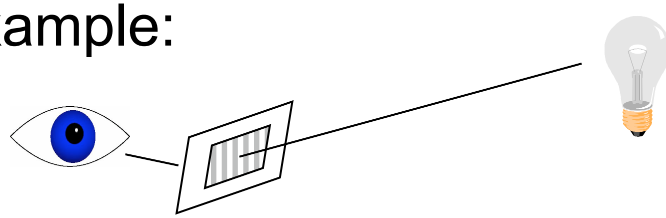
# Before Today's Lecture

- Please pick up a diffraction grating from the boxes near the door. Please put it back at the end of the lecture.

- You can practice looking at the demonstration lights.  It is best to hold the slide right up to your eye with the longer dimension horizontal.

- Example:



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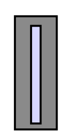
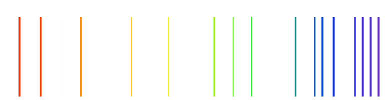
For  you should see 

# Part 2: Stars

- Thursday, February 9 — Reading: Chapter 6 [Ed. 9, 10, 11, 12]
  – The nature of light: How we use spectra to measure the properties of stars
- Tuesday, February 14 — Reading: Chapters 8, 9.1, 9.5 or Orion Nebula
  – Stars: distance, luminosity, mass, composition. Star formation. HW2 assnd
- Thursday, February 16 — Reading: Chapter 7.1 — 7.2 or 7.3 on the Sun
  – Stars: Our Sun.
- Tuesday, February 21 — Reading: Chapters 7 or 9 on fusion, 9.2 — 9.5
  – Stars: Stellar models, energy generation, main sequence life
- Thursday, February 23 — Reading: Chapters 10.1 — 10.3
  – Stars: Evolution from main sequence to white dwarf or Type II supernova
- Tuesday, February 28 — Reading: Chapters 10.4, 11 HW 2 due
  – Stars: Type I supernovae; white dwarf stars, neutron stars, black holes
- Wednesday, March 1 — Help session from 4 — 6 PM in Welch 3.502
- Thursday, March 2 — Exam 2 (Part 2)
- Monday, March 6 — Help session from 4 — 6 PM in RLM 4.102
- Tuesday, March 7 — Exam 3 (Parts 1 + 2)
- Thursday, March 9 — Exam 4 (Parts 1 + 2)

# Review: Spectra

The spectrum of an object is the amount of energy that it radiates at each wavelength.

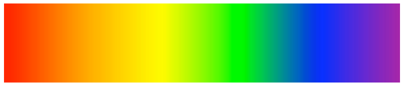
Much of what we know about the Universe comes from spectra.
They tell us much more than images do.

# Continuous Spectra

All macroscopic objects emit radiation at all times. Their atoms jiggle around by an amount that increases with temperature. Accelerated charged particles radiate. So:
Everything radiates with a spectrum that is directly related to its temperature.

# Continuous Spectra

An idealized object that absorbs all radiation that hits it is called a **black body**.
In equilibrium with its surroundings, it emits exactly as much radiation as it absorbs.
Then it emits a spectrum as described in Figure 6-6 of (most editions of) the text.
This **black body** or **thermal radiation** has the following properties:

- It is continuous radiation (there are no emission or absorption lines): 

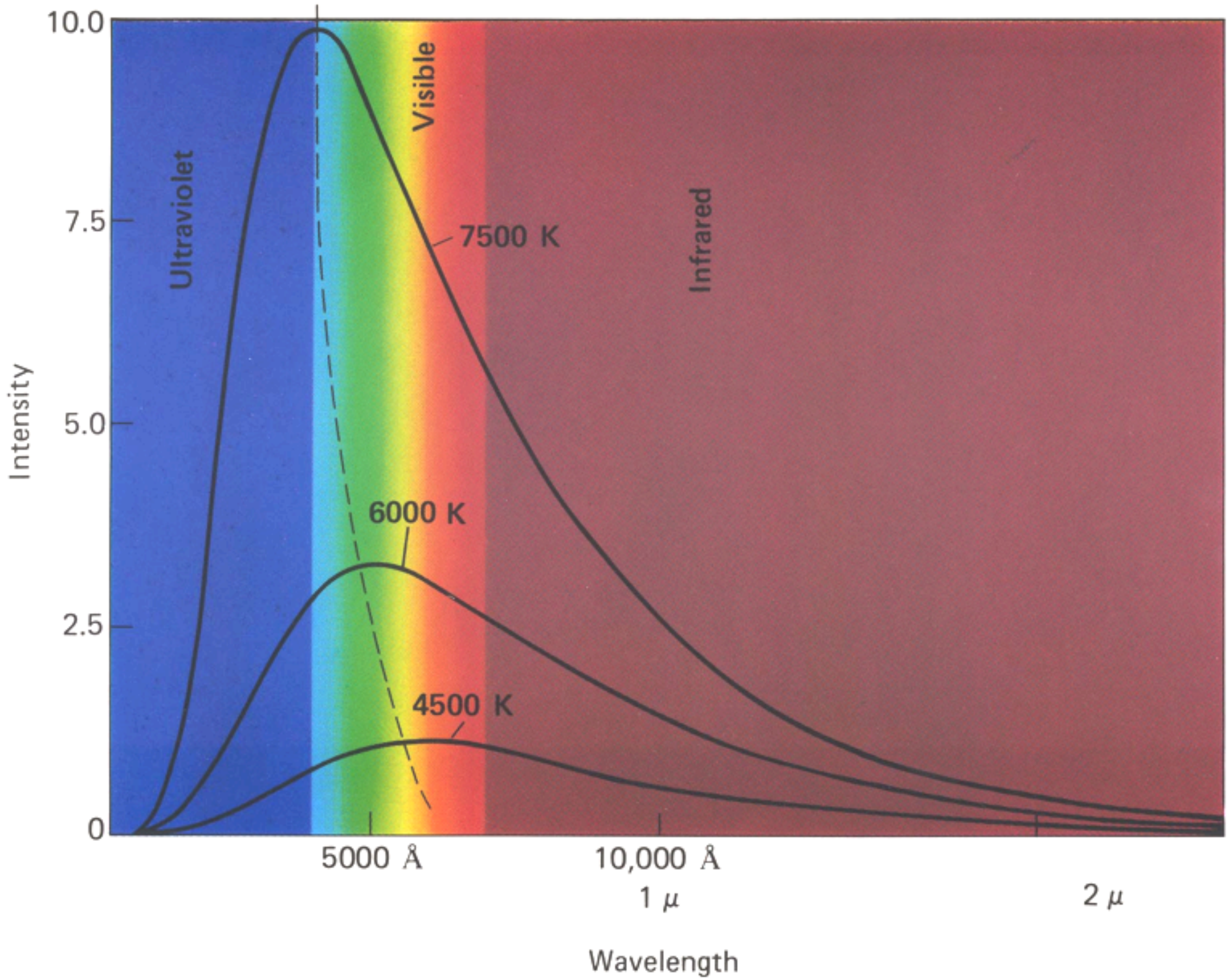
- Its spectrum is brightest at a wavelength that depends on temperature, and the brightness falls more quickly toward the blue than toward the red. Specifically:

- **Wien's Law**: The wavelength of maximum brightness in Å is 30,000,000 K divided by the temperature in K. That is, $l_{max} = 3.0 \times 10^7$ Å / T(K). Hotter things radiate bluer light. If the temperature doubles, the wavelength of maximum brightness gets 2 times shorter.

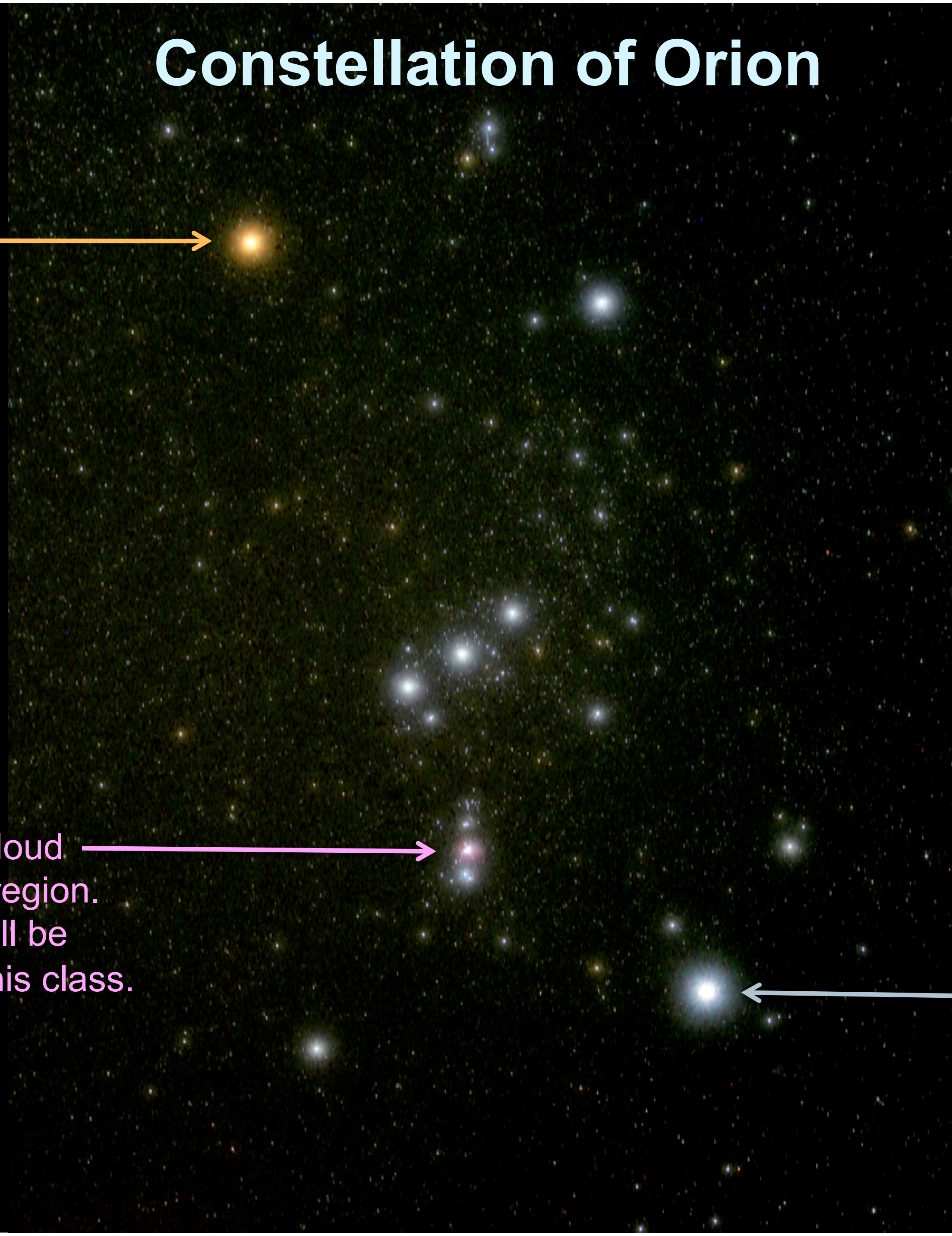
- **Stefan-Boltzmann Law**: The total energy emitted varies as the 4th power of temperature: $E = \sigma T^4 = \sigma \times T \times T \times T \times T$. The Stefan-Boltzmann constant $\sigma$ is given in Box 6 — 1.

A black body is an idealized concept, but for many objects (including stars), the above are useful approximations.

# Review: Black Body Spectra



# Constellation of Orion



Betelgeuse is a red supergiant star (T = 3500 K).

Orion Nebula gas cloud and star-formation region. Why it looks pink will be discussed later in this class.

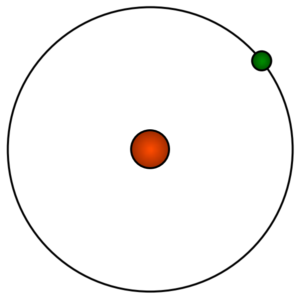
Rigel is a blue supergiant star (T = 12,130 K).

# Electromagnetic Radiation

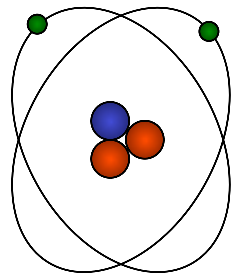
| Type of Radiation | Wavelength Range (Å) | Temperature of Radiating Objects | Typical Sources |
|---|---|---|---|
| Gamma rays | Less than 0.1 | More than $10^8$ K | Neutron stars and black hole accretion disks |
| X-rays | 0.1 — 200 | $10^6$ — $10^8$ K | Gas in clusters of galaxies; solar corona; supernova remnants |
| Ultraviolet | 200 — 4000 | $10^4$ — $10^6$ K | Supernova remnants; hot young stars |
| Visible | 4000 — 7000 | $10^3$ — $10^4$ K | Stars, warm gas clouds |
| Infrared | $10^4$ — $10^7$ | 10 — $10^3$ K | Cool clouds of gas and dust; planets, satellites, asteroids; your body |
| Radio | More than $10^7$ | Less than 10 K | Relic radiation from the Big Bang; cold gas; star forming regions; electrons moving in magnetic fields (synchrotron radiation) |

**1 Å = $10^{-10}$ m**

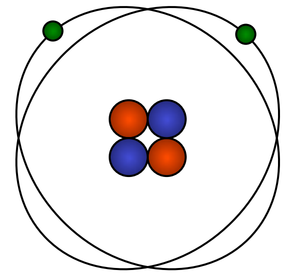
# Everything Is Made Of Atoms



$^{1}$H



$^{3}$He

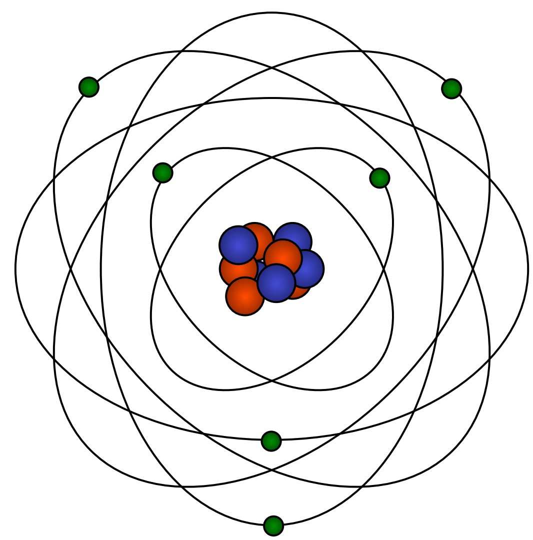


$^{4}$He

| | | |
|---|---|---|
| Proton | | Positive |
| Neutron | | Neutral |
| Electron | | Negative |

Protons, neutrons and electrons are the building blocks of atoms. The proton and electron have opposite electric charges of the same strength, whereas the neutron is neutral. The proton and neutron are about $10^{-13}$ cm across and have about the same mass. The electron has 1/1,836 the mass of the proton.

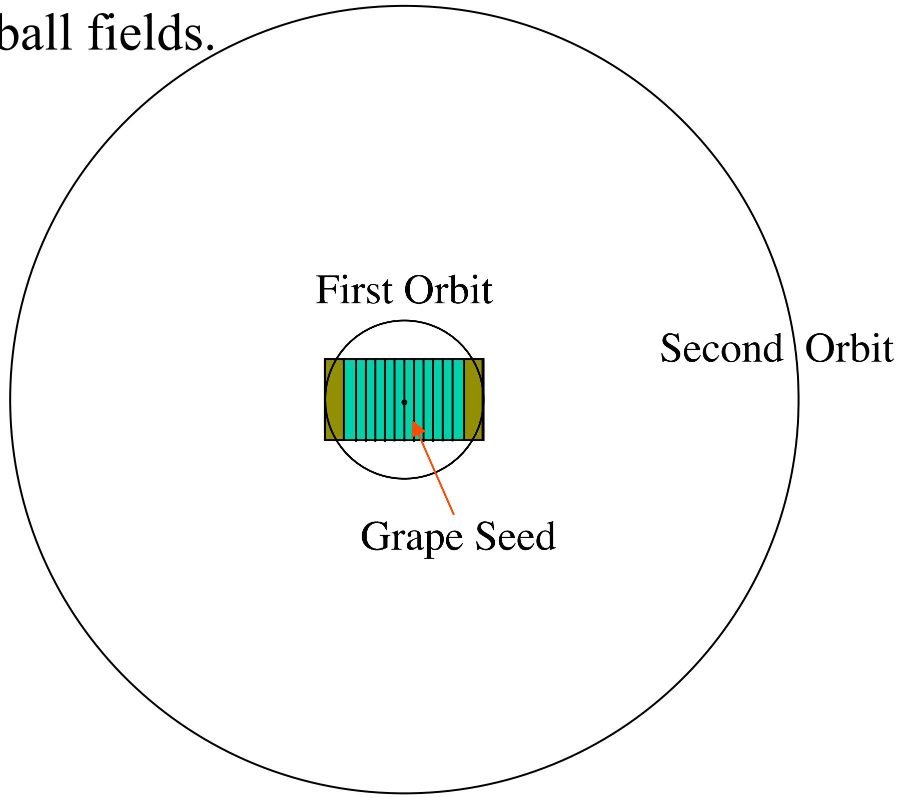
$^{12}$C



# A Scale Model of the Hydrogen Atom

Suppose that we could make a hydrogen atom bigger by a factor of $10^{12}$.

The nucleus now has a diameter of 1.6 mm — it is the size of a grape seed. The innermost possible electron orbit is the size of a football field. The next orbit is the size of 4.5 football fields.



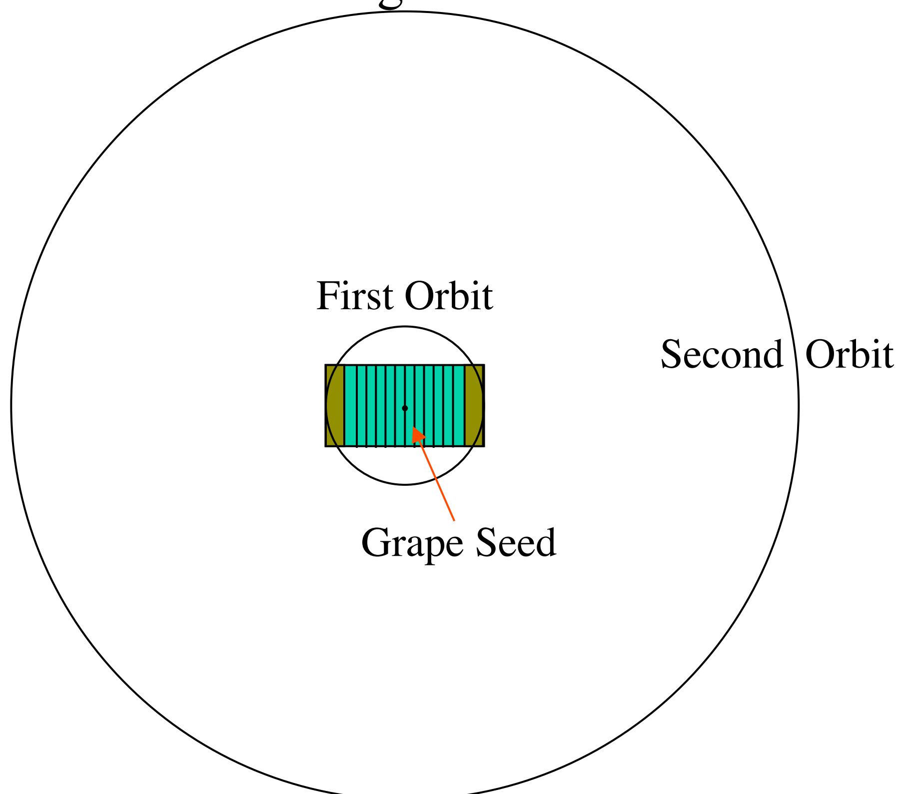

The electron is too small to see.

So: **An atom is mostly empty space!**

# A Scale Model of the Hydrogen Atom

Suppose that we could make a hydrogen atom bigger by a factor of $10^{12}$.

The mass is still less than $2 \times 10^{-15}$ kg. We would have to multiply by another factor of $10^{12}$ to get a mass that we could imagine.



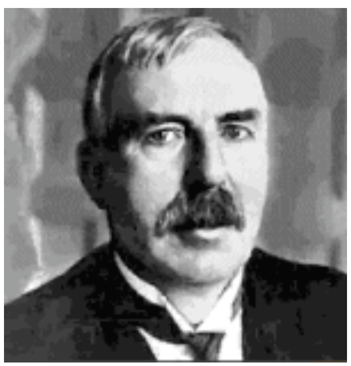

**It takes an enormous number of atoms to make something macroscopic. A grain of table salt contains more than $10^{18}$ atoms — enough to give a billion atoms to every person on Earth.**

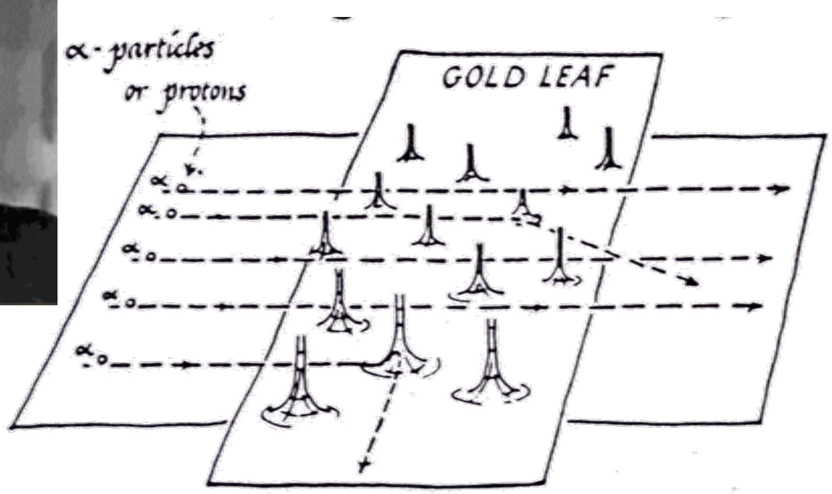
# How Do We Know The Structure Of The Atom?

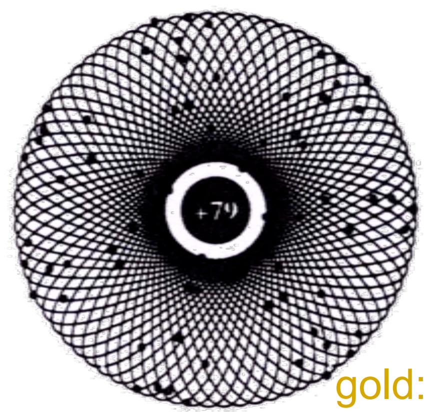
Democritus suggested that matter is composed of tiny objects called atoms. Chemists showed that there are about 90 kinds of atoms, each with different chemical properties.

Rutherford bombarded a thin gold foil with helium nuclei (called $\alpha$-particles). Helium nuclei contain 2 protons and so are positively charged. Gold nuclei contain 79 protons and also are positively charged. So helium nuclei and gold nuclei <u>repel each other</u>. Result:

Most He nuclei went through the foil, but a few bounced off at large angles. This showed that a gold atom is made of a<u> tiny, heavy lum</u>p of positively charged matter – the nucleus– surrounded by a much larger cloud of negatively charged electrons. For this work, Rutherford got the Nobel Prize for Chemistry in 1908.






gold:
79 protons and electrons

Other elements have different nuclear charges and numbers of electrons.

# The Bohr Atom

To understand the structure of electron orbits and atomic spectra, Niels Bohr in 1913 suggested the following new ideas:

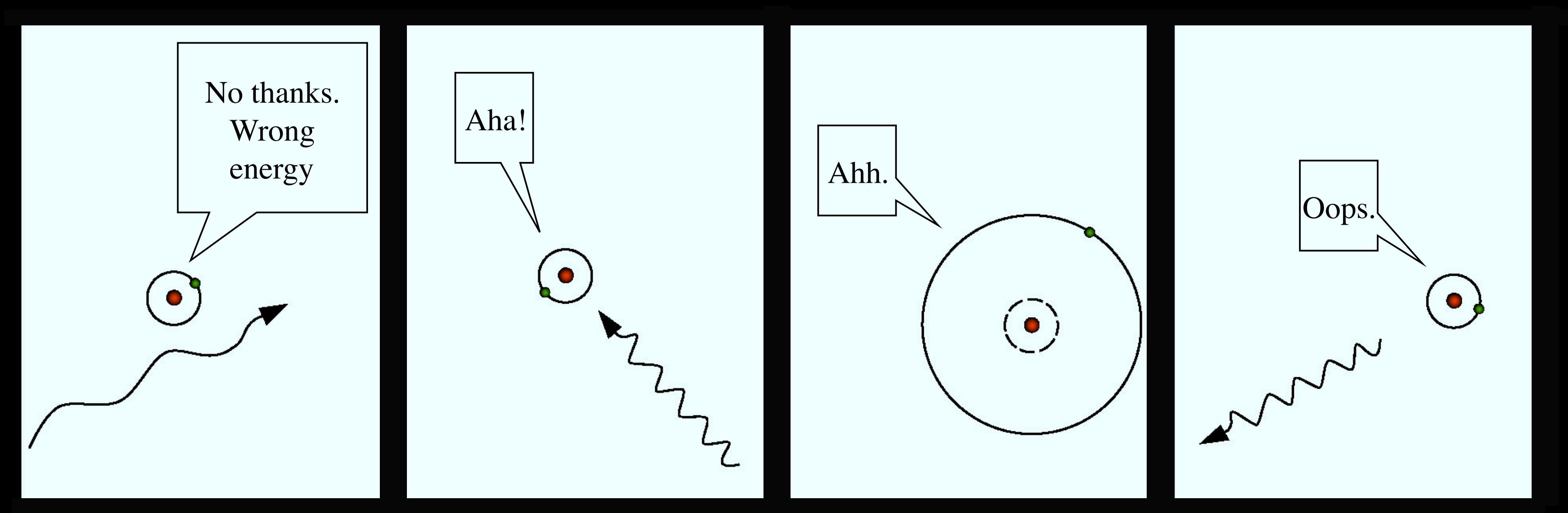
- **Electrons in orbit around an atomic nucleus can only have certain specific energies.** This situation is like that of a person standing on a staircase — he can stand on any step, but he cannot hover between steps.

- **An electron can move from one energy level to another; this changes the energy of the atom.** Since electrons are attracted to protons in the nucleus, we have to add energy to move them farther from the nucleus. One way that an atom can gain energy is by absorbing a photon of light. In contrast, if an electron falls from an outer orbit to an inner orbit, the energy that is lost is emitted as a photon of light. The wavelength λ (Greek letter "lambda") of the photon emitted or absorbed and the **difference** $E$ **in energy** between the two levels are related by $E = hc/\lambda$, where $c$ is speed of light and $h$ is Planck's constant.

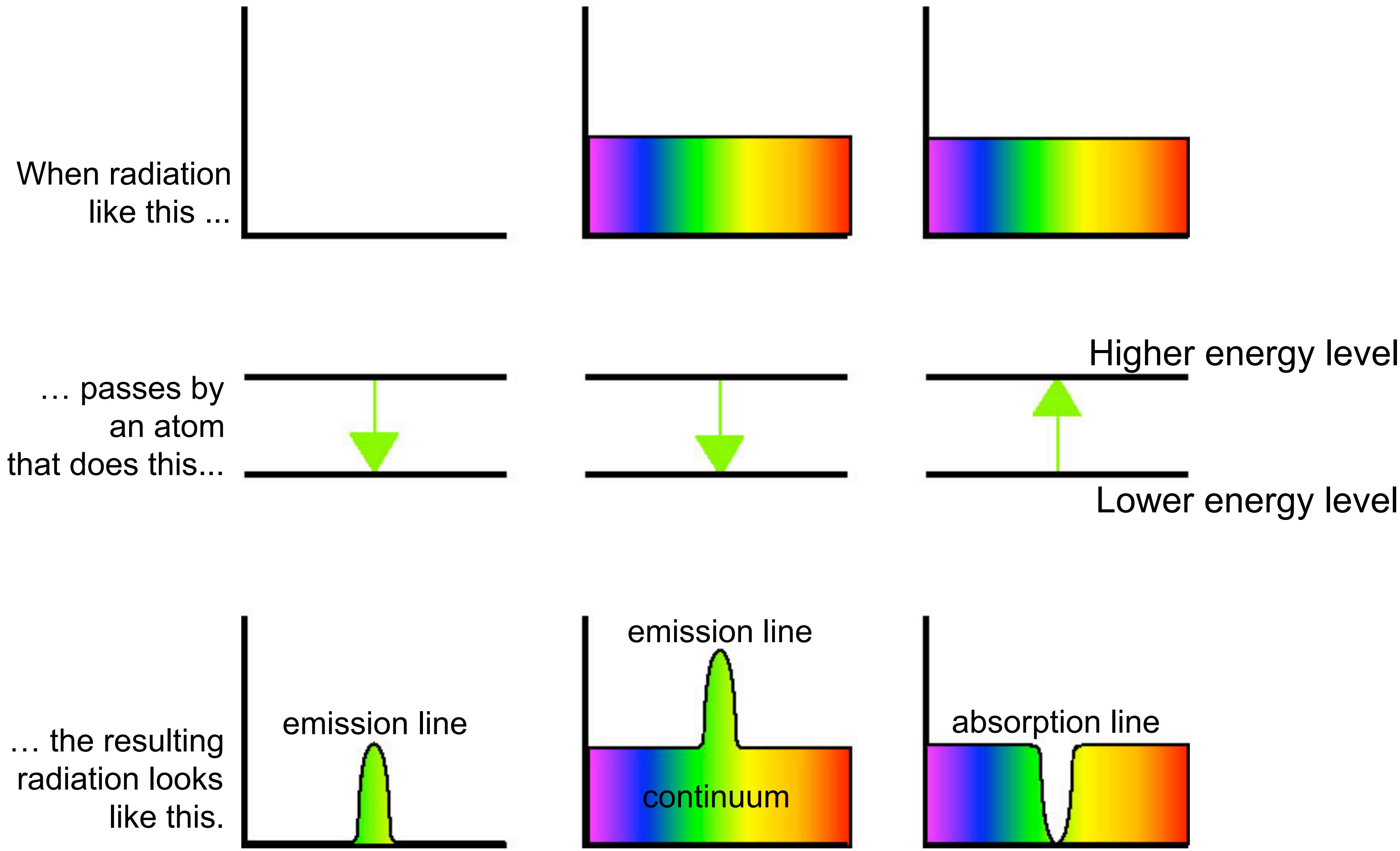
- **An atom has a ground state of lowest energy in which it does not radiate.**

**Therefore: Processes that everybody thought could be continuous can happen only in discrete ("quantum") jumps.**

# Absorption and Emission of a Photon



# Spectra



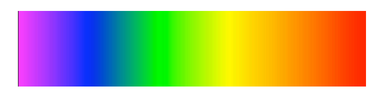
When radiation like this ...
… passes by an atom that does this...
Higher energy level
Lower energy level
… the resulting radiation looks like this.
emission line
emission line
continuum
absorption line

# Kirchhoff's Laws

The observed relationships between continuous spectra, emission-line spectra, and absorption-line spectra were summarized by Gustav Kirchhoff in 1859.

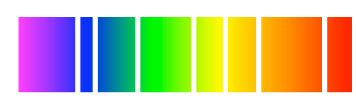
**Kirchhoff's Laws** that describe the formation of spectra are:

1. A solid or liquid or sufficiently dense gas emits light of all wavelengths and so produces a **continuous spectrum** of radiation.

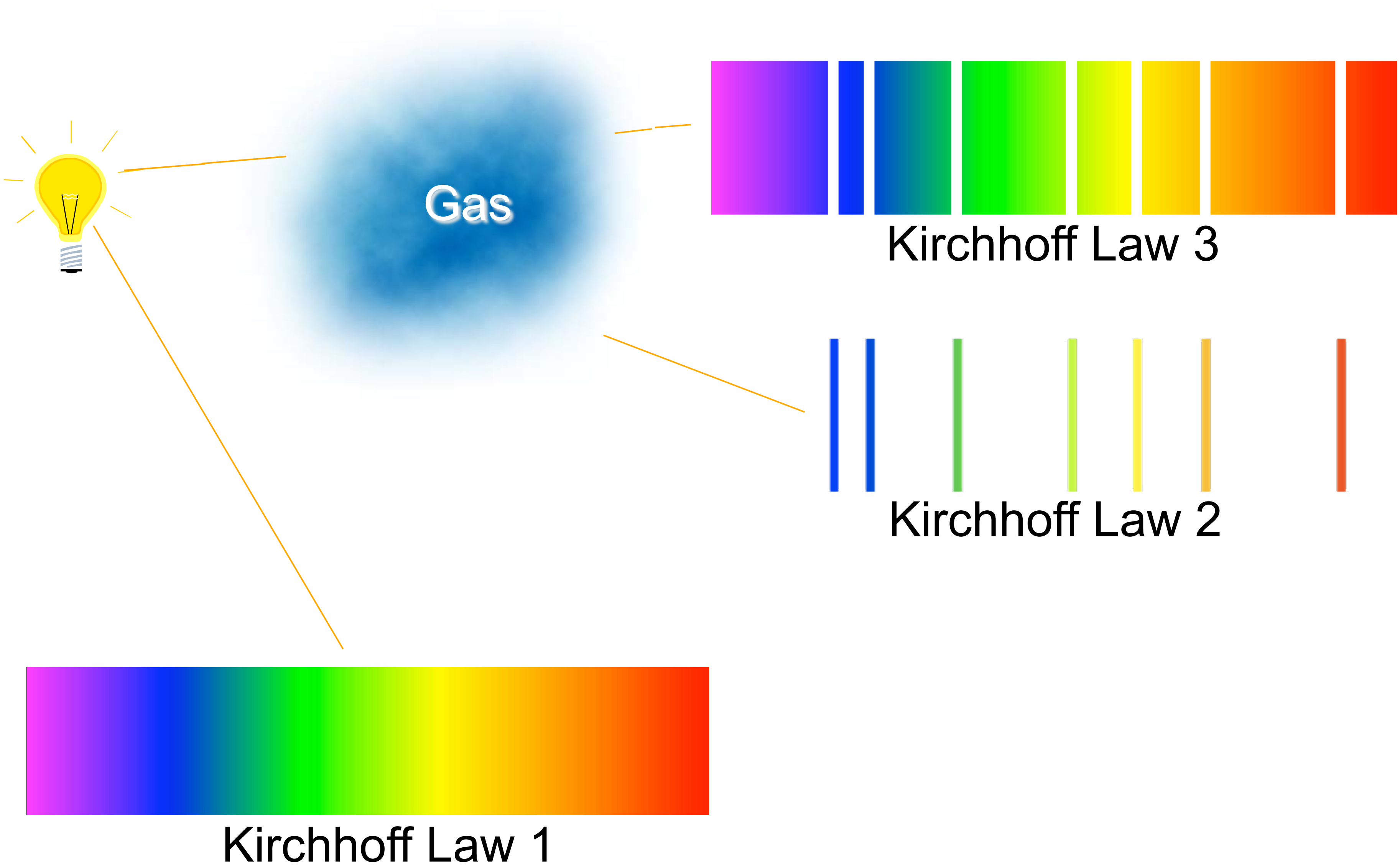


2. A low-density, hot gas emits light whose spectrum consists of bright **emission lines**. These lines are characteristic of the chemical composition of the gas.

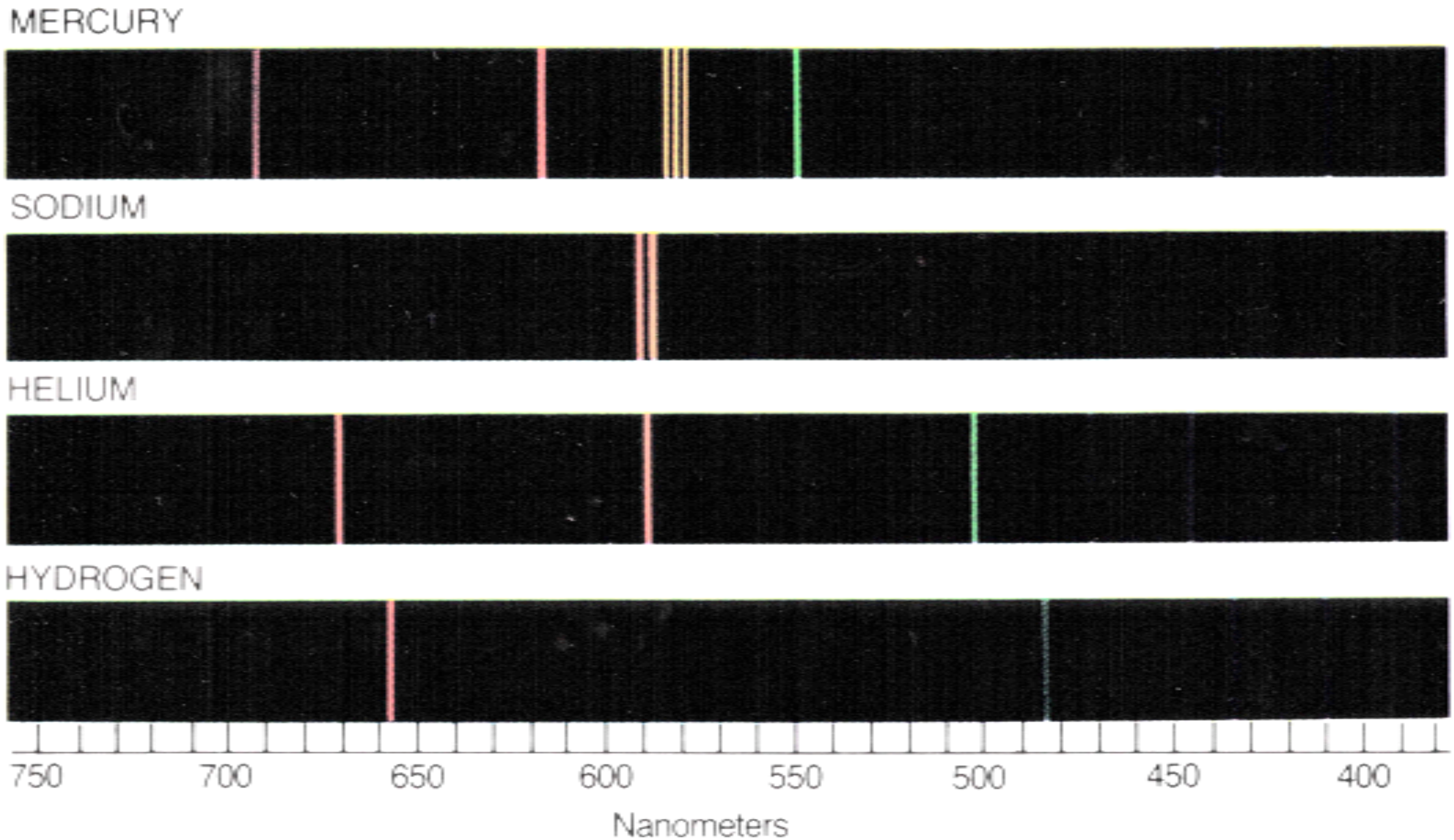
3. A cool, low-density gas absorbs certain wavelengths from a continuous spectrum and leaves dark **absorption lines** in their place, superimposed on the continuous spectrum. Again, the lines are characteristic of the composition of the intervening gas. They occur at precisely the same wavelengths as the emission lines produced by the same gas at higher temperatures.



# Absorption, Emission, and Continuous Spectra

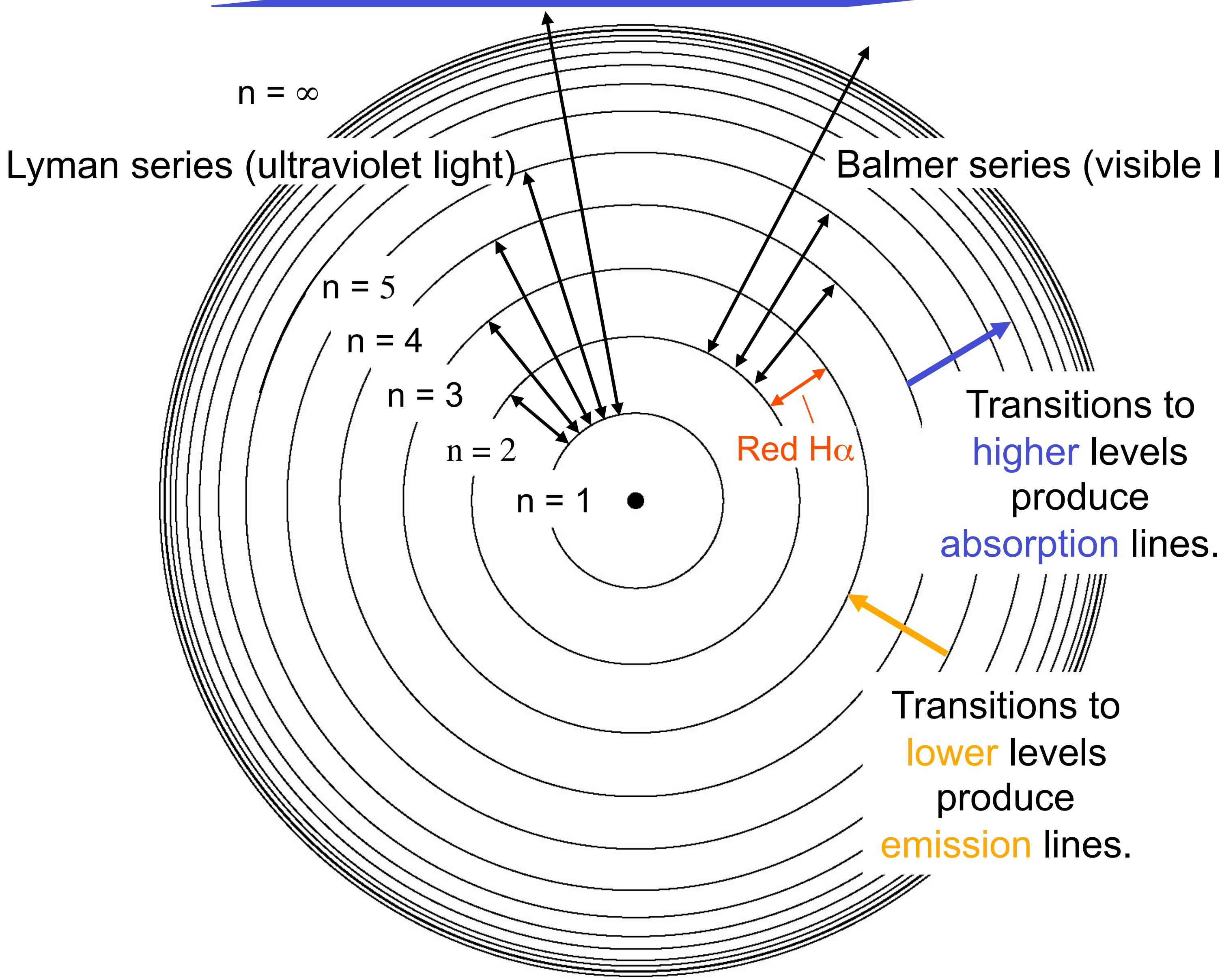


# Examples of Emission Spectra

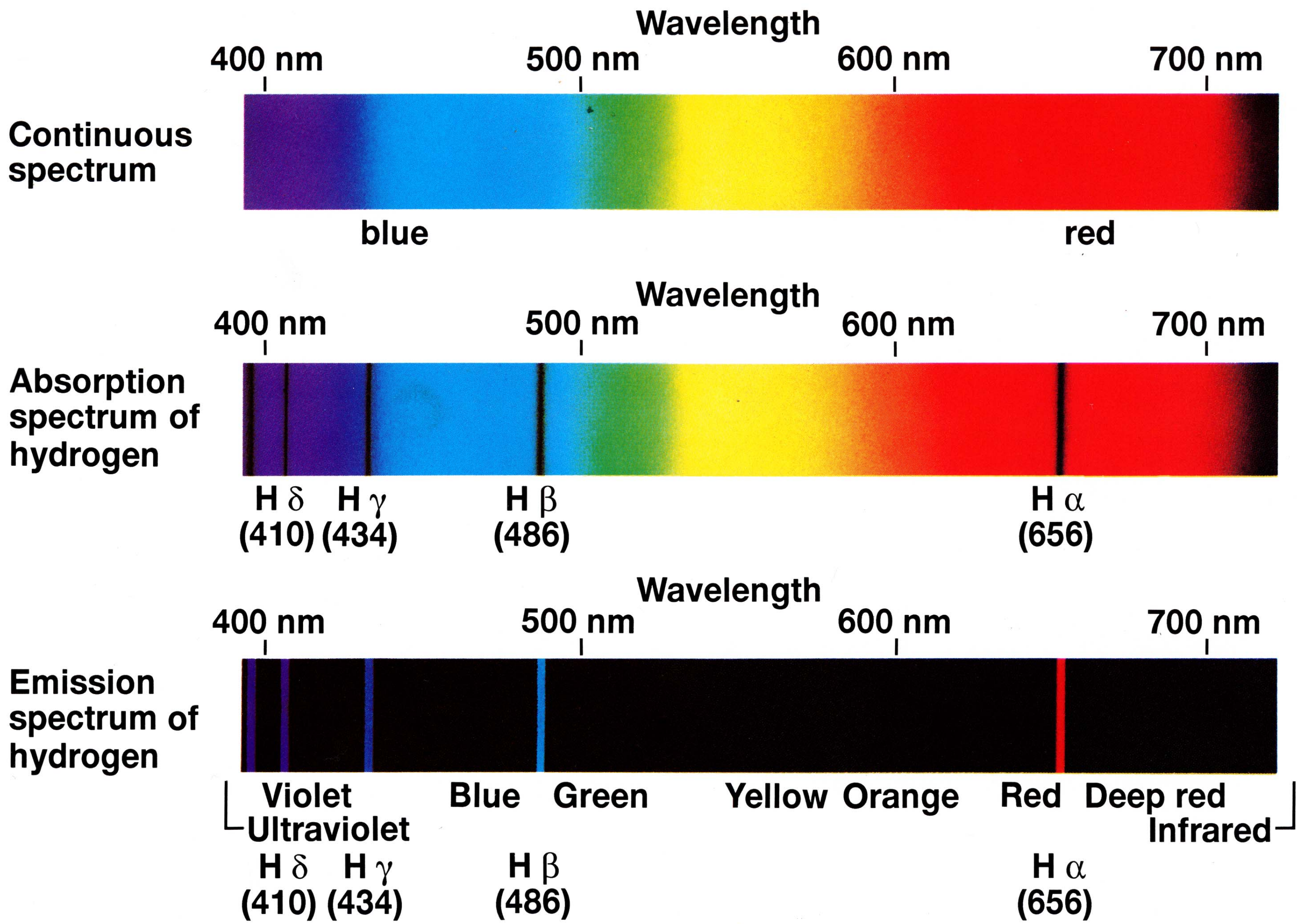


[redacted]

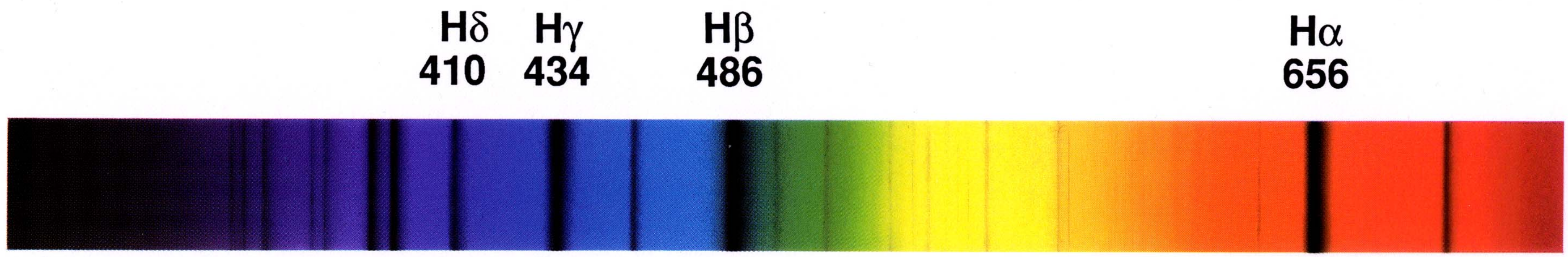
# Hydrogen Atom Transitions



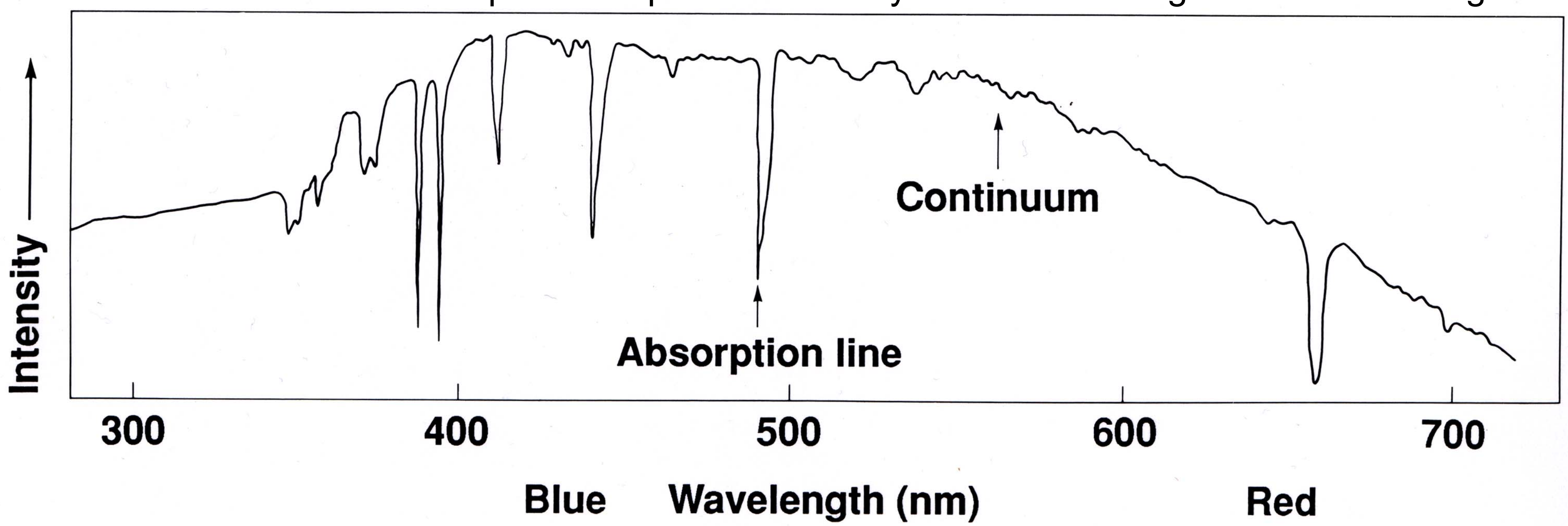
# Spectrum of Hydrogen



# Spectrum of a Hot Star With Strong Hydrogen Lines




Note: We will often see spectra as plots of intensity versus wavelength and not as images.



# Atomic Processes: What Happens In Real Life

Atoms in a star's atmosphere create dark spectral lines by absorbing black-body radiation. The temperature of the star mostly determines which lines are visible, because most stars have similar atomic abundances.

## Excitation and De-excitation

When an electron moves from a low-energy orbit such as the "ground state" to a high-energy orbit, the atom is excited. An atom can become excited by absorbing a photon of the correct energy or by colliding with another atom or electron.

Likewise, when an electron moves to a lower-energy orbit, the atom is de-excited. This can happen because of a collision with another atom or because a photon is emitted.

## Ionization and Recombination

When an electron is not just moved to a higher-energy orbit but is actually ejected for the atom, the atom is ionized. The atom becomes an "ion" with a net positive charge. Because the electron escapes with some energy, any photon that has enough energy can ionize an atom.

When a free electron becomes bound to an ion, the atom recombines and a photon is emitted to carry away the excess energy.

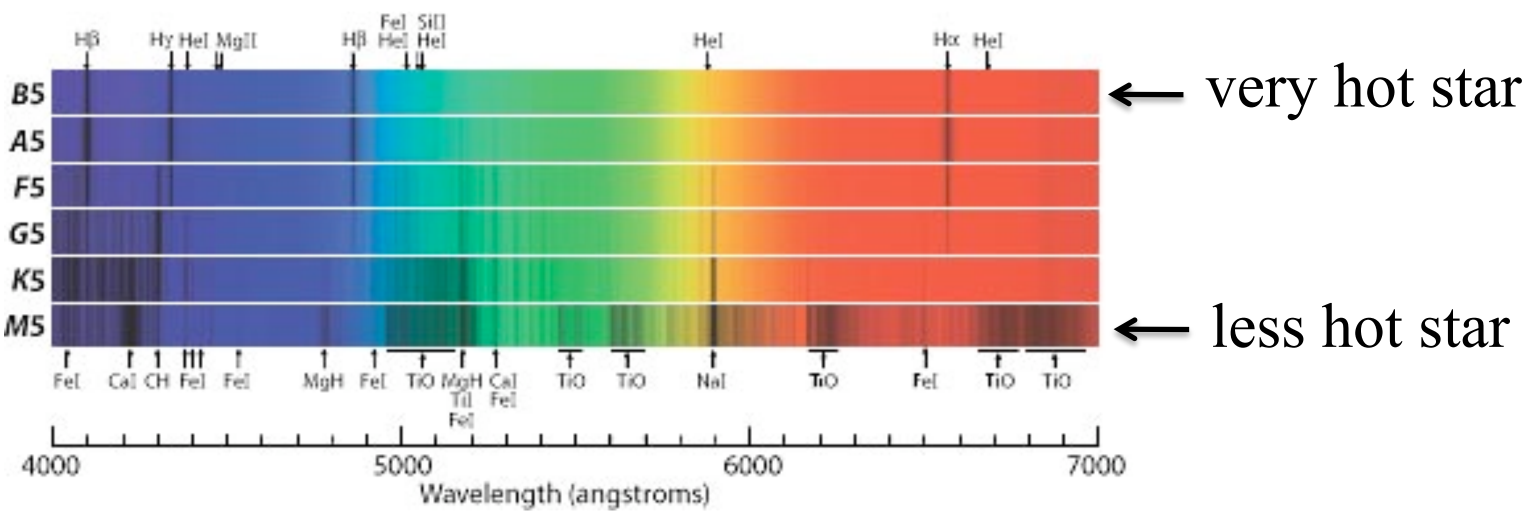
# Stellar Atmospheres

Normal stars do not have solid surfaces; they are balls of hot gas. What looks like the "surface" of a star like the Sun is the place where the atmosphere becomes opaque (like the "surface" of a cloud on Earth). This is called the **photosphere**.

A typical star emits enormous amounts of energy. Energy always flows from hot places to cooler places, so the interior of a star must be much hotter than the "surface".

The photosphere of the Sun is only 300 km thick and has an average temperature of 5800 K.

The temperature of the photosphere decreases with increasing altitude. Therefore **the light emitted from the bottom of the photosphere must pass through cooler gas on its way to us.** Atoms in the cooler layers become excited by absorbing photons of certain energies. **This is why the light that reaches us shows dark lines superimposed on a continuous spectrum.**



# Stellar Spectra

The dark lines seen in stellar spectra depend on the composition of the star: if an element is absent, its spectral lines can never be observed. But **temperature**, not composition, is the main factor that creates the diversity of stellar spectra.

Temperature affects the spectrum in two ways:

1. The relative intensities of different wavelengths in the continuous spectrum depend on the temperature in the lower layers of the photosphere (Wien's Law).

2. To make absorption lines in the continuous spectrum, the atoms must be in the correct state to absorb photons. This is a complicated function of the temperature in the photosphere.

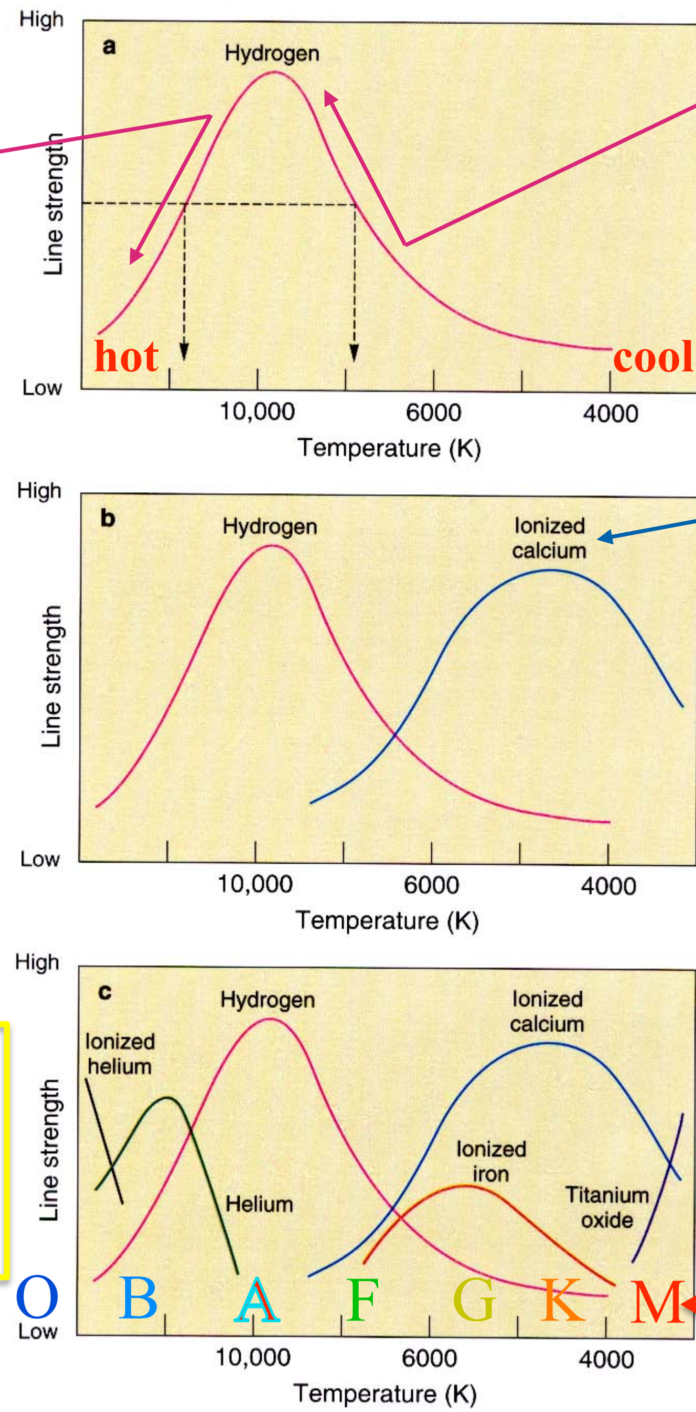
Example of point 2: A hydrogen atom in the ground state cannot absorb a photon of visible light; the jump to the first excited state requires an ultraviolet photon. To produce absorption lines in the visible spectrum, the hydrogen must be hot enough to collisionally excite the atoms to the first excited state. This requires a temperature above about 6000 K. In level 2, an electron can absorb a photon that knocks it up to level 3 or higher: such a photon has an energy corresponding to visible light. Therefore a visible-light photon disappears from the continuous spectrum, producing a (dark) "absorption line". But if the temperature gets much above 10,000 K, then most of the hydrogen is ionized, and it cannot produce any absorption lines at all.

For elements other than hydrogen, the story is similar but more complicated.

Line strength decreases as temperature increases above the optimum value because more hydrogen atoms have their electrons in energy levels that are too high or because hydrogen is ionized by collisions.

Different atoms in the atmosphere of a star have spectral lines that depend differently on temperature.

By observing many lines of many elements, we can measure the temperature accurately.

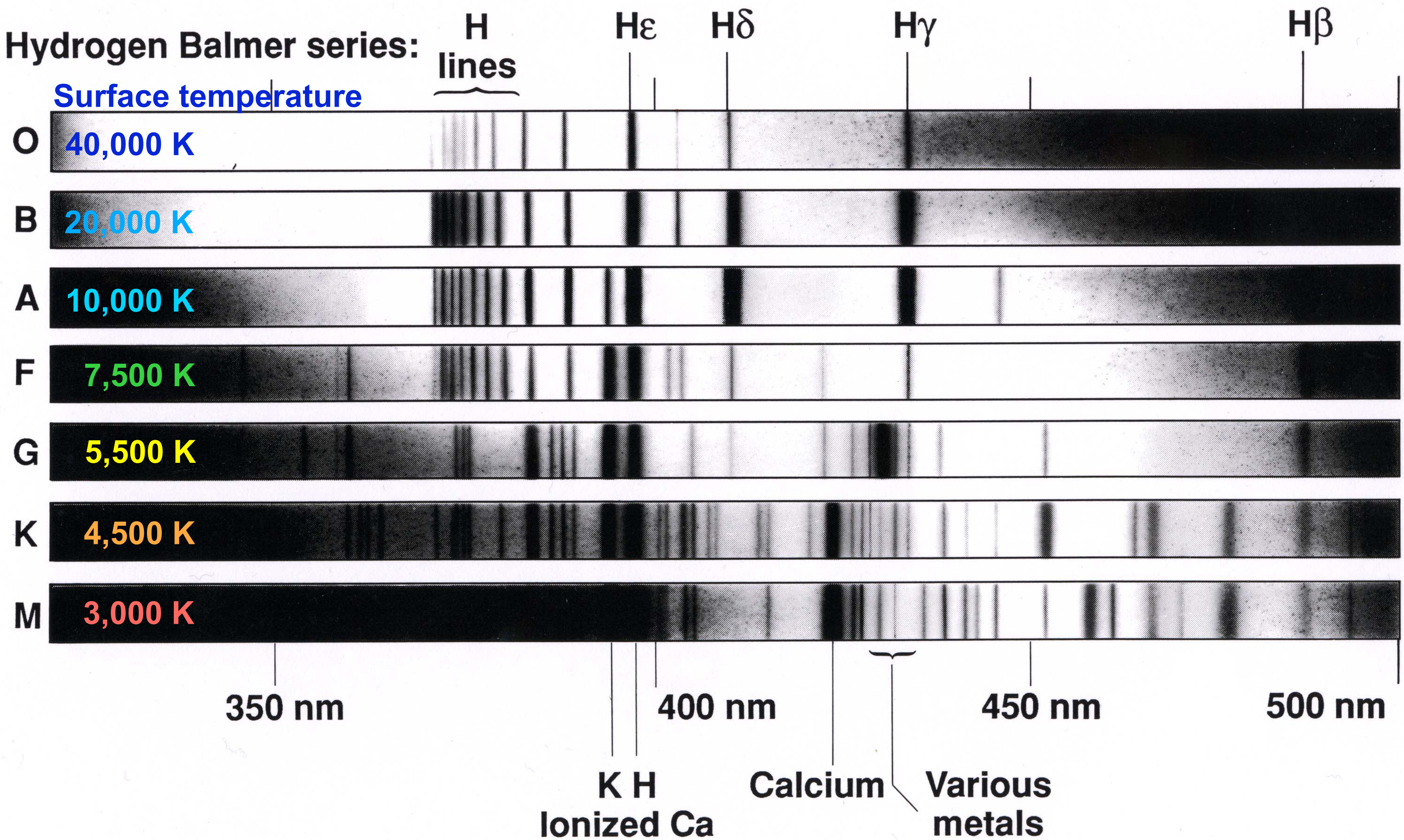



Line strength increases with increasing temperature because more hydrogen atoms' electrons are excited by collisions to energy level 2 **from** which they can cause absorption lines.

Calcium nuclei have more protons than do hydrogen nuclei, so they also have more electrons. The outer electrons are less tightly bound than in hydrogen. So it takes less energy — and hence a lower temperature — to excite the outer electrons to the proper levels to make spectral lines.

Stellar spectral types

# Spectral Types of Stars



# Spectral Types of Stars

With apologies for our sexist past,
the standard mnemonic to help you remember spectral types is:

or: Guy

Oh Be A Fine Girl, Kiss Me

hottest stars

coolest stars

# Compositions of Stars

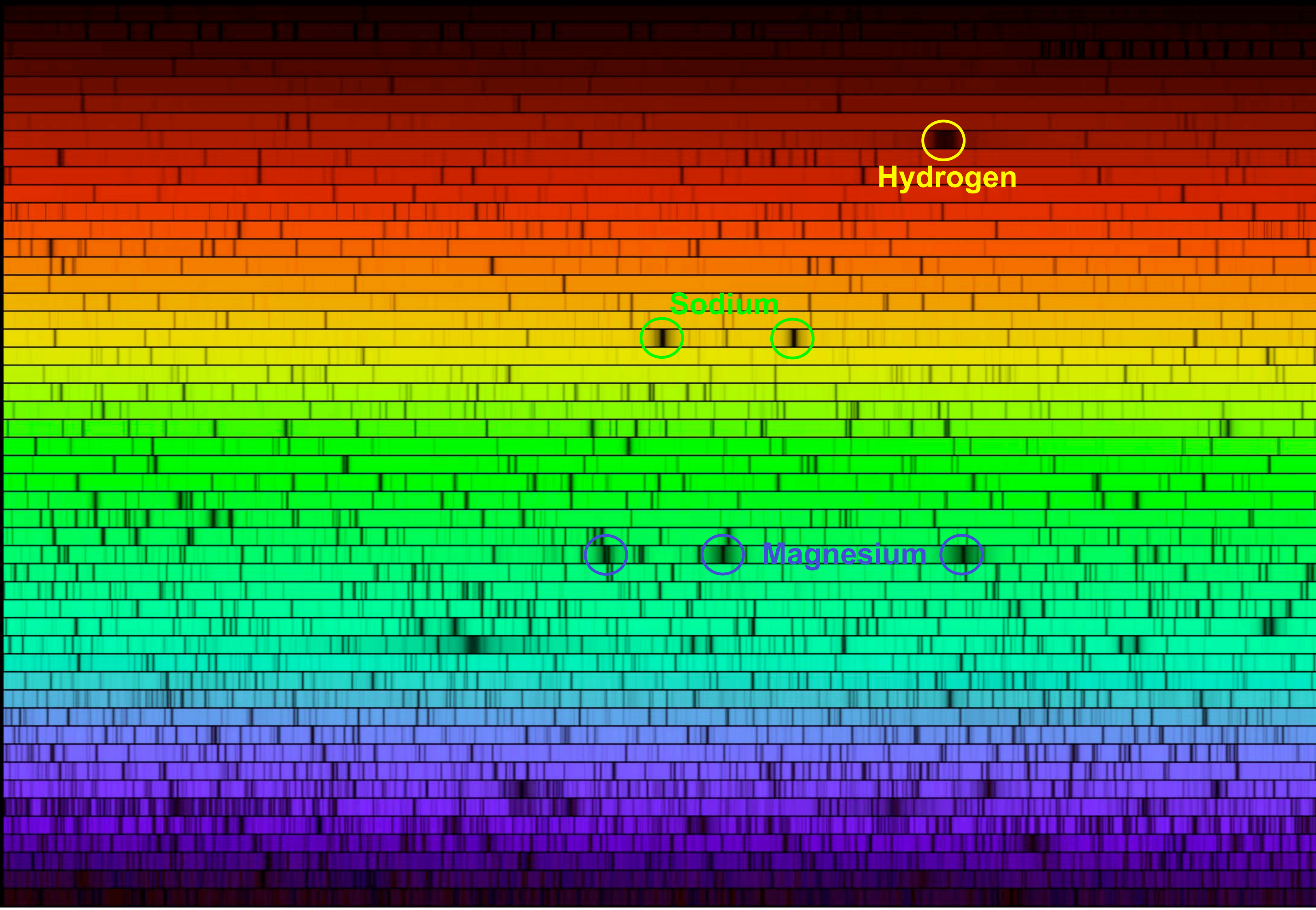
By taking the effects of temperature into account, we can use spectral lines to measure the compositions of stars. Despite their different spectra, most stars turn out to have very similar compositions.

The Sun's composition is typical of most stars in our neighborhood. Some of the more common elements are listed below with their abundances in the Sun.

| | | | |
|---|---|---|---|
| Hydrogen | 73.4% | | |
| Helium | 25.0% | | |
| "metals" | 1.6% | Oxygen | 0.8% |
| | | Carbon | 0.3% |
| | | Iron | 0.2% |
| | | Nitrogen | 0.1% |
| | | others | 0.2% |

In other stars, the ratio of Hydrogen to Helium is generally very close to 3:1, as it is in the Sun. "Metals" are everything else. Their contribution varies from less than 0.01% to as much as 3%. However, the mixture of different metals is almost the same over this entire range.

# The spectrum of the Sun



# Stellar Velocities

Wavelengths of spectral lines in gas that is at rest have been measured very accurately in laboratories on Earth. The wavelengths of the same spectral lines can be measured very accurately in stars.

## The Doppler Effect

When we observe that the lines are shifted from the wavelengths that we see on Earth, then we know that the star is moving away from us or toward us.

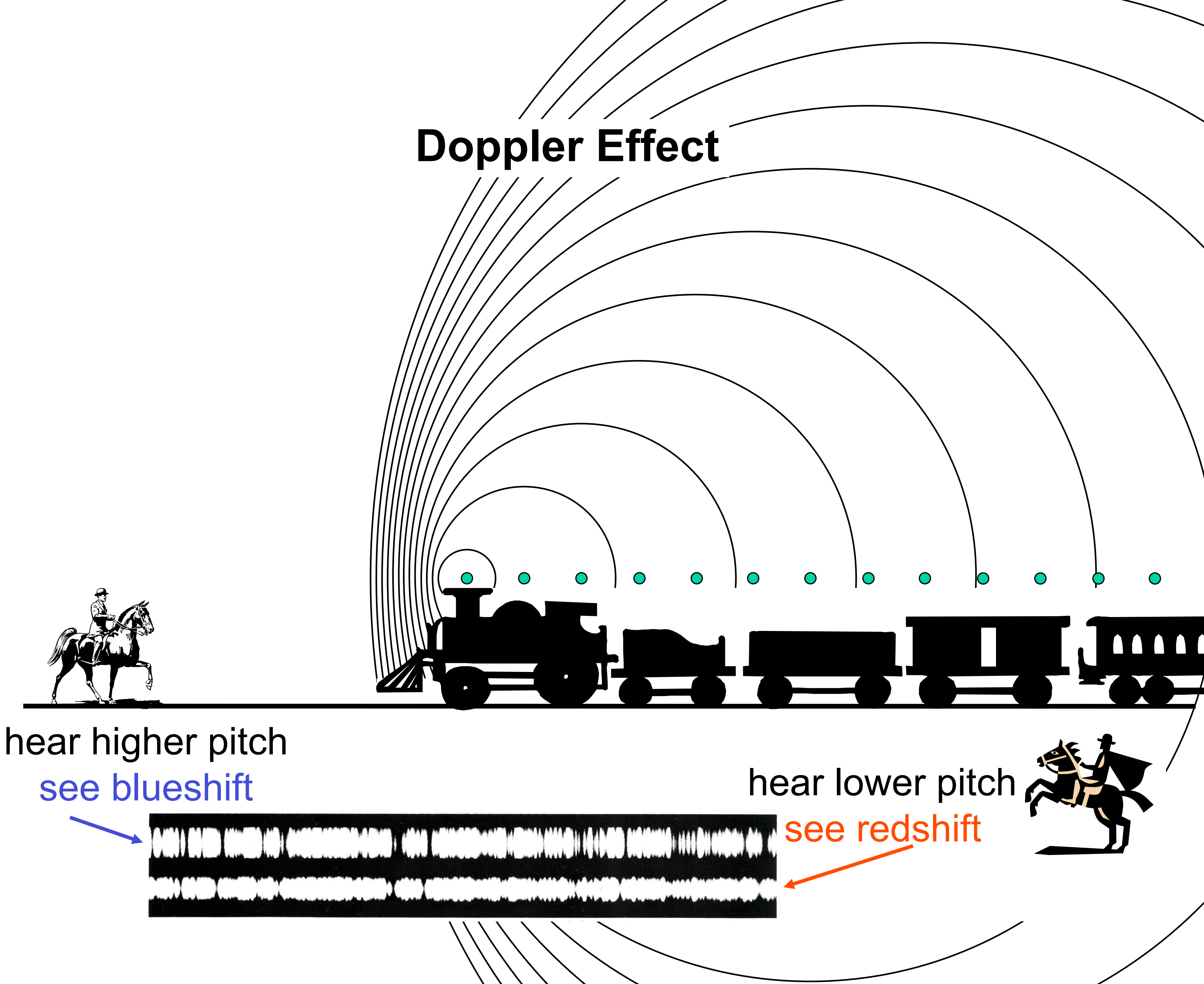
When a star moves toward us, the wavelengths of spectral lines are blueshifted.

When a star moves away from us, the spectral lines are redshifted.

The Doppler effect is familiar as applied to sound. The pitch of a siren is higher when the emitting vehicle moves toward us than when it moves away from us.

**The class web site has an applet and a movie illustrating the Doppler effect**.

# Doppler Effect



# Measuring Velocities Using The Doppler Effect

$$\frac{\text{velocity}}{\text{speed of light}} = \frac{\text{change in wavelength}}{\text{wavelength}}$$

The speed of light is 300,000 km/s.

Example 1: Suppose that we observe a spectral line whose laboratory wavelength is known to be 6000 Å, but we see it at 6001 Å. Therefore the star is moving away from us at (300,000) x (1/6000) = 50 km/s.

Example 2: Suppose that the same line is observed in another star at 5990 Å. This star is moving toward us at (300,000) x (10/6000) = 500 km/s.