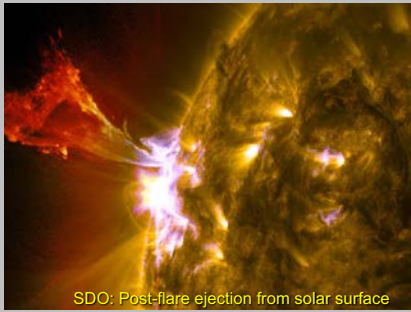


ASTR 1040
Stars & Galaxies



SDO: Post-flare ejection from solar surface

Prof. Juri Toomre TAs: Max Weiner, Daniel Segal, Loren Matilsky

Lecture 3 Tues 21 Jan 2020

zeus.colorado.edu/astr1040-toomre

Reading for today's and Thur class:

- Read Chap 5, carefully (Light and Matter)
- This chapter covers a lot – read it at least twice!
- Start reading Chap 6, telescopes

Continuing Topics for Today

- Electromagnetism: Light as waves and photons
- Coupling of atoms and light
- Yields “spectral lines” that are fingerprints unique to each atom
- How gas can emit or absorb light
- Hope you completed HW #0 on MA, now well underway with HW #1 (due Thur classtime)
- Recitations / AHR office hours can help

Light: The Cosmic Messenger

CONTINUING TOPIC

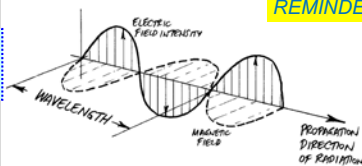


Barred Spiral Galaxy NGC 1672

E-M (LIGHT) AS WAVES

ELECTROMAGNETIC RADIATION AS A WAVE

REMINDER



$$\lambda \times f = c$$

WAVELENGTH x FREQUENCY = SPEED OF "LIGHT"

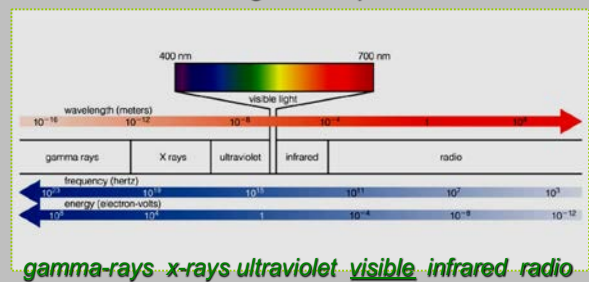
$$\lambda = c/f, \quad f = c/\lambda$$

PROPAGATION SPEED OF ALL EM WAVES IS THE SAME!

C IS A CONSTANT $\approx 300,000 \text{ km/sec}$
 $= 3 \times 10^{10} \text{ cm/sec}$

Speed of light SAME for all wavelengths

Electromagnetic Spectrum



gamma-rays · x-rays · ultraviolet · visible · infrared · radio

$$c = \lambda \cdot f$$

ATOMS
 protons, neutrons, electrons
 (and quarks ..)
 Building blocks for everything

ATOMS

NUCLEI: POSITIVELY CHARGED PROTONS AND UNCHARGED NEUTRONS
 OUTER SHELL(S) OF NEGATIVELY CHARGED ELECTRONS

HYDROGEN
 ONE PROTON, NO NEUTRONS
 ONE ELECTRON
 BUT ELECTRONS CAN BE IN ONE OF MANY DIFFERENT ORBITS, WITH DIFFERENT ENERGIES

HELIUM
 TWO OF EACH
 (ALSO ISOTOPES WITH ADDITIONAL NEUTRONS)

CARBON
 SIX OF EACH
 NUCLEI RELATIVELY SMALL (10^{-8} Å)

"ORBITS" OF ELECTRONS
 Popping from one orbit to another involves particular PHOTONS
 (like DNA prints)

POSSIBLE ORBITS FOR ELECTRON IN HYDROGEN ATOM
 TRANSITIONS (USUALLY) EMIT OR ABSORB PHOTON

ONLY LIGHT OF CERTAIN COLORS (ENERGIES) CAN BE ABSORBED OR EMITTED
 EACH CHEMICAL ELEMENT HAS ITS OWN UNIQUE NUMBER AND PATTERN OF ELECTRON ORBITS
 ⇒ UNIQUE PATTERN OF COLORS (SPECTRAL LINES ARE LIKE A FINGERPRINT!)

Revolution of "Quantum Mechanics"

- Discrete spectral lines and electron energy levels go hand in hand, but WHY?
- Classical physics had no real explanations, even if Bohr's model of electron orbits for H looked good
- A new mathematics/physics had to be invented in the 1920s, with solutions of the "Schrodinger wave equation" giving probabilities (orbitals) of where electrons could be located
- Such "quantum mechanics" also explained why light (photons) act both like waves and particles, and so too electrons!

Electron in Hydrogen Atom (S4.3)

In quantum mechanics, an electron in an atom does not orbit in the usual sense
 We can know only the probability of finding an electron at a particular spot (orbital)

Orbital solutions from Schrodinger wave equation

ENERGY LEVELS (of electrons) IN HYDROGEN
 Each transition involves photons of specific color
 (like fingerprints)

ENERGY LEVELS AND SPECTRAL LINES IN HYDROGEN ATOM

IONIZATION LIMIT
 CONTINUUM (FREE ELECTRONS)
 LEVEL 5
 LEVEL 4
 LEVEL 3
 LEVEL 2
 LEVEL 1
 GROUND STATE
 GROUND LEVEL (min)

ULTRAVIOLET
 VISIBLE
 INFRARED
 IR RADIATION
 EMISSION LEVELS
 ABSORPTION LEVELS

EACH TRANSITION OF ELECTRON IN ENERGY PRODUCES ONE SPECTRAL LINE (EMISSION/ABSORPTION OF PHOTON)

Hydrogen's Energy Diagram
 Emission
 Absorption

Ionization

level 5
 level 4
 level 3
 level 2
 level 1

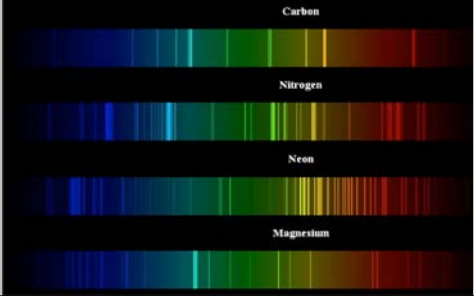
121.6 nm
 102.8 nm
 97.5 nm
 91.1 nm

656.3 nm
 486.1 nm
 434.0 nm
 410.1 nm
 1875.1 nm
 121.5 nm

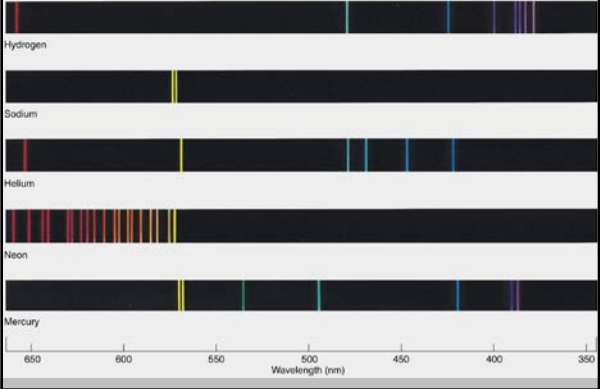
410.1 nm
 434.0 nm
 486.1 nm
 656.3 nm

Each atom has a different set of energy levels

- Just like no two people have the same fingerprints, no two elements have the same emission spectrum



As in our emission tube demo last Thur




Very important Idea #2

$$E = h \times f$$

Photon's **Energy** =
Planck's constant x Photon's **Frequency**

Idea #1 $c = \lambda \cdot f$

Colors of Light



- Newton showed: White light is made up of many different colors

Clicker Question

Infrared light can have a wavelength of 3 microns (3×10^{-6} m) and a frequency of 1.0×10^{14} Hz. What is the wavelength of light that has a frequency of 0.5×10^{14} Hz? (Hint: What is the relationship between wavelength and frequency?)

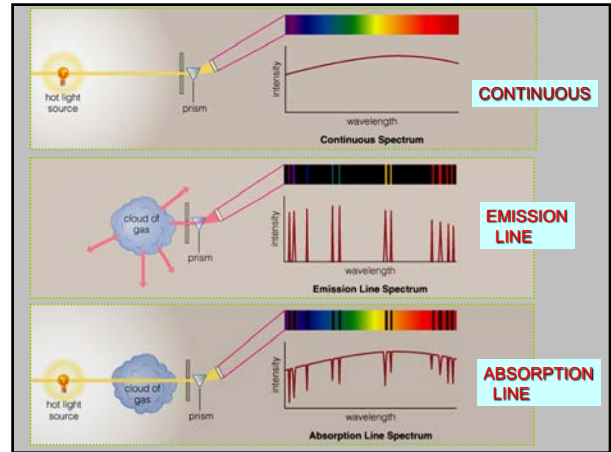
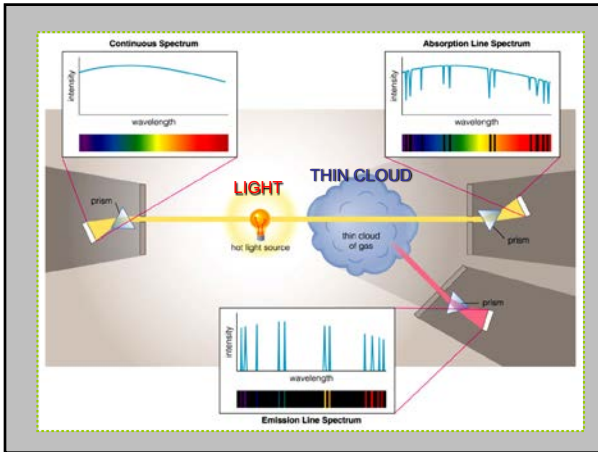
- A. 1.5 microns
- B. 2.0 microns
- C. 2.5 microns
- D. 3.5 microns
- E. 6.0 microns

NATURE OF SPECTRA

Kirchoff's laws

SPECTRA (KIRCHOFF'S LAWS)

- RADIATING SOLID, LIQUID, OR HIGH-PRESSURE GAS (OFTEN VERY THICK) \Rightarrow CONTINUOUS SPECTRUM
- HOT (THIN) RADIATING RARIFIED GAS (LOW DENSITY) \Rightarrow BRIGHT-LINE SPECTRUM (EMISSION) **Emission**
- COOL LIGHT OF CONTINUOUS SPECTRUM VIEWED THROUGH A COOLER GAS \Rightarrow DARK-LINE (ABSORPTION) SPECTRUM **Absorption**



Emission Spectra

- Emission for thin, hot gas: Gas glows in specific colors.

The Crab nebula: remains of an exploded star (supernova, 1054 AD)

Spectrum shows bright emission lines from various elements

Most common visible light emission line: Hydrogen Alpha

- Hydrogen Alpha
- Level 3 to level 2 energy jump at 656.3 nm
- The universe is mostly red!!

All-sky map of H Alpha emission

"BLACK-BODY" (THERMAL) SPECTRUM

CONTINUOUS SPECTRUM OF EMISSION BY "BLACK BODY"

PLANCK'S RADIATION LAW: BEHAVIOR OF THERMAL RADIATION AS TEMPERATURE IS VARIED

Planck

Peak emission and total energy VARY with temperature

"Law1" Stefan-Boltzmann

$$\text{TOTAL ENERGY EMITTED} \sim (\text{TEMPERATURE})^4$$

$$E = \sigma T^4 \text{ STEFAN-BOLTZMANN LAW}$$

"Law2" Wien

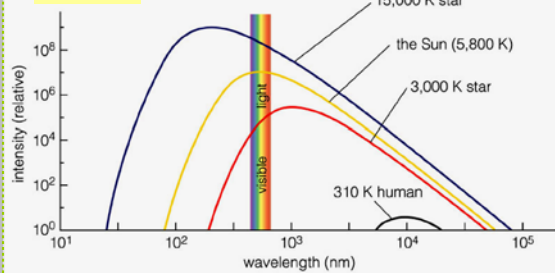
$$\text{WAVELENGTH OF PEAK EMISSION} \sim 1 / \text{TEMPERATURE}$$

$$\lambda_{\text{MAX}} \sim \frac{1}{T} \text{ WIEN'S LAW}$$

{ IF INCREASE T FROM 3000 K TO 6000 K, E INCREASES BY FACTOR: $6 \times 6 \times 6 \times 6 = 1296!$ }

Spectra of Continuous Emission (from us and stars)

PLANCK



Thermal radiation spectrum

Law 1: Power emitted (per square meter surface area)

$$\epsilon = \sigma T^4$$

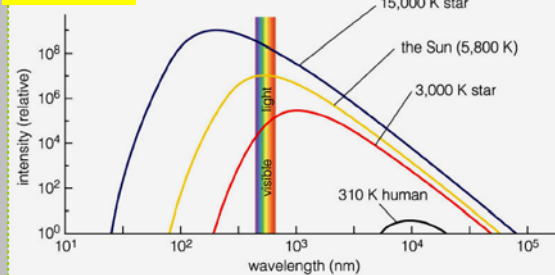
"Luminosity" = "Law 1" x Surface Area of star

Law 2: Wavelength of peak emission

$$\lambda_{\max} \sim 1/T$$

Thermal Radiation Emission

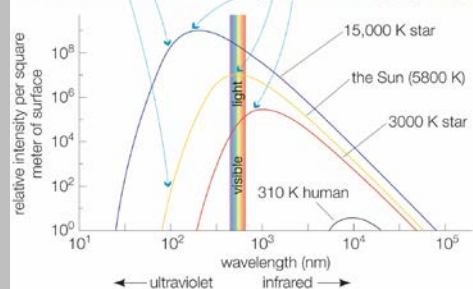
REMEMBER



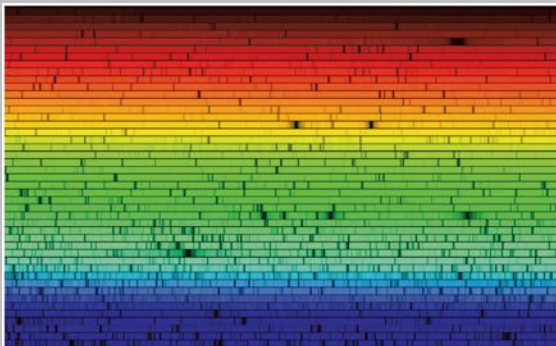
UP the temperature: FAR MORE emission peak at SHORTER wavelengths

Law 1: The curve for a hotter object is everywhere above the curve for a cooler object, showing that hotter objects emit more radiation per unit surface area at every wavelength.

Law 2: The peak wavelength is further to the left for hotter objects, showing that hotter objects emit more of their light at shorter wavelength (high energy).

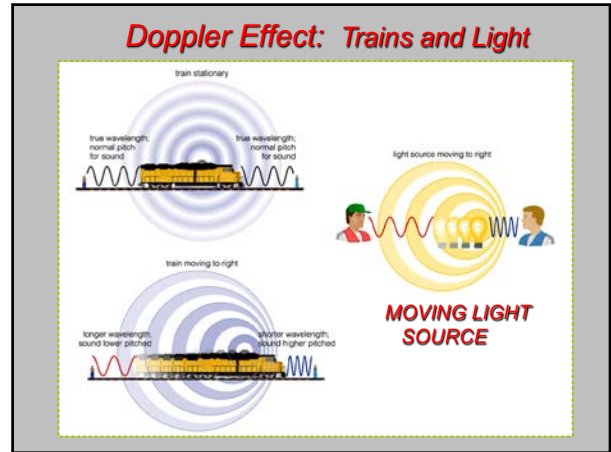
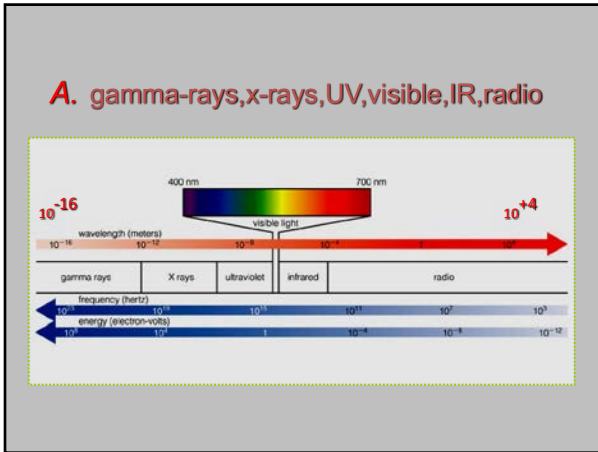


Visible light spectrum of the Sun (optically folded)



Clicker Q – EM Waves

- From shortest to longest wavelength, what is the correct sequence of EM radiation?
- **A.** gamma-rays, x-rays, UV, visible, IR, radio
- **B.** gamma-rays, x-rays, visible, UV, IR, radio
- **C.** IR, visible, UV, x-rays, gamma-rays, radio
- **D.** radio, IR, visible, UV, x-rays, gamma-rays



DOPLER EFFECT

Applied to positions of spectral lines

Doppler Demo

RECEDING SOURCE IS RED SHIFTED
 LIGHT FROM APPROACHING SOURCE IS BLUE

CRESTS FURTHER APART LONGER WAVELENGTH
 WAVECRESTS CLOSER TOGETHER SHORTER WAVELENGTH OR HIGHER FREQUENCY f

$$\text{CHANGE IN WAVELENGTH} = \frac{\Delta \lambda}{\lambda} = \frac{v}{c} = \frac{\text{VELOCITY OF SOURCE}}{\text{SPEED OF LIGHT}}$$

CAN USE TO CALCULATE LINE-OF-SIGHT VELOCITY OF SOURCE:
 "DOPPLER VELOCITY" v

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

IF ABSORPTION LINE AT SKY 5000 \AA REDSHIFTED BY 0.5 \AA

$$v = \frac{(+0.5 \text{ \AA}) (300,000 \text{ Km/sec})}{5,000 \text{ \AA}}$$

$$= + 30 \text{ Km/sec}$$

Measuring the Line Shift

The diagram shows four spectra: Laboratory spectrum (stationary), Object 1 (Moving Away/redshifted), Object 2 (Away Faster), Object 3 (Moving Toward/blueshifted), and Object 4 (Toward Faster). A wavelength arrow is shown for the laboratory spectrum.

- Measure the Doppler effect from shifts in the wavelengths of spectral lines