine <u>the same star</u> viewed at two distances:

- its real distance (d in parsecs) - with magnitude m

- an absolute distance (d_{10}) of 10 parsecs – with magnitude M

$(m-M) = 2.5 \log (d^2/d^2{}_{10})$

$m-M = 5 \log (d) - 5$

$m-M = -5 \log (p) - 5$, where p = parallax angle in arcsec

m-M is called the *"distance modulus"*

Problem

- **Compare human eye to Hubble Space Telescope (HST)**
  - **eye can see to a visual magnitude of $m_v = 6$**
    - **abbreviation: $m_v \equiv V$, so $V = 6$**
  - **HST: $V \approx 31$**

- **What is the flux ratio of these two objects?**

Problem Solution

- $\Delta m = (m_1 - m_2) = 2.5 \log (F_2/F_1)$
- $31 – 6 = 2.5 \log (F_2/F_1)$
- $25 / 2.5 = \log (F_2/F_1)$
- $10^{10} = \log F_2/F_1$

- In words: "ten billion"

- <u>Check</u>: Remember that 5 magnitudes corresponds to flux (brightness) ratio of 100
  – $(100)^5 = (10^2)^5 = 10^{10}$

Problem

Assume you have two stars with individual apparent magnitudes of 3 and 4. What is the apparent magnitude of the unresolved pair of stars?

[Since magnitudes are logarithmically related to flux, you cannot simply add two magnitudes together to find the total apparent magnitude of an unresolved binary star.]

Problem Solution
fluxes add – magnitudes do not

- $m_1 \quad = -2.5 \log (F_1/F_{m=0}) \quad = 3$
- $m_2 \quad = -2.5 \log (F_2/F_{m=0}) \quad = 4$
- $m_{total} \quad = -2.5 \log [(F_1 + F_2) / F_{m=0}] \quad = ?$

- $-0.4m_1 = \log (F_1/F_{m=0})$
- $F_1 = F_{m=0} * 10^{-0.4m1}$

- $m_{total} = -2.5 \log[10^{-0.4m1} + 10^{-0.4m2}]$
- $m_{total} = -2.5 \log (0.082)$
- $m_{total} = 2.64$

- Does this magnitude make sense?

Problem
What is the absolute visual magnitude of the Sun?

Absolute visual magnitude of Sun = M_V = ?

Apparent visual magnitude of Sun = m_V = -26.7

$$m - M = 5 \log (d) - 5$$

Problem Solution

- Absolute visual magnitude of Sun = M_V = ?
- Apparent visual magnitude of Sun = m_V = -26.7

- $m_v - M_v = 5 \log (d) - 5$
- $M_v = m_v - 5 \log (d) + 5$

- $M_v = (-26.7) - 5 \log (1/206265 \text{ pc}) + 5$
- $M_v = 4.8$

- Does this answer make sense?
- Distance modulus = -26.7 – 4.8 = -31.5

“Magnitudes”
very useful rules of thumb

- Every 5 magnitudes = ??
- Every 2.5 magnitudes = ??

- Every 1.0 magnitudes = ??
- Every 0.5 magnitudes = ??

- Homework:
  - Astronomers often use the approximation that a 1% change in brightness of a star corresponds to a change of 0.01 magnitudes. Justify this approximation.

$F_0(\lambda) = F_0(\nu) \cdot c/\lambda^2$

flux for zero-magnitude

- **Here's an online calculator:**
  - **https://www.gemini.edu/sciops/instruments/midir-resources/imaging-calibrations/fluxmagnitude-conversion**

Table 1. UBVRIJHKLM Filters

Band	$\lambda_{\rm eff}$ μm	FWHM μm	$f_X(m_X = 0)$* Jy**	
U	0.365	0.066	1780	ultraviolet
B	0.445	0.094	4000	blue
V	0.551	0.088	3600	visible
R	0.658	0.138	3060	red
I	0.806	0.149	2420	
J	1.220	0.213	1570	↓ near-infrared ↓
H	1.630	0.307	1020	
K	2.190	0.390	636	
L	3.450	0.473	281	
M	4.750	0.460	154	

*$m_X = 0$ for a star with spectral type and luminosity A0 V.

**Note: 1 Jy = 10^{-26} W m^{-2} Hz^{-1}.

- f_X (m_X = 0) = zero point flux density of *X*. I.e., the flux density of a zero magnitude star (the star Vega)
- If the flux density of wavelength *X* is measured, then the mag is,

$$m = -2.5 \log \frac{f_x(\text{source})}{f_x(m_x = 0)}$$

Another "Magnitude" Problem
"color index"

- $m_U - m_B$
  - aka, U-B

- $m_B - m_V$
  - aka, B-V

- For an object with B-V > 0, is the object reddish or bluish?

“Blackbody Spectrum”

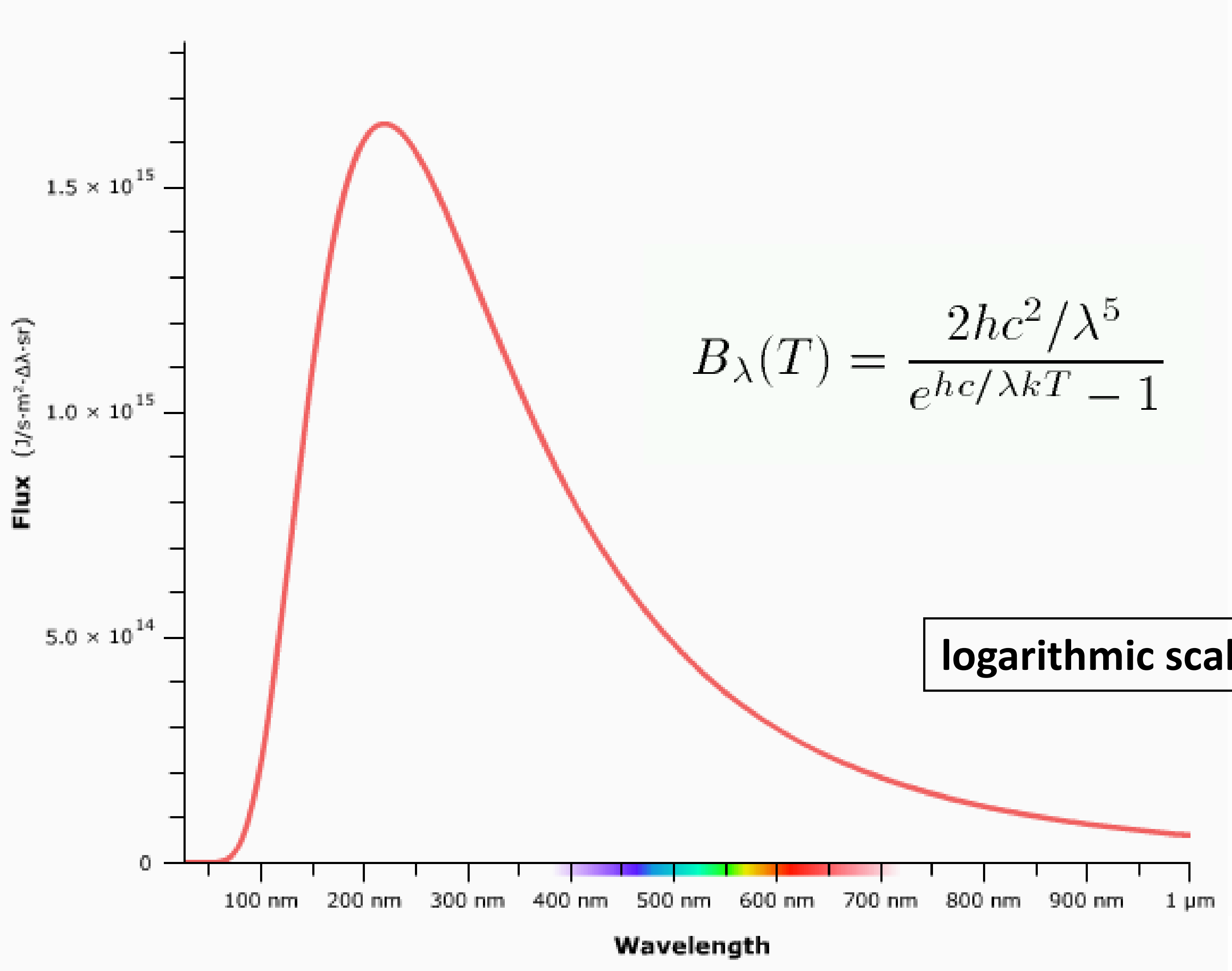
- **In your junior year Quantum Mechanics course, you will derive a formula for the flux of light emitted at different wavelengths (frequencies) from a perfectly absorbing body (“opaque”).**
  - **the “Planck function”**

- **The monochromatic flux emitted from the surface of such an object is**

- $F_\lambda = \pi\ B_\lambda(T)$ **erg sec^{-1} cm^{-2} Hz^{-1}**
- $F_\nu = \pi\ B_\nu(T)$ **erg sec^{-1} cm^{-2} cm^{-1}**

- $\pi\ B_\lambda(T) = (\pi c/\lambda^2) \cdot B_\nu(T)$ **because** $d\lambda \neq d\nu$

"Blackbody Spectrum"

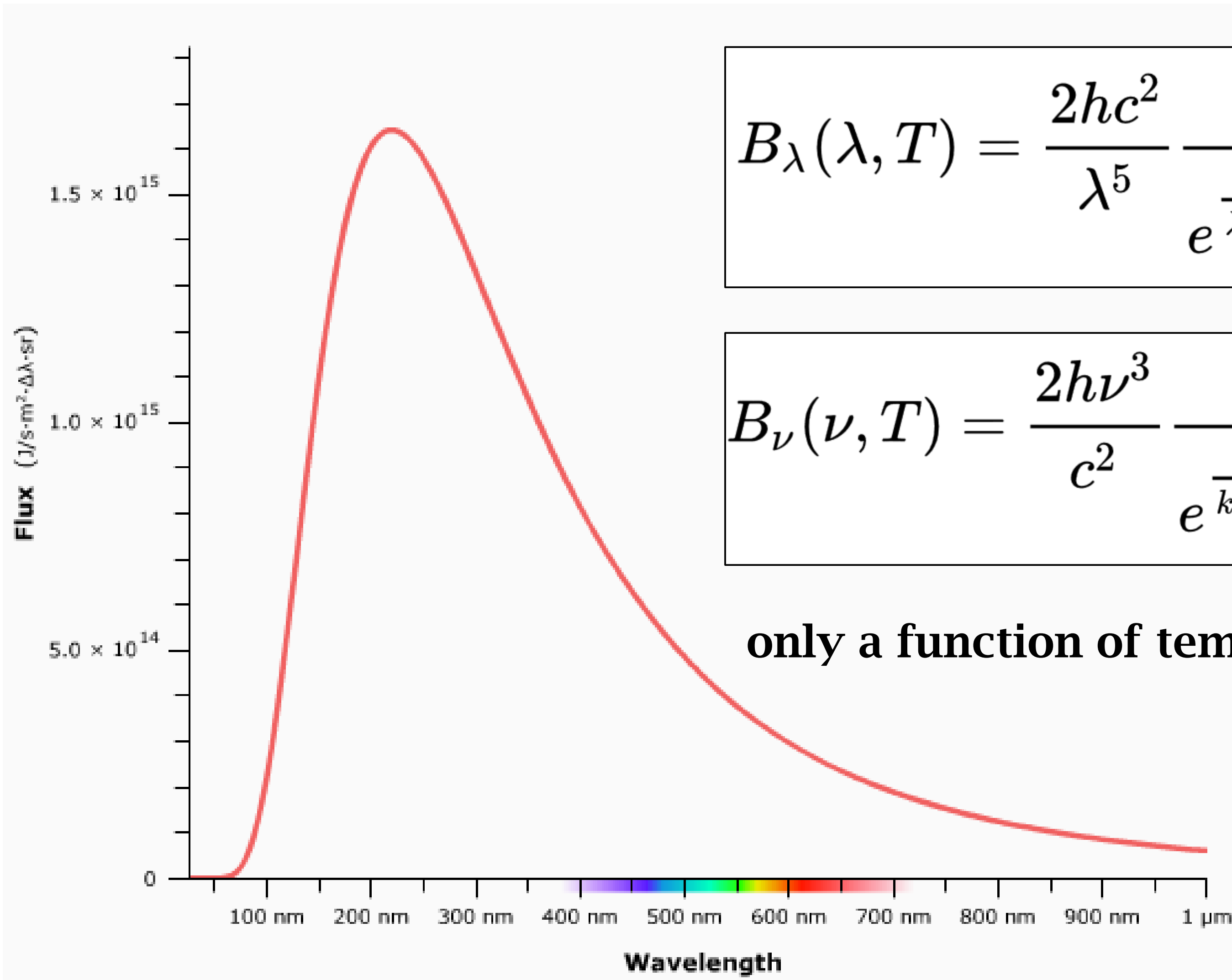


$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}$$

logarithmic scale

What are the terms?

What's missing?



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

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

only a function of temperature!

Approximations to the Planck Function

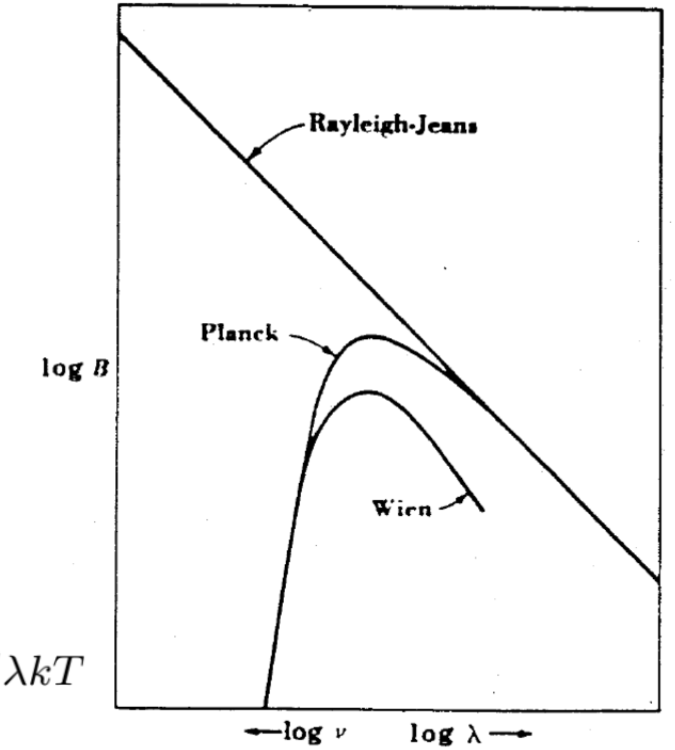
$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}$$

- **For long wavelengths:**
  - **Rayleigh-Jeans distribution**
  - **For λ >> hc/kt**

$$B_\lambda(T) = \frac{2ck_{\mathrm{B}}T}{\lambda^4}$$

- **For short wavelengths:**
  - **Wien distribution**
  - **For λ << hc/kt**

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



Stefan-Boltzmann Law
total emitted flux over all wavelengths

- **Integrate over wavelength (frequency):**

$$F = \pi \int_0^\infty B_\lambda(T)\, d\lambda$$

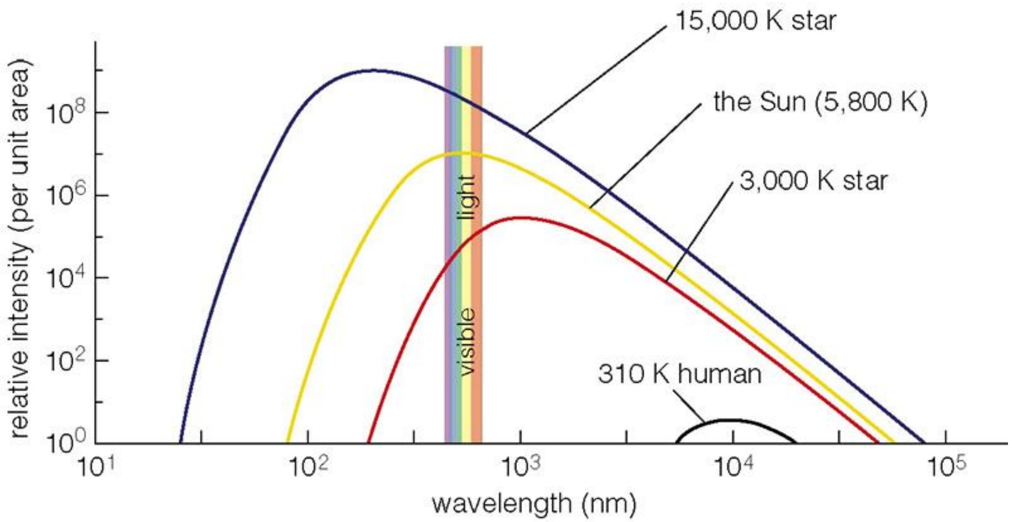
$$F = \sigma T^4$$

- **So, the luminosity of a star is:**
  - $L = 4\pi R^2 F_{obs} = 4\pi R^2 \sigma T^4$ erg sec^{-1}
  - Stellar Luminosity α (Radius)^2 · (Temperature)^4

A Continuous "Spectrum"

A spectrum is like a recipe!

contains light of all wavelengths but not in equal amounts



<u>Wien's "Law"</u>

The hotter the object, the bluer its color.

$$\lambda_{max} = \frac{3 \times 10^6}{T} \text{ nm}$$

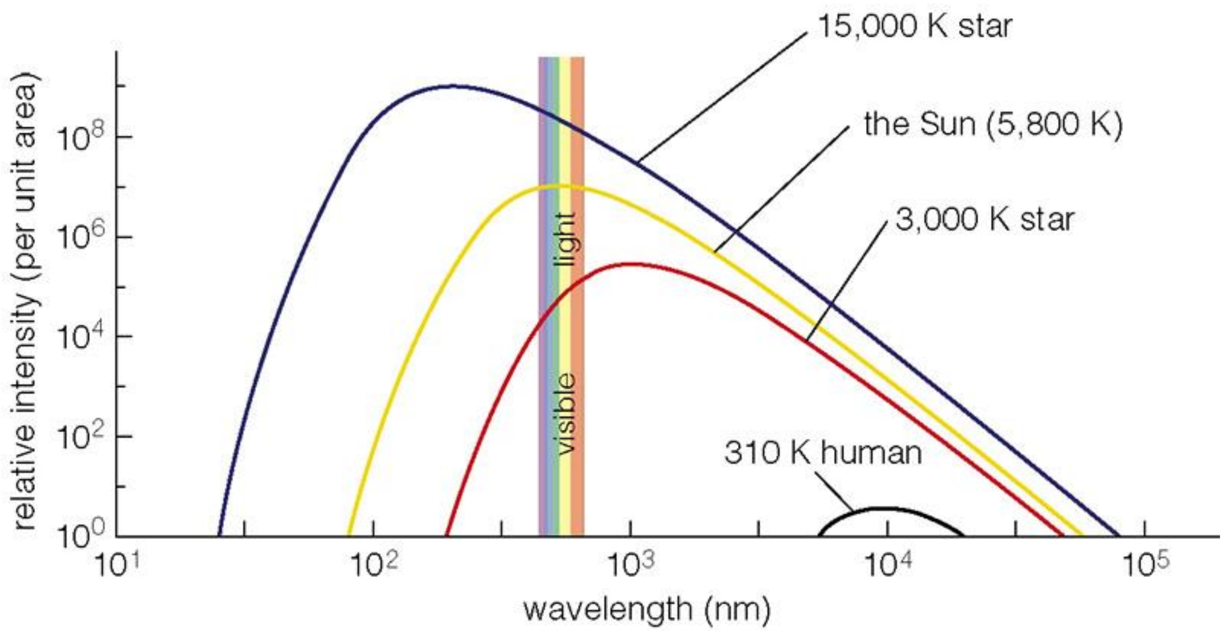
<u>Stefan-Boltzmann "Law"</u>

The total amount of light emitted from a given area depends on the temperature to the 4th power!!

(Total Emitted Energy) α **T^4**

Emphasize a consequence of Stefan-Boltzmann

Curves of different temperature never cross each other.



Spectrum of Our Sun
with and without Earth's atmosphere