

PHYS 320

Lecture 4

The Nature of Light II

Jiong Qiu

MSU Physics Department

Wenda Cao

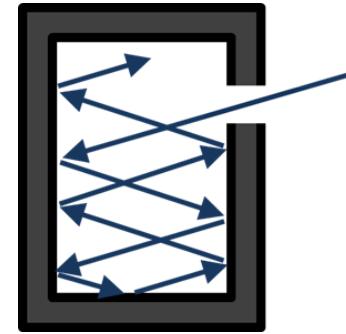
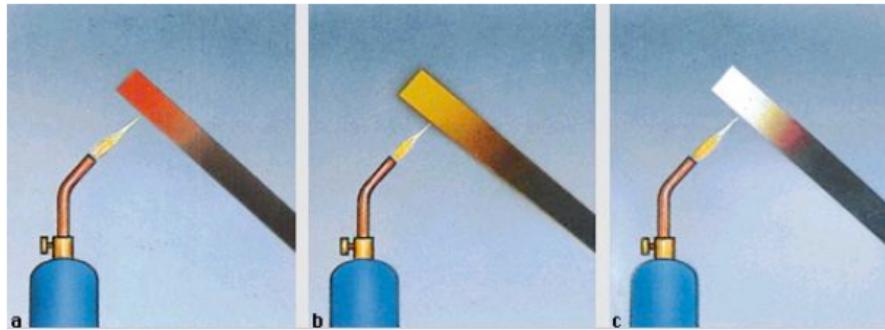
NJIT Physics Department

Outline

- How fast does light travel? How can this speed be measured?
- How can astronomers measure the temperatures of the Sun and stars?
- How is the light from an ordinary light bulb different from the light emitted by a neon sign?
- 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?

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.



Planck Function

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

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

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)

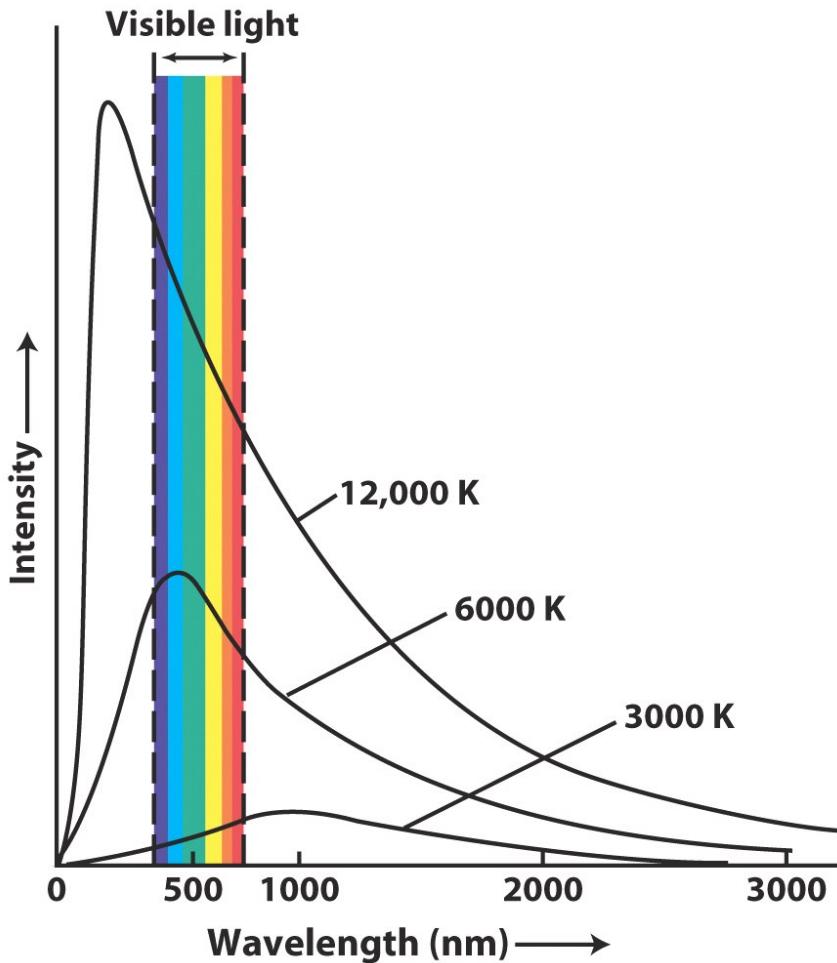
k : $= 1.6 \times 10^{-23}$ J/K, Boltzmann constant

c : $= 3 \times 10^8$ m/s, speed of light in vacuum,

h : $= 6.625 \times 10^{-34}$ J s, Planck's constant



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.



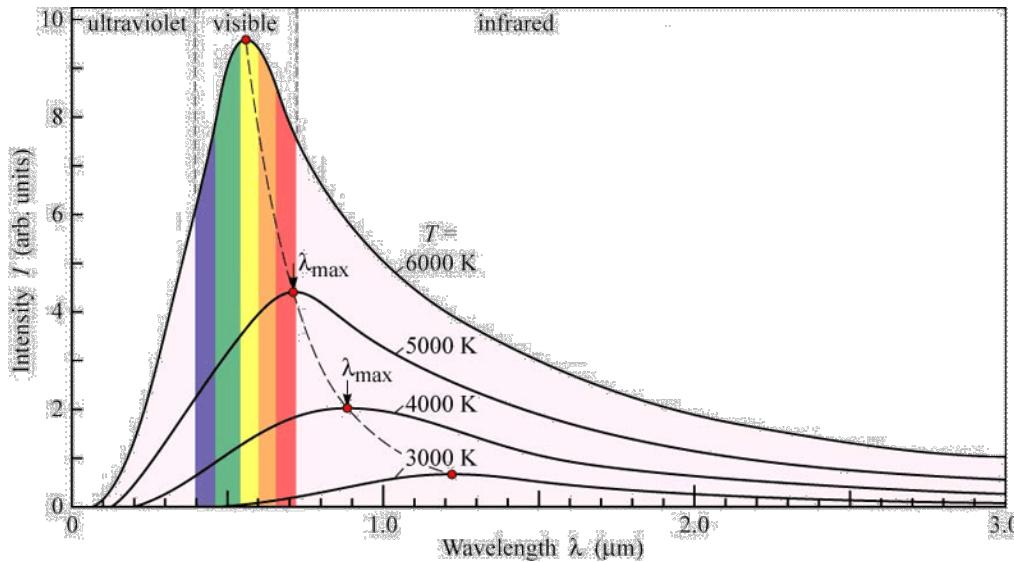
Wien's Displacement Law

$$\lambda_{\max} = \frac{0.0029 \text{ K m}}{T}$$

λ_{\max} : wavelength of maximum emission of the object (in meters)

T : temperature of the object (in kelvins)

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



Ex.5: The maximum intensity of sunlight is at roughly 500 nm. What's the surface temperature of the Sun?

$$T = \frac{0.0029 \text{ K m}}{\lambda_{\max}}$$
$$= \frac{0.0029 \text{ K m}}{5.0 \times 10^{-7} \text{ m}} = 5800 \text{ K}$$



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:

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

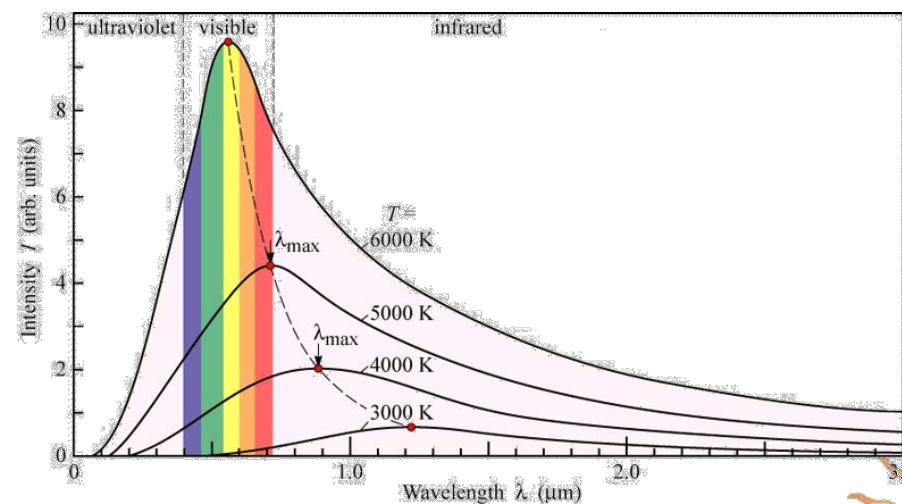
F = energy flux, in joules per square meter of surface per second

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

T = object's temperature, in Kelvin

Ex: Calculate the radiant flux at the solar surface?

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





What do stars' color tell us?

Q: If we treat Betelgeuse and Rigel as blackbodies,

- Which one has higher surface temperature?
- Which one has greater radiant flux?

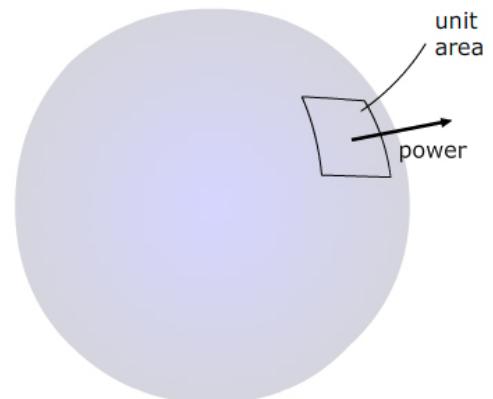


Luminosity of a Star

- **Luminosity** is the total amount of energy radiated into space each second from a star's surface.
- It is the rate of energy emission - not just the energy of visible light, but also the energy of any type of EM radiation, from radio waves to gamma-rays.
- It does not depend on the location or motion of the observer.
- **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.

Ex: The Sun's radius is $R_\odot=6.955\times10^8 \text{ m}$ and its radiant flux is $F = 6.316\times10^7 \text{ W m}^{-2}$, calculate the Sun's luminosity?

$$L = 4\pi R^2 \sigma T^4 = 3.837 \times 10^{26} \text{ W}$$

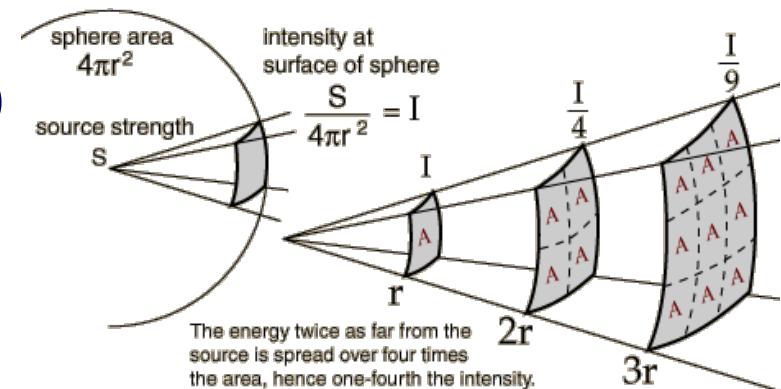


Brightness of a Star

- The **brightness** of a star is measured in terms of the **radiant flux** received from the star by observers.
- The radiant flux is the total amount of light energy of all wavelength that crosses a unit area oriented perpendicular to the direction of the light's travel per unit time.
- It is the number of joules of starlight energy per second received by one square meter of a detector aimed at the star.
- The **brightness** of a star depends on both its intrinsic luminosity and its distance from the observer.

- **Radiant flux (Apparent Brightness)** of the star drops off quickly with the distance r at which it is observed:

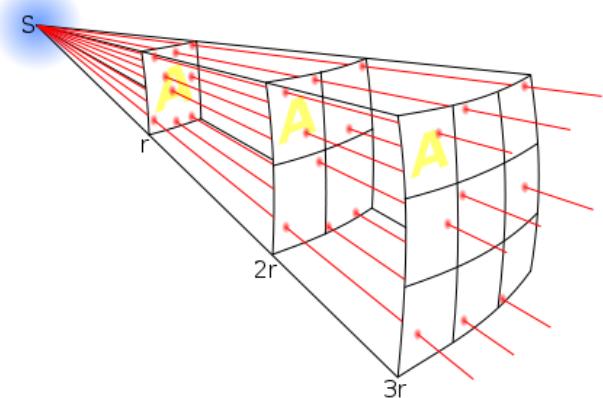
$$F_{obs} = \frac{L}{4\pi r^2} = \frac{\sigma T^4 R^2}{r^2} \text{ (Jm}^{-2}\text{s}^{-1})$$



Brightness of the Sun

- **Radiant flux (Apparent Brightness)** of the star drops off quickly with the distance r at which it is observed:

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



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. At a distance of $1\text{AU} = 1.496 \times 10^{11}$ m, calculate the radiant flux above Earth's absorbing atmosphere?

$$F_{obs} = \frac{L_S}{4\pi r^2} = 1365 \text{ Wm}^{-2}$$

Ex: The normal pupil size in adults varies from 2 to 4 mm in diameter in bright light. Estimate the total power received by a human's eye?

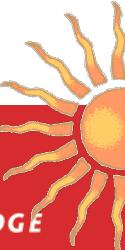




What do stars' color tell us?

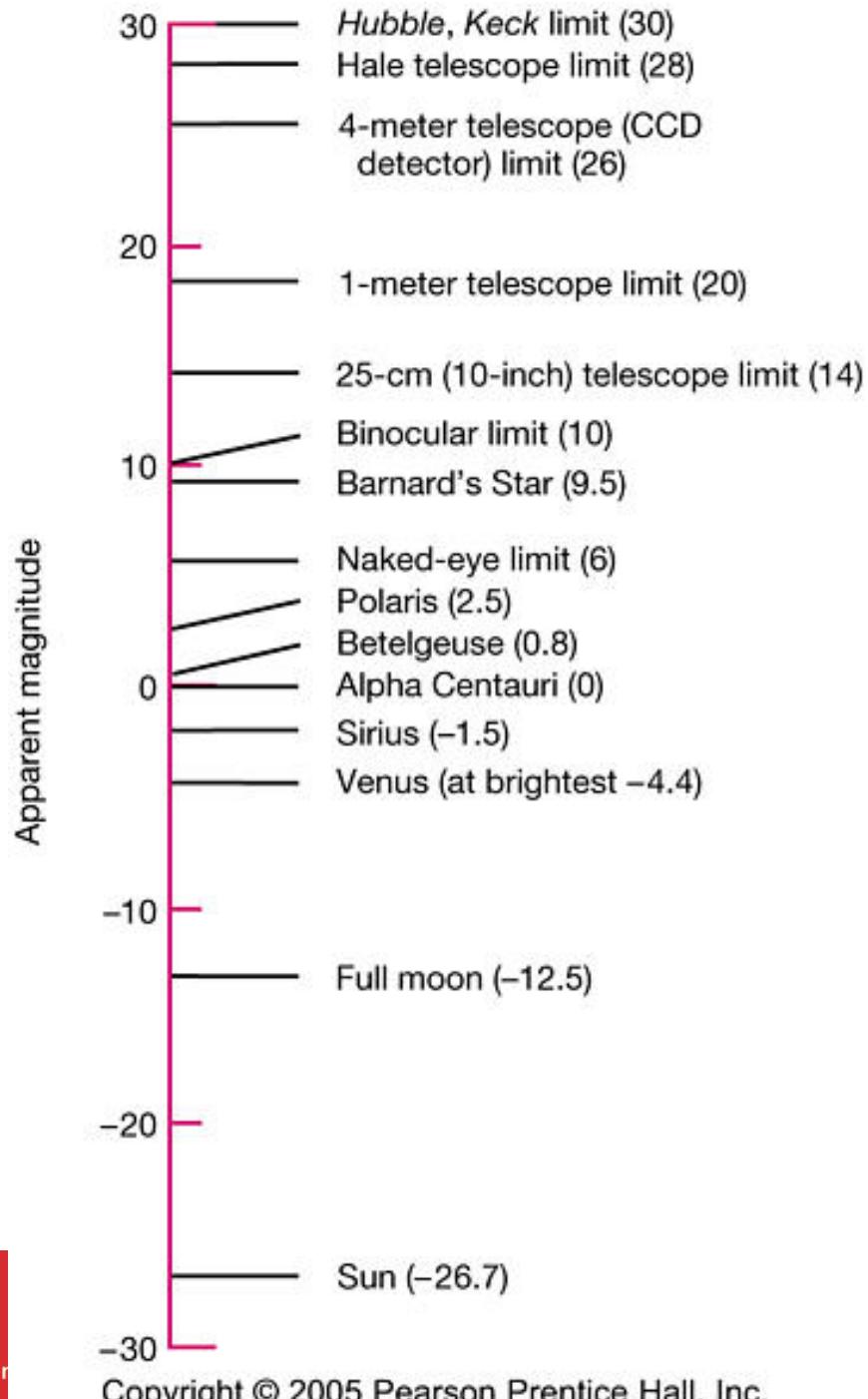
Q: If we treat Betelgeuse and Rigel as blackbodies,

- Which one has higher surface temperature?
- Which one has greater radiant flux?
- Which one has greater luminosity?
- Which one has greater brightness?



Apparent Magnitude

- Brightness can be described in terms of apparent magnitude.
- In 2 B.C., Hipparchus ranked the naked-eye stars into six groups:
 - Magnitude 1 – the brightest stars
 - Magnitude 2 ...
 -
 - Magnitude 5 ...
 - Magnitude 6 – the faintest stars
- Greater magnitude refers to dimmer stars.
- Today the magnitude system has been extended to include much fainter and brighter objects.



Brightness and Magnitude

- Magnitude system is a logarithmic expression of flux or brightness.
- It is also inverted – larger magnitudes are dimmer.
- A change of 5 in magnitude corresponds to a change of a factor of 100 in apparent brightness. Thus, each magnitude corresponds to 2.5 factors of brightness ?
- We can compare the brightness (flux) of stars 1 and 2 by forming a ratio and calculate magnitude difference,
- Consider the following cases:
 - $m_1 > m_2$
 - $m_1 - m_2 = 0$
 - $m_1 - m_2 = 1$
 - $m_1 - m_2 = 2$
 - $m_1 - m_2 = 5$
 - $m_1 - m_2 = 10$

$$\frac{F_2}{F_1} = 100^{(m_1-m_2)/5} = 2.512^{(m_1-m_2)}$$

$$m_1 - m_2 = -2.5 \log_{10} \left(\frac{F_1}{F_2} \right)$$



Ex.: The Sun's magnitude is -26.8. The intrinsic luminosity of Sirius A is about 20 times the Sun's luminosity; at its distance (8.6 ly, 1 ly = 63,240 AU), what is its apparent magnitude?

$$m_1 - m_2 = -2.5 \log_{10} \left(\frac{F_1}{F_2} \right)$$



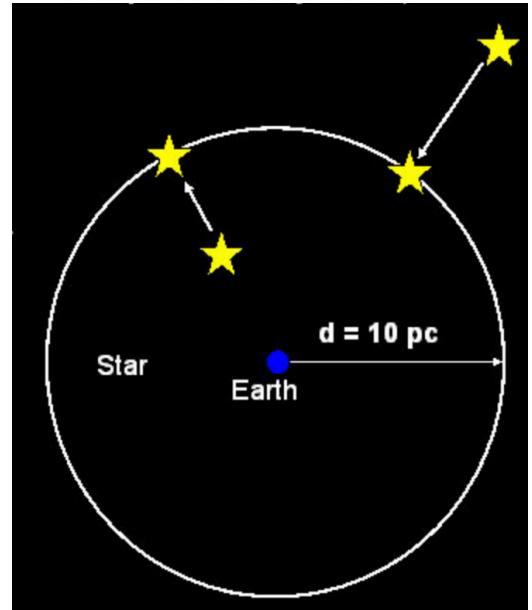
Absolute Magnitude

- Apparent magnitude denotes a star's brightness when viewed at its actual distance from Earth.
- **Absolute magnitude** is the apparent magnitude of a star placed at the 'standard' distance of 10 parsec (pc).

$$100^{(m-M)/5} = \frac{F_{10}}{F} = \left(\frac{d}{10 \text{ pc}} \right)^2$$

- Absolute magnitude is a measure of the intrinsic brightness, or luminosity, of the star itself.

$$m - M = 5 \log_{10}(d) - 5 = 5 \log_{10} \left(\frac{d}{10 \text{ pc}} \right)$$



Ex: A star is 20 parsecs away from us, and its apparent magnitude is +4. What is its absolute magnitude?



Light Behaves like Particles

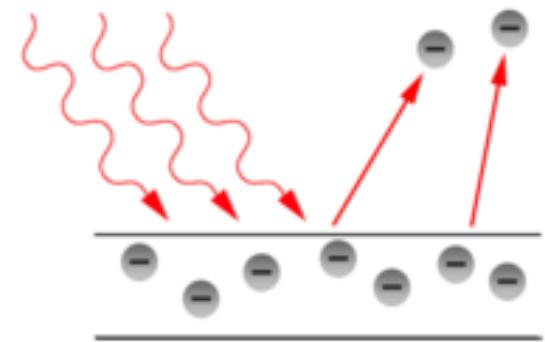
- Light particles are called "photons".
- Each photon carries an amount of energy related to its frequency or wavelength –

Planck's law:

$$E = h\nu = \frac{hc}{\lambda}$$

- E - energy of a photon
- $h = 6.625 \times 10^{-34} \text{ J s}$ - Planck's constant;
- c - speed of light;
- λ - wavelength of light

- Blue light photons are more energetic than red light photons!
- The intensity of light at a color is determined by both its wavelength and the number of photons at that wavelength.

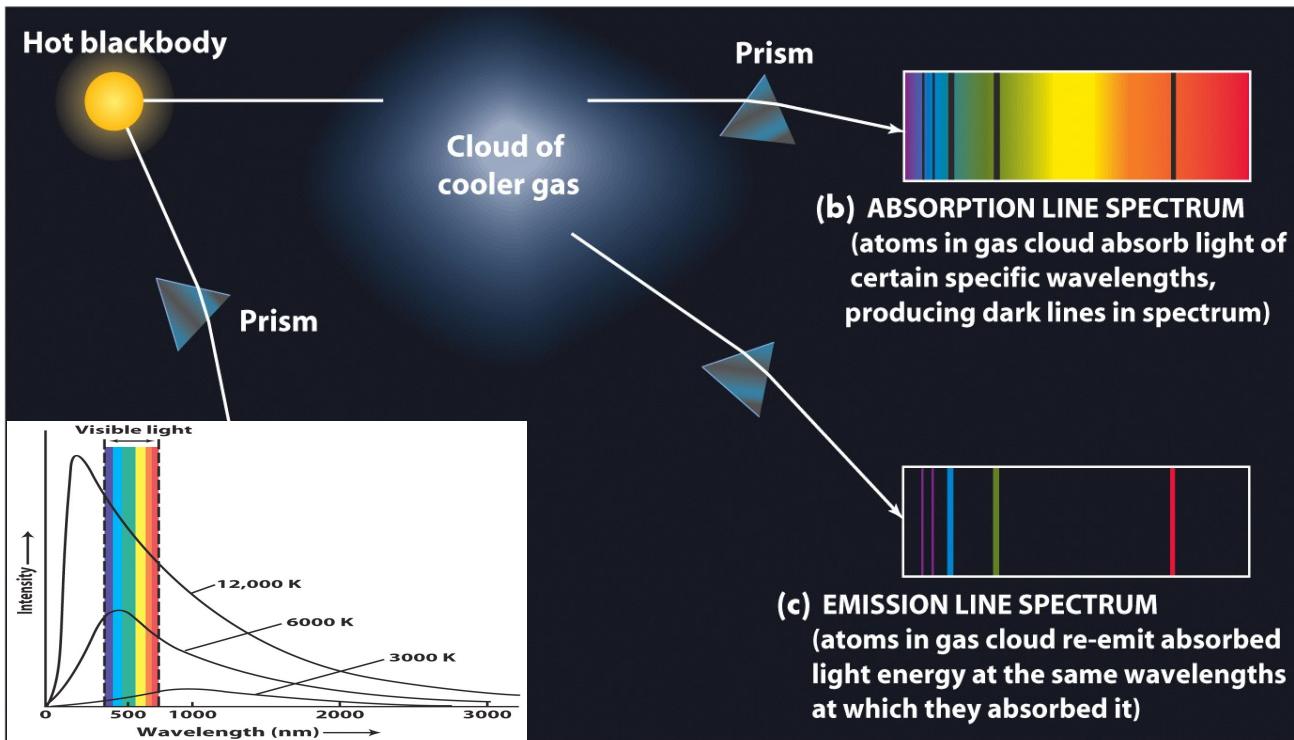


Photoelectric effect

wave-particle
duality of light



Emission and Absorption Lines

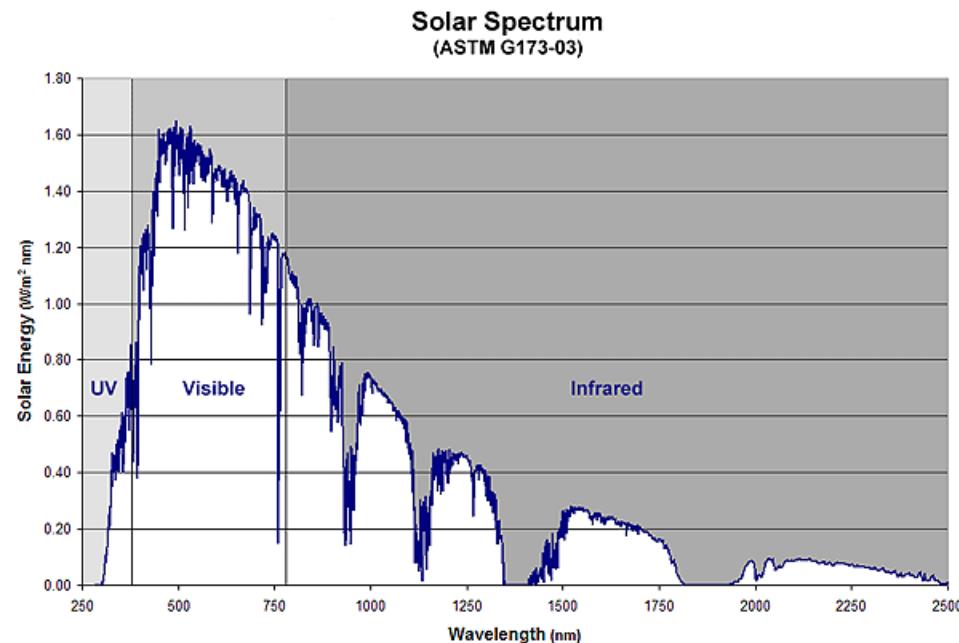
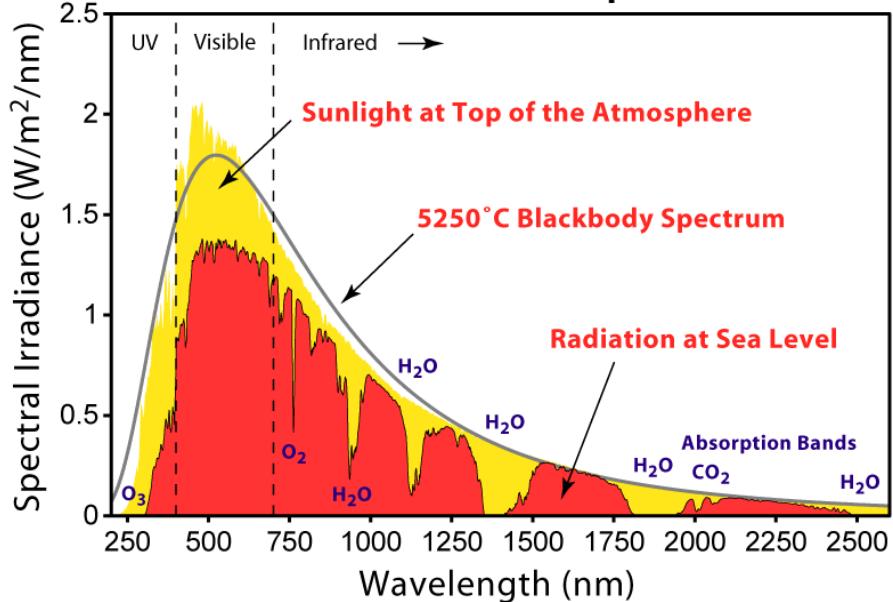


- Kirchoff's Law 1 – A hot, opaque body (like blackbody) produces a continuous spectrum.
- Kirchoff's Law 2 – A hot, transparent gas seen against a cooler background emits an emission line spectrum
- Kirchoff's Law 3 – A cool, transparent gas in front of a hotter source of a continuous spectrum produces an absorption line spectrum



Solar Spectrum

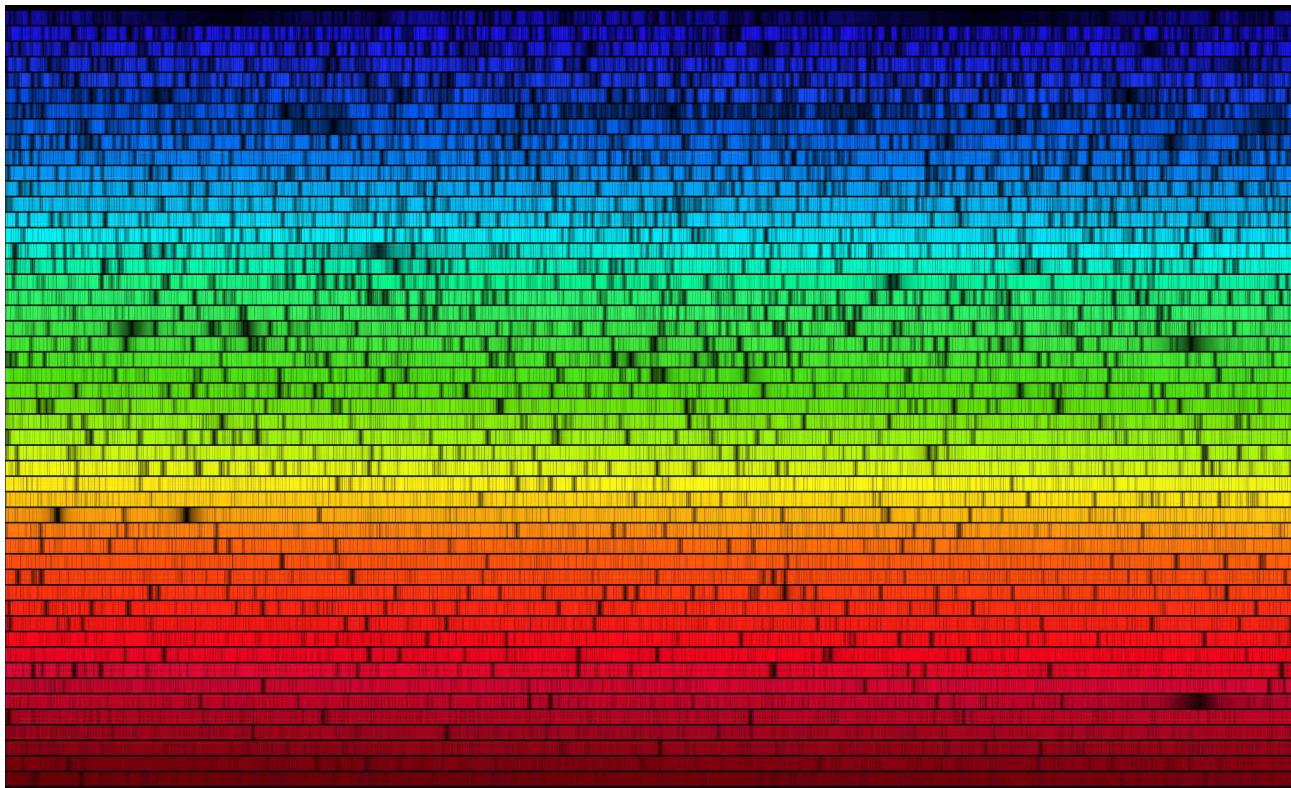
Solar Radiation Spectrum



- The sun produces light with a distribution similar to what would be expected from a 5525 K (5250 °C) blackbody.
- As light passes through the atmosphere, some is absorbed by gases with specific absorption bands.
- Additional light is redistributed by Rayleigh scattering, which is responsible for the atmosphere's blue color.

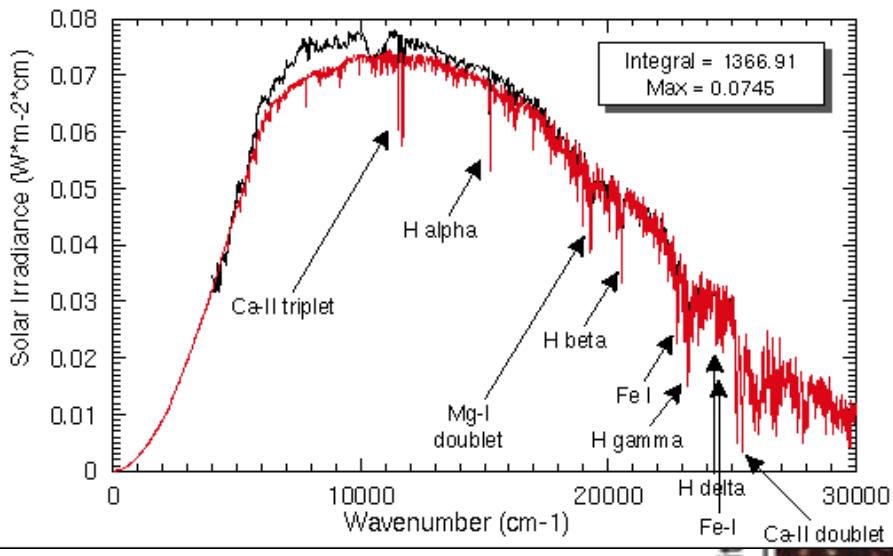


Solar Spectrum

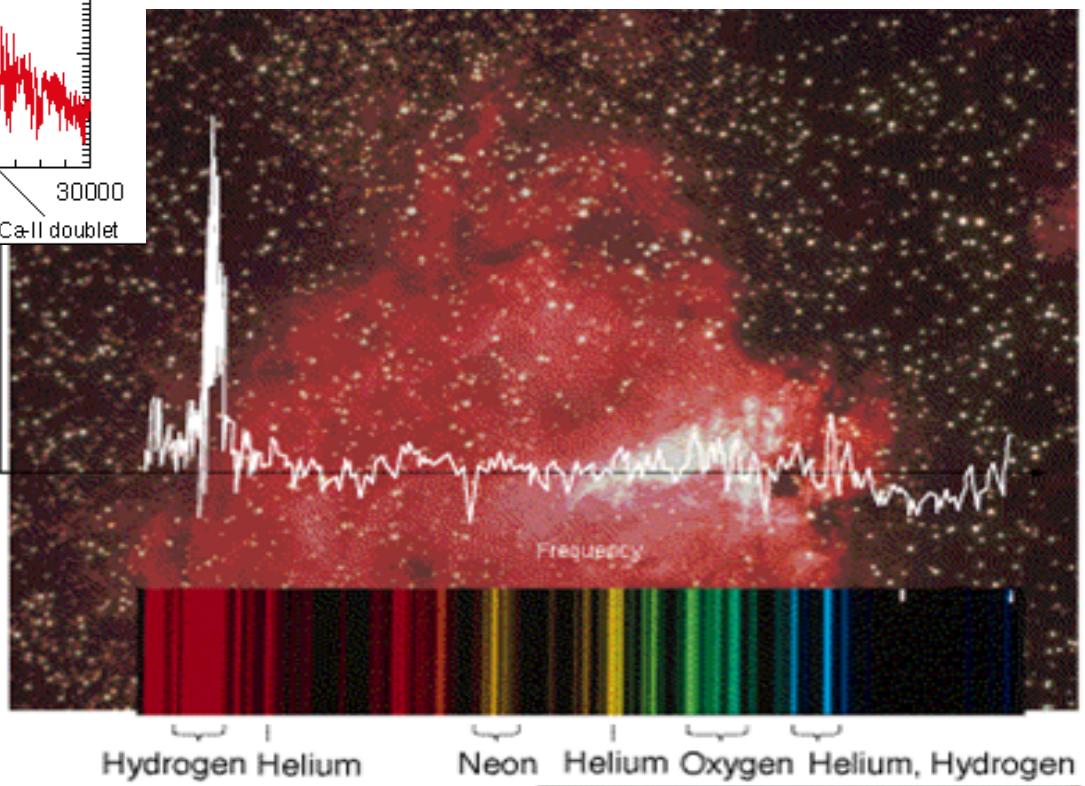


- ❑ In 1821, Joseph von Fraunhofer discovered numerous absorption lines superposed on the solar continuum -- **Fraunhofer lines**
- ❑ Solar spectrum at 392 to 692 nm as observed with the Fourier Transform spectrograph at Kittpeak NSO in 1981





Ex.9: solar spectrum, Fraunhofer lines, and discovery of the helium element.

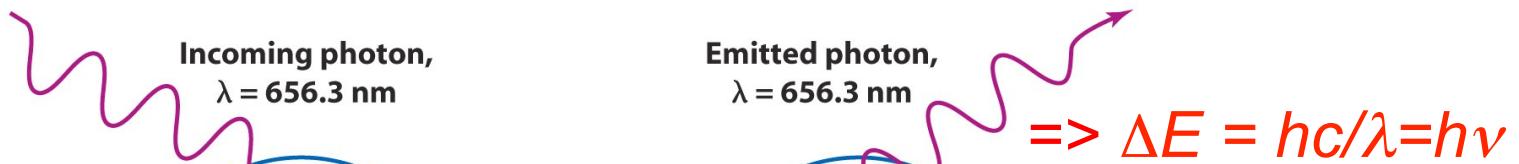


Q: how is a line formed and why each atom is characterized by more than one line?



Formation of Spectral Lines

- An atom comprises of a nucleus surrounded by electrons circling the nucleus at certain orbits. When an electron jumps from one orbit to another, the atom either emits or absorbs a photon, whose energy equals the difference in energy between the two orbits.



Emitted photon,
 $\lambda = 656.3 \text{ nm}$

$$\Rightarrow \Delta E = hc/\lambda = h\nu$$

Q: which orbit, the inner orbit or outer orbit, has higher energy?

(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up to the $n = 3$ orbit

(b) Electron falls from the $n = 3$ orbit to the $n = 2$ orbit; energy lost by atom goes into emitting a 656.3-nm photon

A photon is **absorbed** for the electron to jump **from inner orbit to outer orbit**.

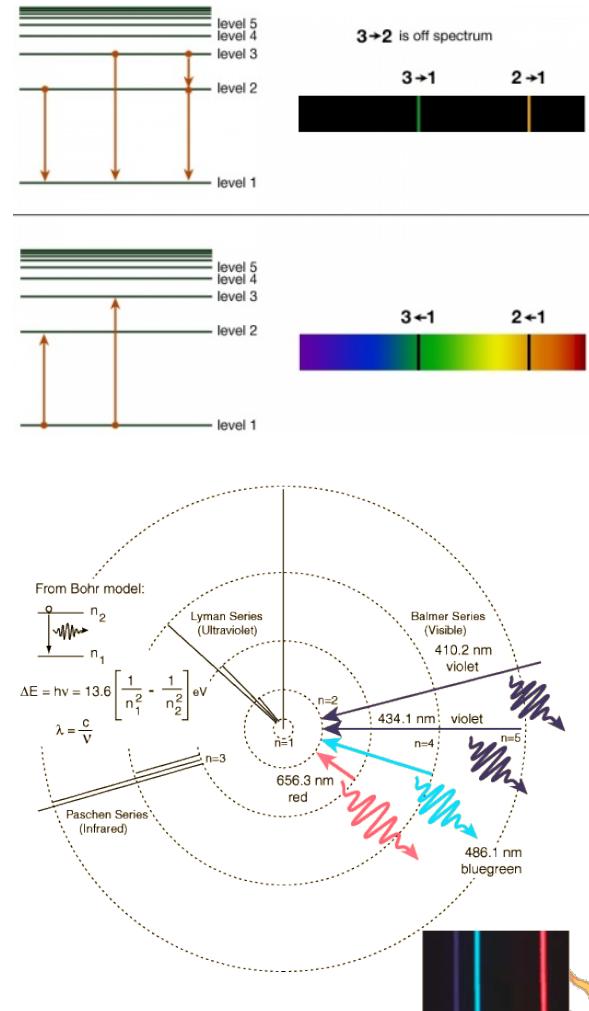
A photon is **emitted** for the electron to jump **from outer orbit to inner orbit**.

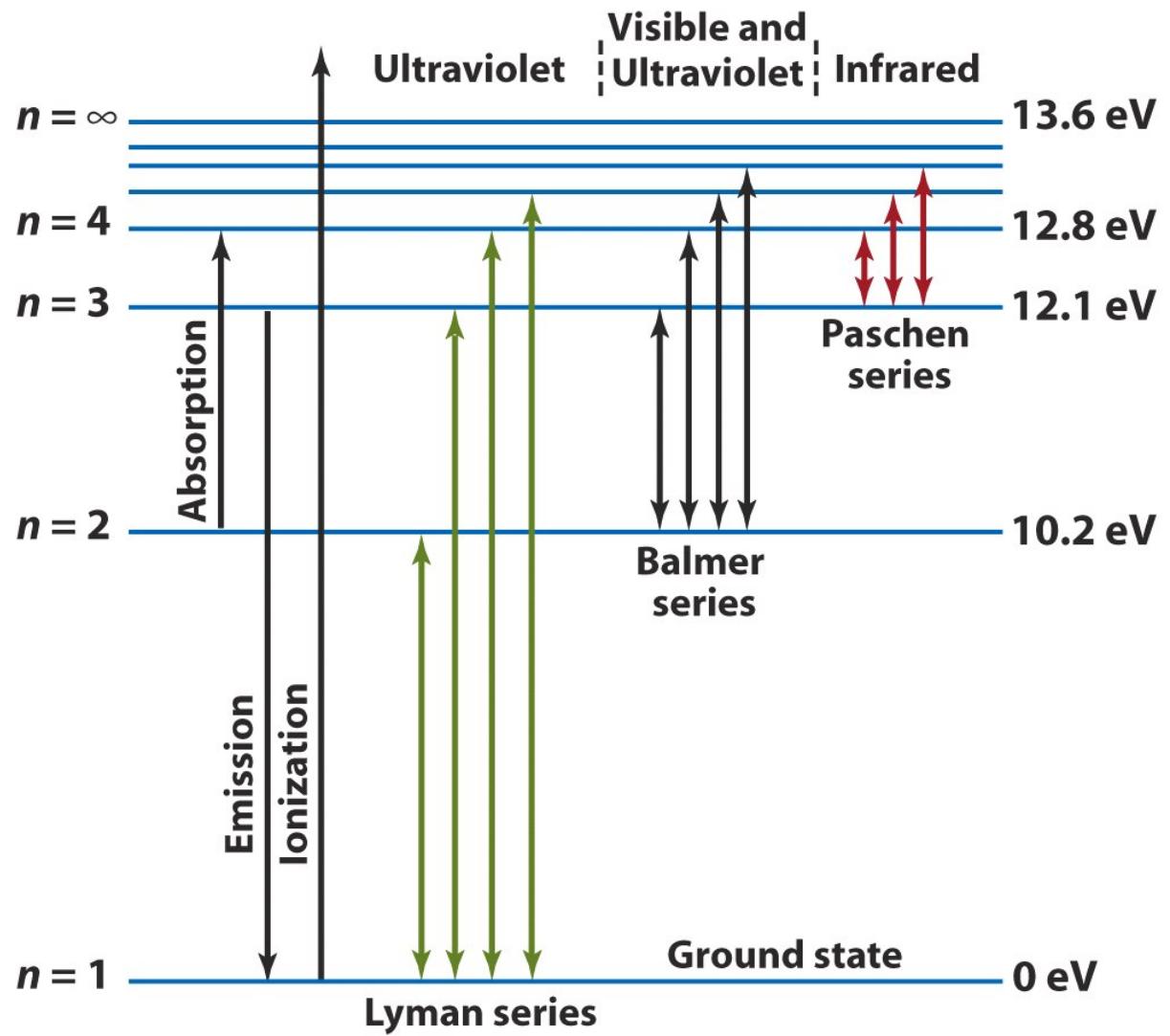


Emission and Absorption

- ❑ Bohr atomic model: the electrons can **only** exist in specific “orbits” around the nucleus.
- ❑ Each orbit has a specific energy associated with it, thus, the orbits can also be referred to as energy levels.
- ❑ If an electron absorbs exactly the energy difference between the level it is in and any higher lever, it can move up to a higher lever and an absorption line left.
- ❑ Once an electron in a higher lever falls down to a lower one, it emits a photon that carries exactly the amount of energy equal to the difference in energy between the starting level and the ending one.
- ❑ Try the PhET Interactive Simulations to investigate models of the Hydrogen atom:

Hydrogen atom simulation





(eV is a unit of energy often used in atomic physics.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

Ex.: Formation of Hydrogen lines.

The jump between the first orbit and outer orbits forms **Lyman** series.

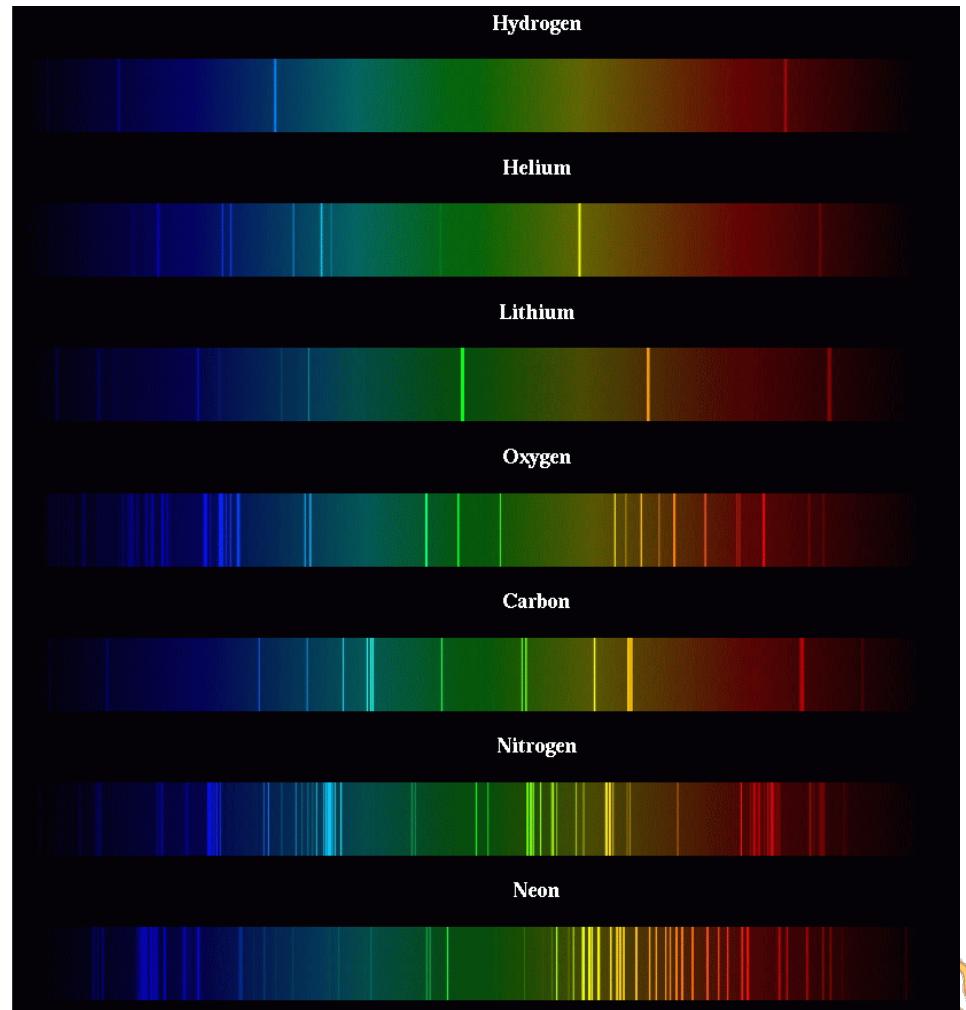
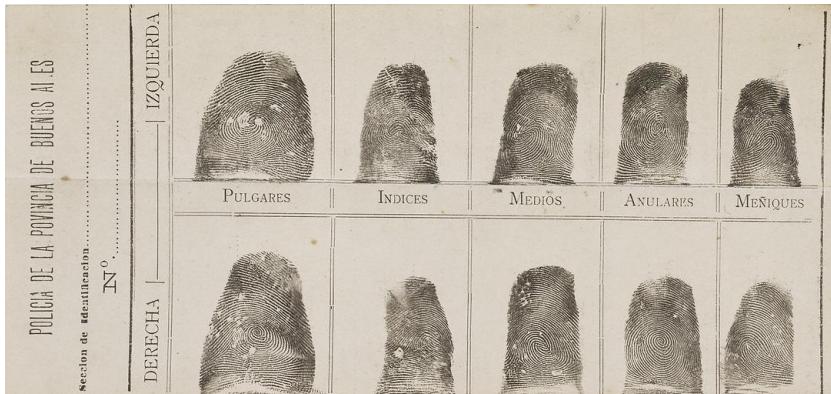
The jump between the second orbit and outer orbits forms **Balmer** series. The first line (between $n = 2$ and $n = 3$) in this series is **H α** line.

The jump between the third orbit and outer orbits forms **Paschen** series.

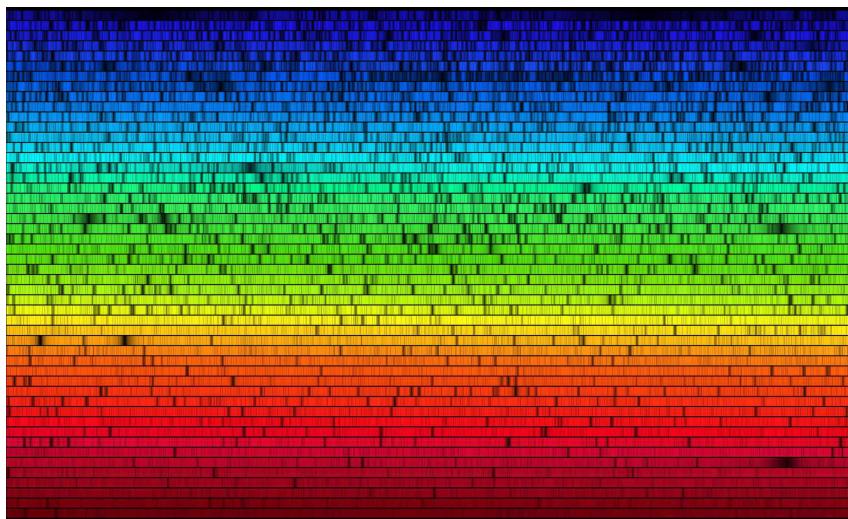
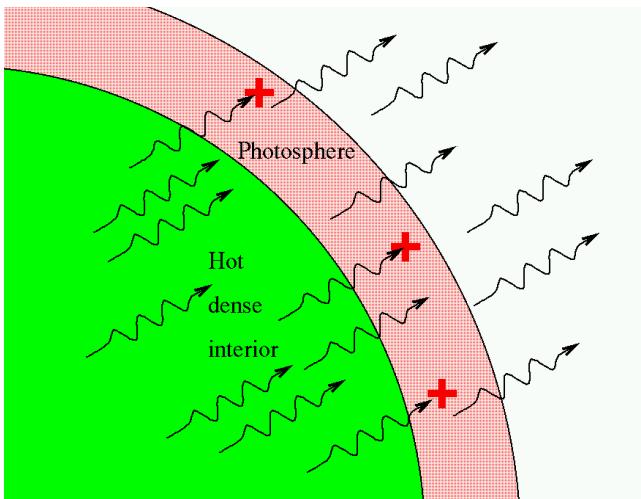


Spectrum and Fingerprints

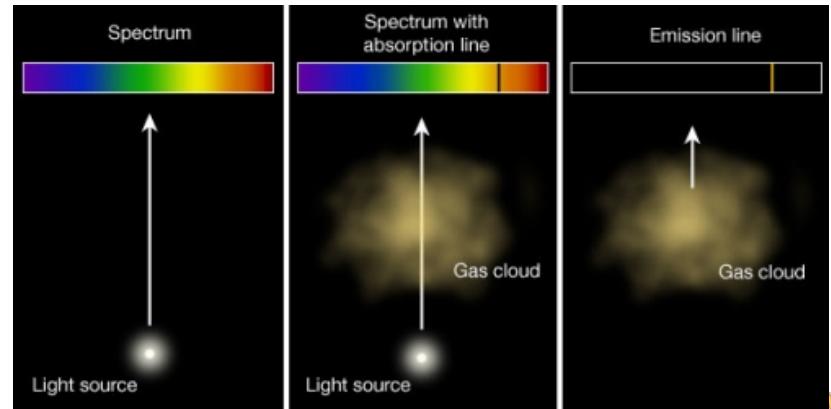
- Each element generates its own unique set of wavelengths of emission or absorption.
- We can use these patterns like fingerprints to identify the material which is emitting or absorbing light.
- Match “known” fingerprint (obtained in the Earth’s lab) to the “unknown” ones from the remote stars.



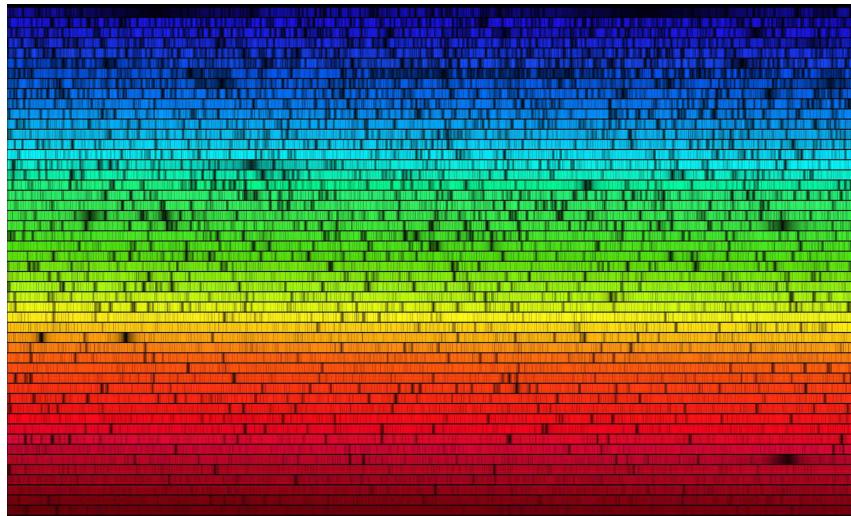
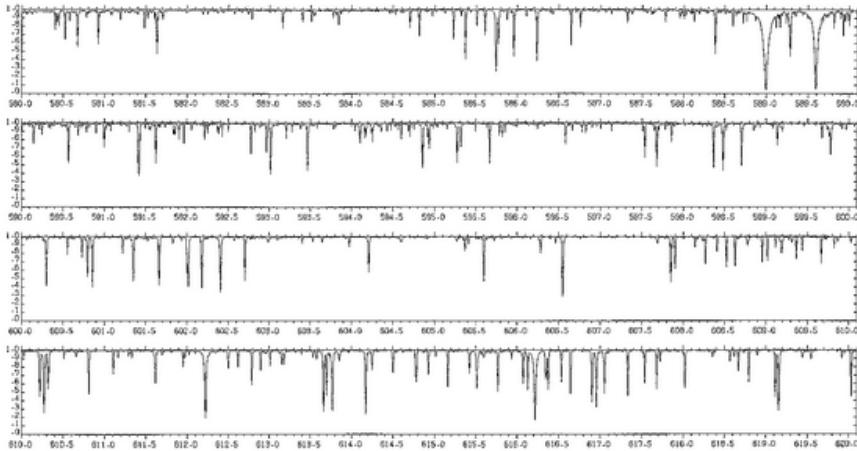
What can we learn ?



- **Composition of solar atmosphere**
- *If the solar atmosphere contain atoms of a particular element, then one would expect to see absorption lines at the wavelengths associated with that element.*
- *Astronomers took spectra of the Sun and tried to identify as many lines as they could.*
- *This isn't easy. As the years went by, we were able to track down the identity of some of the strongest lines.*



What can we learn ?

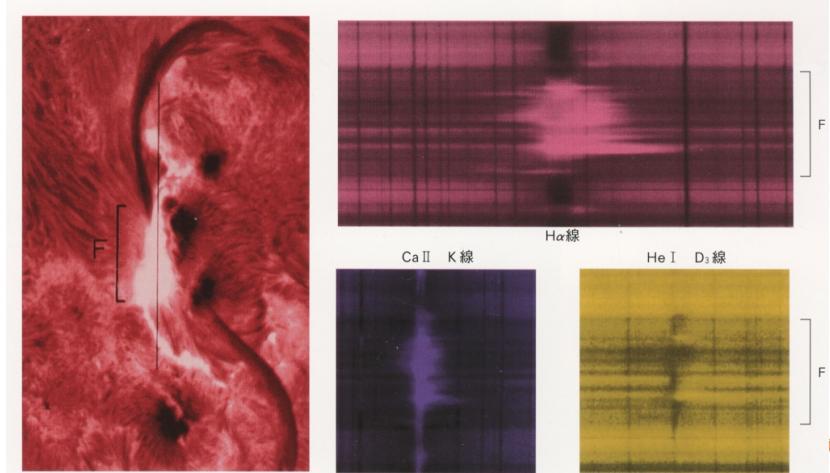
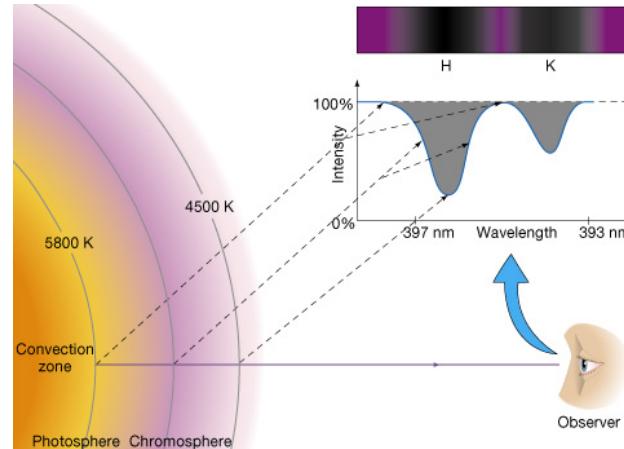
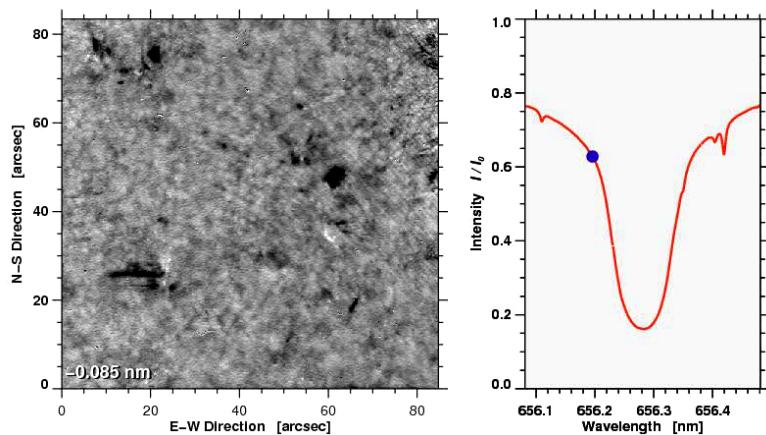
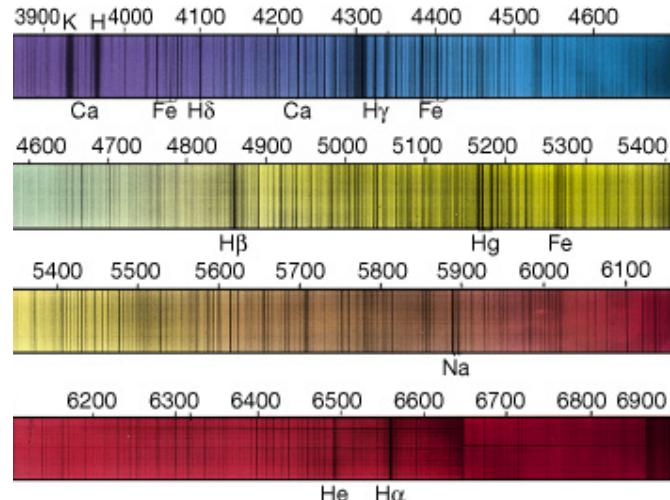


- Elements abundance, temperature and pressure in the solar atmosphere**
- Are the following statements true?
 - Strong absorption line means lots of that element
 - Weak absorption line means little of that element
 - No absorption line means none of that element
- The intensity of the absorption line depend on the abundance of some element, but is a complex function of the temperature, pressure and atomic constants.
- A lot of Hydrogen (92%) and a little Helium (7.8%), with tiny bits of heavier elements: O (0.04%), C (0.02%), Ne, N, Na and Fe ...



What can we learn ?

- ***Provide access to different layer of solar atmosphere.***

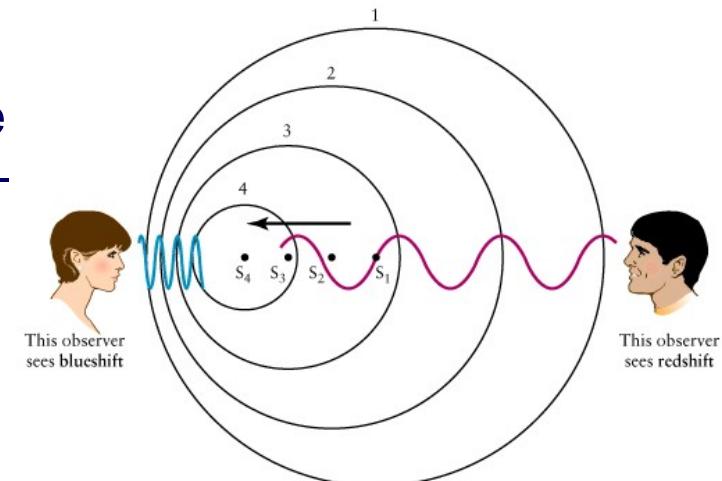


Doppler Shift of Spectral Lines

- The wavelength of a spectral line is affected by the relative motion between the source and the observer.
- Spectral lines of a receding source are shifted toward the longer wavelength – **redshift**.
- Spectral lines of an approaching source are shifted toward the shorter wavelength – **blueshift**.
- The amount of wavelength shift is given by **Doppler shift equation**:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c}$$

$(v \ll c)$



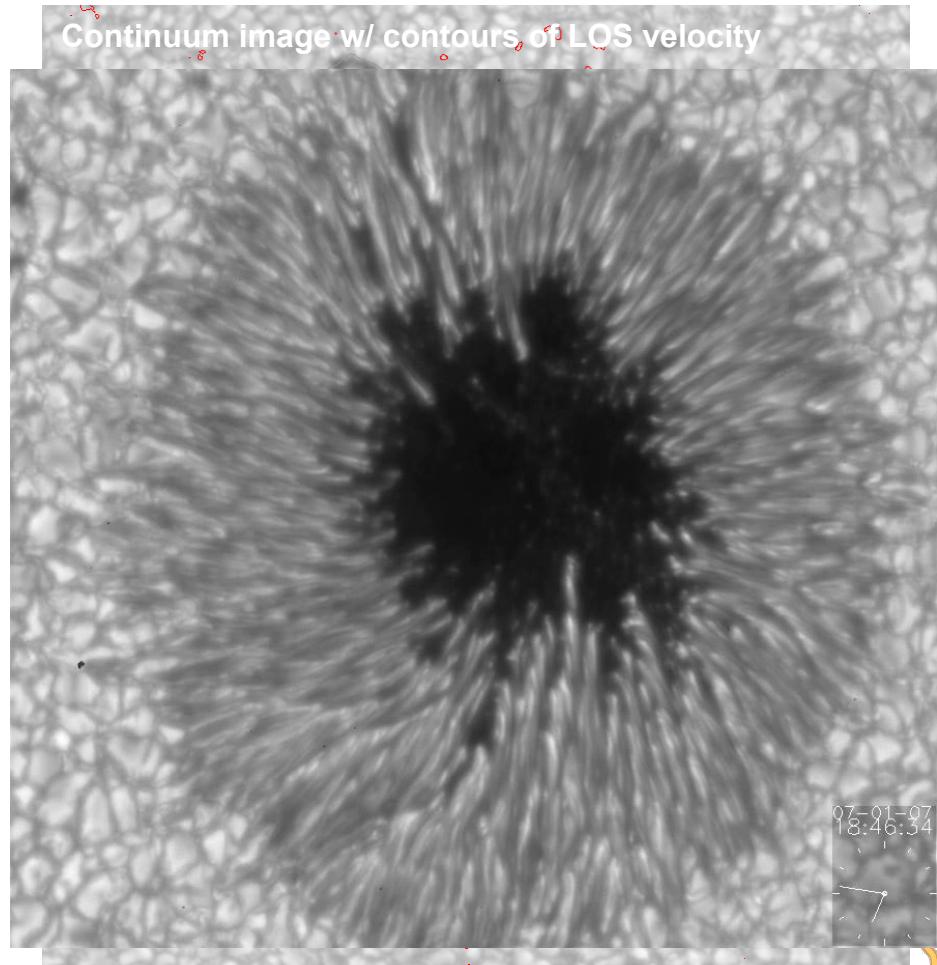
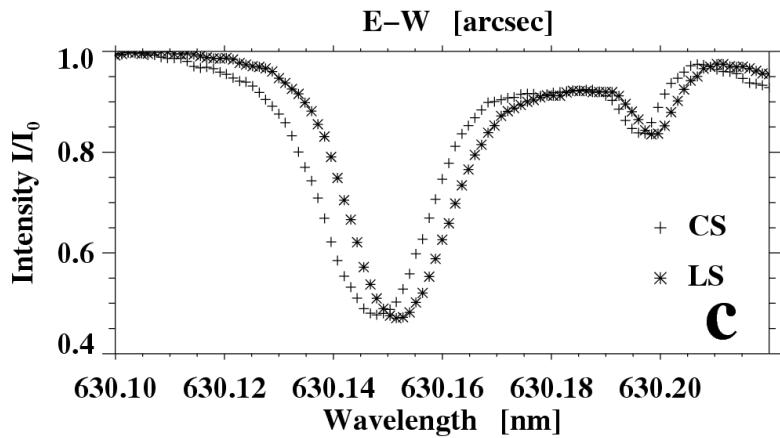
$\Delta\lambda$ = wavelength shift
 λ_0 = wavelength if source is not moving
 v = velocity of the source measured along the line of sight
 c = speed of light = 3.0×10^5 km / s



What can we learn ?

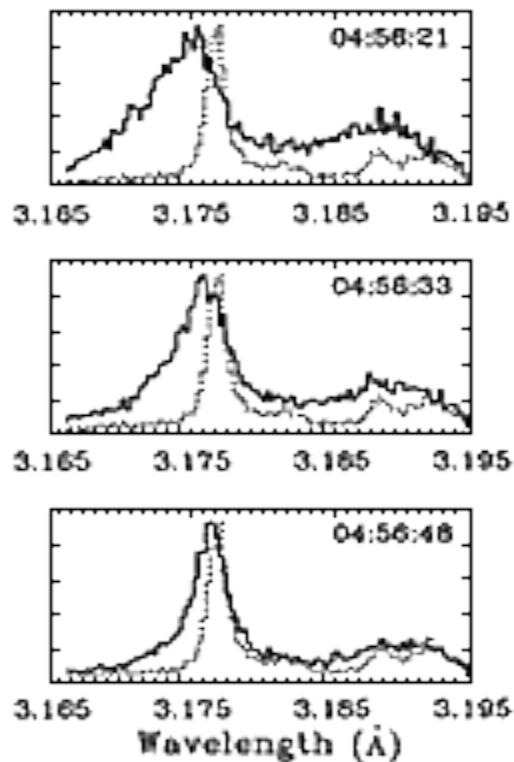
- **Line-of-sight velocity of solar features.**
- Doppler shift is referred to as the difference between the observed wavelength of the line and its actual wavelength.
- By measuring the Doppler shift, we can detect the longitudinal motions of solar features.

$$\lambda = \lambda_0 \left(1 + \frac{v}{c_0}\right)$$



dashed-line: the X-ray line profile before the flare

solid-line: the X-ray line profile during the flare



Ex. 13: Doppler-shifted X-ray line is observed by a satellite during a solar flare, showing motion of plasmas in the Sun's corona.

- (a) emission line other than absorption line is observed. Is the corona hotter or cooler than the photosphere?
- (b) Is the line blue-shifted or red-shifted? Does the plasma move toward or away from the observer?
- (c) suppose that the quiescent profile is centered 3.177 Angstrom, and during the flare the line splits into two components, one not shifted, and the other shifted to 3.174 Angstrom. What does this observation tell you? And what is the velocity of the moving plasma?

$$v = c \frac{\lambda - \lambda_0}{\lambda_0} = (3.0 \times 10^5 \text{ km/s}) \left(\frac{3.174 - 3.177}{3.177} \right) = -283.3 \text{ km/s}$$



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
- spectroscopy
- Stefan-Boltzmann law
- 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: $c = \lambda\nu$
- The Sun, stars, and other objects emit 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.

