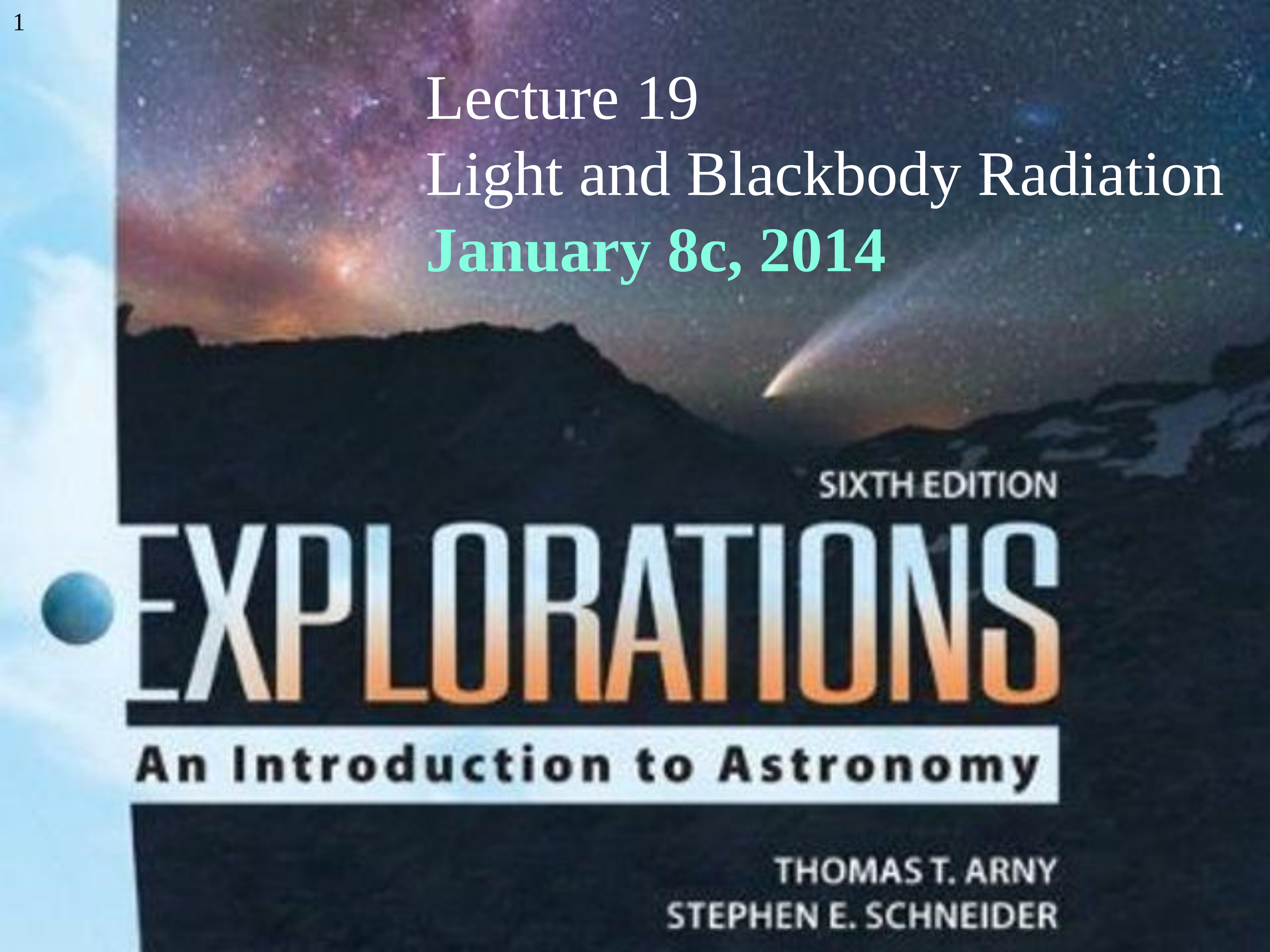
Lecture 19
Light and Blackbody Radiation

January 8c, 2014



Observing the Sky

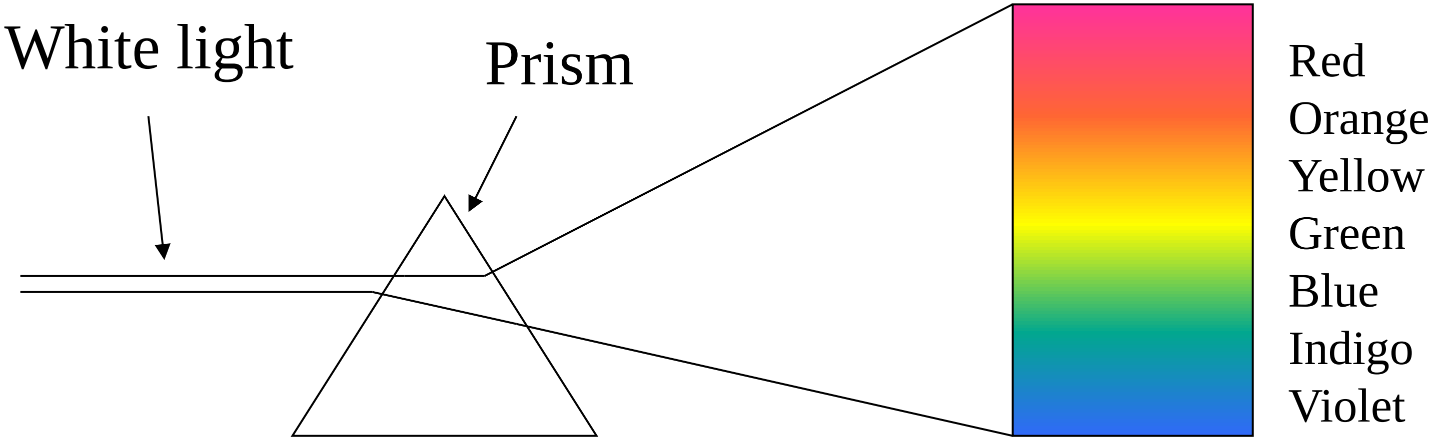
- Almost everything we know about the universe comes from light.
- By understanding the nature of light we can get information about stars, planets and distant galaxies
  - distance
  - size
  - mass
  - motions (direct and rotational)
  - composition

Nature of Light

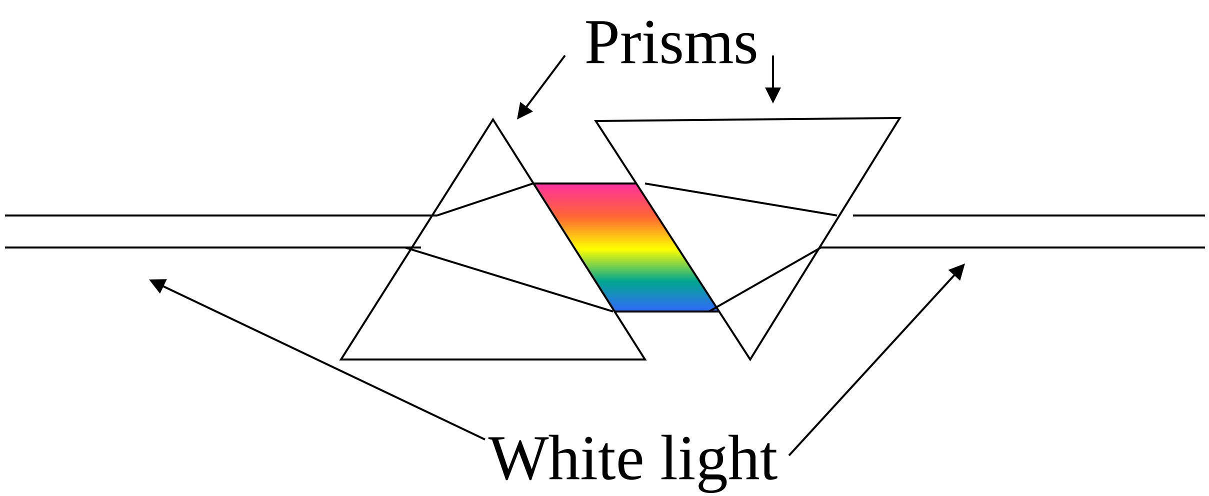
- Light = radiant energy = “radiation”
  - some light we can see (visible light)
  - mostly we cannot (UV, X-rays, radio, etc.)

- Newton was interested in the nature of light
  - Passed light though a prism
  - Light separated into separate colors

Light is made of different colors

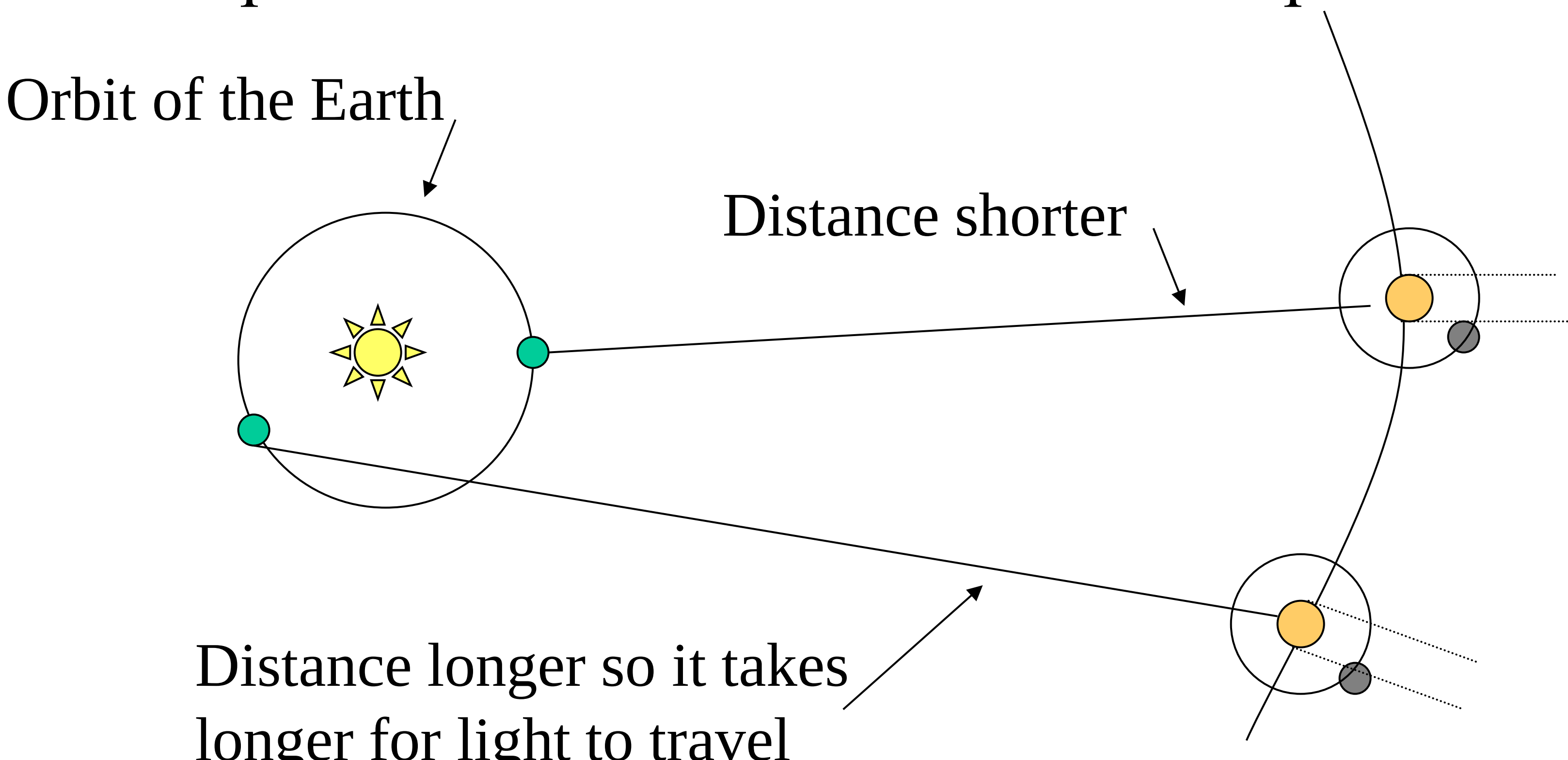


People thought colors came from the glass, but Newton showed that the light itself is made up of many colors.



The Speed of Light

- 1675 -- Ole Roemer
  - Time when Jupiter eclipsed on of its moons did not always agree with that predicted by Kepler’s laws.
  - It depended on the Earth’s distance to Jupiter.



The Speed of Light

- Speed of light, c = 300,000 km/sec (186,000 mi/sec) {precisely known to be 299,792.458 km/s}
  – It takes 8 minutes for light to travel from the Sun to the Earth.

- Light-year = distance light travels in a year
  $= 9.4605 \times 10^{12}$ km

→ All information from outer space is *delayed* …we see everything in the past!

If it takes one hour for light to travel from Saturn to Earth, how far apart are the two planets?

A. 1.0 AU
B. 3.6 AU
C. 7.2 AU
D. 14 AU

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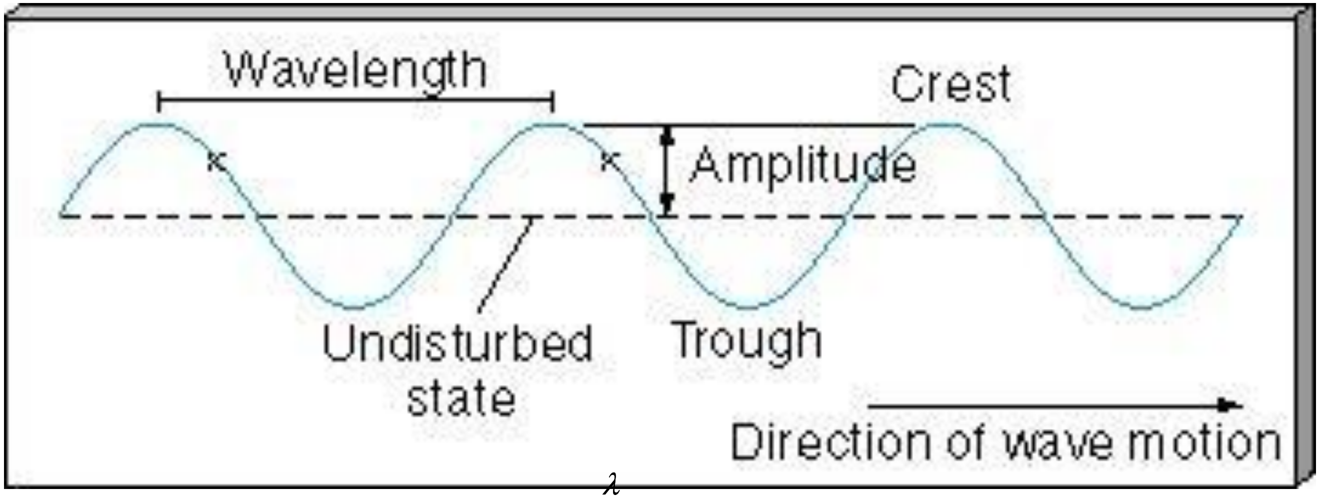
$$d = ct = \left(3.00\times10^{8}\ \text{m/s}\right)\left(3600\ \text{s}\right)$$

$$= 1.08\times10^{12}\ \text{m}\times\frac{1\ \text{AU}}{1.5\times10^{11}\ \text{m}} = \boxed{7.2\ \text{AU}}$$

Light as a Wave

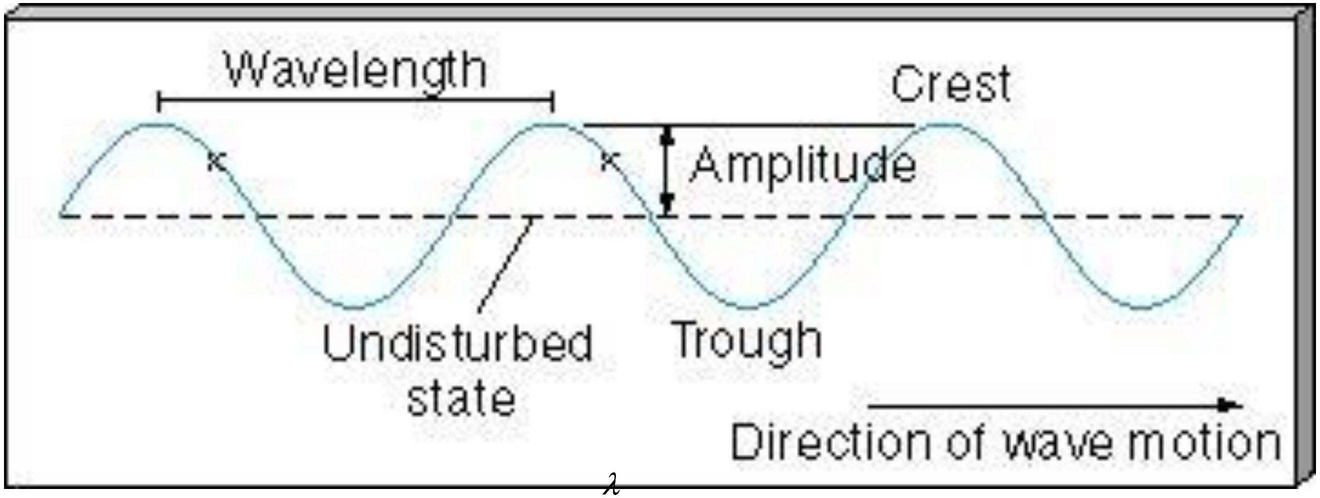


λ

- Wavelength (λ) = distance from peak to peak (measured in meters)
- Frequency (*f*) = number of peaks to pass a certain point (measured in Hertz = #/sec)

[Animation applet]

Light as a Wave

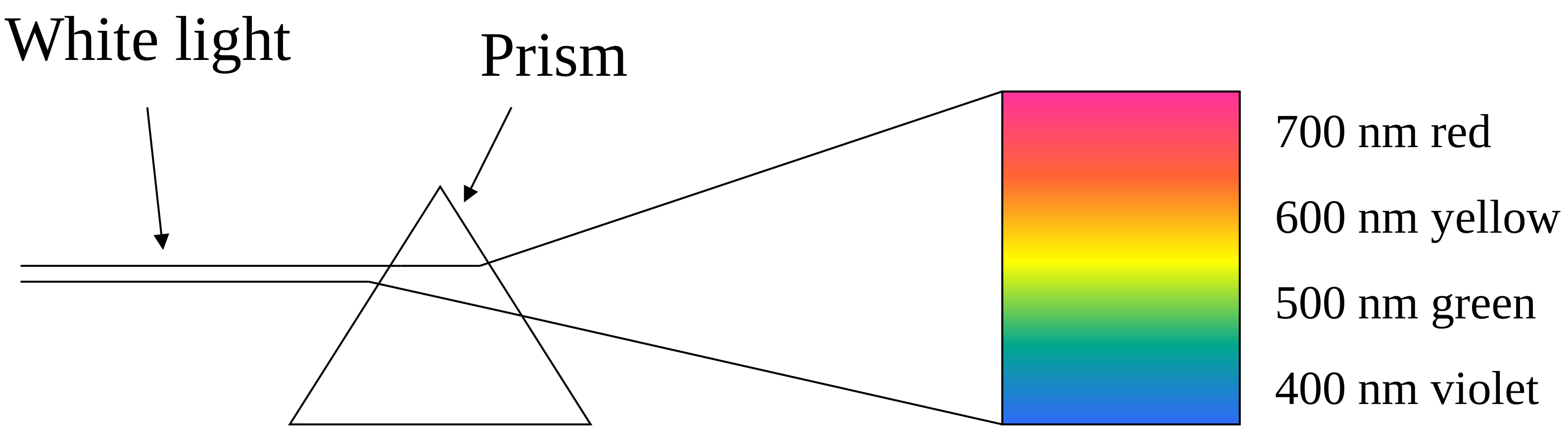


λ

$$c = f\lambda$$

- The greater the frequency, the shorter the wavelength.
- The speed in vacuum always remains the same!

Color is determined by the wavelength of light (λ)



– 1 nanometer (nm) = 1 billionth of a meter

$= 1\times10^{-9}$ m

What is the wavelength of microwaves produced at 2.45 GHz by a microwave oven?

A. 2.45 nm
B. 8.17 μm
C. 12.2 cm
D. 7.35 m

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$$\lambda = \frac{c}{f} = \frac{3.00\times10^{8}\ \text{m/s}}{2.45\times10^{9}\ \text{Hz}}$$

$$= 0.122\ \text{m} = \boxed{12.2\ \text{cm}}$$

Light as a Particle

- Photon = particle of light
- Energy of photon depends on its wavelength

$$\text{Energy} \;=\; h \times \text{frequency} = \frac{hc}{\text{wavelength}}$$

$$E = h\,f \;= \frac{hc}{\lambda} = \frac{1240\ \text{eV} \cdot \text{nm}}{\lambda}$$

– The longer the wavelength, the lower the energy.

– The lower the frequency, the lower the energy

– eV is a unit of energy $1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$

What is the energy of a photon of visible light of wavelength 520 nm?

A. 645 keV
B. 2.38 eV
C. 0.419 eV
D. 520 eV

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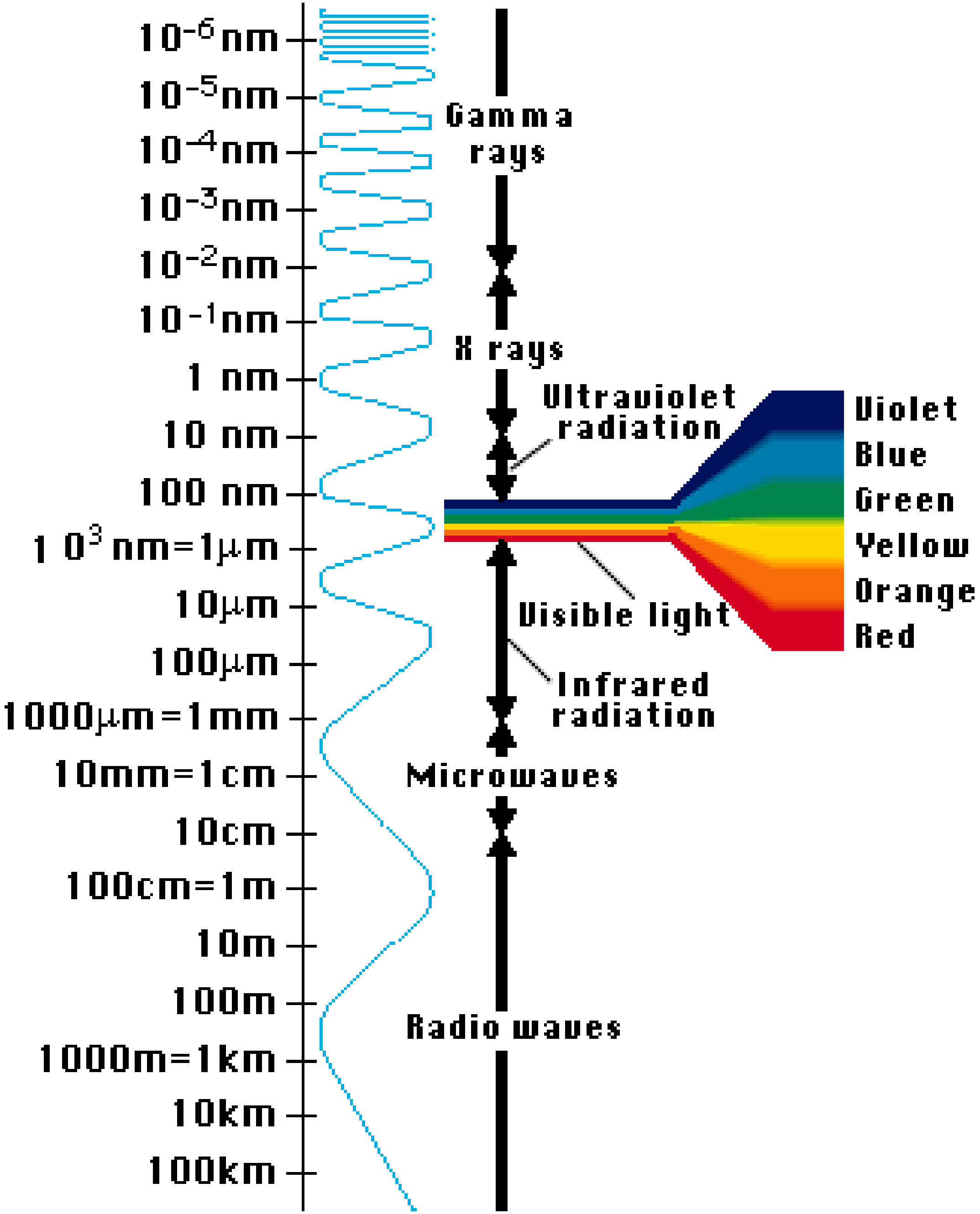
D. 520 eV

$$E = hf = \frac{hc}{\lambda}$$

$$= \frac{1240 \text{ eV} \cdot \text{nm}}{520 \text{ nm}} = \boxed{2.38 \text{ eV}}$$

The Electromagnetic Spectrum

- Light has electric and magnetic properties so all of light is called the *electromagnetic spectrum*.
- The spectrum is divided up by wavelength
- All light, regardless of wavelength, travels at the same speed of light.



Question: What type of light has the

Shortest wavelength?

Longest wavelength?

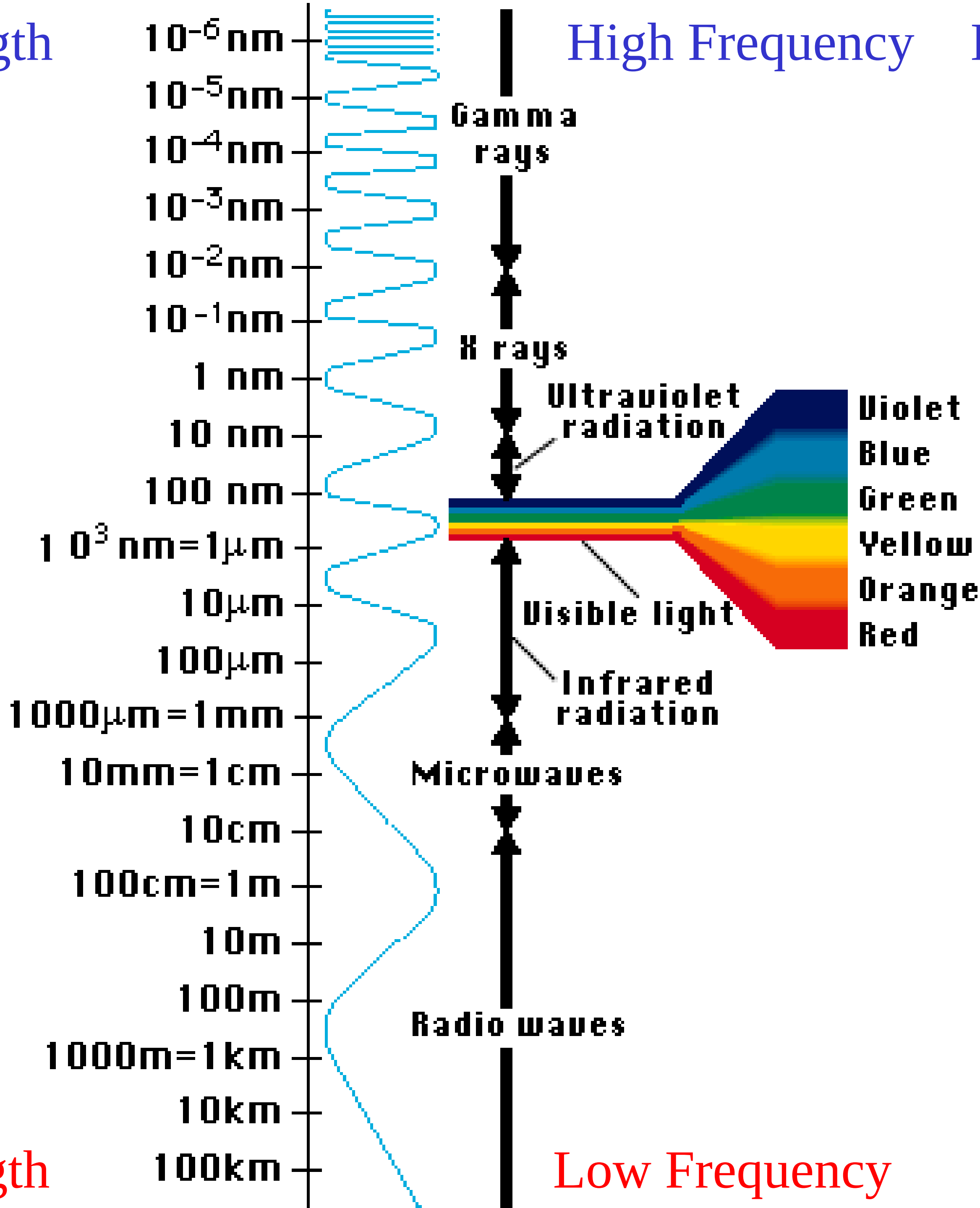
Lowest frequency?

Highest frequency?

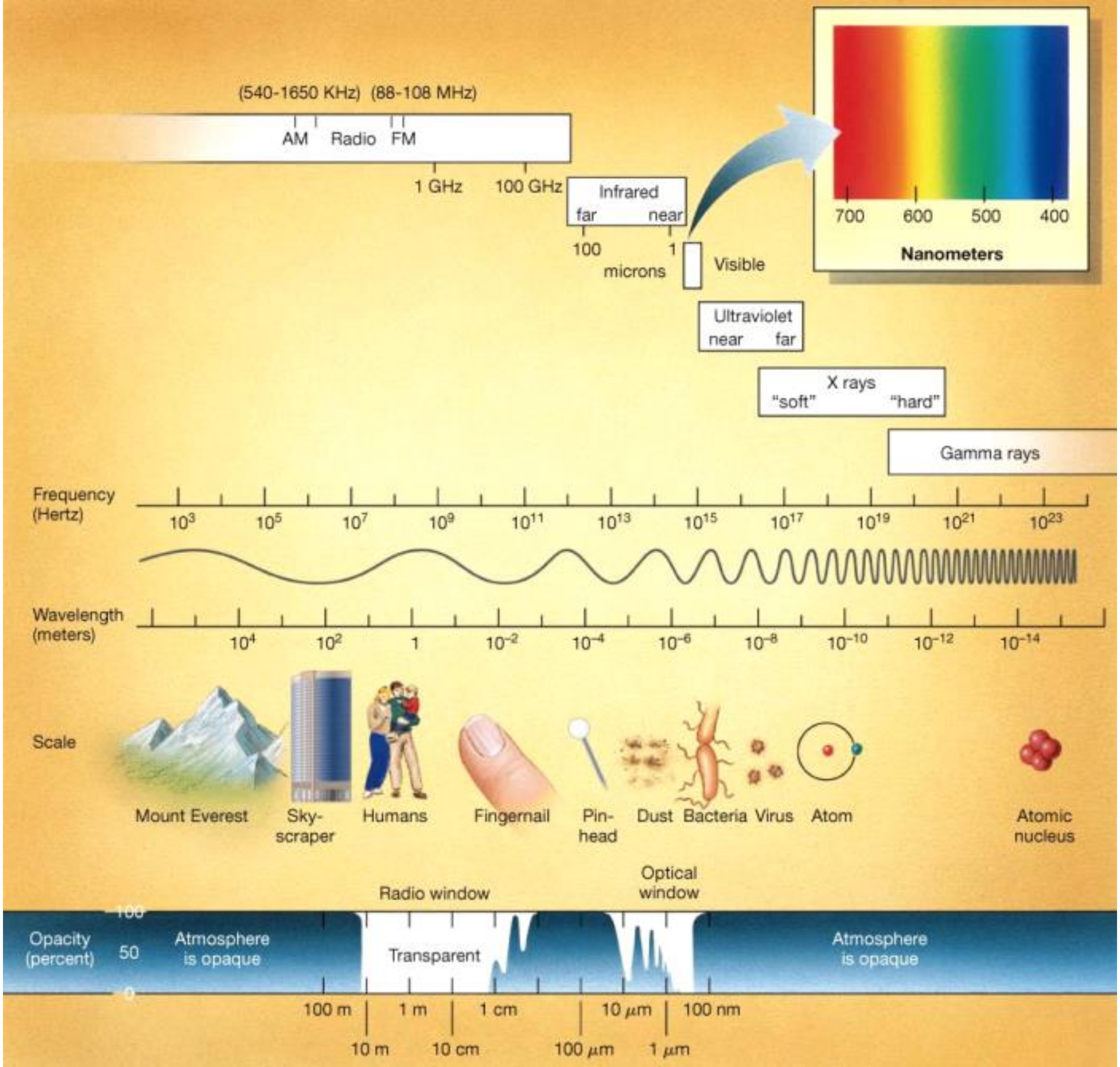
Lowest Energy?

Highest Energy?

Short Wavelength High Frequency High Energy



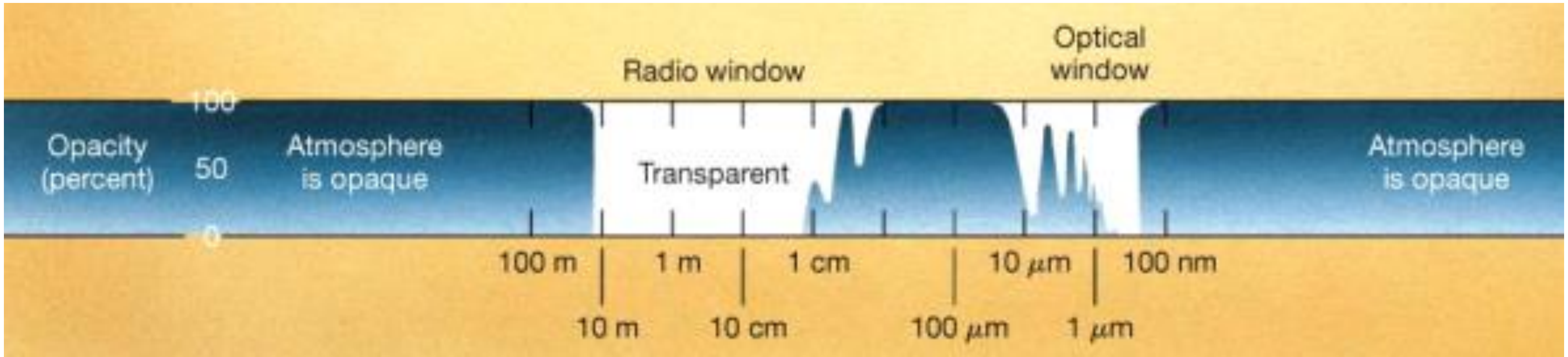
Long Wavelength Low Frequency Low Energy



(540-1650 KHz) (88-108 MHz)
AM Radio FM
1 GHz
100 GHz
Infrared
far near
100 1
microns
Visible
700 600 500 400
Nanometers
Ultraviolet
near far
X rays
"soft" "hard"
Gamma rays
Frequency (Hertz)
10^3 10^5 10^7 10^9 10^11 10^13 10^15 10^17 10^19 10^21 10^23
Wavelength (meters)
10^4 10^2 1 10^-2 10^-4 10^-6 10^-8 10^-10 10^-12 10^-14
Scale
Mount Everest
Sky-scraper
Humans
Fingernail
Pin-head
Dust
Bacteria
Virus
Atom
Atomic nucleus
Radio window
Optical window
Opacity (percent)
100
50
0
Atmosphere is opaque
Transparent
Atmosphere is opaque
100 m
1 m
1 cm
10 μm
100 nm
10 m
10 cm
100 μm
1 μm

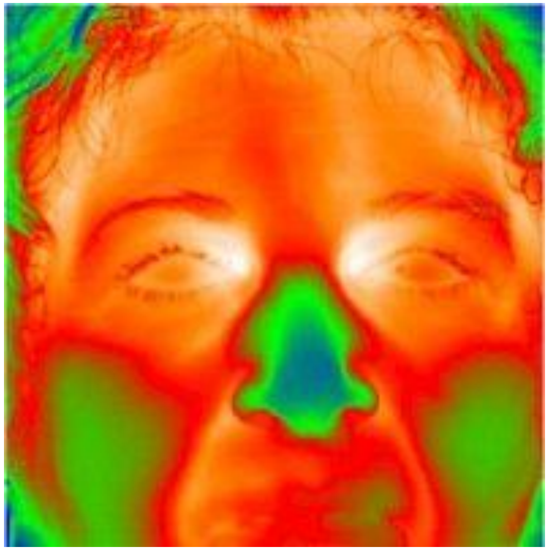
Atmospheric Opacity

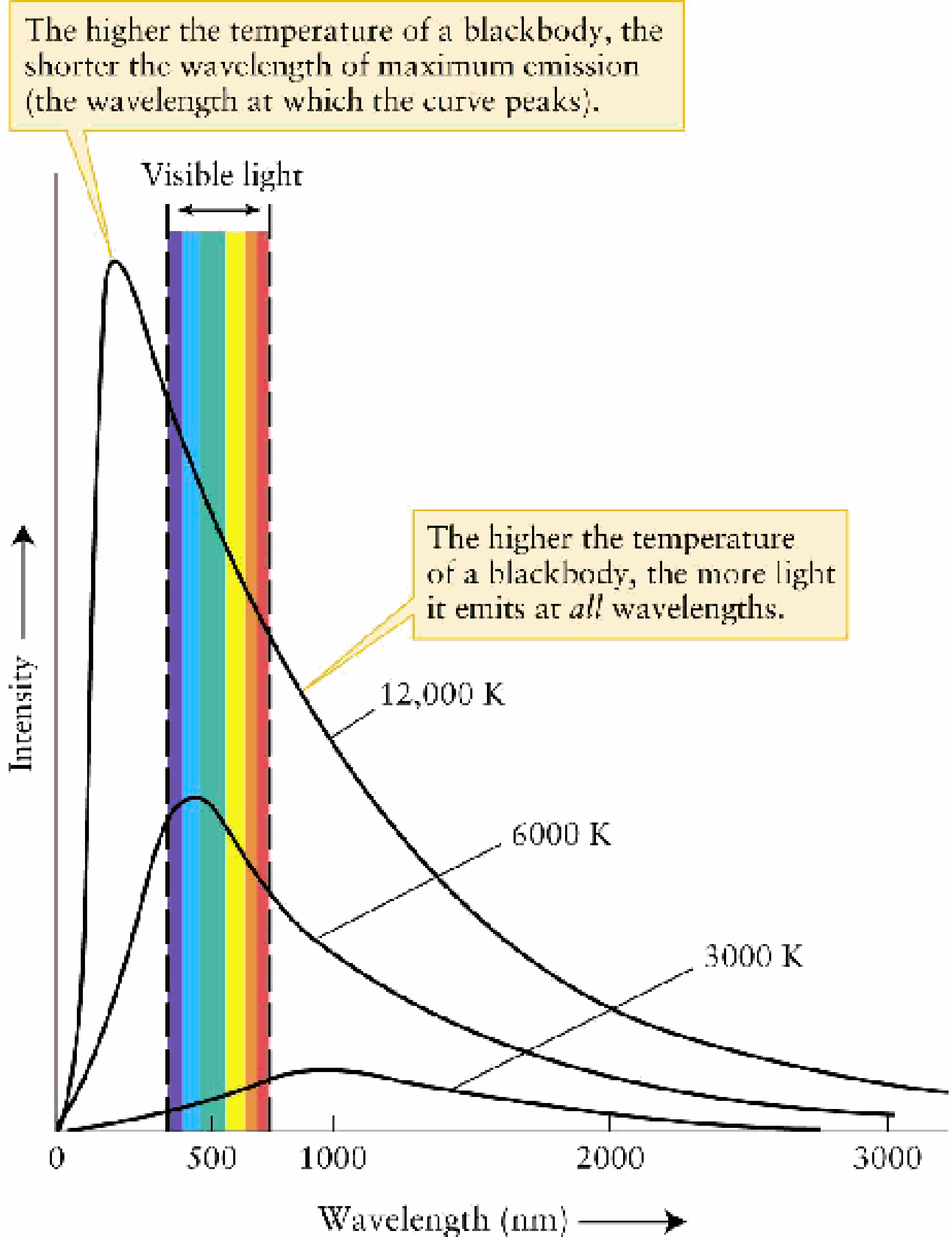
- The atmosphere (and sometimes material in outer space) blocks some wavelengths of light
- Opacity = percentage of light blocked by atmosphere
- Wavelengths where light can get through the atmosphere are called “windows”
  - Low opacity: Visible and Radio:
  - Medium opacity: Infrared and UV
  - High opacity: Gamma Rays, X-rays & some UV

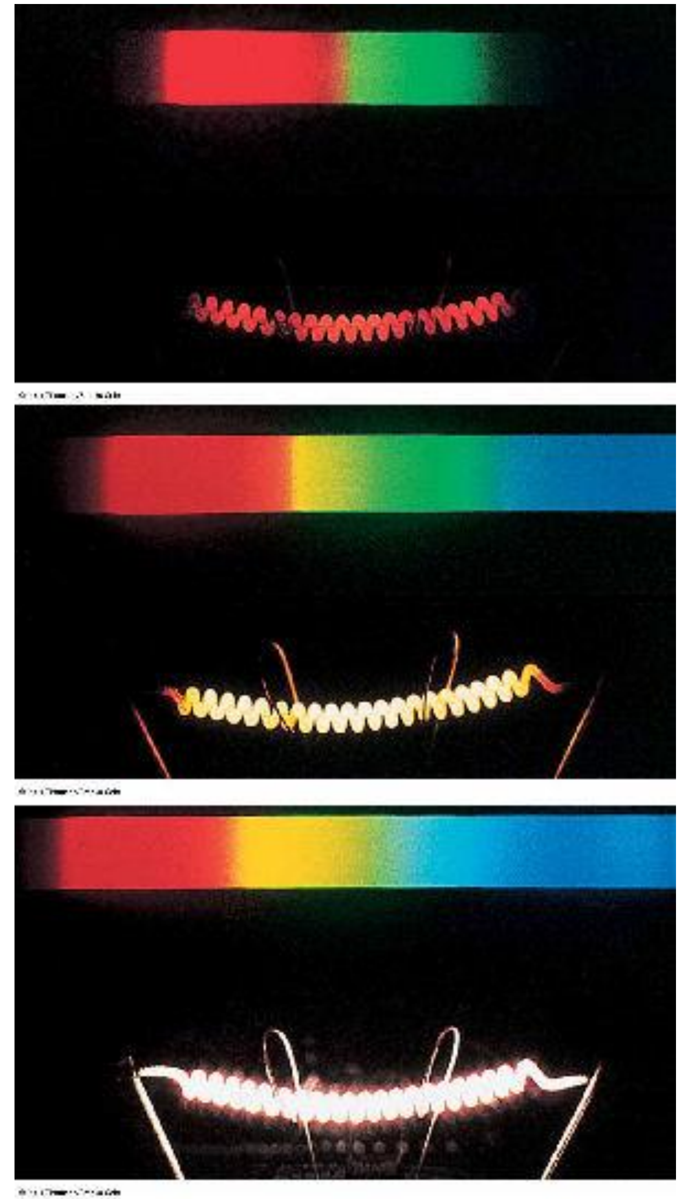


Blackbody Radiation

- Light emitted by a solid, liquid or dense gas
- Light is emitted at all wavelengths
- Amount of light depends on temperature




The higher the temperature of a blackbody, the shorter the wavelength of maximum emission (the wavelength at which the curve peaks).
Visible light
The higher the temperature of a blackbody, the more light it emits at *all* wavelengths.
12,000 K
6000 K
3000 K
Intensity
0
500
1000
2000
3000
Wavelength (nm)



Wien's Law

- The wavelength at which the brightness peaks is inversely proportional to the temperature

$$\lambda_{\text{peak}} = \frac{2.9\times10^{6}}{T} \quad or \quad T = \frac{2.9\times10^{6}}{\lambda_{\text{peak}}}$$

Where T is in Kelvins

λ_{peak} is in nanometers (10^{-9} meters)

  - high temperatures peak at short wavelengths
  - Does not depend on size of object, only temperature

An oven burner is at 1341°F (1000 K). At what wavelength does it emit the most radiation?

A. 2900 nm
B. 345 nm
C. 1341 nm
D. 2160 nm

An oven burner is at 1341°F (1000 K). At what wavelength does it emit the most radiation?

A. **2900 nm**
B. 345 nm
C. 1341 nm
D. 2160 nm

$$\lambda_{\max} = \frac{2.9\times10^{6}\ \text{nm}\cdot\text{K}}{1000\ \text{K}} = \boxed{2900\ \text{nm}}$$

Stefan-Boltzmann Law

- Blackbody spectrum applet
- The energy radiated per area per second from an object (the Flux) increases rapidly with temperature.

$$\text{Flux}\,(F) = \sigma T^4$$

F = Flux (Watts/m^2)
σ = 5.67 $\times 10^{-8}$ W·m^{-2}·K^{-4}
T = Temperature (K)

- As the Kelvin temperature increases, the flux increases.

How much more flux is emitted by a star with an 8000 K surface temperature than one with a 6000 K surface temperature?

A. 1.33×

B. 1.07×

C. 5.33×

D. 3.16×

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A. 1.33×

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$$\frac{F_B}{F_A} = \frac{\sigma T_B^4}{\sigma T_A^4} = \frac{\left(8000\,\text{K}\right)^4}{\left(6000\,\text{K}\right)^4} = \boxed{3.16}$$

Luminosity

$$\text{Luminosity} = \text{Flux} \times \text{surface area}$$

$$L = \sigma T^4 \times 4\pi r^2$$

- The total energy emitted per second (luminosity) depends on the temperature T AND size r of the object
- For the same temperature, a bigger star emits a larger total amount of energy

Questions

- Star A is brightest at radio wavelengths.
- Star B is brightest in X-rays

- Which star has the higher temperature?
  A. Star A B. Star B C. Can't say
- Which star is emitting the most light per area?
  A. Star A B. Star B C. Can't say
- Which star has the highest luminosity?
  A. Star A B. Star B C. Can't say

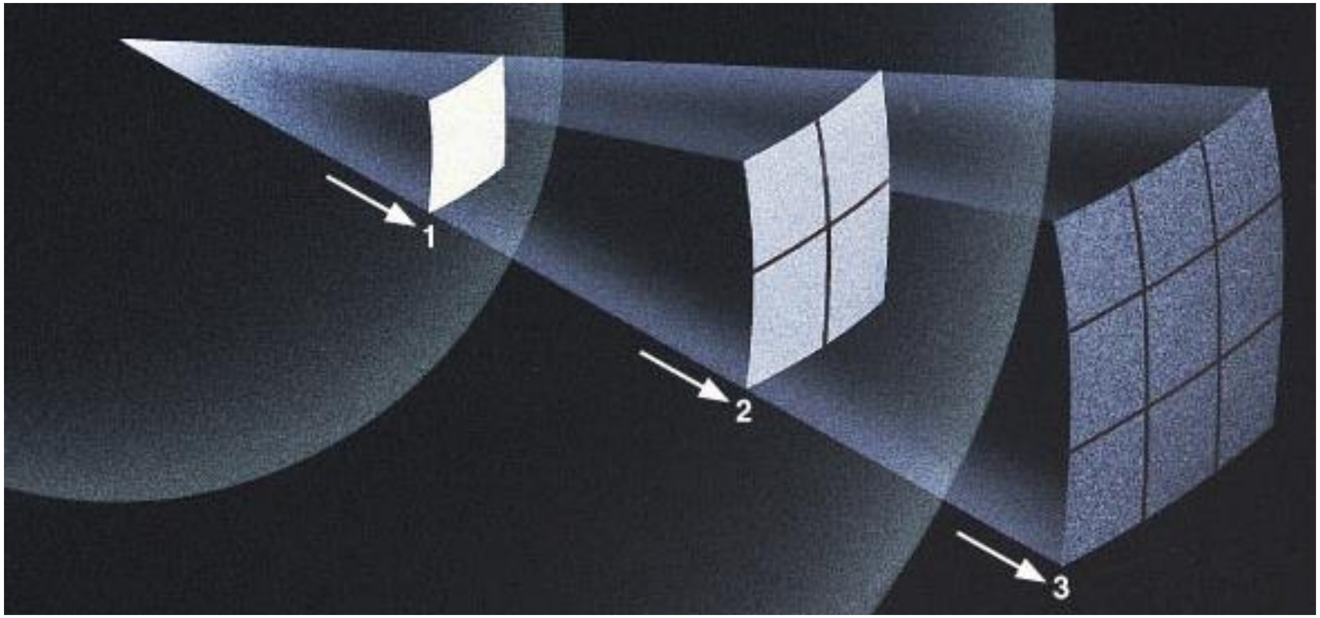
Questions

- Star B has the higher temperature because the higher the temperature, the bluer the color emitted.
- Star B is emitting the most light per area. The Stefan-Boltzman law says the Watts/m^2 emitted is proportional to the temperature to the fourth power.
- We can't tell which star (A or B) is emitting the most energy in general because that depends on both size and temperature, and we only know the relative temperatures of stars A and B.

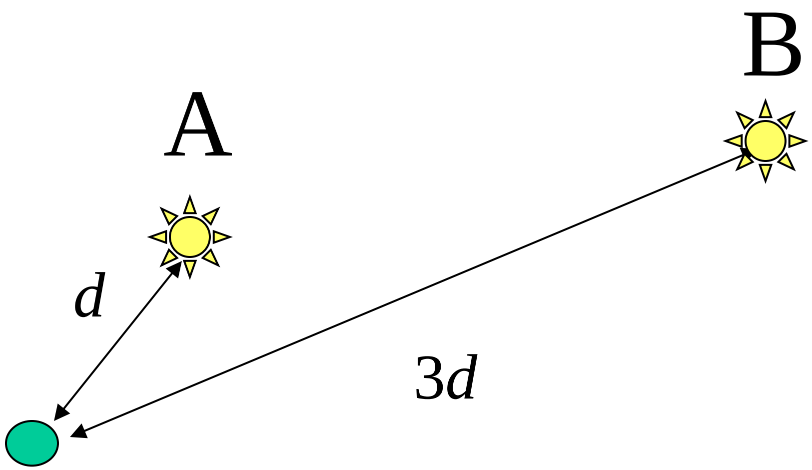
Apparent Brightness

- The brightness an object appears to have.
- The further away the object, the dimmer it looks

$$\text{Apparent Brightness} = \frac{\text{Luminosity}}{4\pi d^2} \qquad d = \text{distance}$$



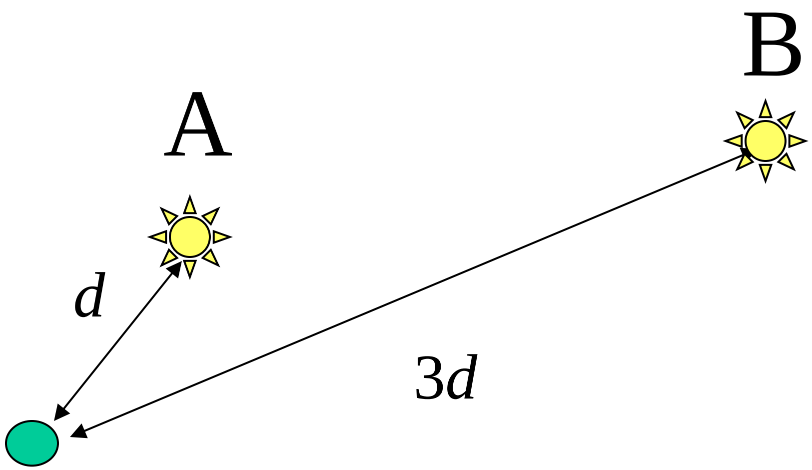
Question



How much brighter or dimmer does Star A appear compared to Star B if both have the same luminosity?

A. Star A is 9 times dimmer than Star B
B. Star A is 3 times dimmer than Star B
C. Star A is 3 times brighter than Star B
D. Star A is 9 times brighter than Star B

Question



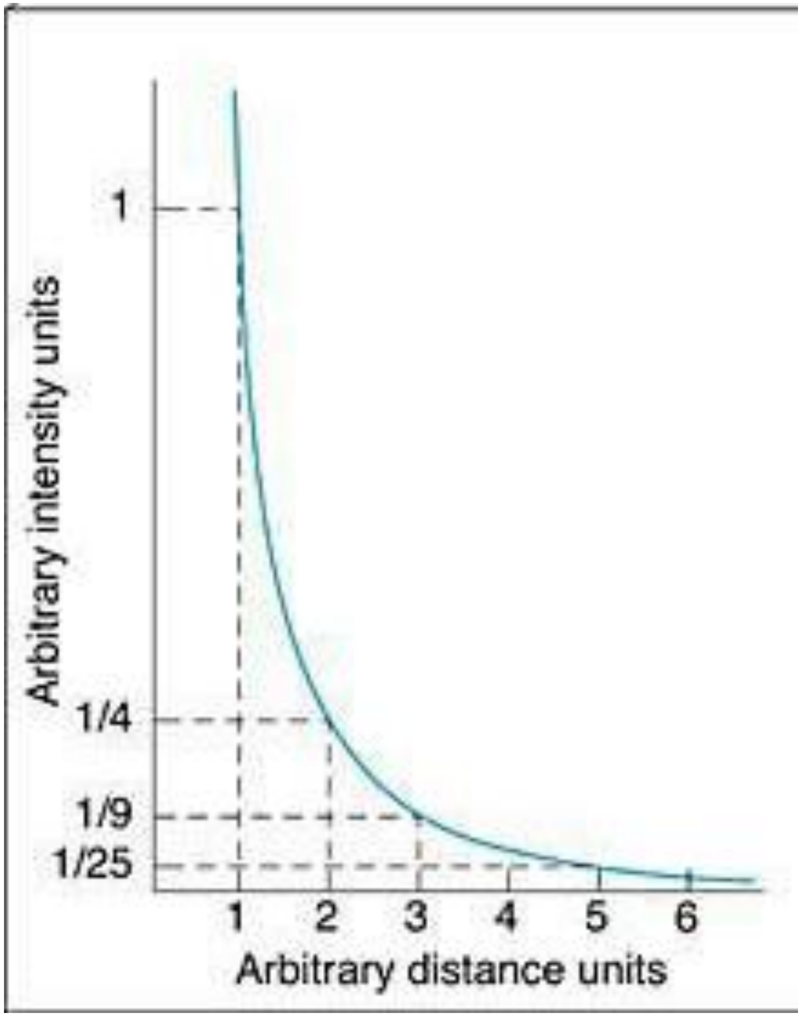
How much brighter or dimmer does Star A appear compared to Star B if both have the same luminosity?

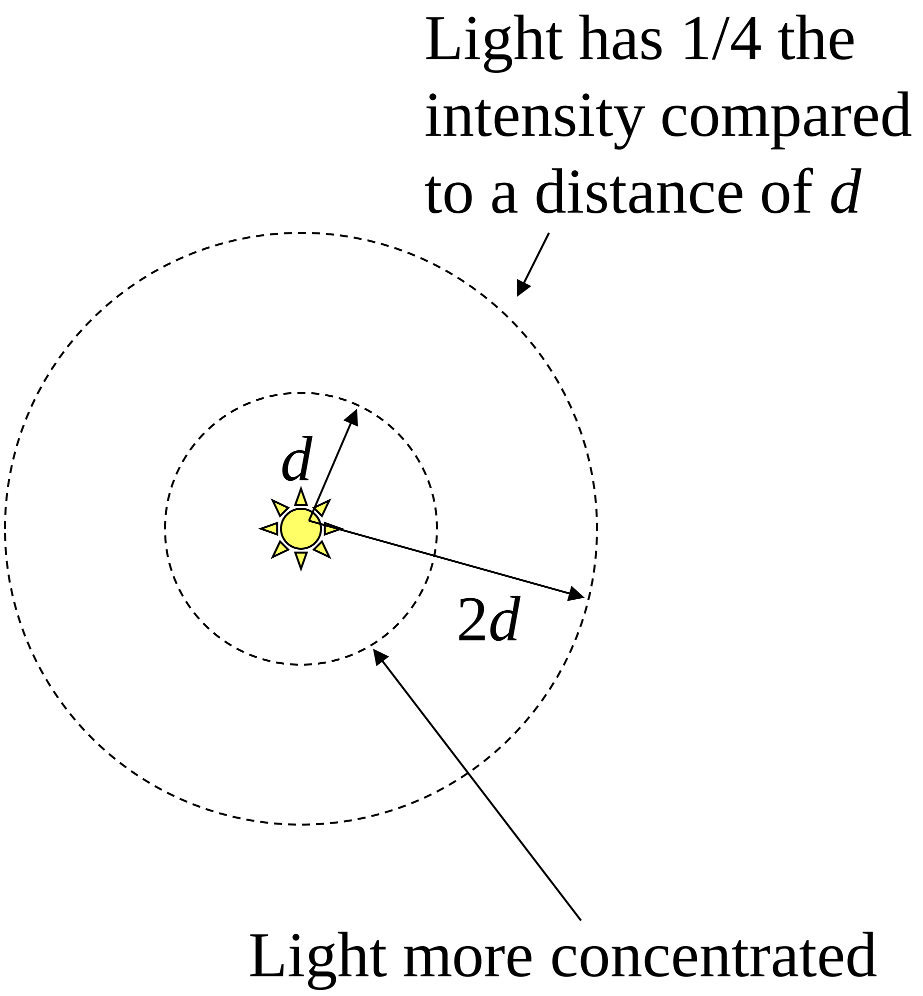
$$B_A = \frac{I}{4\pi d^2}$$

$$B_B = \frac{I}{4\pi (3d)^2} = \frac{I}{4\pi (9d^2)} = \frac{1}{9} B_A$$

Star A appears 9 times brighter than star B.

Inverse Square Law





Determining Distance

- Measure apparent brightness
- Measure intrinsic brightness (luminosity)
  - Need temperature
  - Need size of object

$$L = 4\pi R^2 \times \sigma T^4$$

- Compare intrinsic brightness to apparent brightness to determine distance.
- Problem: the size of objects is rarely known and is hard to measure.