Astro 3 & 4: Chapter 5 – Light, Matter, Heat Flow

- The Atom and its particles
- The electromagnetic field
- Light – traveling electromagnetic waves, quantized as "photons"
- A changing electric field generates… a magnetic field. And, vice versa!
- Accelerate an electric charge, generates changing E field and hence changing M field… = light
- Two ways to create photons.
- Atoms and light; spectra. Emission and absorption lines and how they tell us what stars and planets are made of, their speed, and their temperature

Key Ideas – Chap 5 Light and Matter

- **Photons = quanta of EM field energy as a small bit of wave.**
- **Photon energy; short wavelength=high energy**
- **Doppler Effect: all wavelengths shifted longer ("redshift") if velocity away, shifted to shorter wavelengths ("blue shift") if velocity towards.**
- **Doppler Effect ONLY measures velocity component that's along the line-of-sight**
- **Know the names and order of the different wavelength bands (IR, radio, etc)**
- **Know the two ways to excite an atom or molecule (collisions, and photon absorption)**
- **Molecules have addition quantum degrees of freedom: vibration, rotation, and more complex motions for molecules of 3 or more atoms. Such transitions mostly in the Infrared.**
- **Molecular absorption lines are much broader than for individual atoms. We call them instead "absorption BANDS"**
- **Know the two ways to produce photons; accelerate a charge, emission.**
- **Know the two ways to excite an atom; absorption, and collisions**
- **Different ISOTOPES of an atom have different numbers of neutrons in nucleus**
- **Ionized atom = ion = has one or more electrons knocked off**
- **Temperature corresponds to average kinetic energy per particle**
- **Emission spectra *vs.* absorption spectra – knows which situation gives which**
- **Emission of photon when electron falls to lower orbital. Absorption is running that movie in reverse.**
- **Absorption ONLY happens if the photon has exactly the right energy to lift electron to an allowed orbit, or ionizes it altogether. Molecules can emit/absorb not only by not the electrons moving, but moving between different vibrational quantum states between the bound atoms**

The Three Stable Particles Making up Most Ordinary Matter

- **The Proton: Mass = 1 AMU, net charge= +1**
- **The Neutron: Mass = 1 AMU, net charge = 0**
- **The Electron: Mass = 1/1860 AMU, net charge = -1**

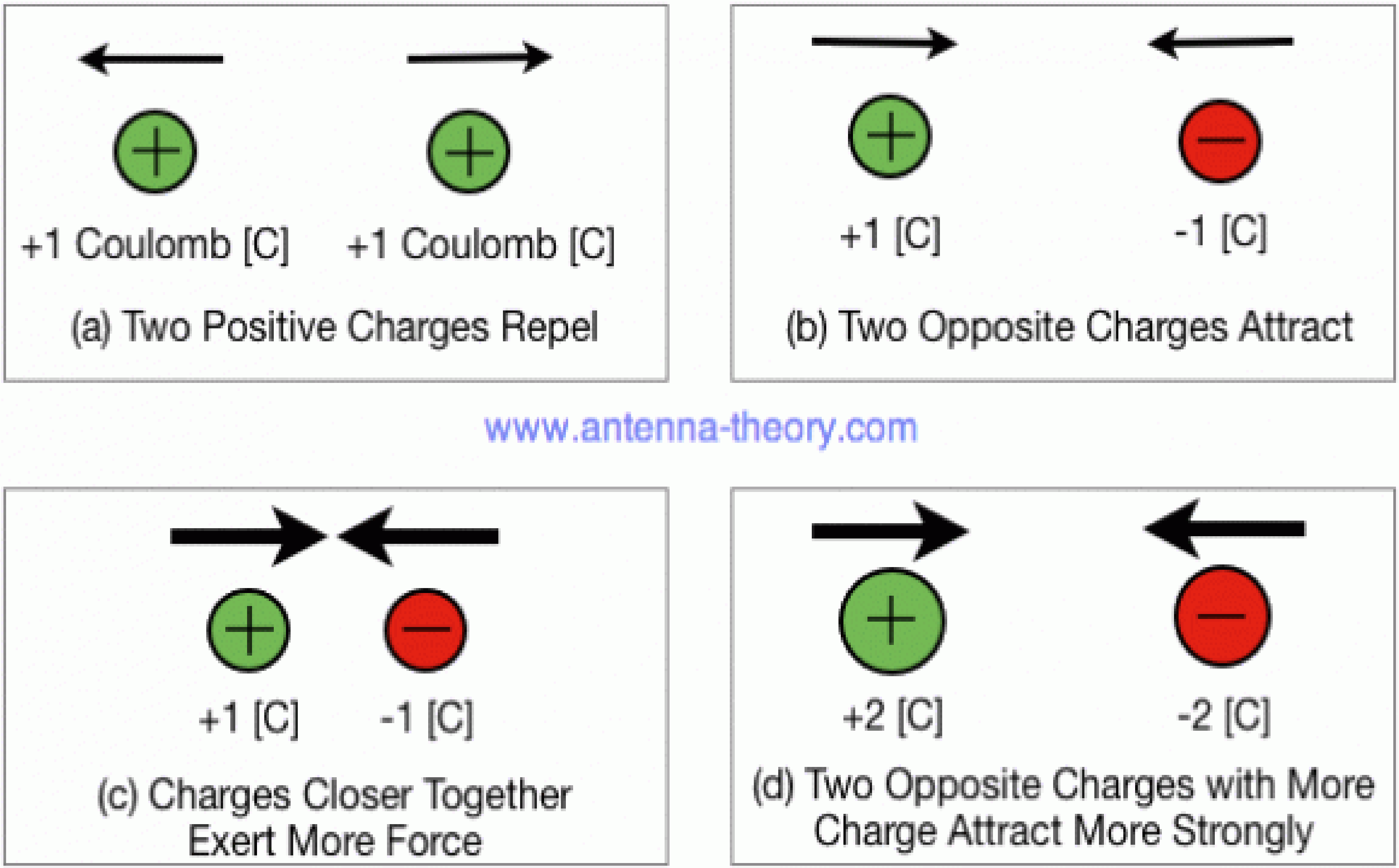
Mass and Charge

- Mass has an associated force: ***Gravity***
- Another quality possessed by elementary particles is *charge*. Comes in two flavors; positive and negative. Likes repel, and opposites attract. The associated force is called ***Electromagnetism***

Only Charges Feel the Electromagnetic Force

- **Likes repel**: proton repels proton. Electron repels electron
- **Opposites Attract**: Proton attracts Electron
- Electromagnetic force drops with increasing separation, just like gravity: as $1/r^2$
- Neutrons have no large interaction with the EM force field, but do have a tiny one (a "magnetic moment" which means they act like a tiny magnet, not needed for our purposes, but if you want, you can read about it here)

Opposites Attract, Likes Repel



An Atom…

- Has: a nucleus of protons (+ charge) and neutrons (zero charge).
- And: a “cloud” of electrons surrounding the nucleus; as many electrons as there are protons.
- Electrons feeling the force of the protons and other electrons allows us to talk about their “energy state”, since differences in position mean differences in the forces of attraction/repulsion.
- We can talk of the “energy state” of the atom, or more informally, the electron orbitals.
- Electron energies are *quantized* – they can only take on certain discrete values. This is the realm of **Quantum Mechanics**, and your intuition will need a heavy dose of new thinking! (see chapter S4 for a start…)

An Atom has As Many Electrons as Nuclear Protons, and it's the Electrons who Interact with the Outer World through Chemistry

- ***Different number of electrons = Different Chemistry = Different names***
- ***Hydrogen*** – 1 proton. ~90% of all atoms are hydrogen
- ***Helium*** – 2 protons – most other atoms are helium
- ***Lithium*** – 3 protons
- ***Beryllium*** – 4 protons
- ***Boron*** – 5 protons
- ***Carbon*** – 6 protons
- Etc, to ***Uranium*** – 92 protons
- And some unstable ones higher up

Anything Bother You About These Nuclei?

Protons Repel Protons – So How Do They Manage to Stick Together?

- **<u>There must be another force of Nature –</u>**
- **Yes! We decided (unimaginatively) to call it the "<u>Strong nuclear force</u>"**
- **It attracts protons to protons, protons to neutrons, and neutrons to neutrons. But, it's only felt over a tiny distance range of ~10^{-13} cm or less**
- **Neutrons have no charge so don't change the chemistry of an atom. Atoms with same number of protons but different numbers of neutrons are called ISOTOPES of that element.**
- **Example, there is carbon-12, carbon-13, carbon-14, which all behave like carbon chemically, but they have 6, 7, and 8 neutrons respectively. So their weight differs (which does affect the <u>speed</u> at which they do their chemistry).**

The Weak Force

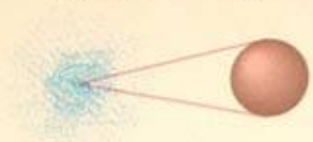
- For completeness, the final force of Nature is the **Weak Force**. It causes neutrons to decay into protons + electrons + neutrinos, and vice versa
- The configuration of protons and neutrons inside a nucleus can make the weak force come into play. It seems clearly to have a relation to the electromagnetic force, although that symmetry is only fully realized at high temperatures far beyond anything a star or planet can produce
- The weak force, acting inside nucleus of the atom, changes it from one chemical element to the neighboring element on the periodic table (see **Beta Decay**).
- Neither the weak nor strong force play much role in planets or climate, except to briefly refer to them in radioactive decay, a useful tool in age dating, as well as heating the insides of planets, as we shall see later.
- The weak force is very important for understanding the details of nuclear fusion and most high-energy astrophysics situations. But we won't talk about it much in Astro 4, and even less in Astro 3 and 7

Isotopes

- An "isotope" of an atom is a variant of the atom with a different number of neutrons
- So, for example, the common isotopes of Carbon are: **C^{12}, C^{13}, and C^{14}.**
- They all have 6 protons and 6 electrons so chemically they all behave like carbon
- But the C^{13} and C^{14} are heavier and this can affect the rate at which they do their chemistry – can be a useful thing helping us in doing our physics sleuthing

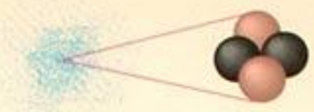
atomic number = number of protons
atomic weight = number of protons + neutrons

Hydrogen (^{1}H)



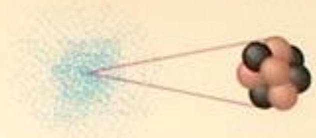
atomic number = 1
atomic weight = 1
(1 electron)

Helium (^{4}He)



atomic number = 2
atomic weight = 4
(2 electrons)

Carbon (^{12}C)



atomic number = 6
atomic weight = 12
(6 electrons)

The number of electrons in a neutral atom equals its atomic number.

Isotopes of Hydrogen

hydrogen

^{1}H
(1 proton)

deuterium

^{2}H
(1 proton + 1 neutron)

Isotopes of Carbon

carbon-12

^{12}C
(6 protons + 6 neutrons)

carbon-14

^{14}C
(6 protons + 8 neutrons)

The 4 Phases of Matter

1. Solid

- Atoms are “elbow-to-elbow” and keep their relative positions, but can still vibrate. A given atom moving through the solid is rare and very slow.
- The material is *incompressible.*

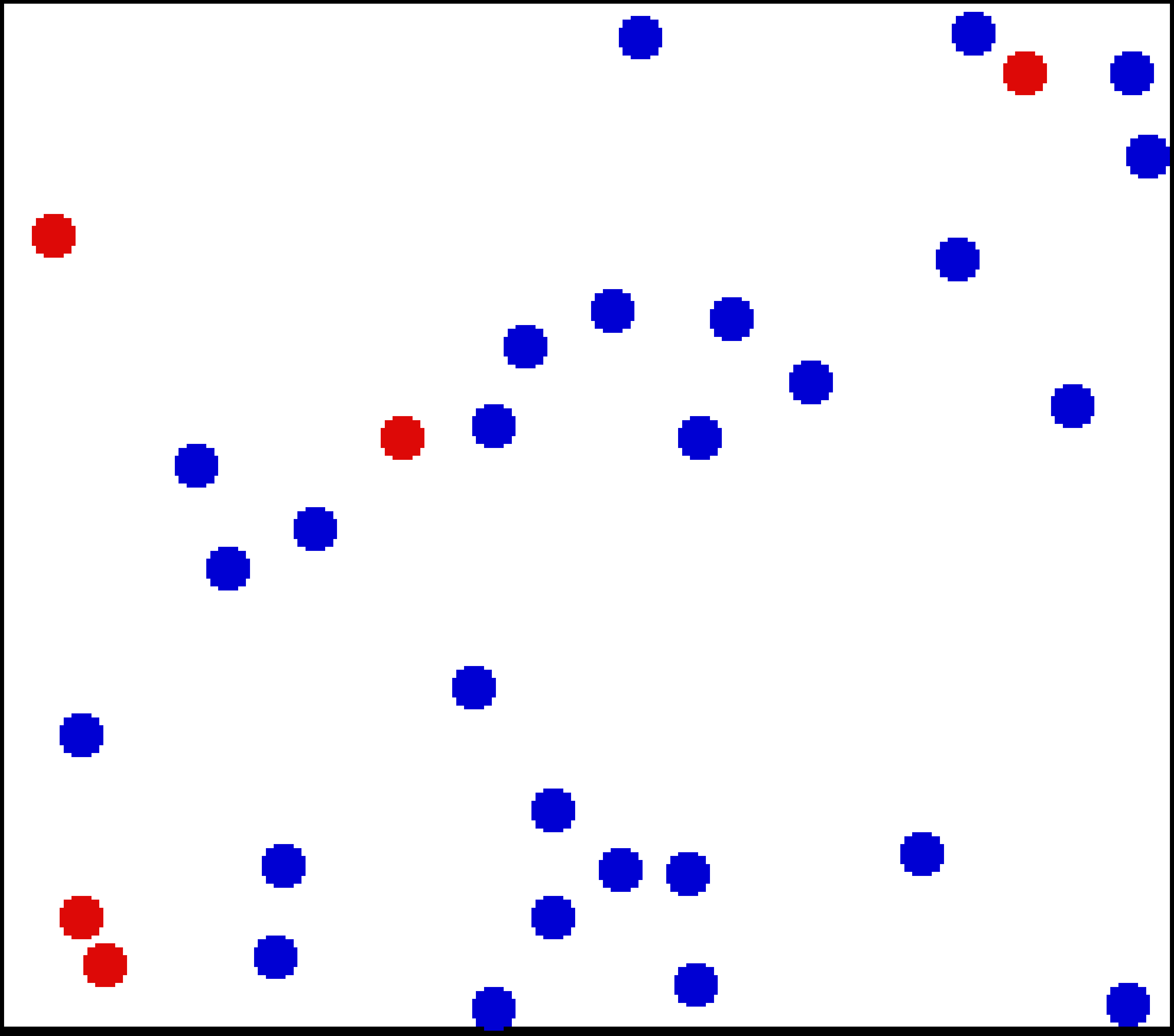
2. Liquid

- Atoms are still “elbow-to-elbow”, but now there’s enough energy to keep the atoms from locking together, and they mill around square-dance fashion.
- The material is still *incompressible*, but now it can flow.

3. Gas

- Atoms now have enough energy to keep from “sticking” at all. They ricochet off each other violently, with empty space around each atom.
- The atoms (or molecules) now are caroming off each other like balls on a pool table.
- With empty space around each atom, the material is now c*ompressible*.

Atoms (or molecules) in a Gas



4. Plasma = Ionized Gas

- At high temp, atoms hit each other so violently they knock electrons off some of the atoms. Each atom now called an “ion” and is positively charged. Negatively charged electrons also bouncing around.
- Charged – so feels the EM force, and in an EM field, behaves in a complex way compared to an ordinary (neutral) gas (more on EM fields later).
- Very roughly, the magnetic field locks together with the ionized gas; on a larger scale, they move around together. Unlike a neutral gas, which hardly notices if it’s in a magnetic field.
- Otherwise, it still is like a gas (compressible, empty space around each ion)
- (An atom can sometimes have one too many electrons too; that’s also an ion. Classic example is the H^- ion)

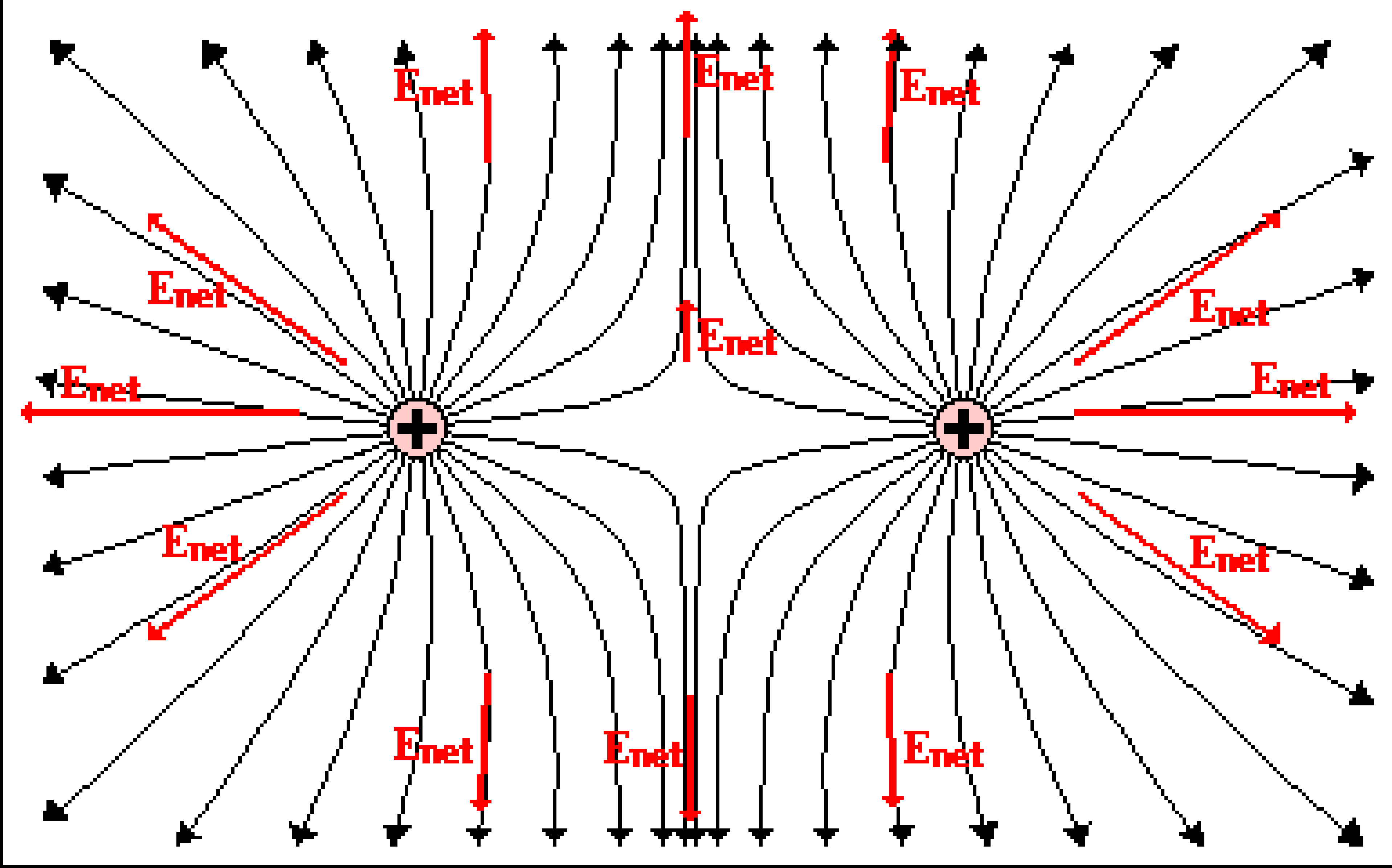
“Action at a Distance” *vs.* Field Paradigms

- Original Newtonian paradigm: charges act on other charges even if separated by large distances – “action at a distance”.
- Modern paradigm: A charge doesn’t really pull on a distant charge, instead, it sets up an **electromagnetic field** around itself and permeating all of space, and this field acts directly on other objects at the location of the field.
- It is the FIELD which has reality, has energy, and yet it has no mass.
- Yes, things can physically EXIST and interact with other existents, and yet have no MASS!
- Mass is just a property that some (most) things have, but not all.

The Electromagnetic Field

- Charge sets up around itself an Electric Field
- Charges will feel a force if they are in that field
- The force felt at a location has an *amount*, and a *direction*, so it's a *vector field*

The Electric Field Lines around Two Protons. Proton Repels Proton



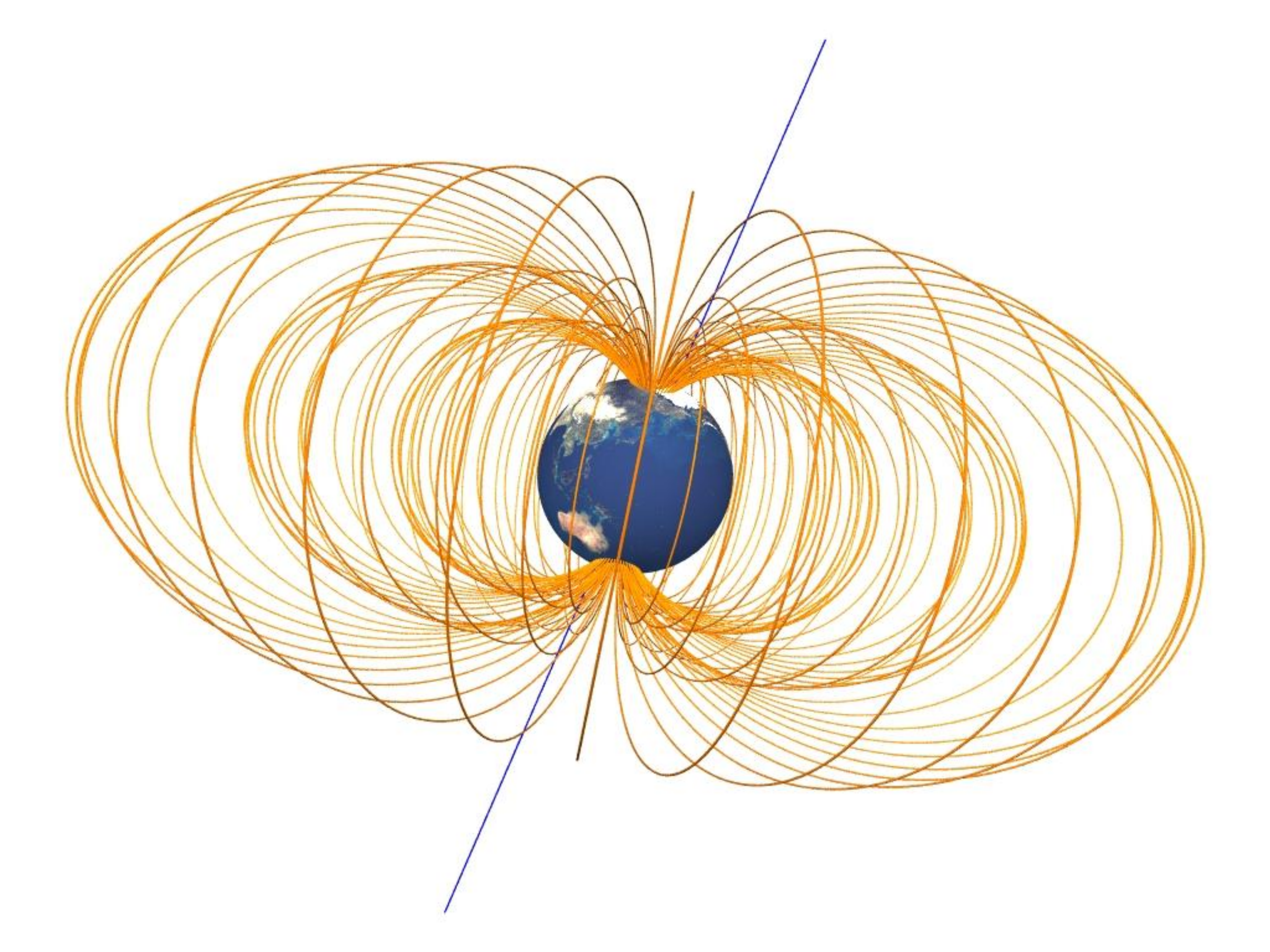
A Changing ***Electric*** field Creates a ***Magnetic*** field…

- Accelerate a charge, you wiggle the associated field, and this wiggle moves outward at the speed of light. 300,000 km/sec
- But this changing electric field creates a magnetic field, and a changing magnetic field creates an electric field
- **And a moving self-propagating electromagnetic field is… LIGHT!**

What is a Magnetic Field?

- Let’s say it this way – Motionless charges feel a force we describe as the electric force, quantifiable as the electric field
- Moving charges additionally feel a different aspect of EM force, called **magnetism**
- The force acts perpendicular to the velocity. We can link these two forces into a single set of equations – Maxwell’s equations – which are partial differential vector equations you’d use if you were in an upper division or graduate physics course in classical electromagnetism.
- Magnetic field lines can be usefully defined, because charges will spiral around the direction of these lines as they move. The “lines” are conceptual mathematical constructs conveying meaning, not literal little strings in space.
- Magnetic field lines carry two pieces of information: the direction of the field at that place, and the number of lines per unit area convey the strength of the field at that place.

Magnetic Field lines for the Earth



Maxwell's Equations – Simplest Case is a Vacuum with No Charges

In a region with no charges (ρ = 0) and no currents (**J** = 0), such as in a vacuum, Maxwell's equations reduce to:

$$\nabla \cdot \mathbf{E} = 0$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}.$$

These equations lead directly to **E** and **B** satisfying the wave equation for which the solutions are linear combinations of plane waves traveling at the speed of light,

The mathematical solution to these equations is travelling waves: Light!

<u>These equations are Nature, talking to us!</u>

They may seem mathematically complicated, but they have a symmetry which, once you get comfortable with differential operators and their physical meaning, have a simplicity and harmony which seems …. Natural! If they're not natural to you, they could be, if you learn the language. The world needs more people like this by the way (*vs.* more, say, burger flippers!)

In General, Maxwell's Equations Look Like this…

- For more, check here.

Differential formulation

Name	"Microscopic" equations	"Macroscopic" equations
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$	$\nabla \cdot \mathbf{D} = \rho_f$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t}$

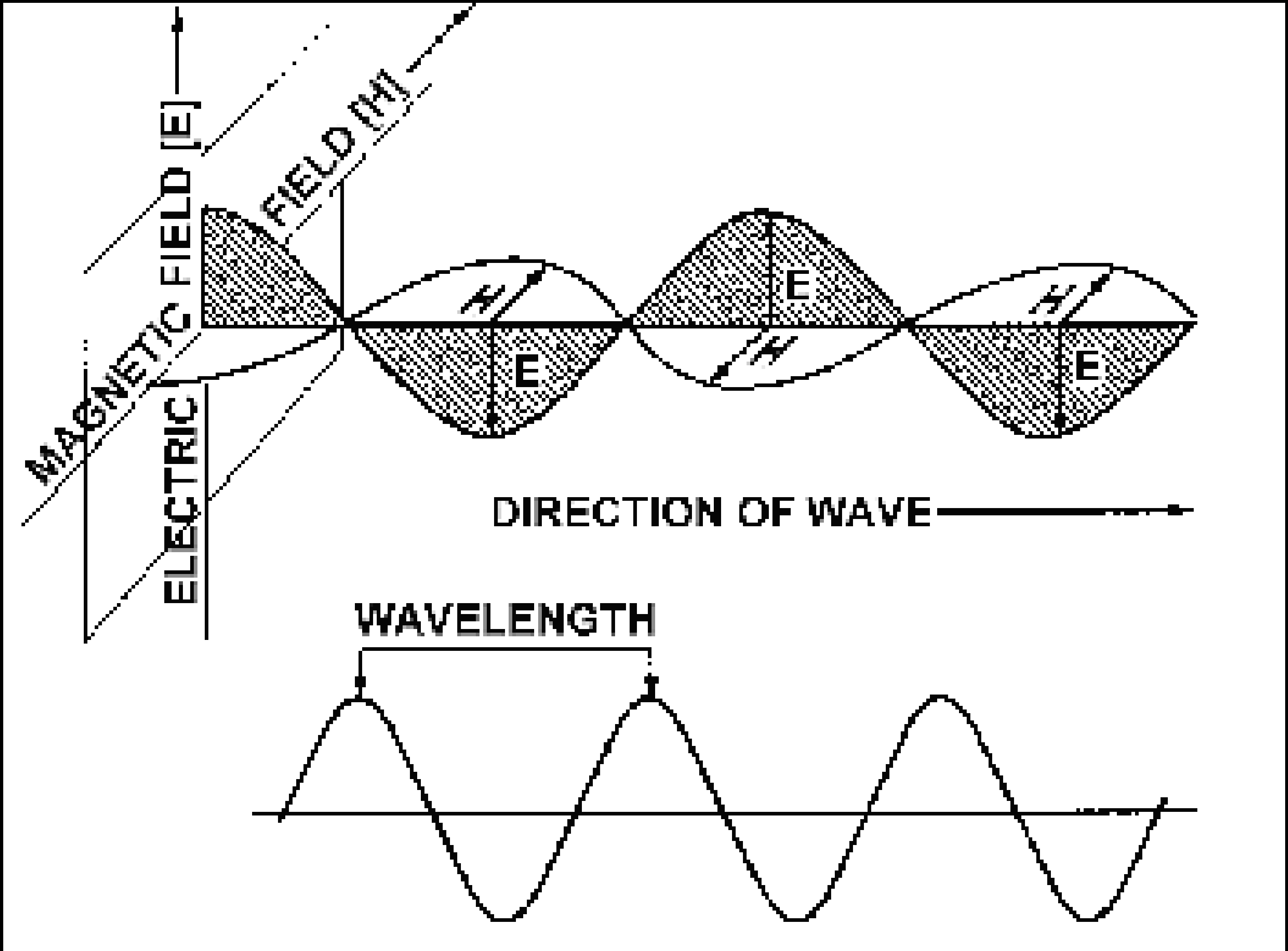
These Equations Show us how Electric Power is Created

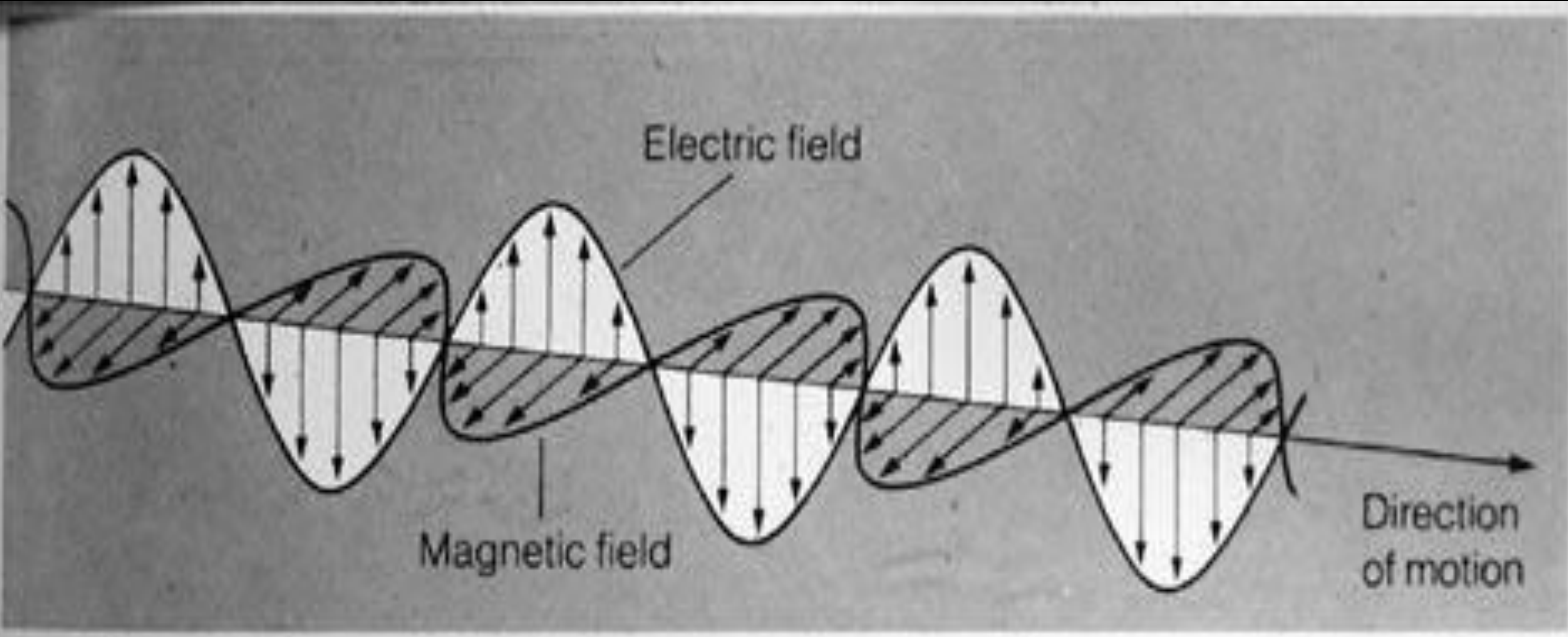
- Take a big magnet, spin it very fast (like, attach it to paddle wheels and run water over the paddle wheels). The “circular” aspect of the magnetic field (the “B”), creates a linear electric field, which pushes free charges in good conductors like copper or silver or aluminum, along the conductor – along at high voltage to get to your home, where they’re converted to safer low voltage, and then run your STUFF.

EM Field Waves are Quantized

- These field changes are not quite like water waves; they’re quantized into individual little bundles of energy possessing wave-like and particle-like characteristics.
- They’re… ***photons!***
- How to picture a photon?....

A Photon: A Travelling Oscillating Electric and Magnetic Field




Electric field
Magnetic field
Direction
of motion

The Energy of a Photon…

Do you suppose shorter wavelength photons have MORE, or LESS energy?

The Energy of a Photon…

- Your intuition is (I expect) correct! …
- More rapidly oscillating waves have more energy
- Said another way; **higher frequency** corresponds to **more photon energy**
- And, **shorter wavelength** corresponds to higher frequency and **higher photon energy**

Nature is Simple Here

- She's decided to go with the simplest mathematical expression which embodies these two correct intuitions
- ***E = hv***, where ***v*** is "frequency" = number of waves passing a location per second, and ***h*** is Planck's Constant. ***v*** is related to wavelength, so that…
- ***E = hc/λ***, where ***λ*** is the wavelength of the wave, and **c** is the speed of light
- (The fact that ***h=6.626 x 10^-27^ erg-seconds, or 6.626 x 10^-34^ joule-seconds***) is so very tiny, is telling us that quantum mechanics, pretty much, is only obvious at very tiny size scales)
- ***For this class, you only need to remember: higher frequency photons = shorter wavelength photons = higher energy***

Two Ways to Produce Photons…

- #1. Accelerate a charge, as we just showed.
- #2. Quantum transitions within atoms or molecules, to lower orbitals

- Let’s talk about the first way, as applied to a large number of atoms or molecules bouncing against each other…

Thermal Radiation

- Imagine atoms in a solid, vibrating against each other, or in a fluid, colliding against each other. This deforms their electron clouds, since electrons repel each other; a kind of "acceleration of a charge" - one of the two ways photons are produced.
- And so… Light is produced by all objects not at absolute zero temperature.
- This light bouncing around will exchange energy with the particles so that the particles and photons come to have the same temperature. In other words, the temperature of the material is directly observable by the distribution of photon energies that are emitted.

- In this way, in a typical gas of huge numbers of atoms, there will be huge numbers of photons produced every second
- Emerging light will have a "grade curve" distribution of photon energy.
- This is called a **"Thermal" spectrum. You'll hear me use an older but still popular term which means exactly the same thing – "Blackbody" spectrum.**

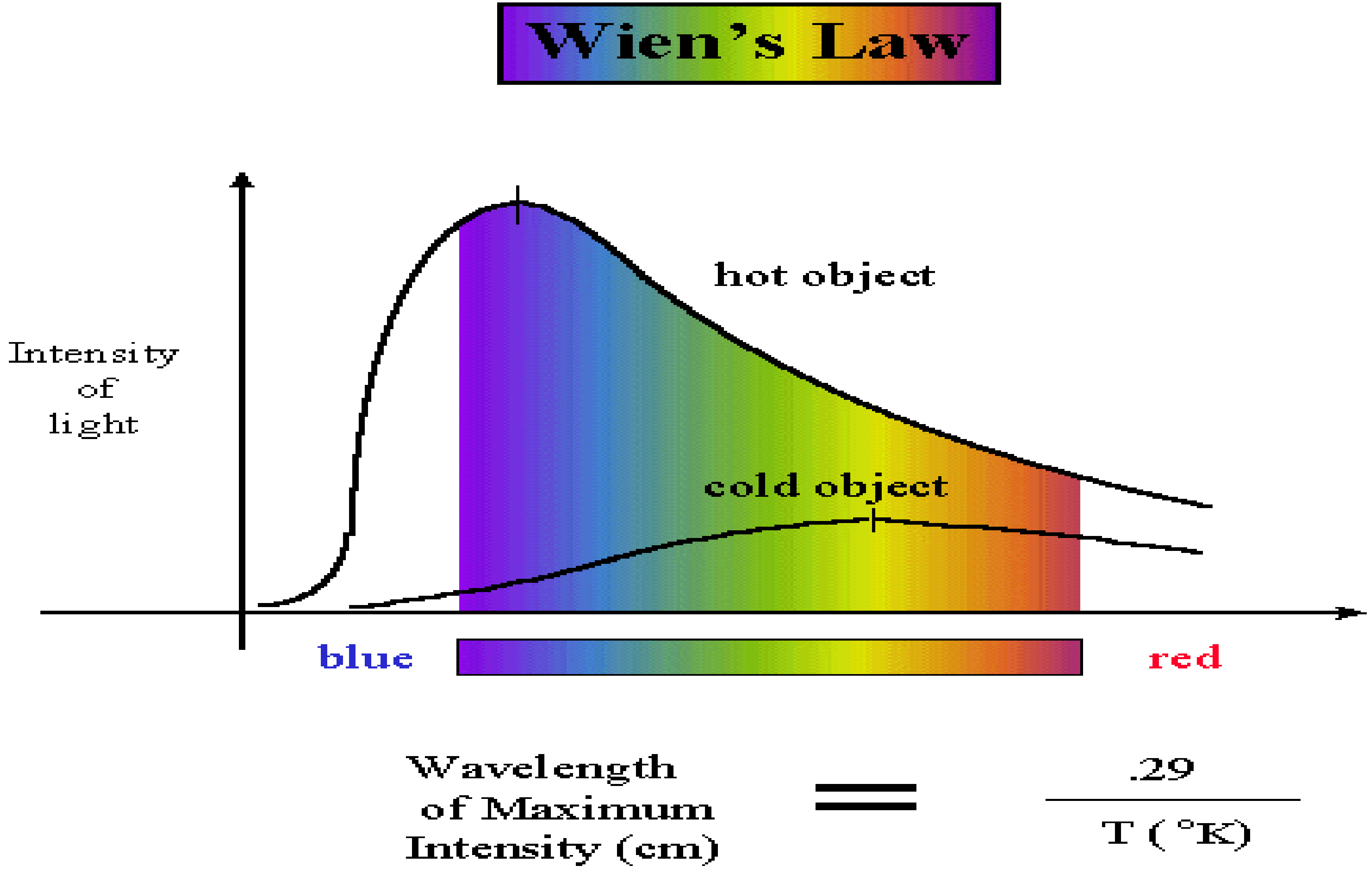
The Two Laws of Thermal Radiation

- **Wien's Law:** the wavelength of the maximum intensity is inversely proportional to the temperature. ***Higher temperature -> shorter wavelength for most of the light***
- **Stefan-Boltzmann Law:** The luminosity per unit area from a thermal radiator is proportional to the temperature to the 4^{th} power. ***Hotter objects are MUCH brighter***
- Here's what they mean…

But First… What is a Spectrum?

- Light (photons) emerge by the billions from objects, usually with a wide range of wavelengths
- A graph of how much energy is emitted at each wavelength is called the object's "spectrum".

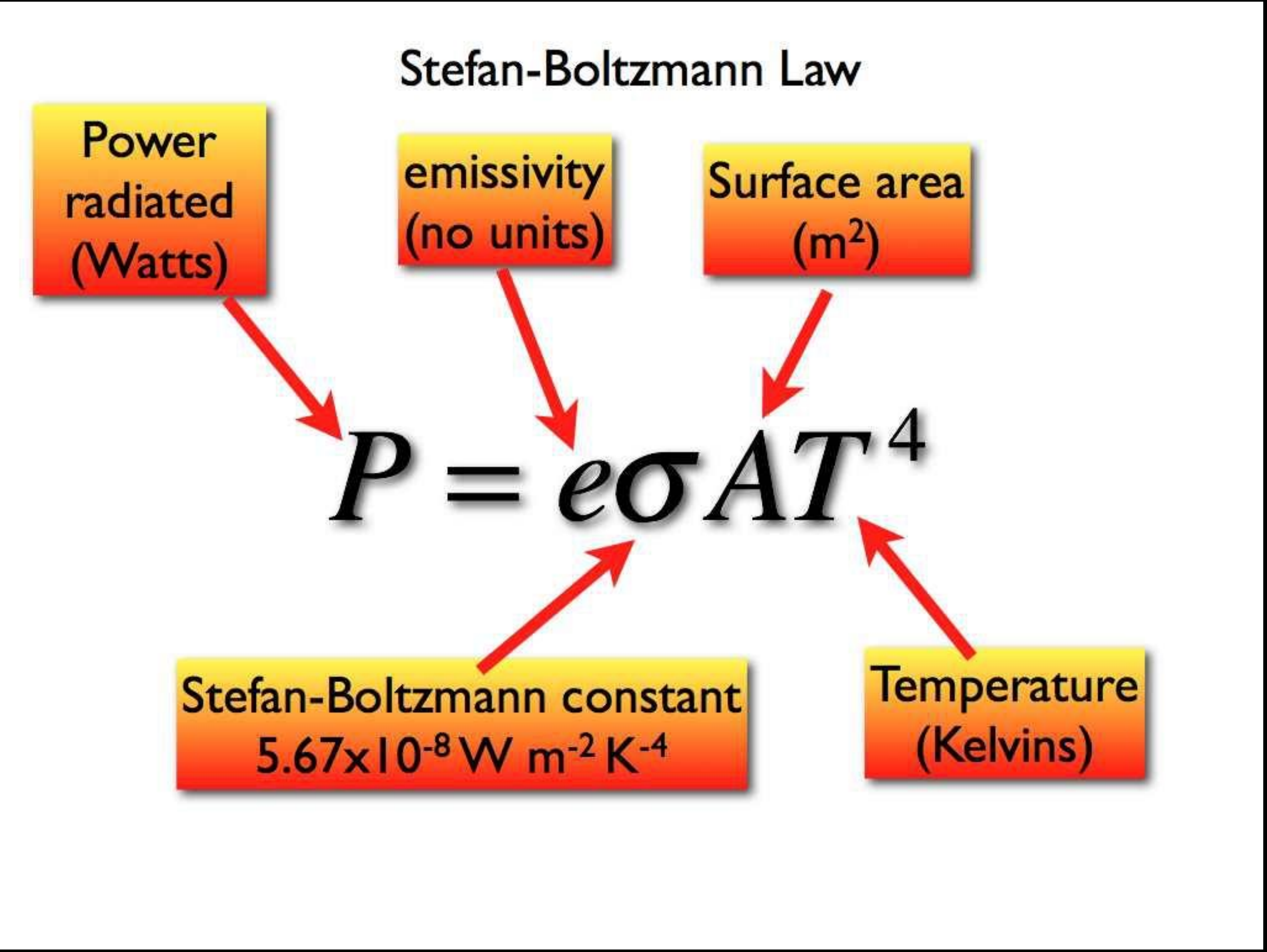
Eyeballs have built-in wavelength detectors; we perceive different wavelengths as having different color.



The Stefan-Boltzmann Law

- At higher temperatures, the particles are banging against each other more often, and with more deformation, and both aspects produce more photons, and each of these, on average, is more energetic.
- The net result is a lot more energy for a thermal radiator which is at higher temperature
- Don't bother memorizing the names associated with these laws – only the idea of each is important.

Stefan-Boltzmann Law: Power (called Luminosity in Astronomy), goes as Temp to the 4th power



Wein's and Stefan-Boltzmann Laws: Hotter Stars are BLUER and BRIGHTER

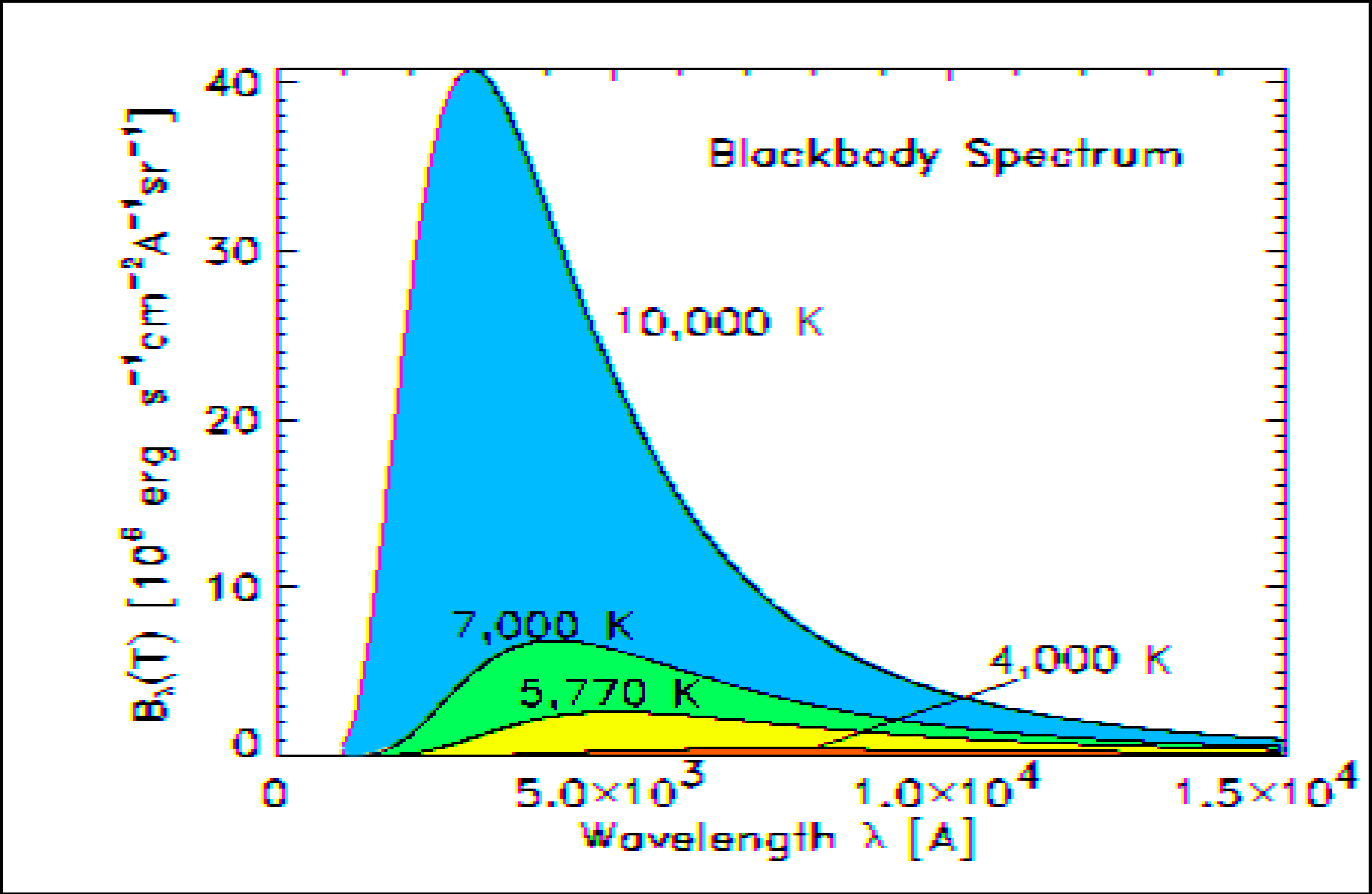
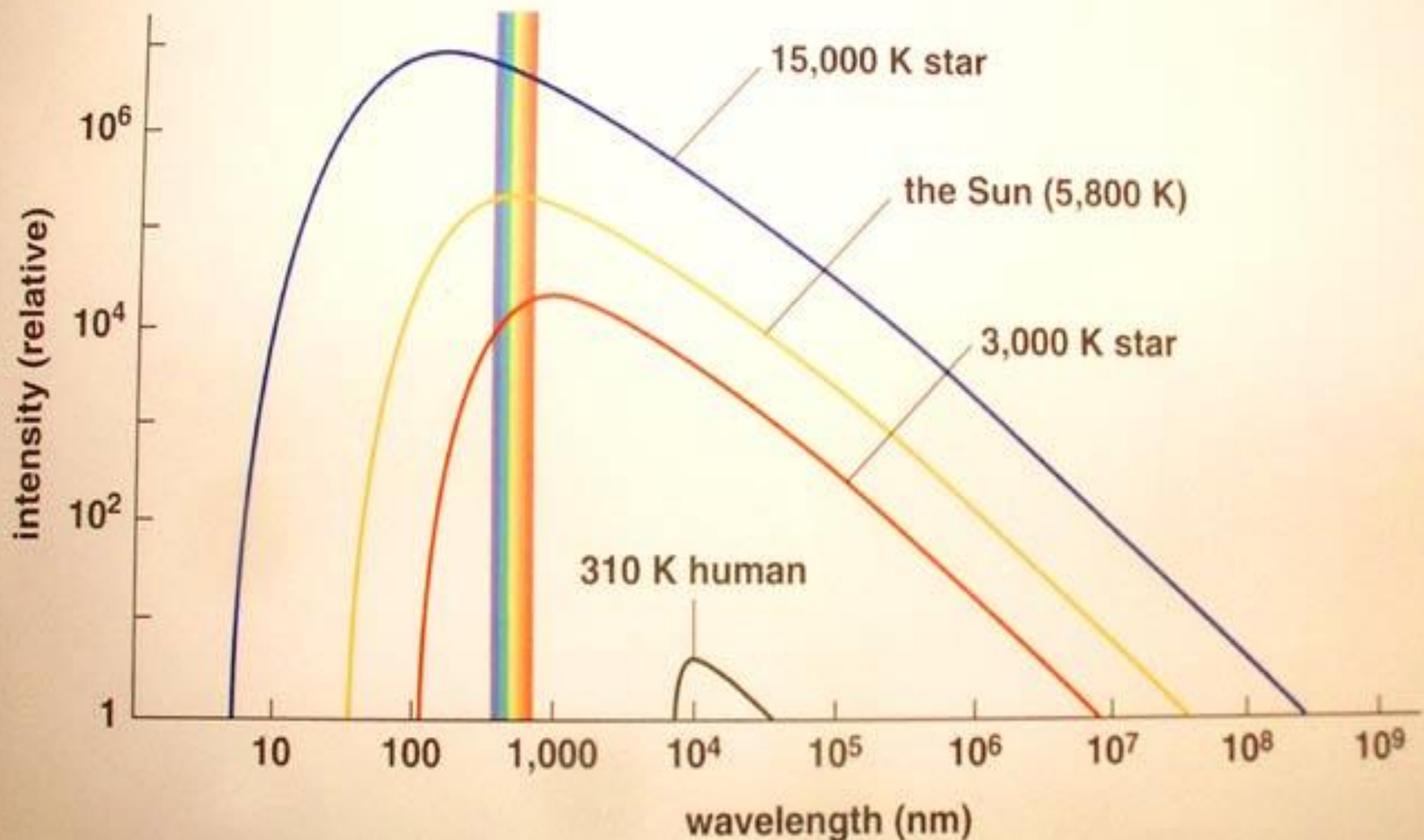


Figure 6.10 Graphs of idealized thermal radiation spectra



Thermal Radiators: What temperature goes with what peak wavelength?

- Billions of Kelvins: gives **Gamma rays**
- Millions of Kelvins: gives **X-rays**
- 10's-100's thousands Kelvins: gives **UltraViolet**
- Few thousand Kelvins: gives **visible light**
- Few hundred Kelvins: gives **Infrared (like planets)**
- Few Kelvin: gives **Microwaves**
- Radio waves are produced non-thermally, nothing in the universe is colder than a few K, because of the residual Big Bang radiation.

Note Where Stars and Planets Radiate their Light

- **Stars** are a few thousand degrees Kelvin, so they give off mostly **VISIBLE light**
- **Planets** are a few hundred degrees Kelvin (room temperature such as you're feeling now, is about 280 Kelvin, for example), and so planets radiate in the **INFRARED light**

The Second Way to Produce Photons…

- #2. Downward transitions between the allowed energy levels in an atom or molecule

How Do Electron Orbital Transitions Work?

- **Absorption** – an electron can be bumped to a higher orbit if a photon hits the atom and it has *exactly* the same energy as the energy difference between the two orbitals.
- **Emission** – an electron will fall down to a lower orbital if it is available, giving off the energy difference between the orbitals <u>**as a photon**</u>

How Does the Atom or Molecule Get into a Higher Energy State in the First Place?

- We say the atom is “in an excited state”.
- We can **excite an atom in either of two ways:**
- **1.** Hit it with a photon with the right energy to take it a higher allowed orbital (absorption)
- **2.** A collision with another atom or molecule could also move the electron to a higher level

The Energy Levels for Hydrogen

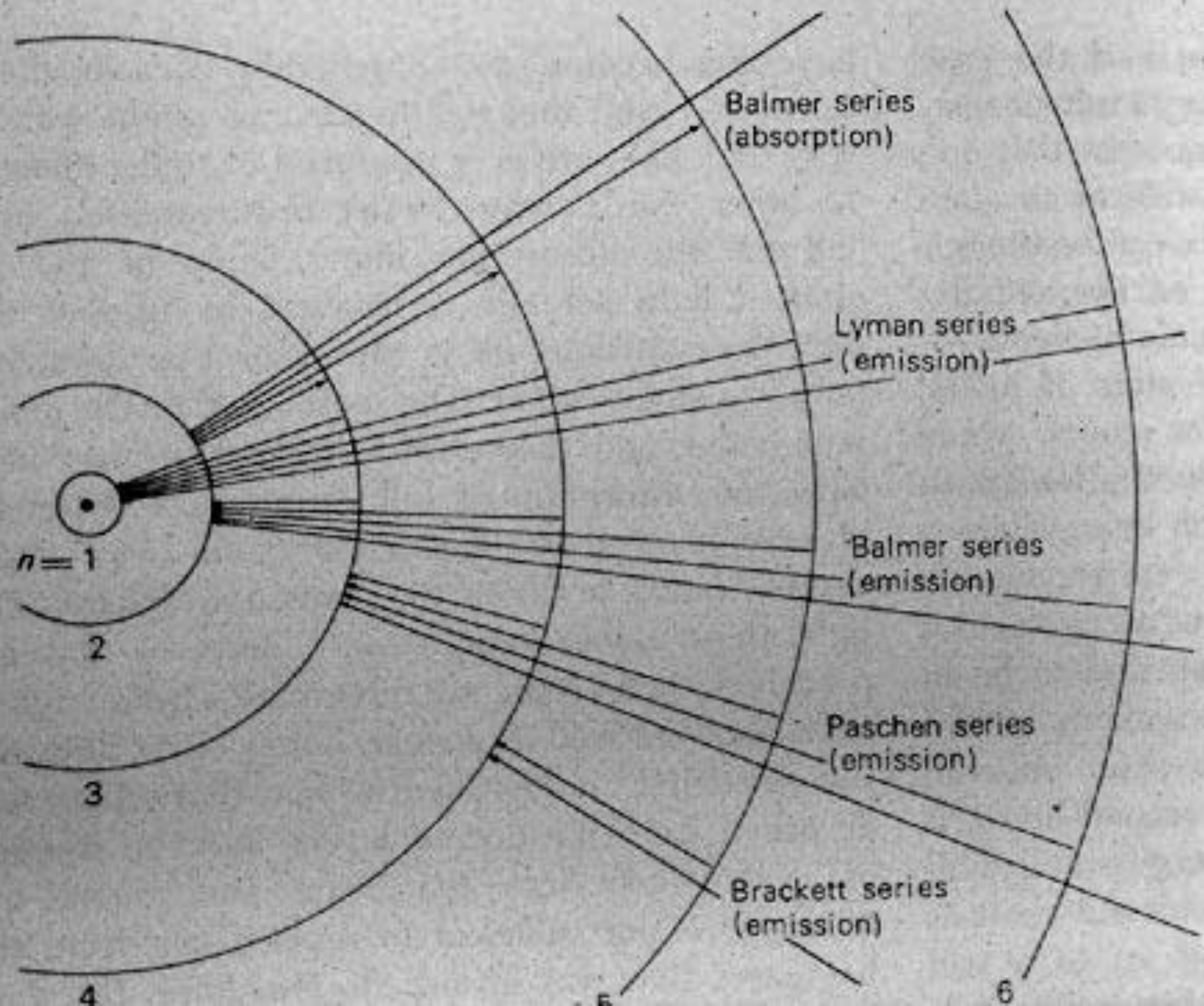
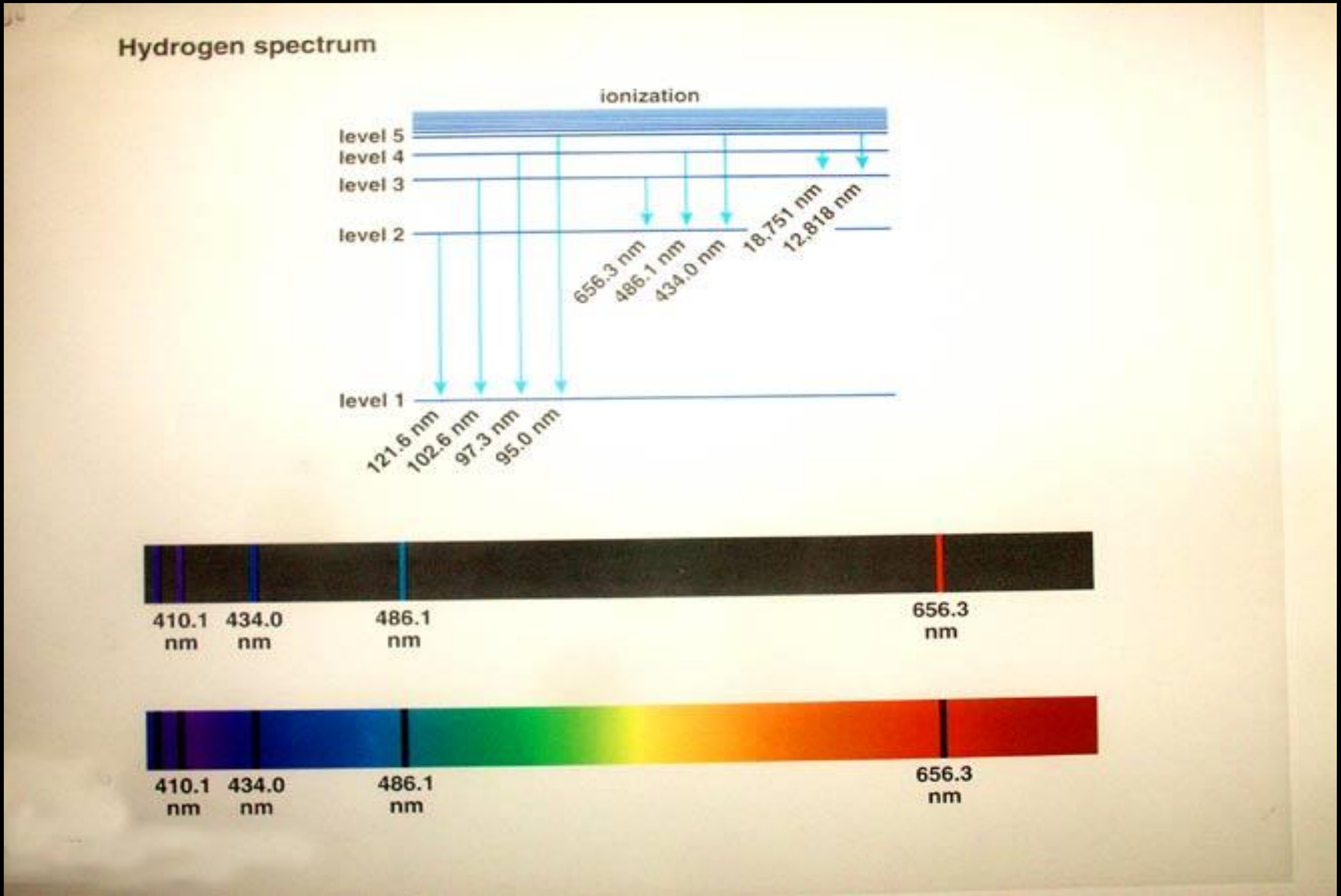


FIG. 10-20 Emission a[n]d absorption of light by th[e] hydrogen atom accordin[g] to the Bohr model.

Hydrogen Spectrum in the Visible Range: Emission spectrum (top) and Absorption spectrum (bottom)



Emission, Absorption: it all depends on the background. Looking at a blackbody through a foreground cloud, and the cloud takes out dark absorption lines. But look at the same cloud against a black background and you see only those lines: emission lines

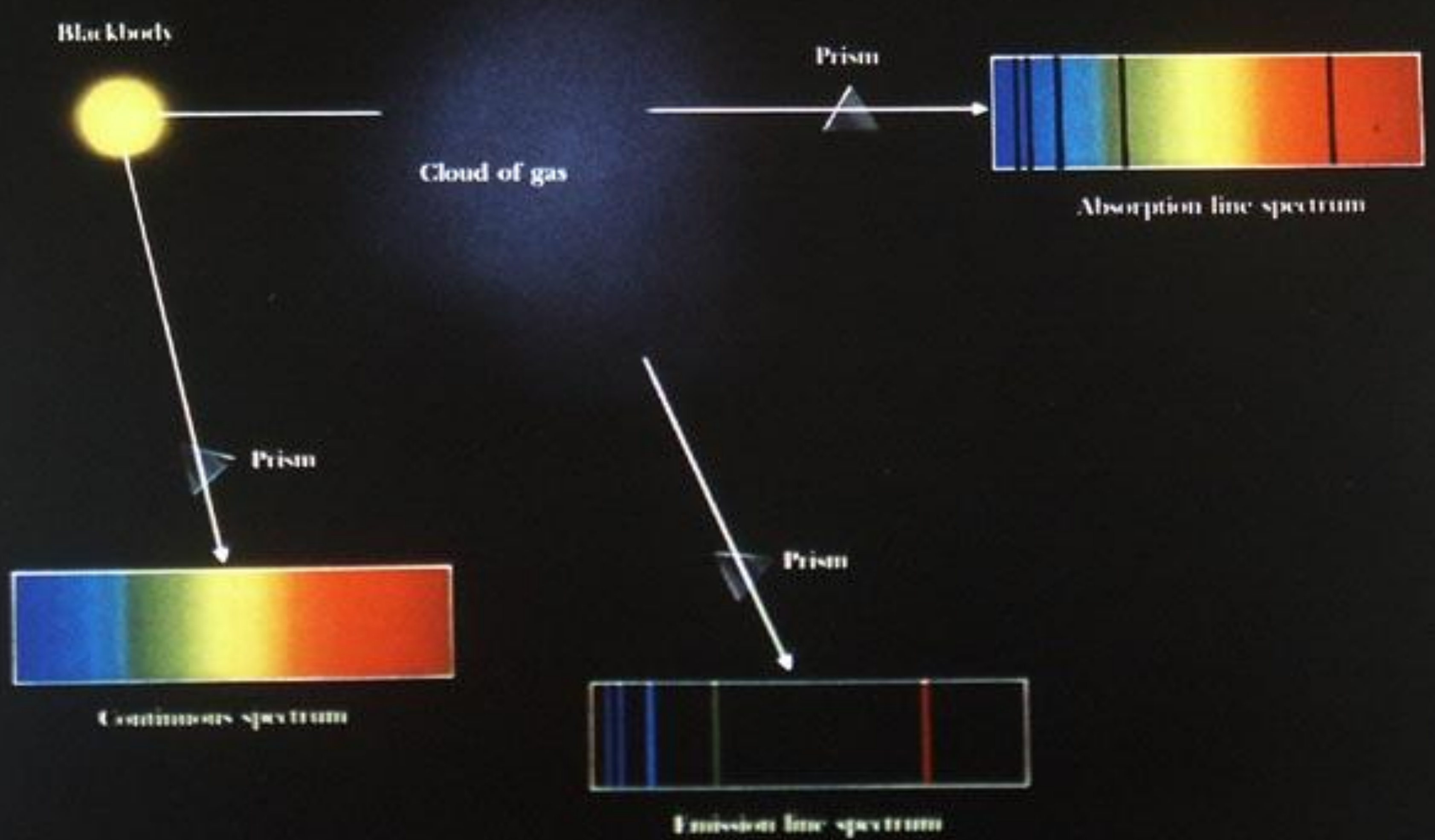
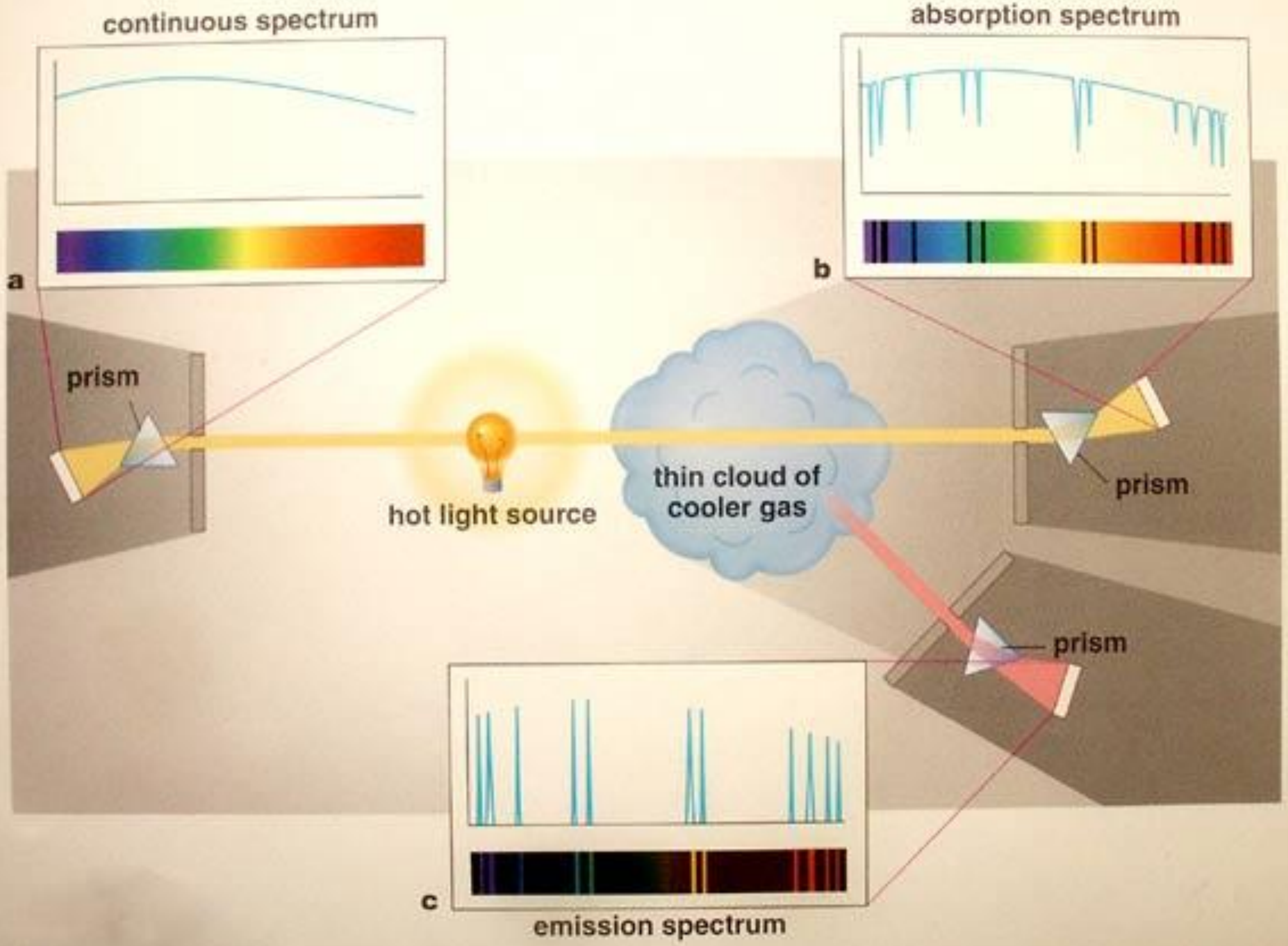


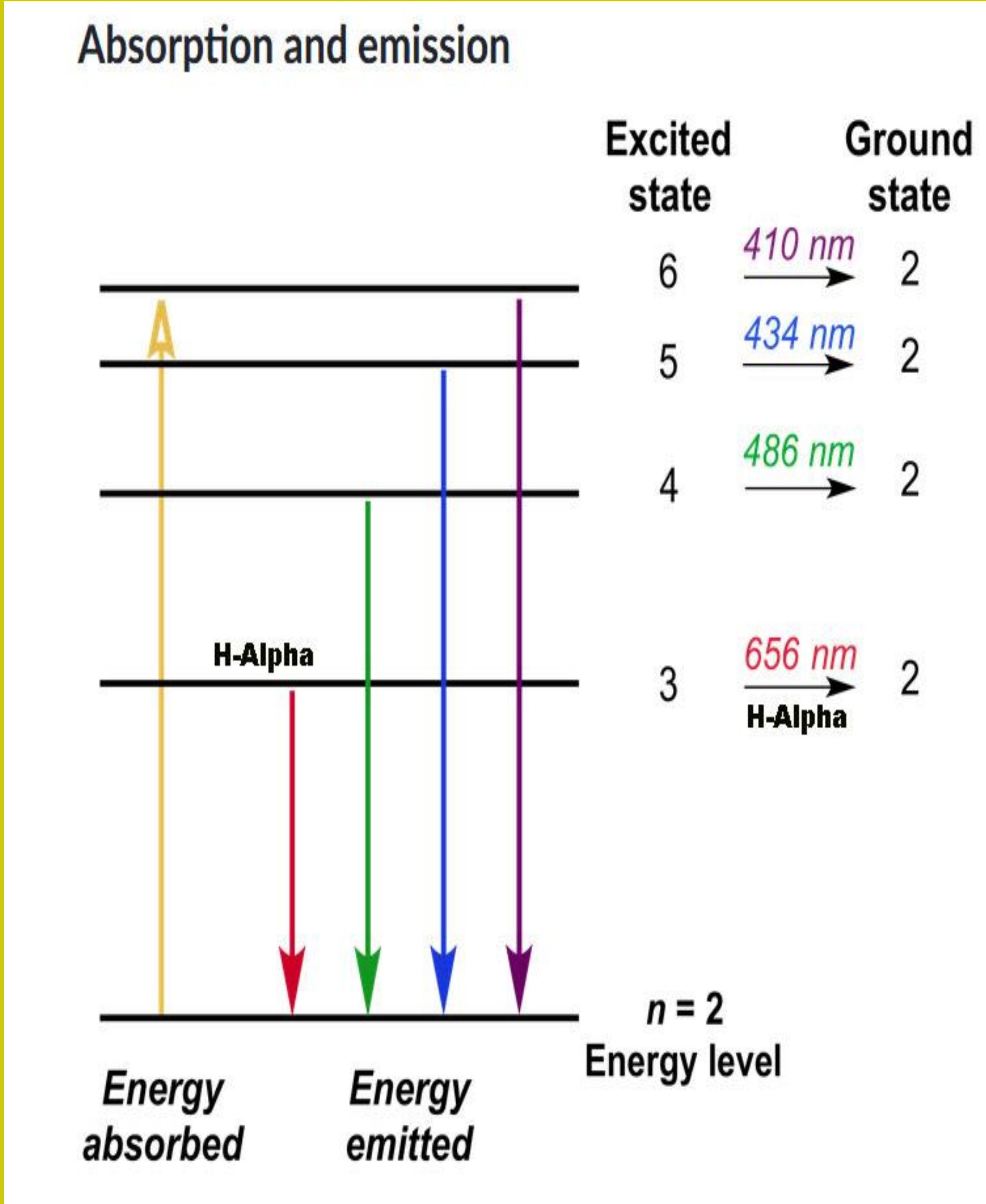
Figure 6.11 Summary of spectral formation (Kirchhoff's laws)



Summarizing Types of Spectra…

- ***Thermal spectrum*** – a spectrum produced by an object purely because of its temperature (reflected light doesn't count). In a gas, must be opaque enough for photons to bounce around hitting lots of particles and so be in temperature equilibrium with the particles. For a solid, an example is the filament of a light bulb
- ***Emission spectrum*** – a spectrum dominated by emission lines. **Clouds of gas** with hot stars shining on them produce this kind of spectrum
- ***Absorption spectrum*** – a smooth continuous range of wavelengths, but certain wavelengths have less energy than surrounding wavelengths and so appear dark by contrast. **Stars** usually have this kind of spectrum
-

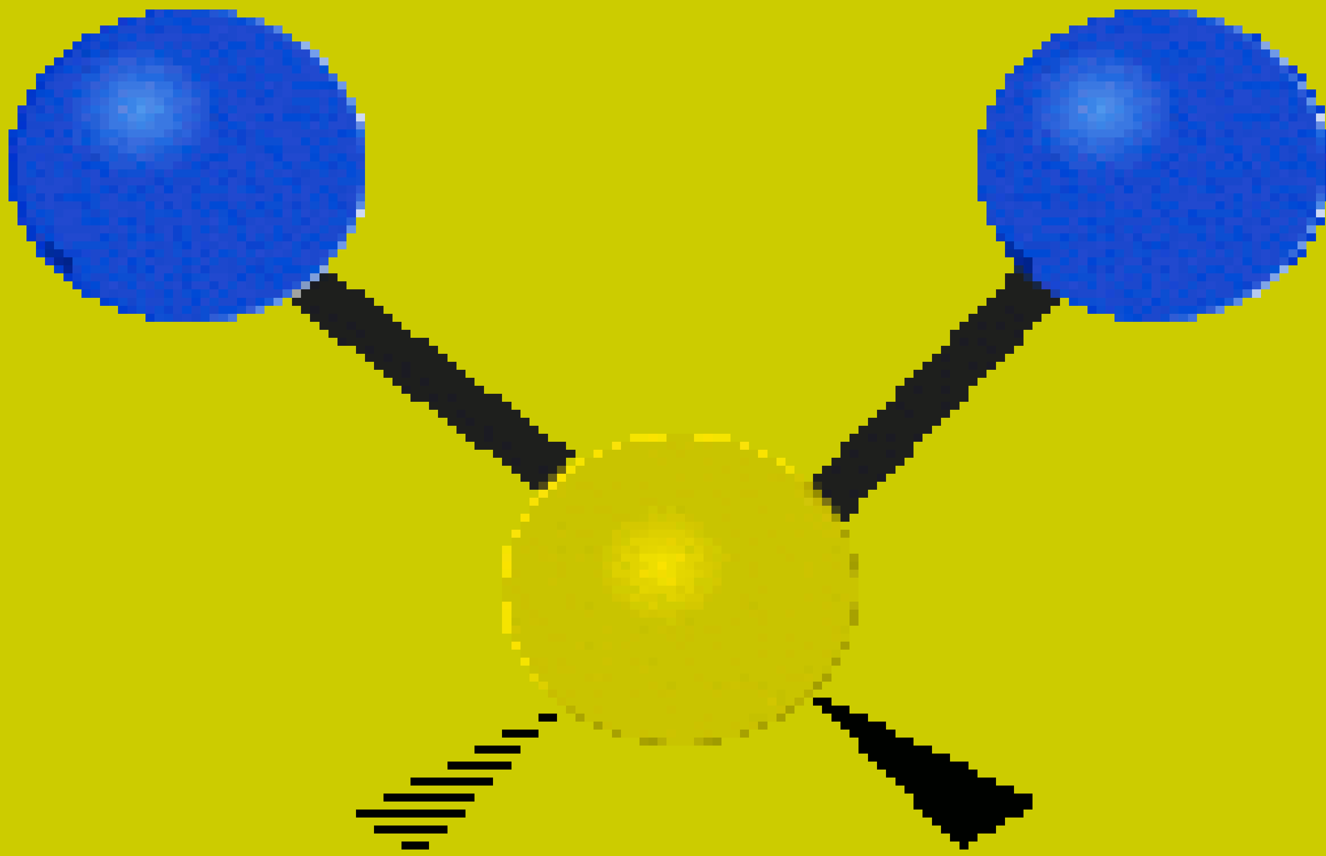
The "PacMan Nebula" – What kind of Spectrum Does it Show?

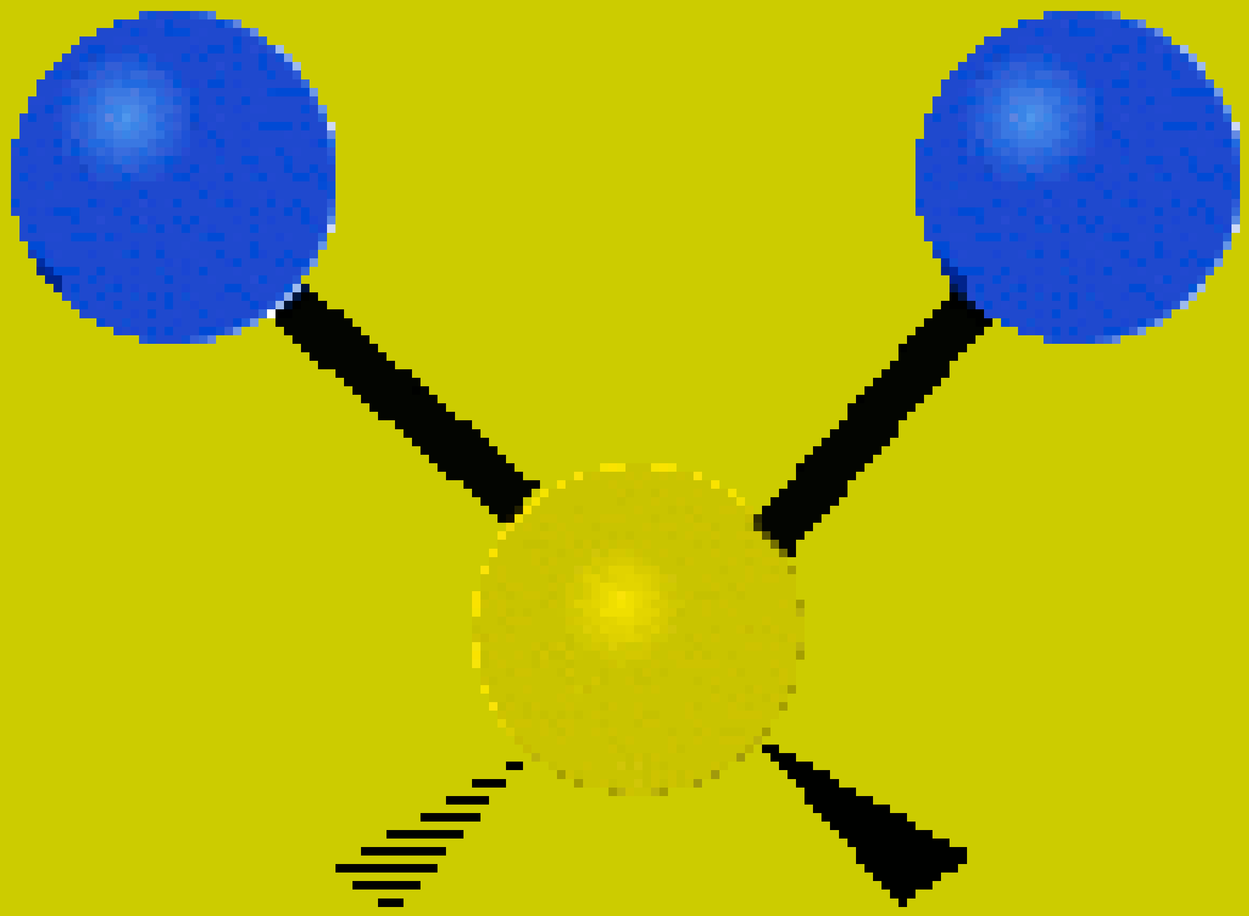


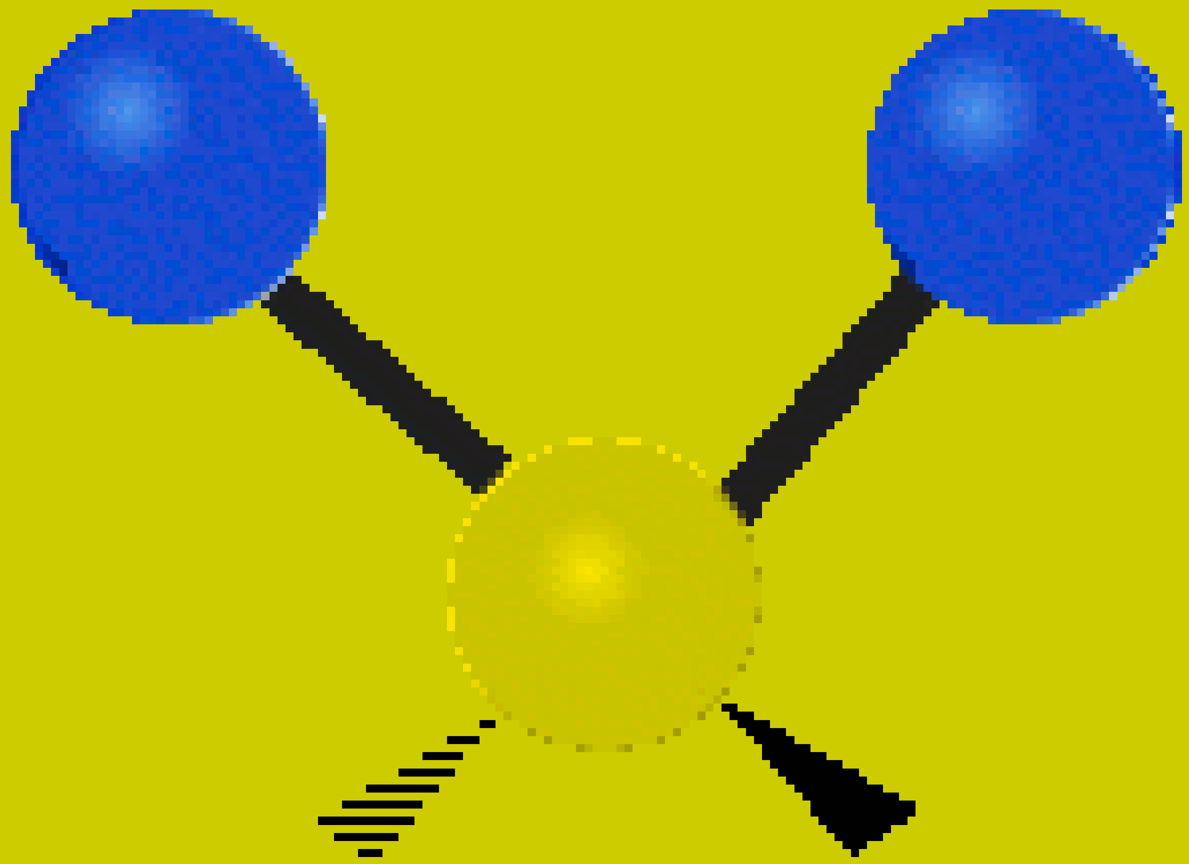
The transition of electrons from orbit 3 to orbit 2 is the most **visible** and dominant of all spectral lines, since 90% of all atoms are Hydrogen. We name it**:** the **H-Alpha** line. Most nebulae are red because of this line!

Absorption by Molecules

- Molecules have additional degrees of freedom which can be excited
- Collisions or absorption of photons can excite these
- These degrees of freedom are…
- Vibration, rotation for molecules with 2 or more atoms
- And more… (“wagging” of various kinds) for more complex molecules
- To see a few of the **vibration modes of CO2**, check this link





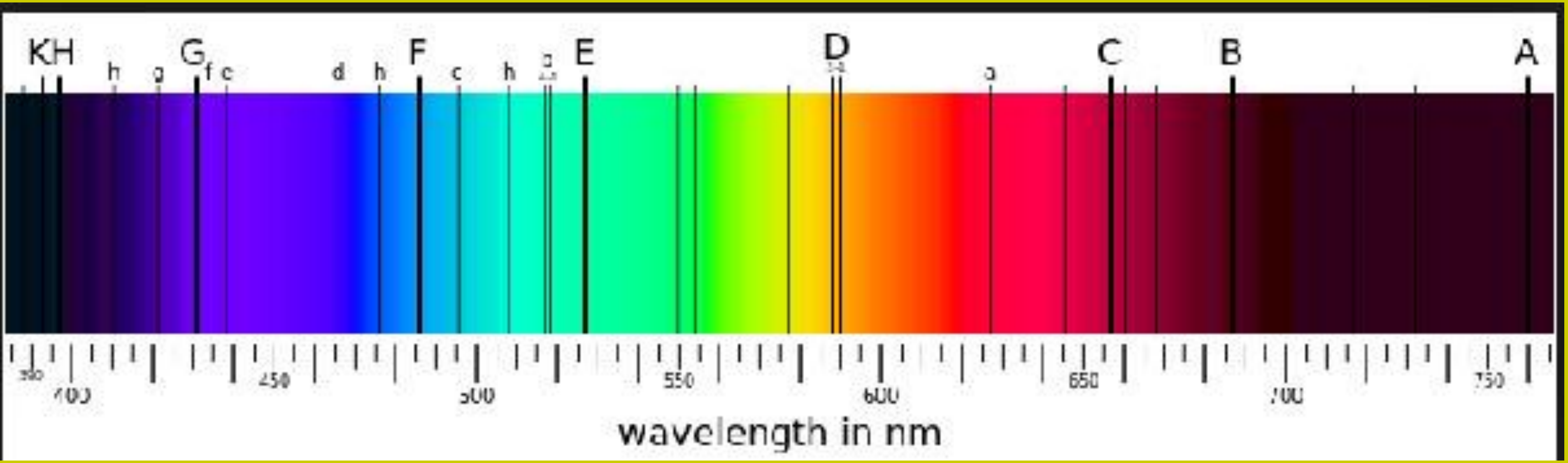


These Internal Excitations Are Additional Ways that Molecules can Soak Up Energy

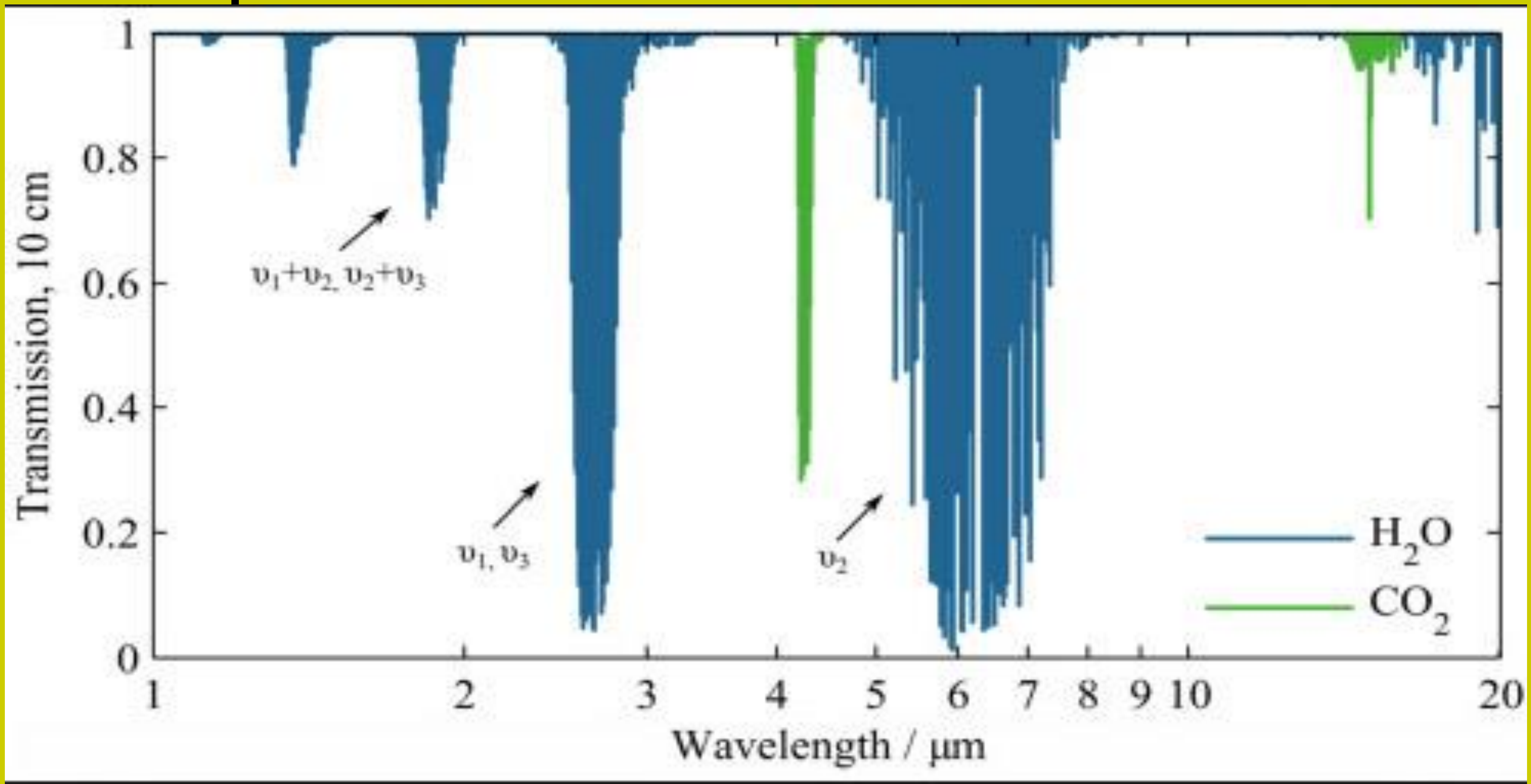
- If you add an increment of heat to a gas of molecules, some of the heat goes into adding to these internal excitations, and this part does not go into kinetic energy of the molecule as a whole.
- This partly explains why water H_2O can absorb a lot of heat energy without raising its temperature much; a good deal of the energy goes into those hydrogen bonds.
- These excited states, just like for atoms, are quantized. The transitions between these produce “lines” but they are much broader than for atoms. Big ranges of wavelengths are absorbed, and we call these **Absorption Bands**. **So molecules can take out large swaths of passing light – essential for understanding the Greenhouse Effect, for example.**

Absorption Lines from Atoms, vs Absorption Bands from Molecules

Absorption LINES come from electrons transitioning between orbitals in a single atom. The Energy of that transition will be very tightly confined to the precise proper value. Lines on a spectrum image will be dark and narrow



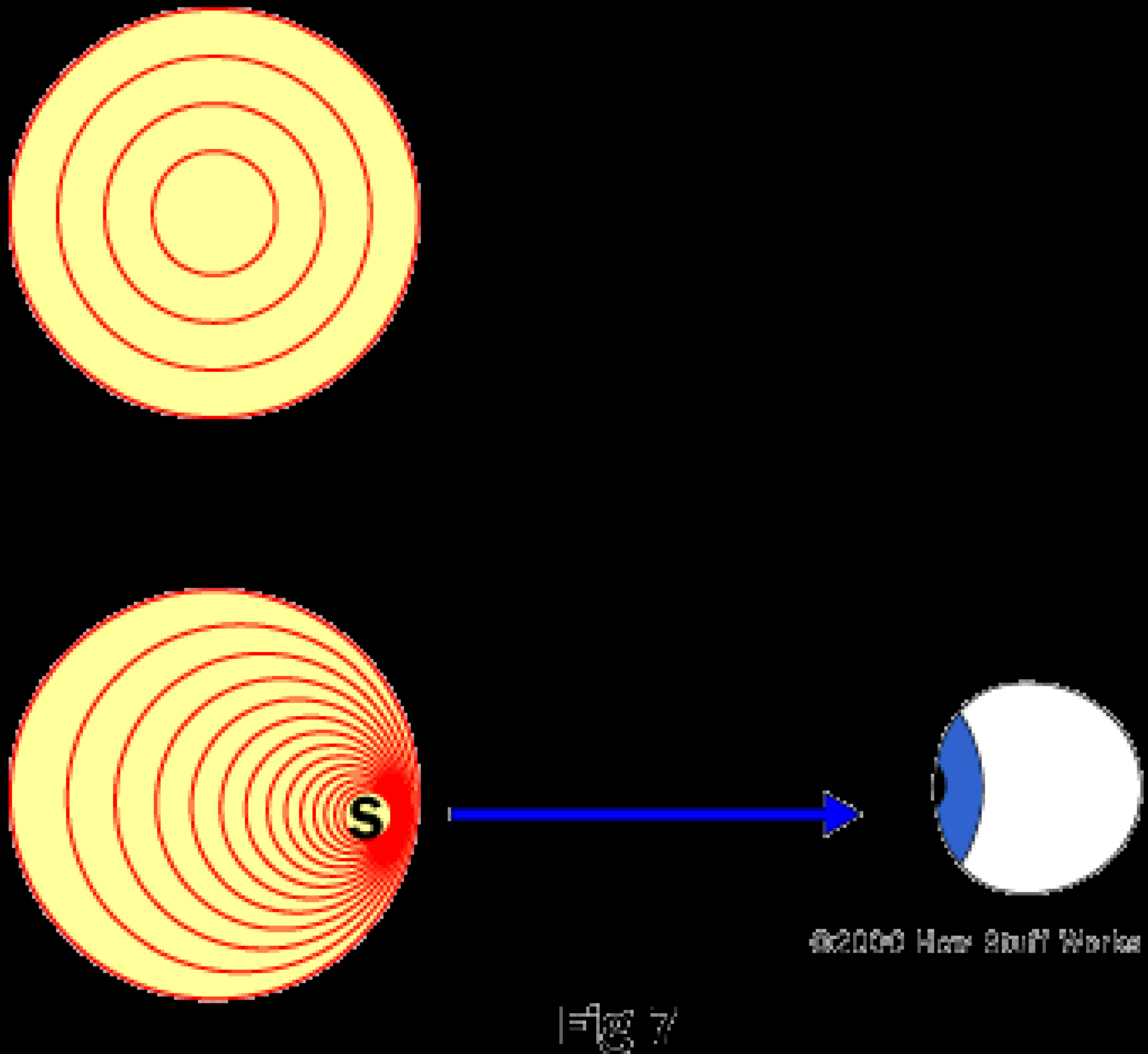
Absorption BANDS are from transitions in vibration states in molecules. The laws of quantum mechanics here allow these energies to be much “fuzzier” and broader. A spectrum will show broad **BANDS**



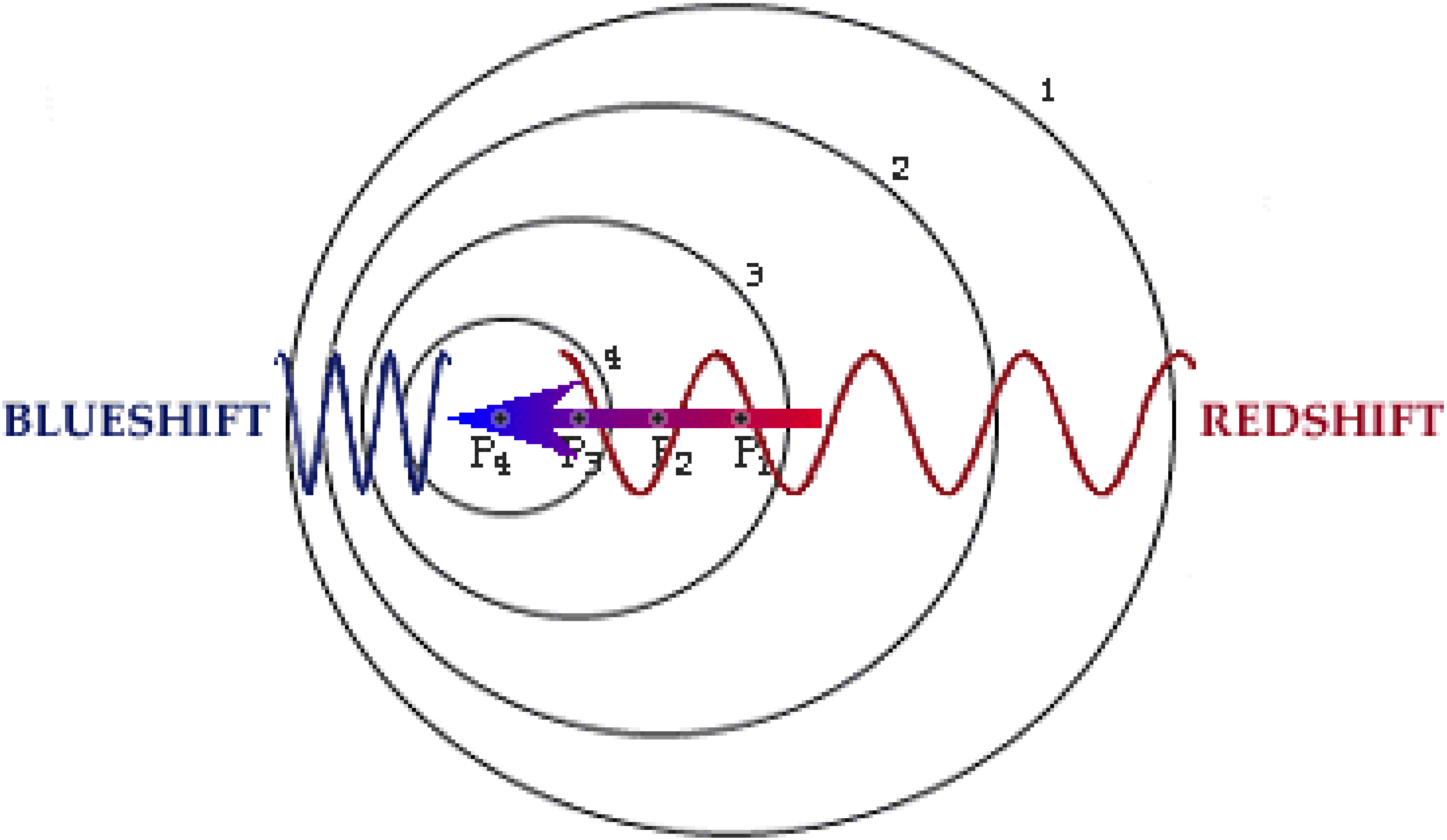
The Doppler Effect

- The Doppler Effect is the change in the observed energy (and therefore frequency and wavelength) of a wave, caused by line-of-sight motion between the source and the observer.
- Not just light, but sound, or surface waves, or in fact *any* wave.
- Source, observer approach each other *blueshifts* the light, i.e. photon wavelengths are shorter.
- Source, observer moving apart *redshifts* the light; i.e. photon wavelengths are longer.
- **<u>Doppler shifts only occur due to velocity along the line of sight, not transverse velocity.</u>**
- We LOVE the Doppler Effect – it gives us a way to measure velocities in the Universe! (But, transverse velocities are much harder to measure because the Doppler Effect doesn’t apply)

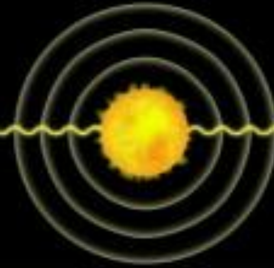
The Doppler Effect: Here, blueshifted light (note the spooky eyeball)



Redshifted *vs.* Blueshifted light



DOPPLER EFFECT



When a star is stationary relative to an observer, the light produced looks the same no matter what what direction it is seen from. Our sun is a good example of a star that is not moving much nearer or farther from the Earth.

If stars move either towards or away from our vantage point, however, the motion shifts the way their light looks to us.

RED SHIFT

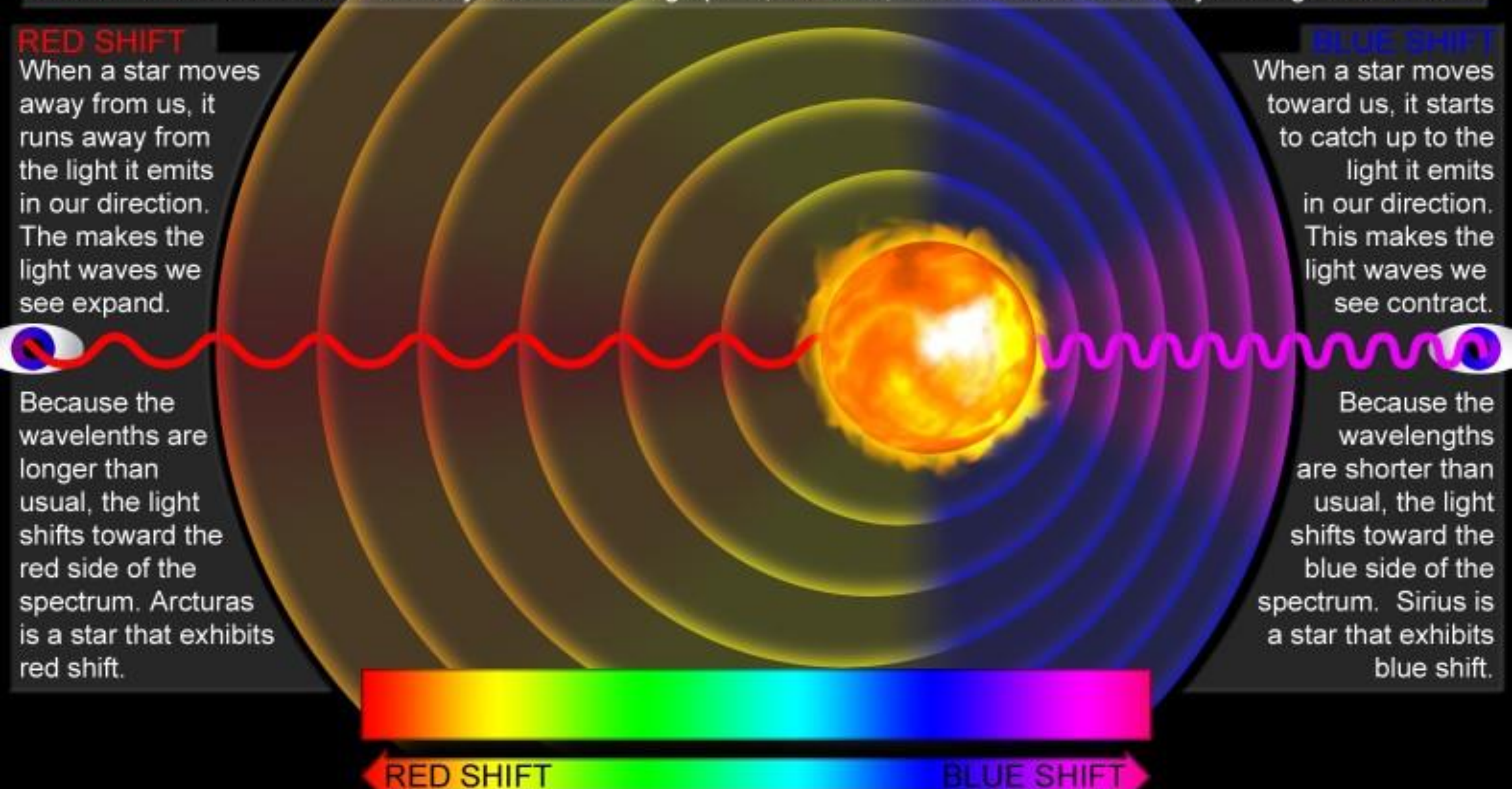
When a star moves away from us, it runs away from the light it emits in our direction. The makes the light waves we see expand.

Because the wavelenths are longer than usual, the light shifts toward the red side of the spectrum. Arcturas is a star that exhibits red shift.

BLUE SHIFT

When a star moves toward us, it starts to catch up to the light it emits in our direction. This makes the light waves we see contract.

Because the wavelengths are shorter than usual, the light shifts toward the blue side of the spectrum. Sirius is a star that exhibits blue shift.



Most shifts can not be seen with the naked eye, but astronomers can measure them to learn whether other stars are advancing or receeding.

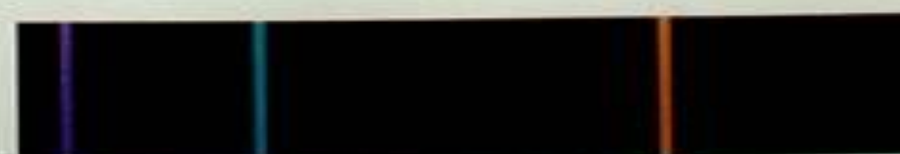
Laboratory spectrum
Lines at rest wavelengths.

Object 1
Lines redshifted: Object is moving away from us.

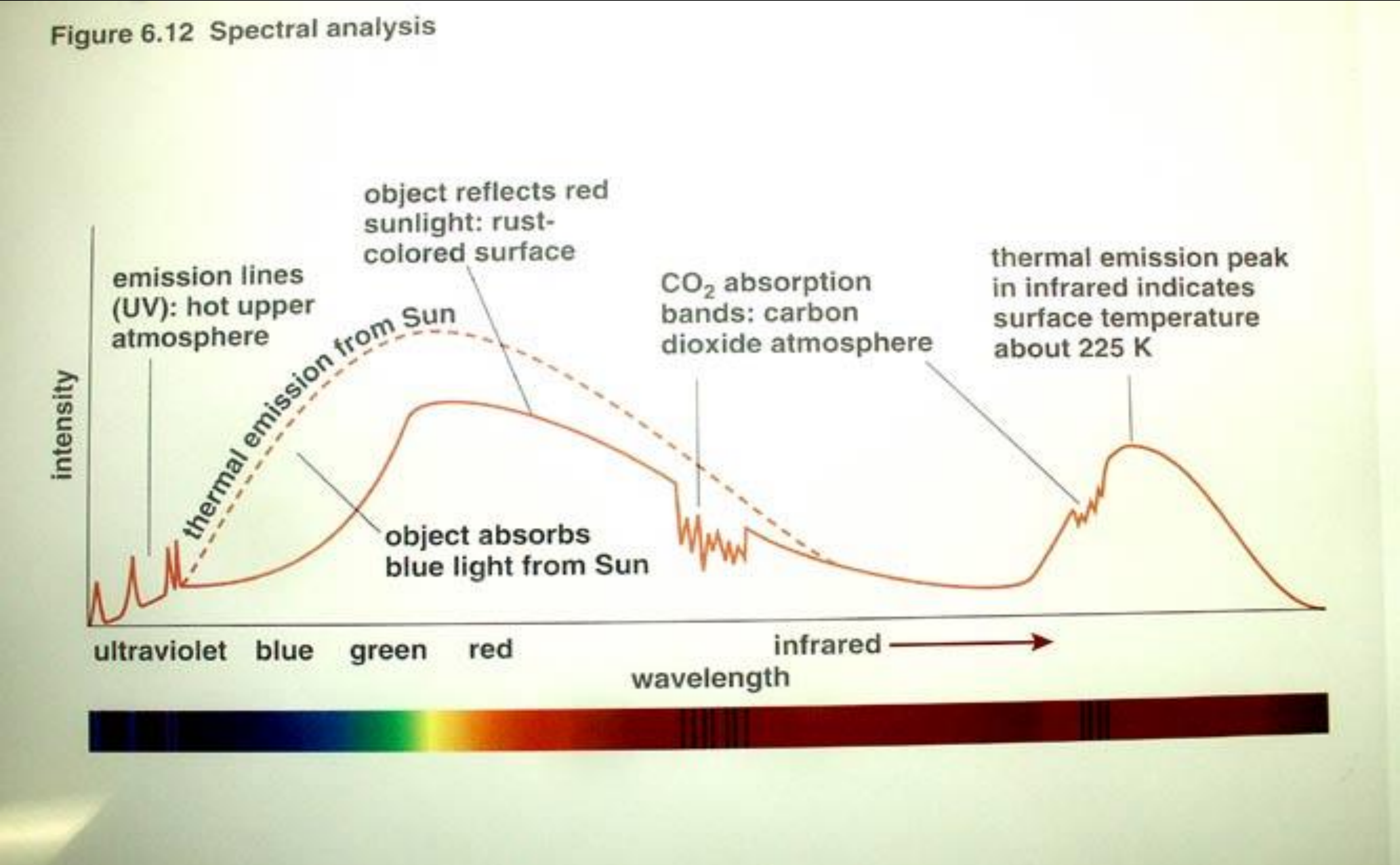
Object 2
Greater redshift: Object is moving away faster than Object 1.

Object 3
Lines blueshifted: Object is moving toward us.

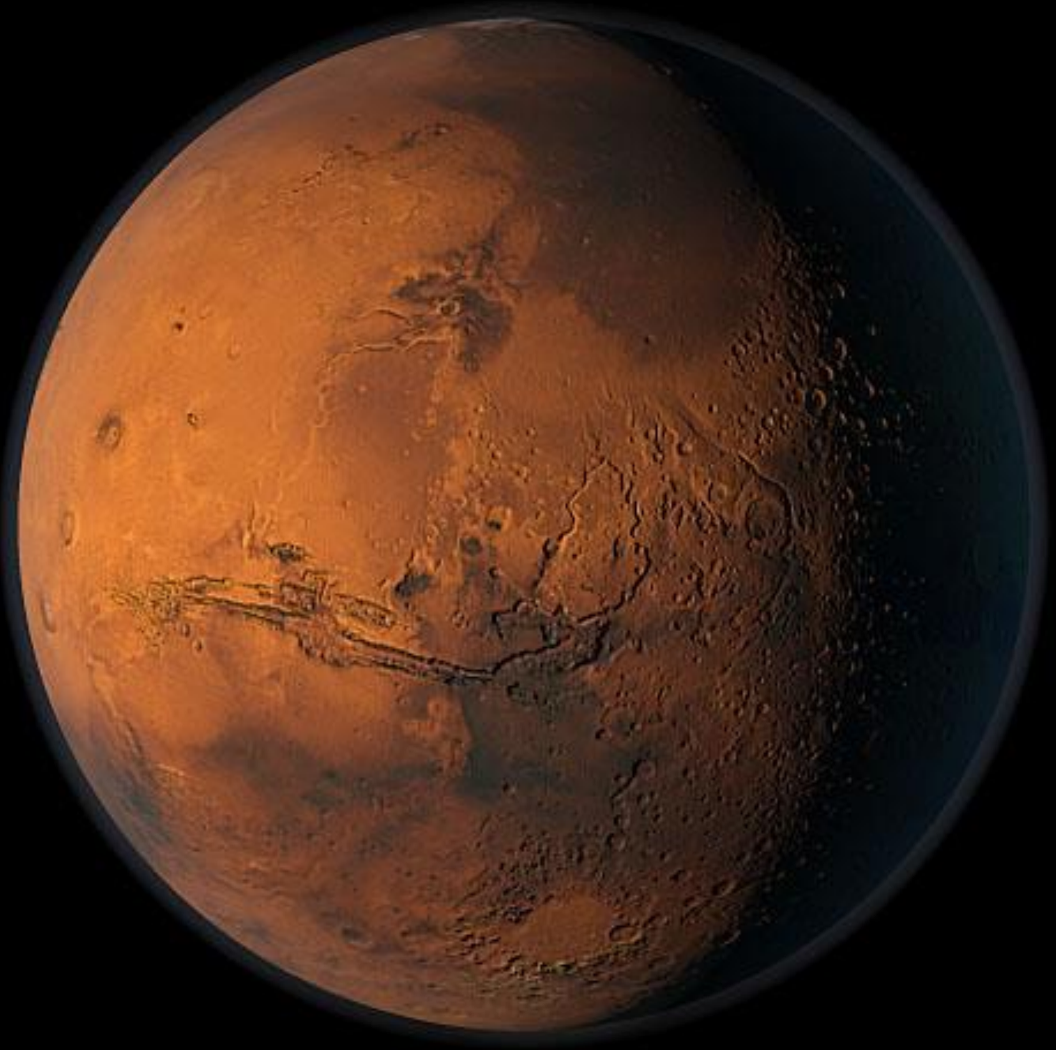
Object 4
Greater blueshift: Object is moving toward us faster than Object 3.



Look at All the Great Detective Insight a Spectrum Provides… Can You Guess What Object This Is?



It’s the Planet Mars



So the Spectrum Tells us:

- The temperature of the source, from Wien's law
- The chemical composition, from the spectral lines
- The velocity towards/away from us, from the Doppler shifts of spectral lines
- Even the pressure (pressure broadening of lines), magnetic field (Zeeman effect, see PP on the sun) and other subtle effects

Key Ideas – Chap 5 Light and Matter

- **Photons = quanta of EM field energy as a small bit of wave.**
- **Photon energy; short wavelength=high energy**
- **Doppler Effect: all wavelengths shifted longer ("redshift") if velocity away, shifted to shorter wavelengths ("blue shift") if velocity towards.**
- **Doppler Effect ONLY measures velocity component that's along the line-of-sight**
- **Know the names and order of the different wavelength bands (IR, radio, etc)**
- **Know the two ways to excite an atom or molecule (collisions, and photon absorption)**
- **<u>Molecules</u> have addition quantum degrees of freedom: vibration, rotation, and more complex motions for molecules of 3 or more atoms. <u>Such transitions mostly in the Infrared.</u>**
- **<u>Molecular absorption lines are much broader than for individual atoms. We call them instead "absorption BANDS"</u>**
- **Know the two ways to produce photons; accelerate a charge, emission.**
- **Know the two ways to excite an atom; absorption, and collisions**
- **Different ISOTOPES of an atom have different numbers of neutrons in nucleus**
- **Ionized atom = ion = has one or more electrons knocked off**
- **Temperature corresponds to average kinetic energy <u>per particle</u>**
- **Emission spectra *vs.* absorption spectra – knows which situation gives which**
- **Emission of photon when electron falls to lower orbital. Absorption is running that movie in reverse.**
- **Absorption ONLY happens if the photon has exactly the right energy to lift electron to an allowed orbit, or ionizes it altogether. Molecules can emit/absorb not only by not the electrons moving, but moving between different vibrational/rotational quantum states between the bound atoms**