

Lecture 3

The Nature of Light I

Jiong Qiu SU Physics Department Wenda Cao

NJIT Physics Departmen

Courtesy: Prof. Jiong Qiu

9/22/15

Outline

- How fast does light travel? How can this speed be measured?
- How is the light from an ordinary light bulb different from the light emitted by a neon sign?
- How can astronomers measure the temperatures of the Sun and stars?
- How can astronomers tell what distant celestial objects are made of?
- How can we tell if a celestial object is approaching us or receding from us?

New Jersey's Science & Technology University

THE EDGE IN K<u>NOW</u>

Light travels with a very high speed

New Jersey's Science & Technology University

- Galileo first tried but failed to measure the speed of light. He concluded that the speed of light is very high.
- In 1675, Roemer first proved that light does not travel instantaneously from his observations of the eclipses of Jupiter's moons.
- Modern technologies are able to find the speed of light; <u>in an empty space</u>:

one of the most important numbers in modern physical sciences!



THE EDGE IN KNOWLEDG

- Ex.1: The distance between the Sun and the Earth is 1AU (= 1.5x10¹¹m).
 (a) how long does it take the light to travel from the Sun to an observer on the Earth? (b) A concord airplane has a speed of 600 m/s; how long does it take a traveler on a Concord airplane to travel from the Earth to the Sun?
- Ex.2: A lunar laser ranging retro-reflector array was planted on the Moon on July 21, 1969, by the crew of the Apollo 11. Since then, the

distance between the Earth and the Moon has been measured many times.

With our knowledge, nothing travels faster than light !

Physics

at



New Jersey's Science & Technology University

THE EDGE IN KNOWLEDGE

Light is Colorful

□ Newton found that when sunlight passes through a glass prism, it spreads into the colors of a rainbow. This is a **spectrum**.



□ Sunlight is a mixture of all the colors of a rainbow.



Light Exists in Waves

- Light exists in the form of waves
- □ Light in the form of waves travel through the space with light speed
- Think about water ripples



<u>Wavelength (λ)</u>: distance from one peak to the next peak

Frequency(v): how many wavelengths passes a point within 1 second.

Q: sound is also a train of waves. What's the sound speed? What does its frequency determine?



New Jersey's Science & Technology University

THE EDGE IN KNOWLEDGE

Light is Electromagnetic Radiation

- Light is electromagnetic radiation existing in the form of waves.
- Electric field and magnetic field travel through the space.
- Electric field and magnetic field are always perpendicular.
- EM is transverse wave.



Wavelength and Frequency

Light is characterized by its wavelength or frequency, which determine the color of the light.

Frequency and wavelength of an electromagnetic wave

$$v = \frac{c}{\lambda}$$

- v = frequency of an electromagnetic wave (in Hz)
- c = speed of light = 3×10^8 m/s
- λ = wavelength of the wave (in meters)

 $[1m = 10^9 \text{ nm} = 10^{10} \overset{\circ}{\text{A}} (\text{Angstroms})]$



THE EDGE IN KNOW

Ex.3: The wavelength of yellow light is 550 nm, or a half of a millionth of a meter, and its frequency is 500 trillion Hz. In comparison, the audible frequency range of sound waves is 20 - 20,000 Hz.

Frequency and wavelength of an electromagnetic wave

$$V = \frac{C}{\lambda}$$

- v = frequency of an electromagnetic wave (in Hz)
- c = speed of light = 3×10^8 m/s
- λ = wavelength of the wave (in meters)

 $[1m = 10^9 \text{ nm} = 10^{10} \overset{\circ}{\text{A}} (\text{Angstroms})]$

Electromagnetic Spectrum

← Increasing energy				Region	Wavelength
				Gamma Ray	λ < 0.01 nm
Increasing wavelength				X-ray	$1 \text{ nm} < \lambda < 10 \text{ nm}$
Gamma rays	X-rays	Ultra- Infrared	Radio waves	Ultraviolet	$10 \text{ nm} < \lambda < 400 \text{ nm}$
			Radar TV FM AM	Visible	$400 \text{ nm} < \lambda < 700 \text{ nm}$
Visible light				Infrared	700 nm < λ < 1 mm
400 nm 500 nm 600 nm 700 nm				Microwave	$1 \text{ mm} < \lambda < 10 \text{ cm}$
				Radio	10 cm < λ

Q: An electric spark, such as lightening, generates electromagnetic radiation over a wide range of wavelengths. How much longer does a pulse of radio energy take to travel between two detectors 100m apart than a pulse of ultraviolet radiation from the same spark?

New Jersey's Science & Technology University

THE EDGE IN



THE EDGE IN KNOWLEDG

10" cm

Gamma

High Frequency

High Energy

ShorfWavelength

10° cm

X-Rav



Colorful Stars

Q: why Sunlight is whiteyellowish, and stars appear red/yellow/blue?

THE EDGE IN KNOWLEDG

Blackbody and EM

- Any object with a temperature above absolute zero emits light of all wavelengths with varying degrees of efficiency.
- Blackbody is an ideal object that absorb all of the light energy incident upon it and reradiates this energy in a special way.
- Blackbody (NOT black) emits EM radiation according to its temperature.
- Planck function describes radiation from a blackbody.
- Stars and planets are blackbodies, at least to a rough first approximation.





THE EDGE IN KNOWLE

Planck Function

- Planck function describes radiation from a blackbody
- Intensity is a function of wavelength
- Intensity is a function of temperature

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \quad (J \text{ s}^{-1} \text{ m}^{-2} \text{ A}^{-1} \text{ sr}^{-1})$$

- B_{λ} : specific intensity, energy per unit time per unit surface area per unit solid angle per unit wavelength.
 λ: wavelength
- *T* : temperature (in K degree)
- $k := 1.6 \times 10^{-23}$ J/K, Boltzmann constant
- $c := 3 \times 10^8$ m/s, speed of light in vacuum,
- $h: = 6.625 \times 10^{-34} \text{ J s}$, Planck's constant

New Jersey's Science & Technology University

THE EDGE IN KNOWL

Blackbody Radiation



- An object, like the Sun, does not emit equal amount of radiation at all wavelengths.
- At a higher temperature, an object emits more intensely.
- At a higher temperature, an object emits most strongly at the shorter wavelength.
 - Ex.4: The brightest star, Sirius A, is a blue star and has a higher temperature than the Sun.

THE EDGE IN KNOWLEDG

Temperature scales: three temperature scales are in common use: **Celsius (°C), Kelvin (K), Fahrenheit (°F).** In Kelvin scale, nothing can be colder than 0 K.

You can convert one temperature scale to another by:

Celsius
$$\leftarrow \rightarrow$$
 Kelvin: $T_K = T_C + 273, \ T_C = T_K - 273$
Celsius $\leftarrow \rightarrow$ Fahrenheit $T_F = \frac{9}{5}T_C + 32, \ T_C = \frac{5}{9}(T_F - 32)$

Ex.5: temperature at the freezing point: $T = 0^{\circ} C = 273 \text{ K} = 32^{\circ} \text{ F}$ temperature at the boiling point: $T = 100^{\circ} C = 373 \text{ K} = 212^{\circ} \text{ F}$ room temperature: $T = 20^{\circ} C = 203 \text{ K} = 68^{\circ} \text{ F}$

 $T = 20^{\circ} C = 293 K = 68^{\circ} F$



THE EDGE IN KNOW

- Q: An example of an object that emits no radiation at all is:
- a. A very dark object
- b. A transparent object
- c. An object made of ice
- d. An object at the temperature of 0 K

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \quad (J \text{ s}^{-1} \text{ m}^{-2} \text{ A}^{-1} \text{ sr}^{-1})$$

 B_{λ} : specific intensity, energy per unit time per unit surface area per unit solid angle per unit wavelength.

- λ : wavelength
- *T* : temperature (in K degree)
- $k := 1.6 \times 10^{-23}$ J/K, Boltzmann constant
- $c: = 3 \times 10^8$ m/s, speed of light in vacuum,
- $h: = 6.625 \times 10^{-34} \text{ J s}, \text{ Planck's constant}$



THE EDGE IN KNOWLEDG

Wien's Displacement Law



□ Wien's Displacement law tells how to find the temperature of a star if we know the wavelength of its maximum emission.





Colorful Stars

Q: Betelgeuse has a surface temperature of 3600 K. If we treat it as a blackbody, Wien's displacement law shows that its continuous spectrum peaks at a wavelength of

Rigel, with a surface temperature of 13,000K, has a continuous spectrum that peaks at a wavelength of

THE EDGE IN KNOW

Q: Astronauts in the space see Earth as a blue planet. Does it mean that Earth's temperature is higher than the Sun's? Or is Earth's ocean hotter than deserts?



Q: Instead, how will you sketch the blackbody radiation curve by the Earth, eg., compared with the Sun?

at

New Jersey's Science & Technology University

THE EDGE IN KNOWL

Stefan-Boltzmann Law

Stefan-Boltzmann law states that a blackbody radiates electromagnetic waves with a total energy flux *F* at the surface of the star directly proportional to the fourth power of the Kelvin temperature *T* of the object:

$$F_{surface} = \sigma T^4 (J m^{-2} s^{-1})$$

F = energy flux, in joules <u>per square meter of surface per second</u> σ = a constant (Stefan-Boltzmann constant) = 5.67 x 10⁻⁸ W m⁻² K⁻⁴ T = object's temperature, in Kelvin



Luminosity of a Star

- □ Stefan-Boltzmann law states that a blackbody radiates electromagnetic waves with a total energy flux *F* at the surface of the star directly proportional to the fourth power of the Kelvin temperature *T* of the object: $F_{surface} = \sigma T^4 (J m^{-2} s^{-1})$
- □ **Intrinsic luminosity** of a star -- its total radiation energy -- is given by $L = 4\pi R^2 \sigma T^4$ (J S⁻¹), where *R* is the radius of the star.
- Radiant flux (Apparent Brightness) of the star drops off quickly with the distance r at which it is observed:

$$F_{obs} = \frac{L}{4\pi r^2} = \frac{\sigma T^4 R^2}{r^2} \ (\text{Jm}^{-2} \text{s}^{-1})$$

 The Sun in SXR by Yohkoh

 New Jersey's Science & Technology University
 THE EDGE IN KNOWLEDGE

Ex: The luminosity of the Sun is $L\odot=3.839\times10^{26}$ W and its radius is $R\odot=6.95508\times10^{8}$ m. Estimate the temperature of the Sun's surface

$$T_{S} = \left(\frac{L_{S}}{4\pi R_{S}^{2}\sigma}\right)^{\frac{1}{4}} = 5777K$$

Ex: Calculate the radiant flux at the solar surface

$$F_{Surf} = \sigma T^4 = 6.316 \times 10^7 Wm^{-2}$$



Ex: At a distance of 1AU = 1.496×10^{11} m, calculate the radiant flux above Earth's absorbing atmosphere

$$F_{obs} = \frac{L_s}{4\pi r^2} = 1365 W m^{-2}$$
 $\lambda_{max} T \approx (500 \text{ nm})(5800 \text{ K})$

Ex: According to Wien's displacement law, the Sun's continuous spectrum peaks at a wavelength of

$$\lambda_{\rm max} = \frac{0.0029 \,{\rm m \, K}}{5777 \,{\rm K}} = 501.6 \,{\rm nm}$$

Key Words

- absorption line
- Balmer series
- blackbody radiation
- blueshift
- chemical composition
- Doppler effect
- electromagnetic radiation
- emission line
- frequency
- gamma rays
- infrared radiation
- microwaves

- photon
- radio waves
- redshift
- solar constant
- spectral line
- spectrocopy
- Stefan-Boltzmann law

THE EDGE IN KNOWL

- ultraviolet radiation
- visible light
- wavelength
- Wien's law
- X-rays

Summary

- □ Light is electromagnetic radiation. The speed of light in the empty space is a constant, $c = 3.0 \times 10^5$ km/s. Light has wavelike properties and can be described by wavelength and frequency: $c = \lambda v$
- The Sun, stars, and other objects emits EM radiation according to their temperatures. Wien's law and the Stefan-Boltzmann law describe the peak wavelength and the total radiation power emitted by an object with a certain temperature.
- Emission or absorption spectral lines can be produced according to the chemical composition of the radiating object or the gas (e.g. atmosphere) the radiated light passes through.
- Spectral lines are produced when an electron jumps from one energy level (one orbit) to another within an atom.
- The Doppler shifts of spectral lines enable us to determine the motion of a light source along the line-of-sight.

New Jersey's Science & Technology University

9/22/15

THE EDGE IN KNO