

Starlight and Atoms

In the middle of the 19th century one physicist said, “What the stars are we do not know, and we will never know.”

He was wrong.

The simplest element is hydrogen. A neutral atom of hydrogen consists of one positively charged proton and one negatively charged electron.

If an electron in a hydrogen atom is as close to its proton as it can get, it is said to be in the **ground state** (the state of lowest energy).

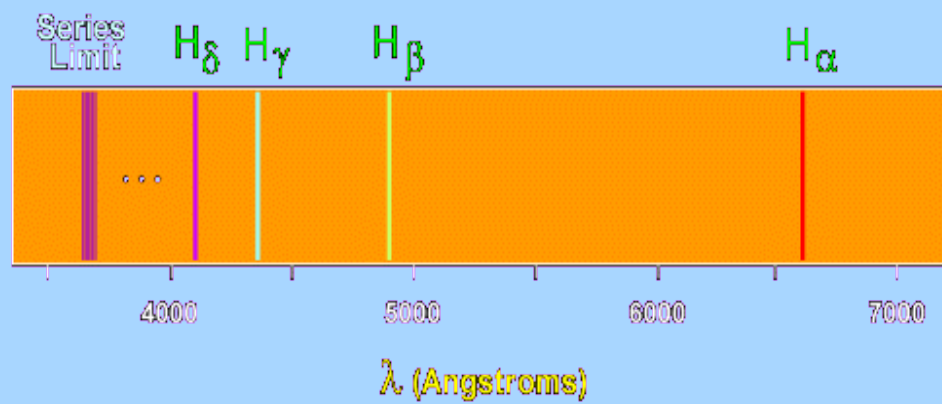
If the electron is still bound to the proton, but is found further away, it is in an **excited state**.

If it becomes unbound from the proton, the atom is said to be **ionized**.

If you take an evacuated glass tube, fill it with hydrogen gas, and apply a voltage (i.e., “light it up like a neon sign”), it will produce light at very specific wavelengths. If viewed with a diffraction grating or spectrograph, the bright lines produced will have wavelengths of:

| | |
|----------------|----------------|
| 6563 Angstroms | (red) |
| 4861 | “ (blue-green) |
| 4340 | “ (blue) |
| 4102 | “ (violet) |

Then more lines, closer and closer together, ending at a wavelength of 3646 A.



Consider the following expression:

$$(1/2^2 - 1/n^2) = (0.25 - 1/n^2)$$

For $n = 3, 4, 5, 6 \dots$ infinity, the expression is equal to 0.13889, 0.187500, 0.21000, 0.22222 ... 0.250000. Now, divide 911.5 by these numbers and you get

6563

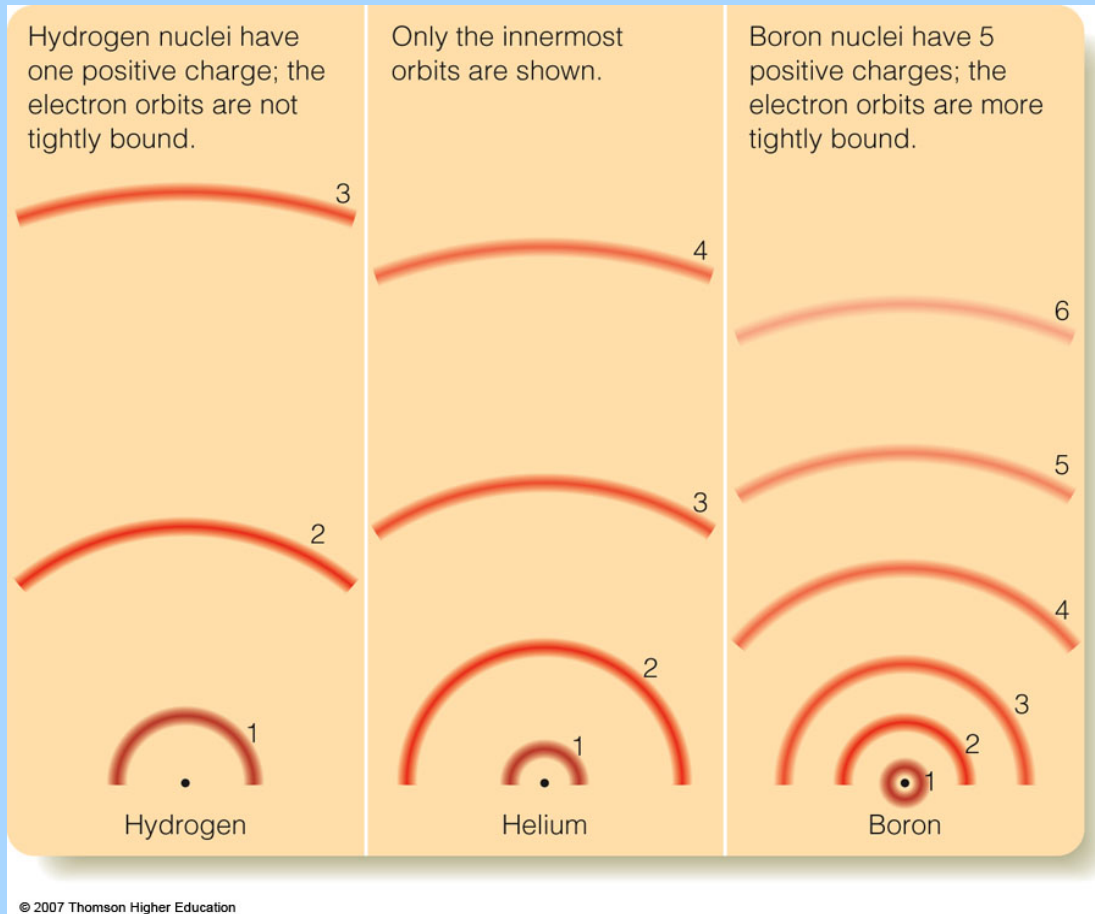
4861

4340

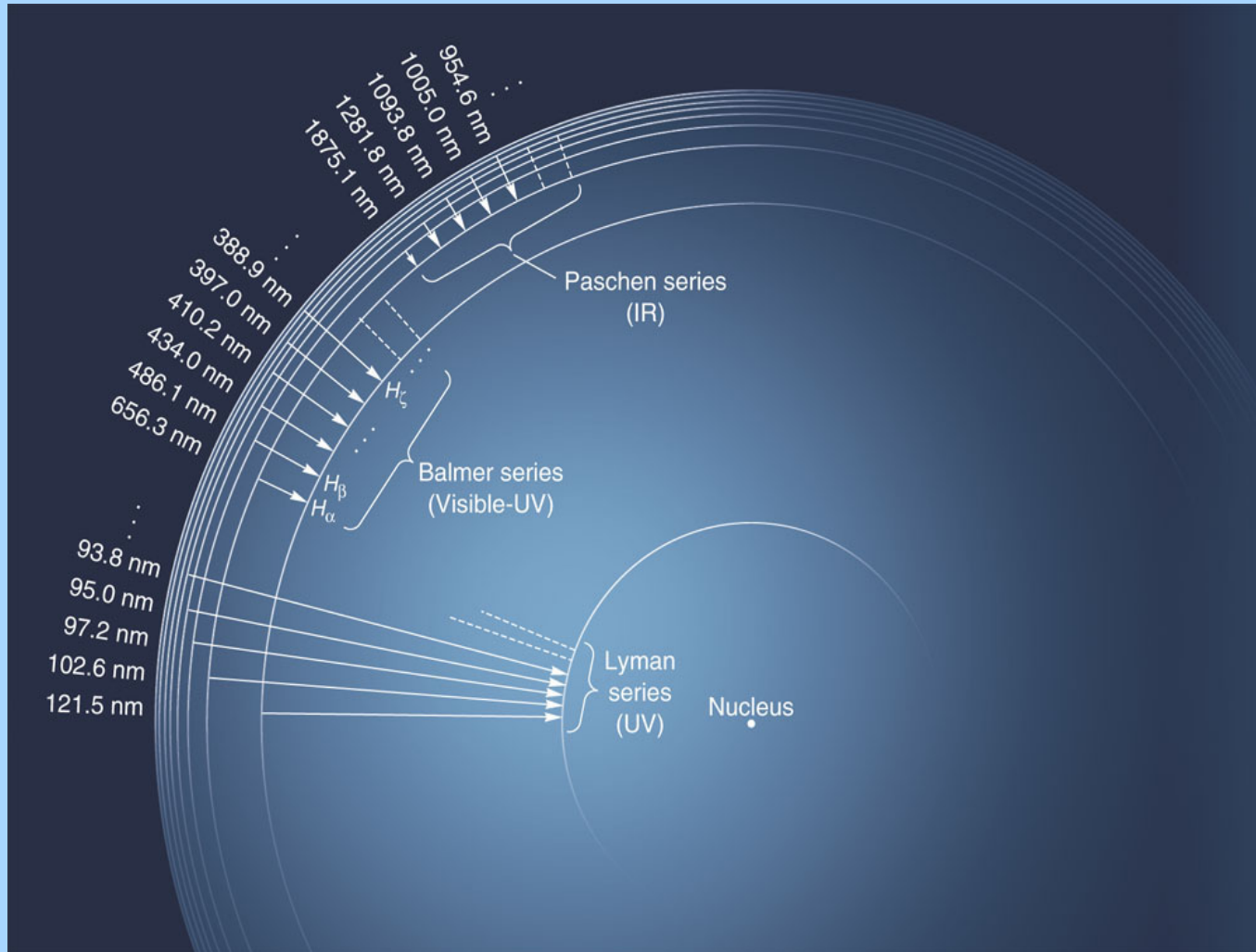
4102 3646

Exactly the wavelengths of the hydrogen lines we see!

So – there is a specific pattern to the hydrogen lines.
This is the result of the *energy levels* of the atoms.

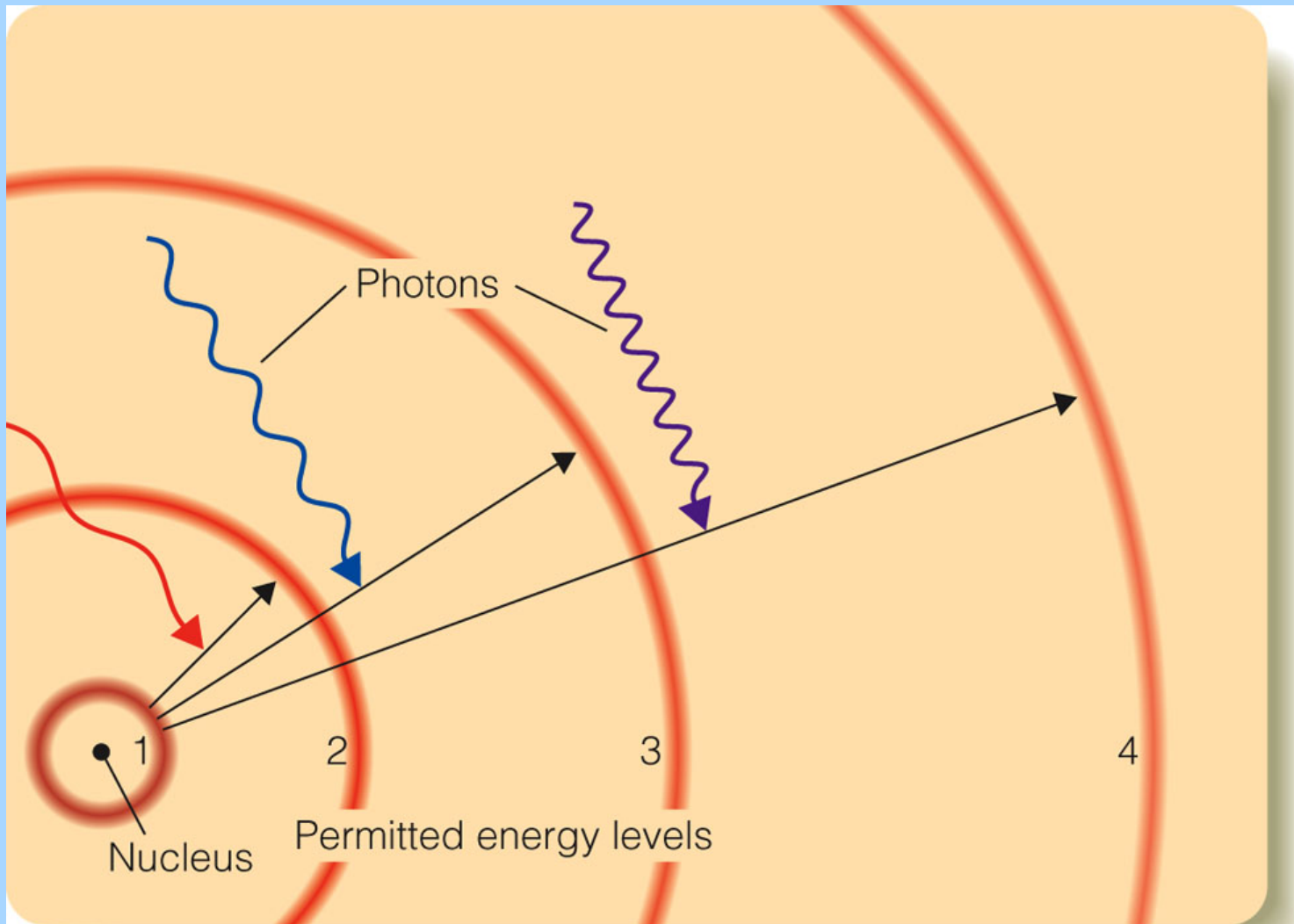


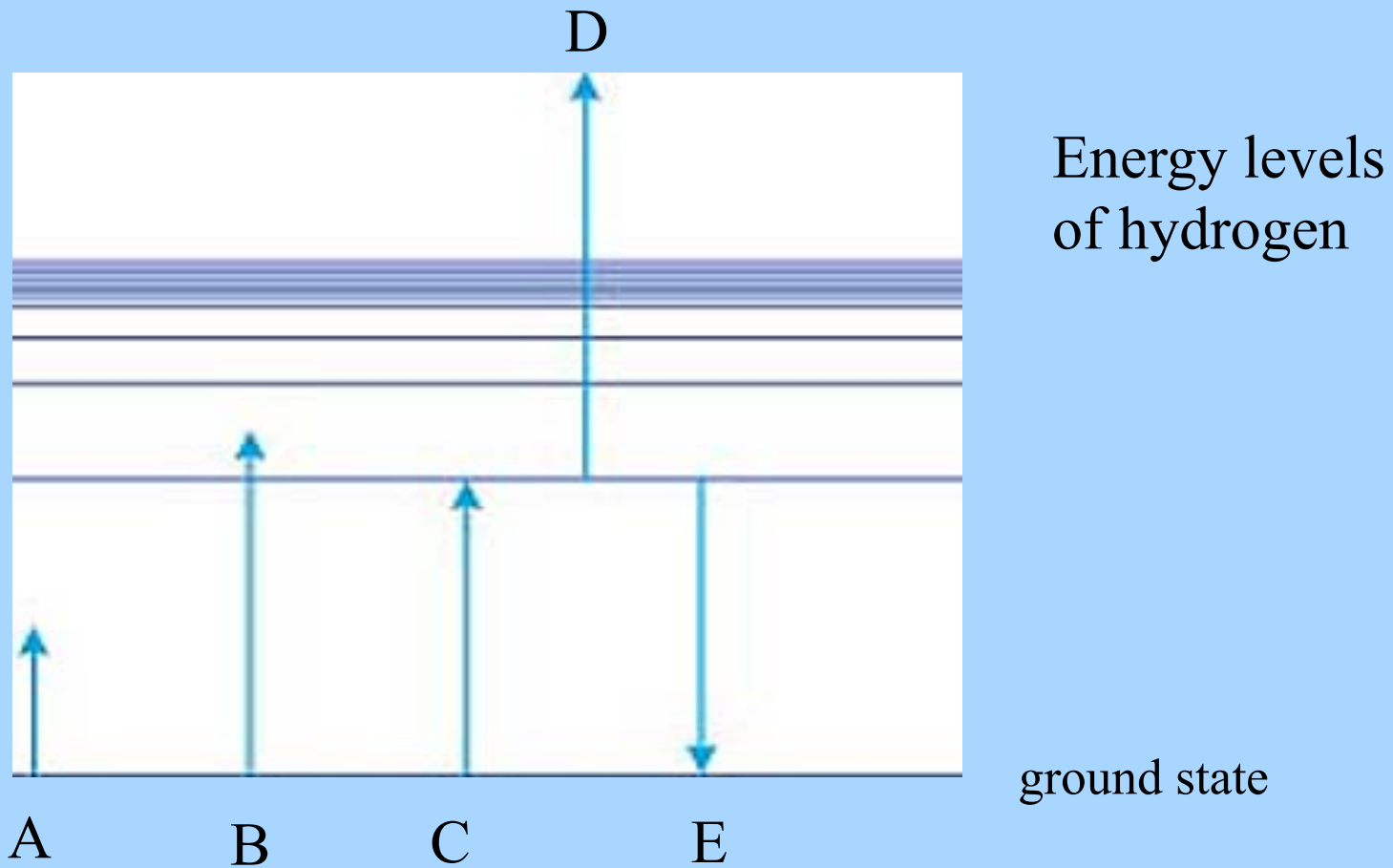
It turns out that there is an ultraviolet sequence of hydrogen lines and various infrared sequences.





In 1913 the Danish physicist Niels Bohr (1885-1962) worked out a model of the hydrogen atom which explained the observed patterns of lines. There are specific energy levels for the electrons which correspond to different distances from the corresponding protons. When an electron undergoes a transition to a lower energy level, it emits a photon of a very specific wavelength.





Situations A and B do not allow an electron in the ground state to reach the first excited state. Situation C does. Case D is an electron that obtains enough energy to escape the atom. In Case E the electron gives up a specific amount of energy.

The series of hydrogen lines seen at visual wavelengths arises from transitions to the second excited state ($n = 2$), while the ultraviolet series arises from transitions to the ground state of hydrogen ($n = 1$). The infrared lines arise from transitions to other excited states.

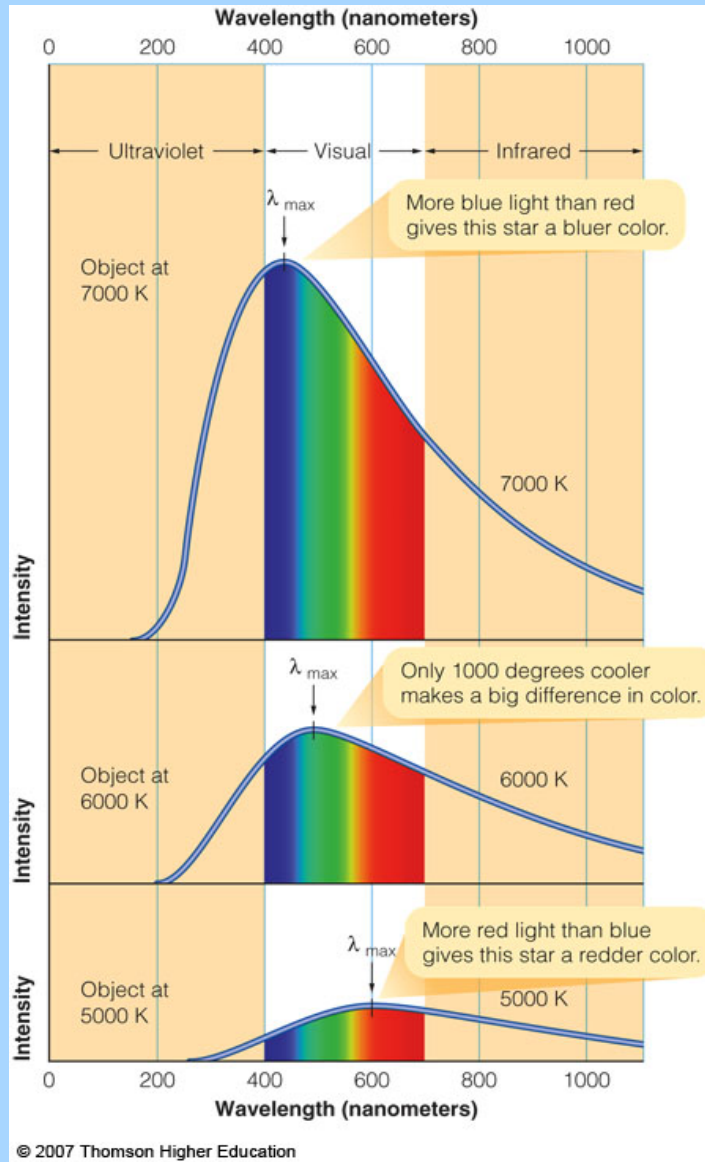


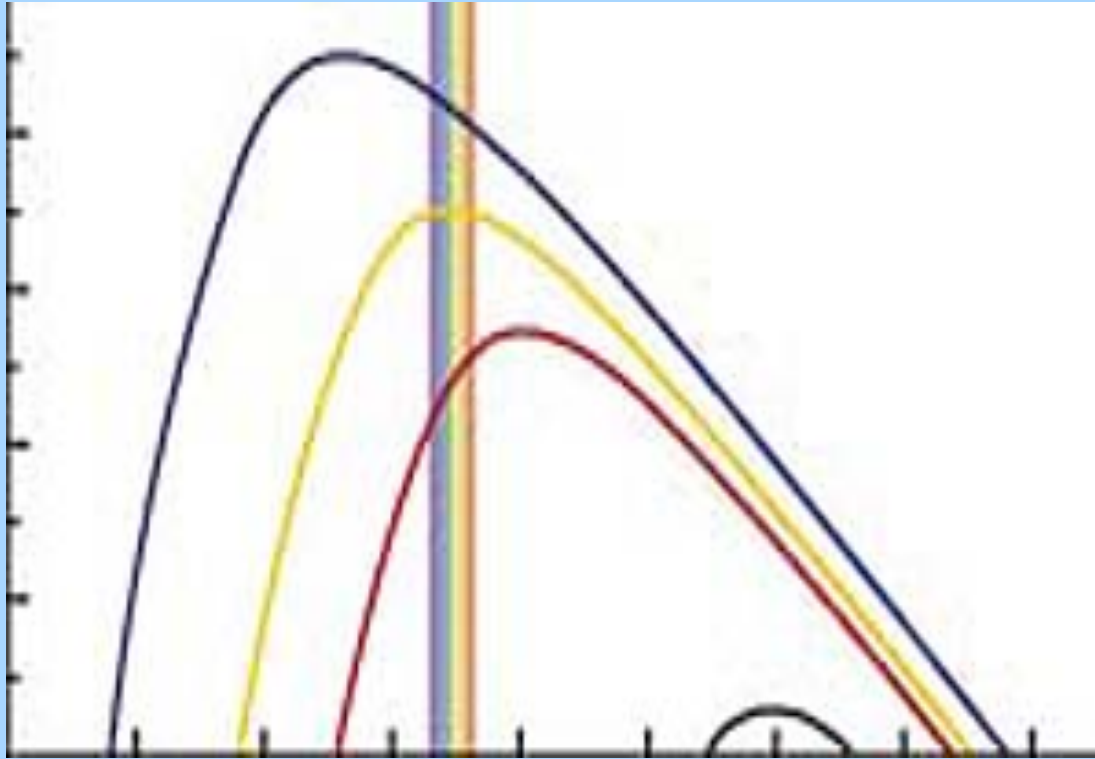
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Hot stars can ionize interstellar hydrogen. When the electrons recombine with protons, the spectral lines of hydrogen are produced.

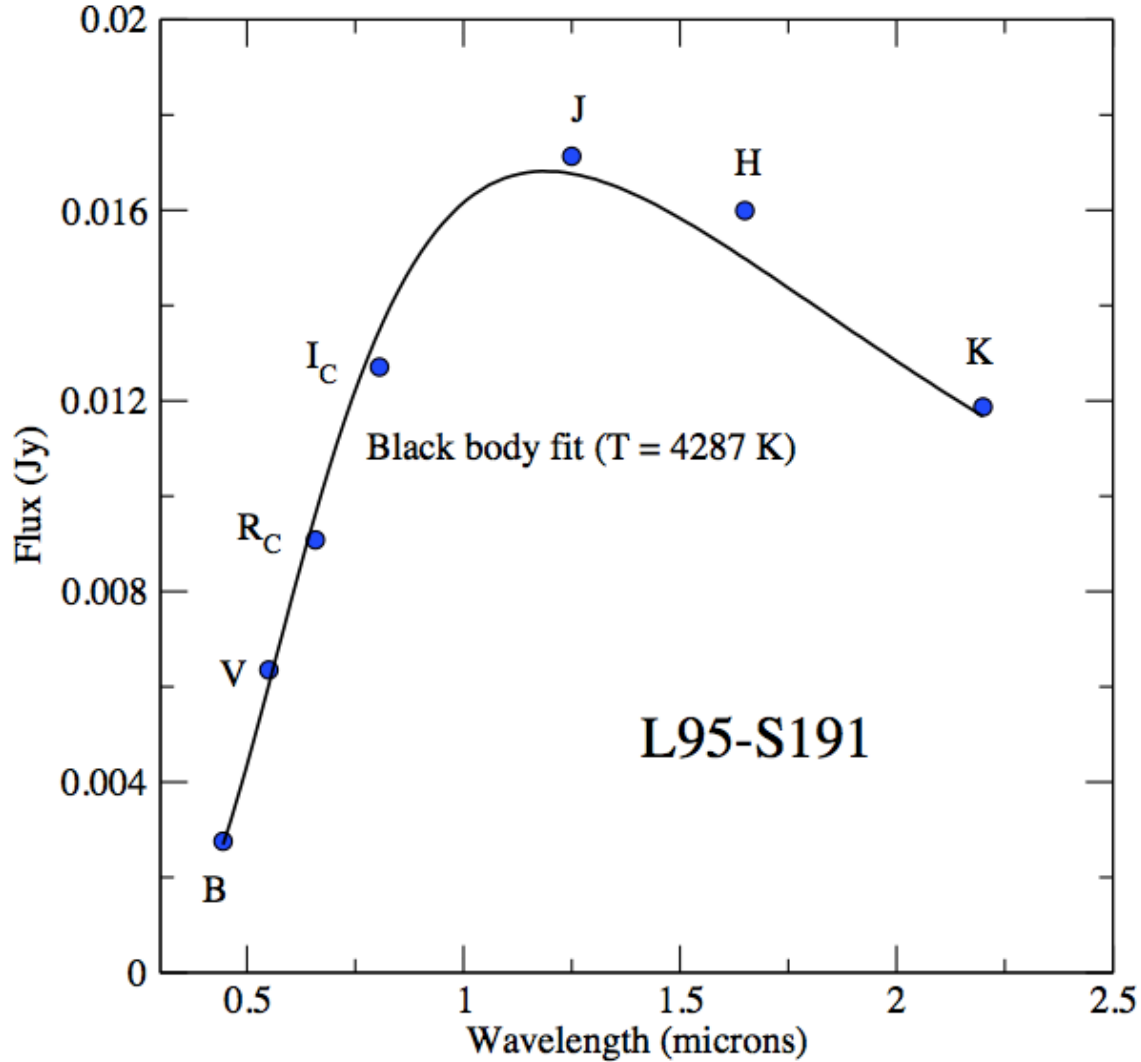
A solid, liquid, or dense gas is composed of atoms which are agitated according to the temperature of the substance. As long as the temperature is above absolute zero ($-273 \text{ deg C} = 0 \text{ degrees Kelvin}$), the substance also gives off light. In fact, it gives off light at all wavelengths. This is called *continuous radiation*, also known as **black body radiation**.

What color such a substance appears to be depends on its temperature. If $T = 10,000 \text{ deg K}$, the object glows white-hot. If $T = 4500 \text{ deg K}$, the object appears orange.

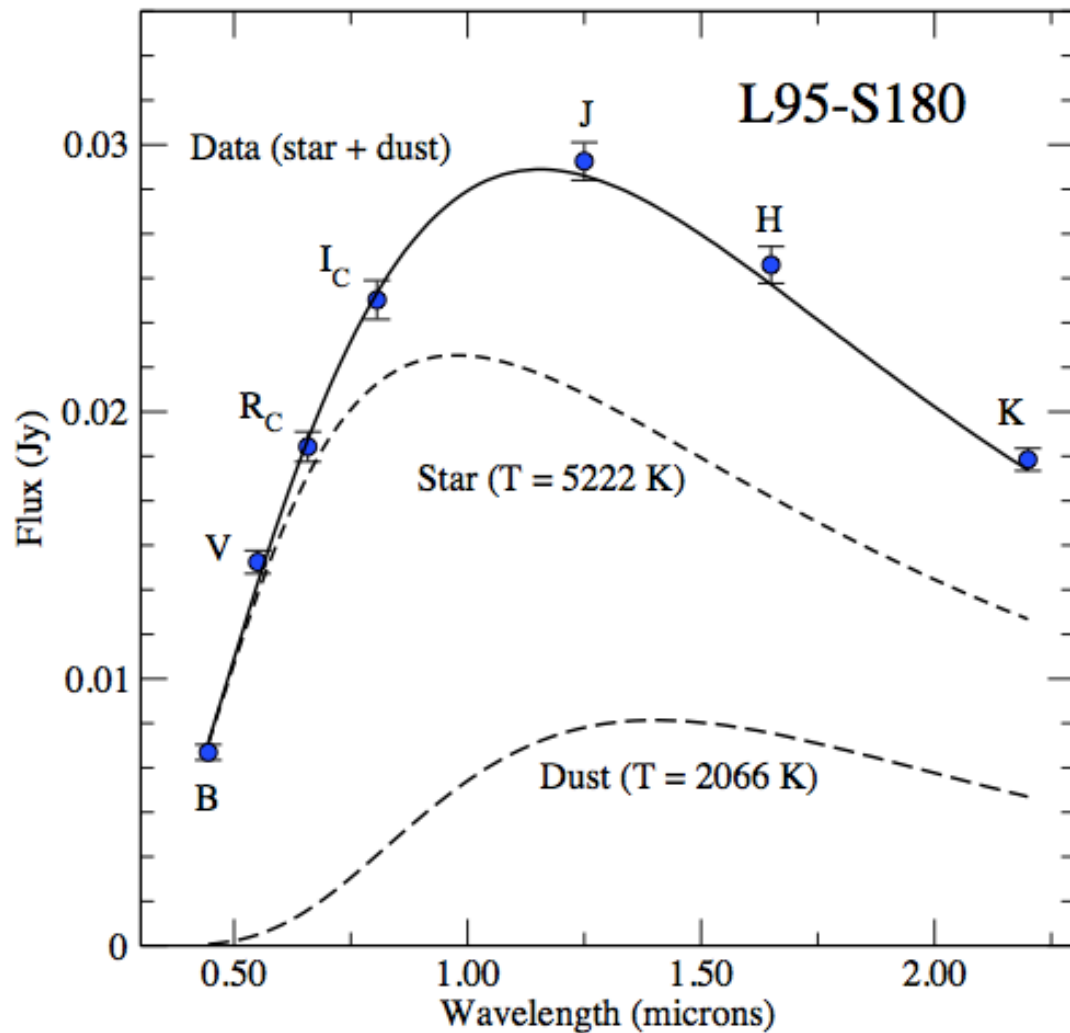




This is a plot of the relative intensity per square meter of surface vs. the wavelength of light for four different idealized black bodies. A hotter object produces more light at *every* wavelength. Also, hotter objects produce more light at a higher average energy.



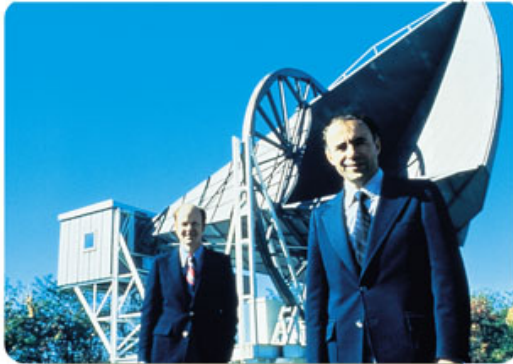
Example of
black body fit
to photometry
of normal star.



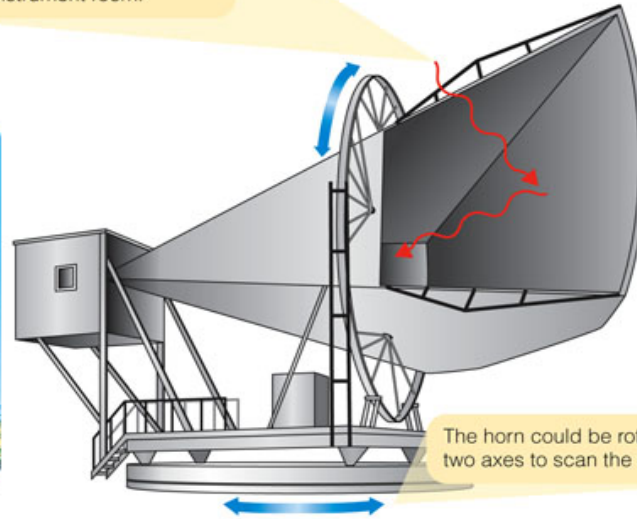
More complicated situation. Star with something else nearby - either hot circumstellar dust, protoplanetary disk, or brown dwarf companion.

Even the empty vacuum of space gives off black body radiation. This is the **cosmic microwave background radiation**. It is observed as short-wavelength radio waves. The corresponding temperature of the radiation is 2.725 degrees above absolute zero. This is evidence that the universe originated long ago in a fiery **Big Bang** and has been expanding ever since. The original radiation has spread out owing to the expansion of the universe.

In 1965, Arno Penzias (right) and Robert Wilson first detected the background radiation with an unused horn antenna.

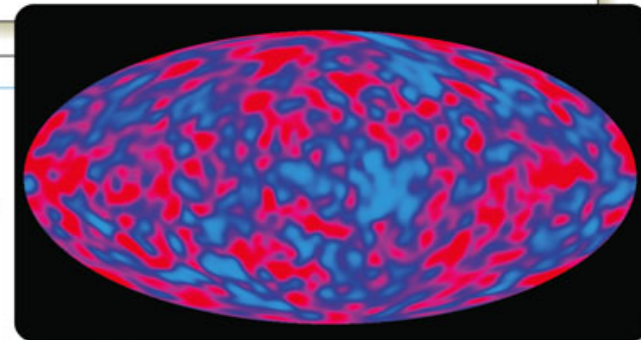
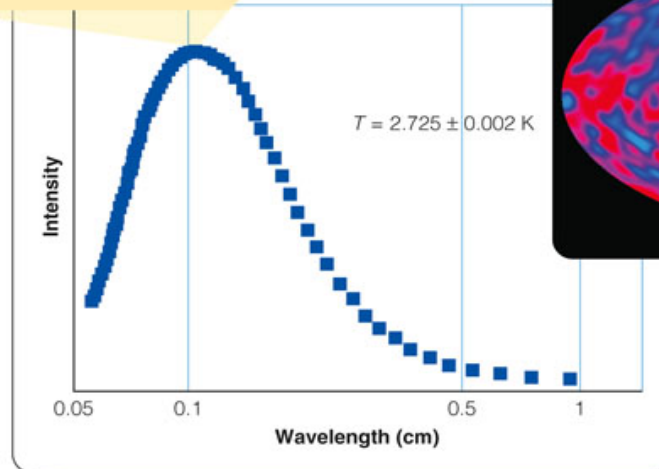


Microwave radiation from the sky enters the horn and is focused into the instrument room.



The horn could be rotated about two axes to scan the entire sky.

Launched in 1989, the COBE satellite showed the background radiation followed the black body curve.



All-sky COBE map of tiny variations in the background radiation.

The amount of energy that a black body emits per square meter is a strong function of its temperature.

$$E = \sigma T^4$$

T is the temperature above absolute zero (deg K).
Thus, if one object is twice as hot as another, it gives off 16 times as much continuous radiation per square meter.

The luminosity (L) of a star of area A is:

$$L = A \sigma T^4 = 4 \pi R^2 \sigma T^4$$

Consider two stars of the same temperature/color. If one has twice the diameter of the other, its surface area is four times as great, so it will give off four times as much light.

Now consider a cool star of temperature 3000 K and a hot blue star of temperature 30,000 K. But the cool star is a red giant with 100 times the diameter of the smaller star. Each square meter of the hotter star gives 10,000 times as much light, but the larger star has 10,000 times as much area. So the two stars have the same total luminosity.

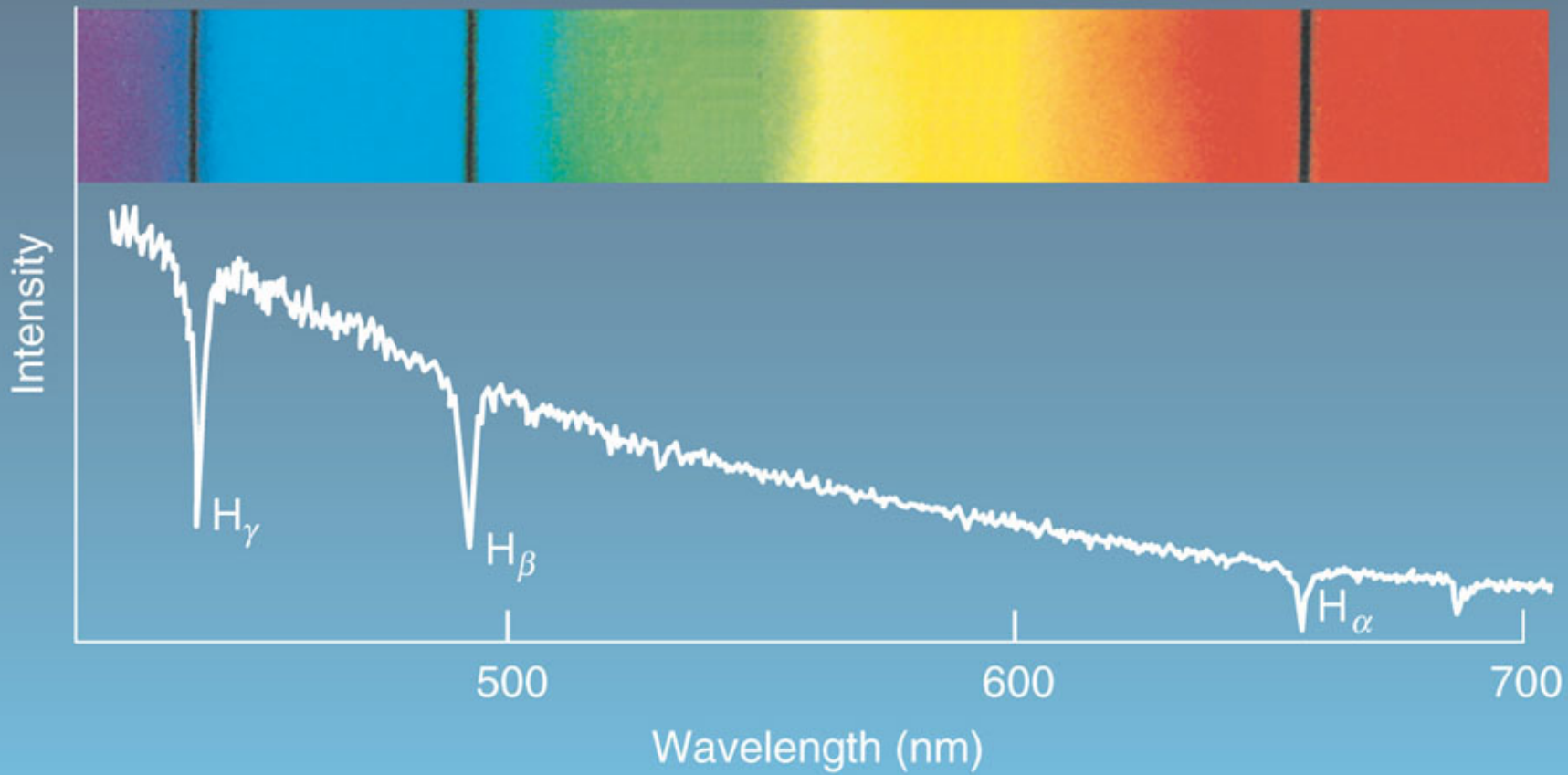
Wien's ("Veen's") law relates the temperature of the black body radiation to the wavelength that the distribution of energy has its maximum:

$$\lambda_{\text{max}} = 2,900,000 / T \quad ,$$

where T is in degrees Kelvin, and λ_{max} is measured in nanometers. (The constant is 2900 if the wavelength is in microns.) If a star's temperature is 2900 K, its black body curve peaks at a wavelength of 1000 nm (= 10,000 Å = 1 micron) in the near infrared. The cosmic microwave background radiation, with T ~ 3 deg K, peaks at a wavelength of about 0.1 cm.

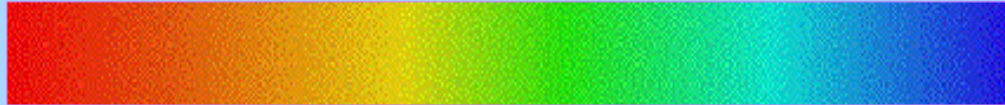
Say there is a source of black body radiation out there in space. It gives off light of all wavelengths, but puts out a lot of its light around some wavelength corresponding to its temperature. Now say there is some cooler hydrogen gas along the line of sight. What happens?

Some of that continuous light coming our way has just the right wavelength to be absorbed by the electrons in the hydrogen gas, so the electrons become excited (i.e., absorb those photons and jump to other energy levels). When the electrons jump back down to lower levels, photons of specific energies will be produced. But these photons go off in all directions. Thus, the light of the black body source is *diminished* at specific wavelengths corresponding to the spectral lines of hydrogen.

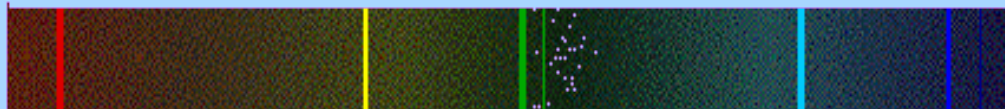


Thus, there are three kinds of spectra:

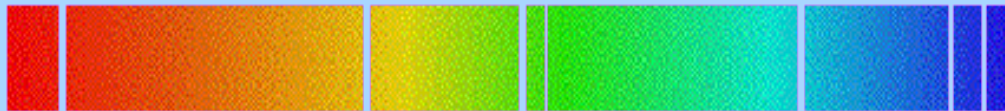
Continuous Spectrum



Emission Spectrum

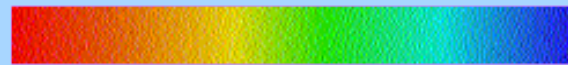


Absorption Spectrum





Continuous Spectrum



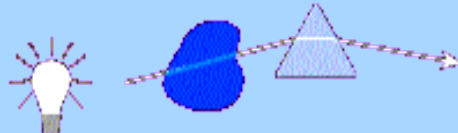
Hot Gas



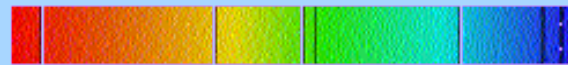
Emission Spectrum



Cold Gas



Absorption Spectrum



The dark lines in the spectrum of the Sun were catalogued by an optician named Joseph von Fraunhofer in 1814, but they were not explained until 1859. Gustav Kirchhoff and Robert Bunsen (as in Bunsen burner) showed that if you sprinkle various salts into a candle flame, bright lines were observed that corresponded to the particular salt involved. But, to their surprise, if the flame is placed between the observer and a bright source of continuous radiation, one observes the continuous spectrum of that source, *minus* the light at the specific wavelengths one saw in the bright line spectrum.

Kirchhoff's Laws

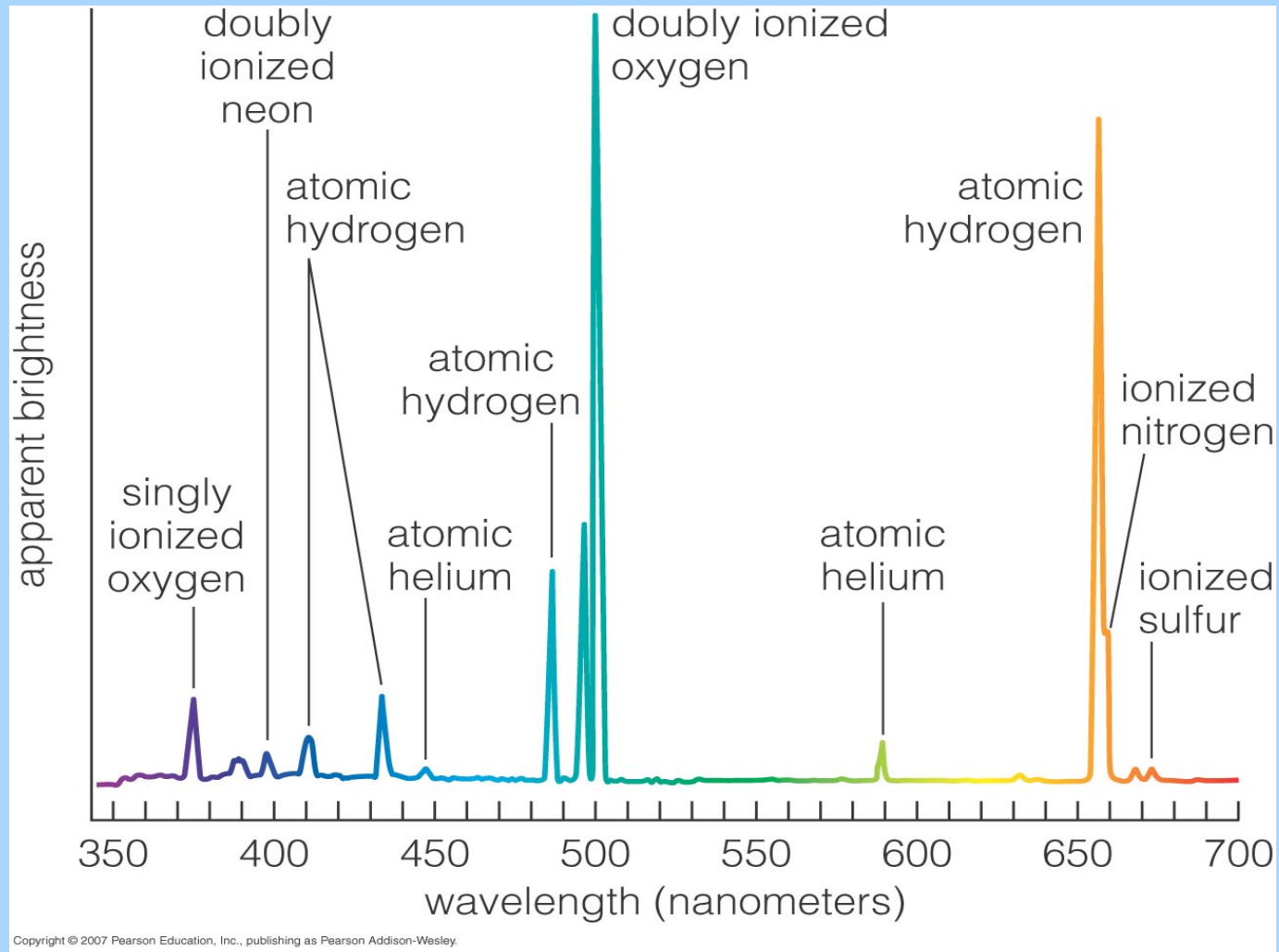


G. Kirchhoff
(1824-1887)

- I. A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths and thus produce a continuous spectrum.

- II. A low-density gas excited to emit light will do so at specific wavelengths and thus produce an emission spectrum.

- III. If light comprising a continuous spectrum passes through a cool, low-density gas, the result will be an absorption spectrum.

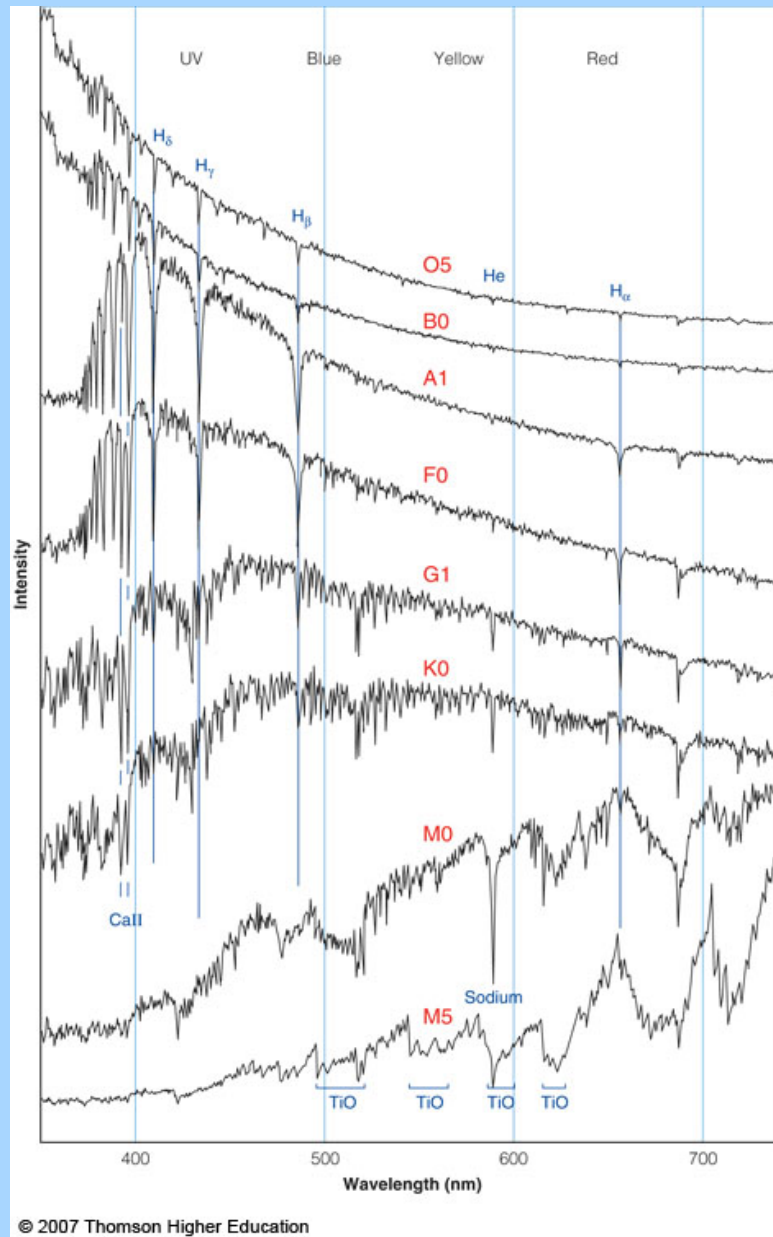


A spectrum of the Orion Nebula reveals many *emission* lines.

A star is a hot source of black body radiation.

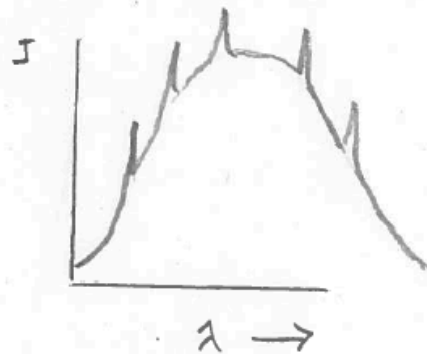
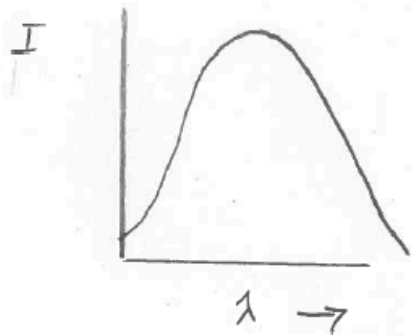
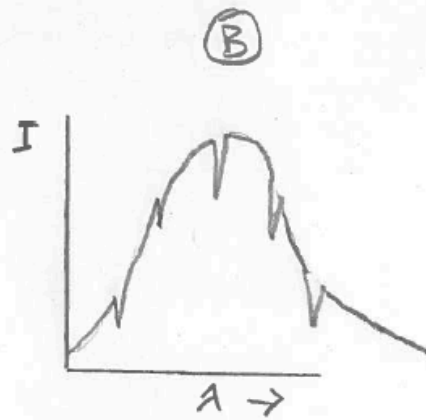
But – its outer atmosphere is cooler than the layers closer to the center of the star.

So – a star will produce an absorption line spectrum.



Stellar spectra in order from the hottest (top) to coolest (bottom).

From the early 1890's to the mid 1920's Harvard Univ. operated an observing station in Arequipa, Peru. They took photographic plates of the heavens and also obtained many low-resolution spectra of stars. First they classified the spectra on the basis of the strength of the hydrogen lines (A, B, C, ... O). They later realized that this scheme did not make the most physical sense, so they reorganized the scheme and eliminated many letters, so that the order by temperature comes out OBAFGKM. They later added types R, N, and S. Various mnemonics can be used to remember the order.



Which spectrum best represents the spectrum of a normal star?

■ **Table 7-1** | **Spectral Classes**

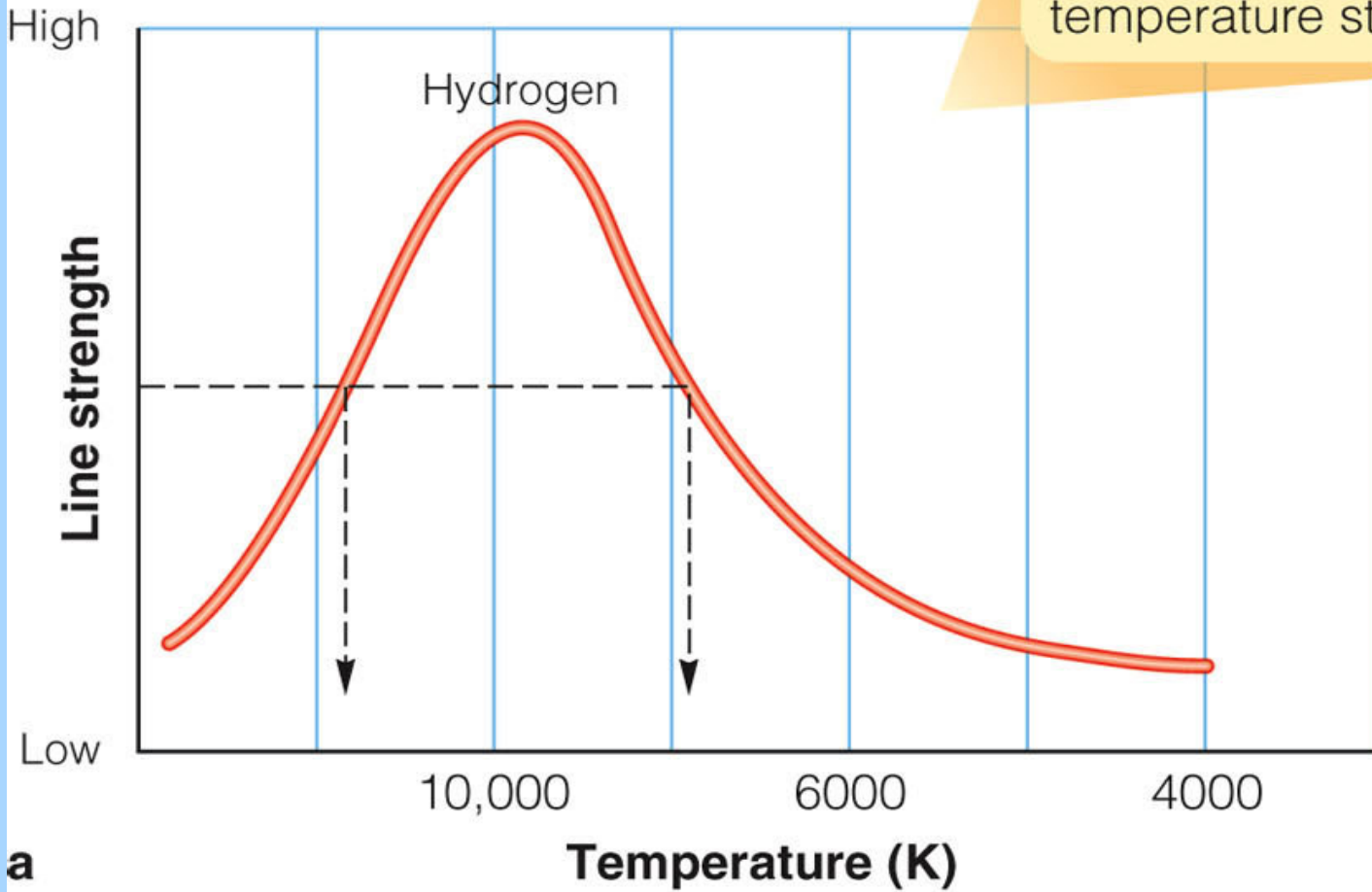
| Spectral Class | Approximate Temperature (K) | Hydrogen Balmer Lines | Other Spectral Features | Naked-Eye Example |
|----------------|-----------------------------|-----------------------|-------------------------|-------------------|
| O | 40,000 | Weak | Ionized helium | Meissa (O8) |
| B | 20,000 | Medium | Neutral helium | Achernar (B3) |
| A | 10,000 | Strong | Ionized calcium weak | Sirius (A1) |
| F | 7,500 | Medium | Ionized calcium weak | Canopus (F0) |
| G | 5,500 | Weak | Ionized calcium medium | Sun (G2) |
| K | 4,500 | Very weak | Ionized calcium strong | Arcturus (K2) |
| M | 3,000 | Very weak | TiO strong | Betelgeuse (M2) |

Types R, N, and S are stars with various molecular bands in their spectra. Two new types are L and T, which contain iron hydride (FeH) and methane (CH₄) in their spectra. These are very cool stars, detectable at infrared wavelengths only.

If a star like the Sun has iron, calcium, sodium, and other metallic lines in its spectrum, but it has relatively weak hydrogen lines, then its atmosphere must be composed of Fe, Ca, Na, but little H, right?

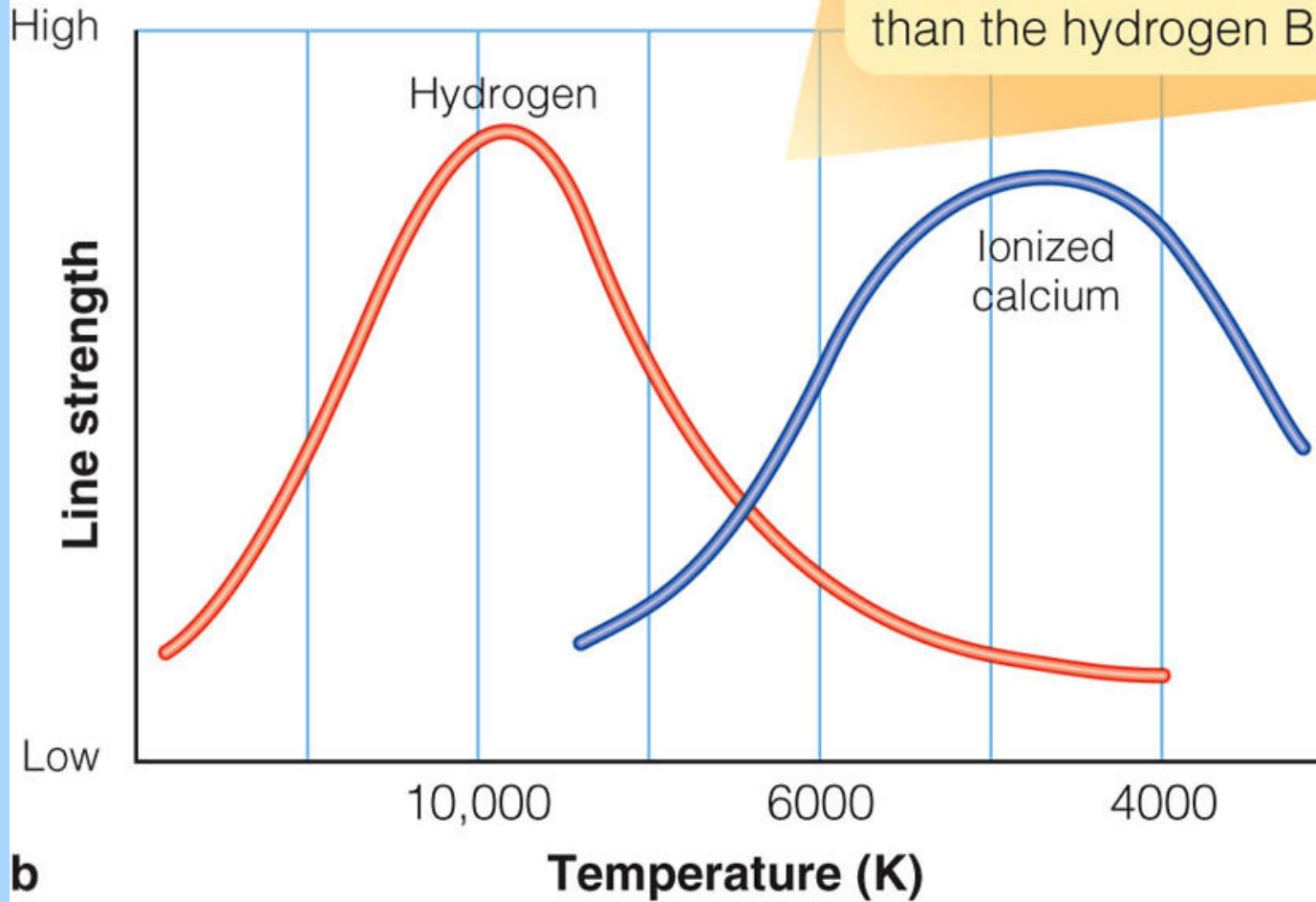
That's what astronomers thought until the 1920's. They then realized that the fraction of atoms that were ionized was critical to understanding which lines were strong and which were weak. In very hot O and B stars, most of the hydrogen is ionized and stays ionized. The electrons are never captured by protons to produce strong Balmer lines. But helium can recombine to show us helium lines.

Hydrogen Balmer lines are strongest for medium-temperature stars.



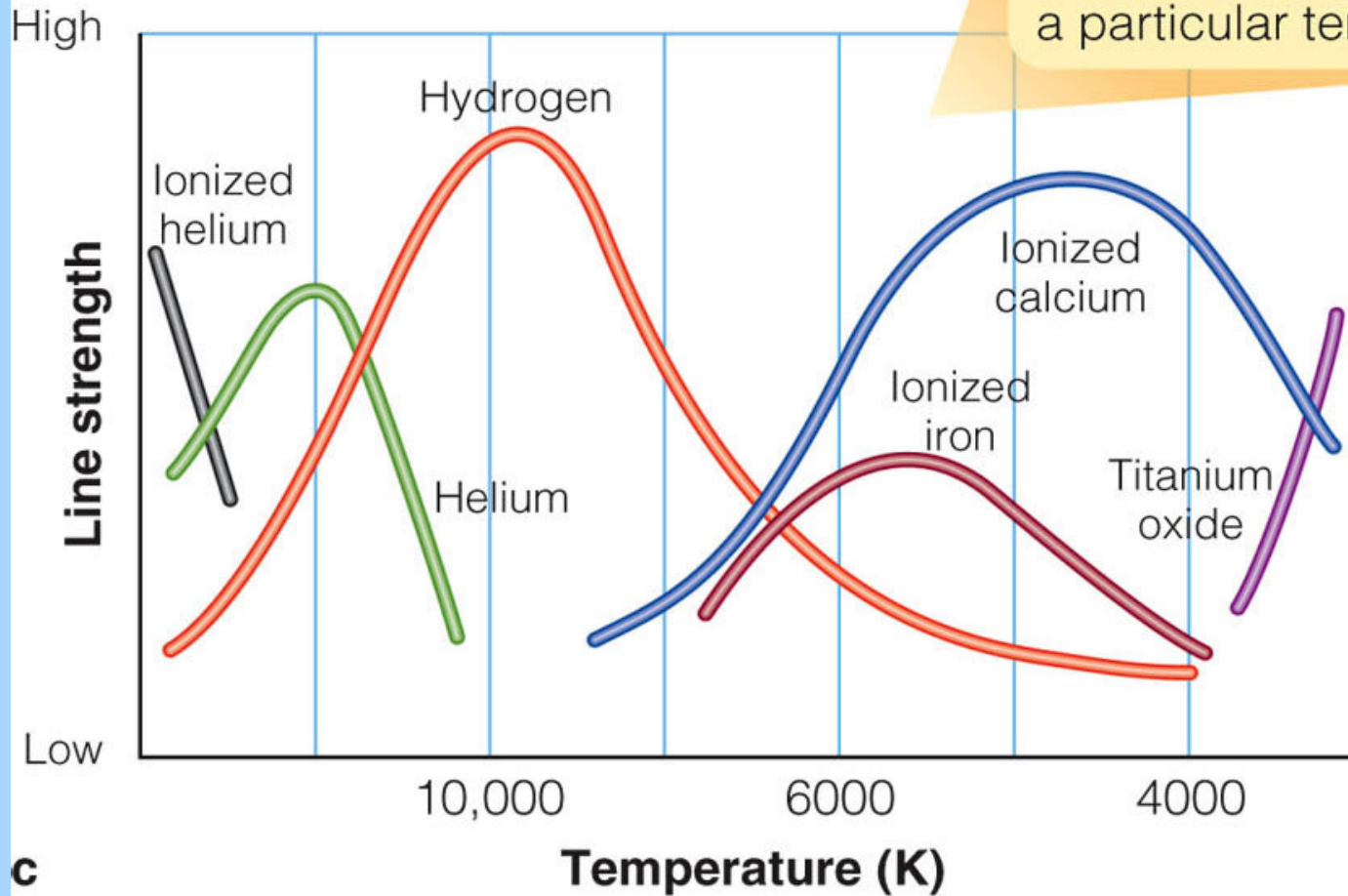
a

Lines of ionized calcium are strongest at lower temperatures than the hydrogen Balmer lines.



b

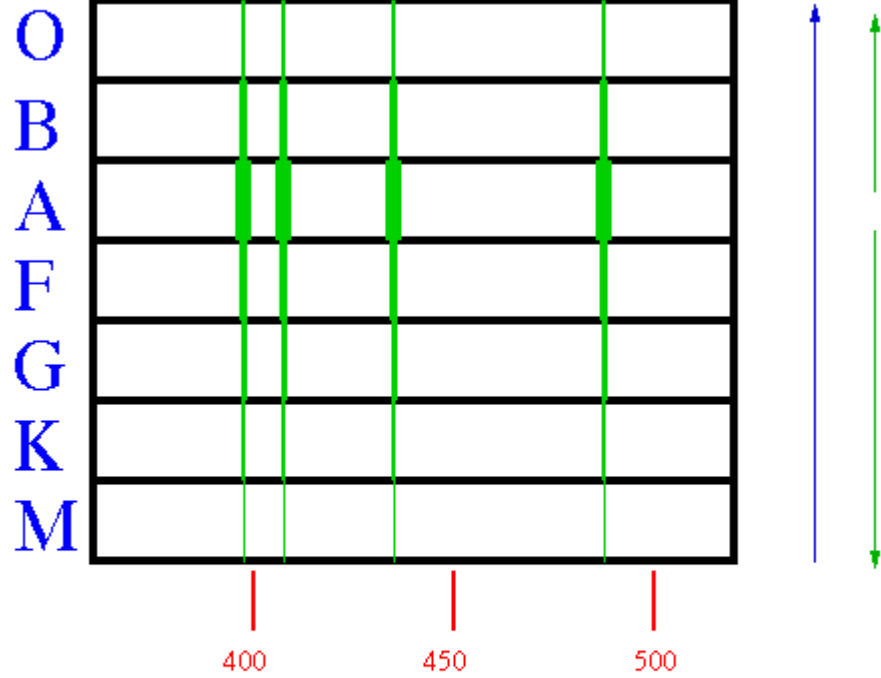
The lines of each atom or molecule are strongest at a particular temperature.



c

Balmer Lines of Hydrogen

H ϵ H δ H γ H β



Wavelength (in Nanometers)

Note: the blue arrow points toward hotter stars.

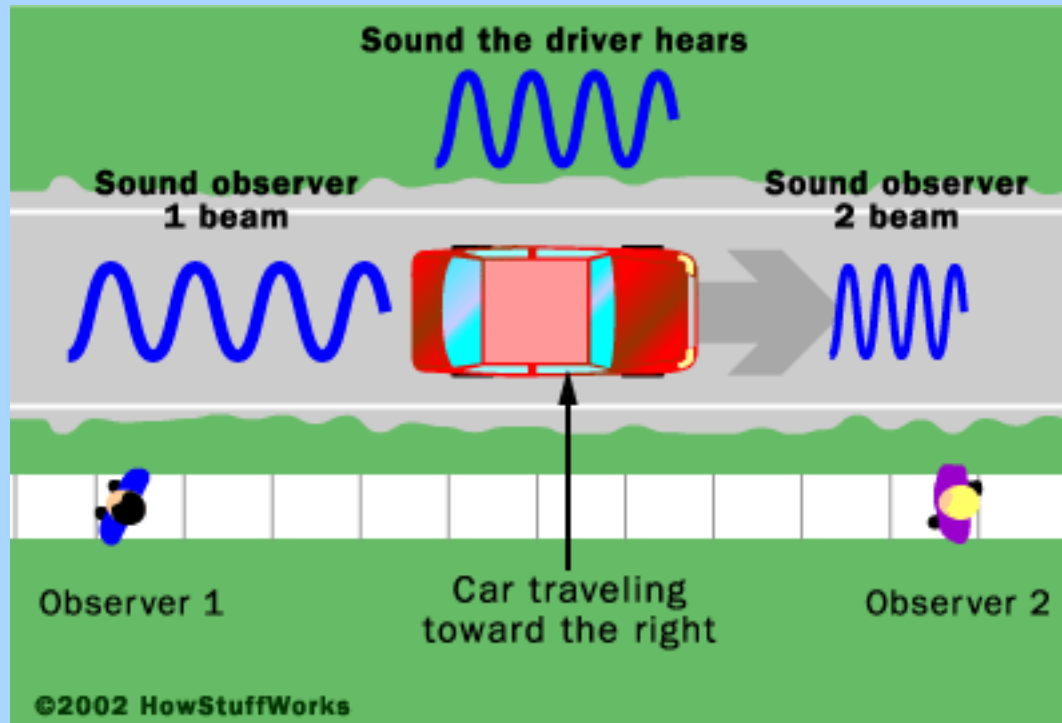
Note: the green arrows point from the strongest to the weakest hydrogen lines.

Doppler shifts

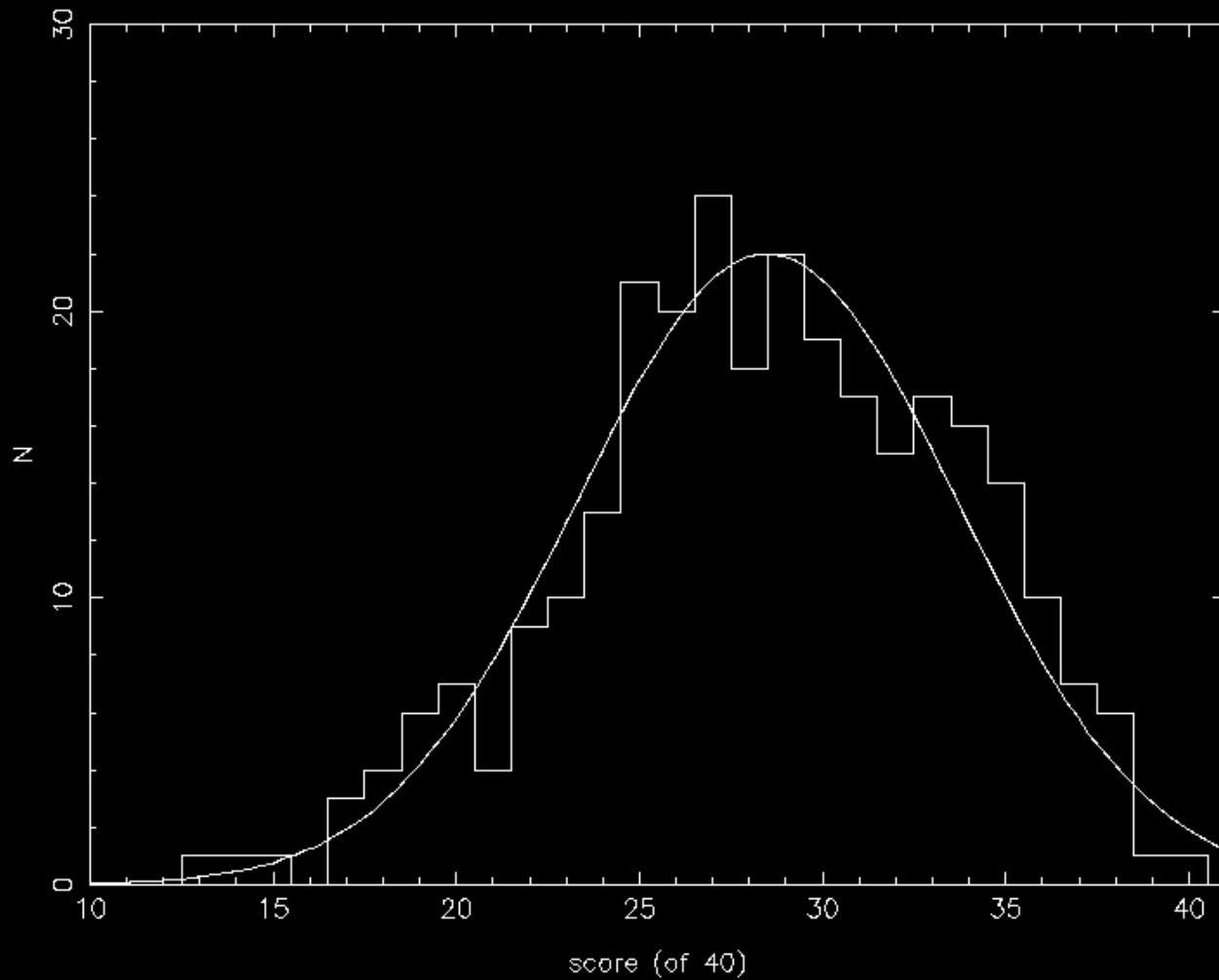
We have all seen Doppler radar maps on the TV weather report. They show how areas of rain or snow are moving one direction or another.

And when a fastball is reported to have been thrown at 97 mph, the device that measured this used the Doppler effect and some kind of radar device.

Sounds waves can be Doppler shifted



ASTR 101 Fall 2020 sections 501 and 502

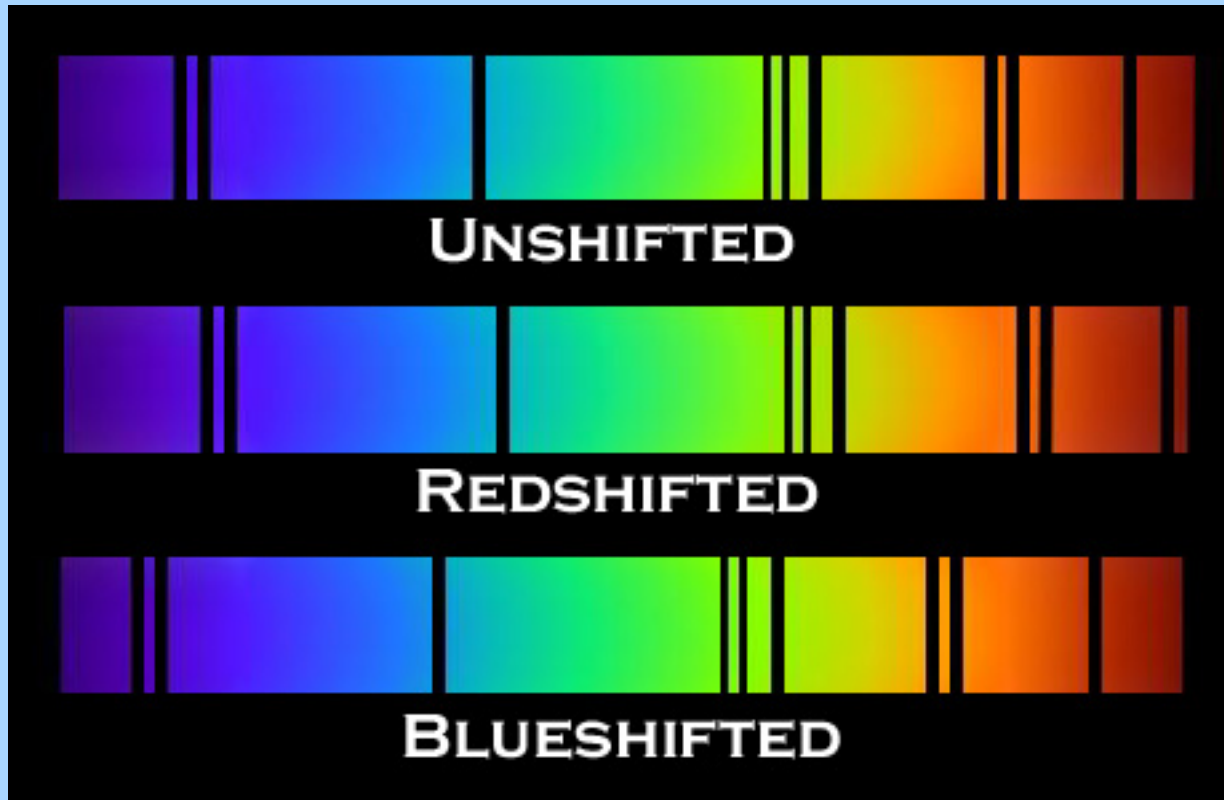


$N = 287$

avg = 28.5
(71%)

median = 29

Light waves can be Doppler shifted



While we measure certain wavelengths of spectral lines in the laboratory, in stars and galaxies the measured wavelengths are slightly different. This is due to motions of the stars and galaxies with respect to the Earth. These velocities along the line of sight are called **radial velocities**. If the observed wavelength shift is $\Delta\lambda$, the radial velocity is:

$$V_r = (\Delta\lambda/\lambda) c \quad .$$

If the red line of hydrogen is observed at 6564 Å instead of 6563 Å, the source of that radiation is moving 46 km/sec away from us.

How do we do the calculation?

Let $\lambda_{\text{obs}} = 6564$ Angstroms and $\lambda_0 =$ the laboratory wavelength, 6563 A. Then

$\Delta\lambda = (6564 - 6563) = 1$ Angstrom. If $\Delta\lambda > 0$, then the object is moving away from us. If $\Delta\lambda < 0$, the object is moving towards us. The radial velocity in this case is

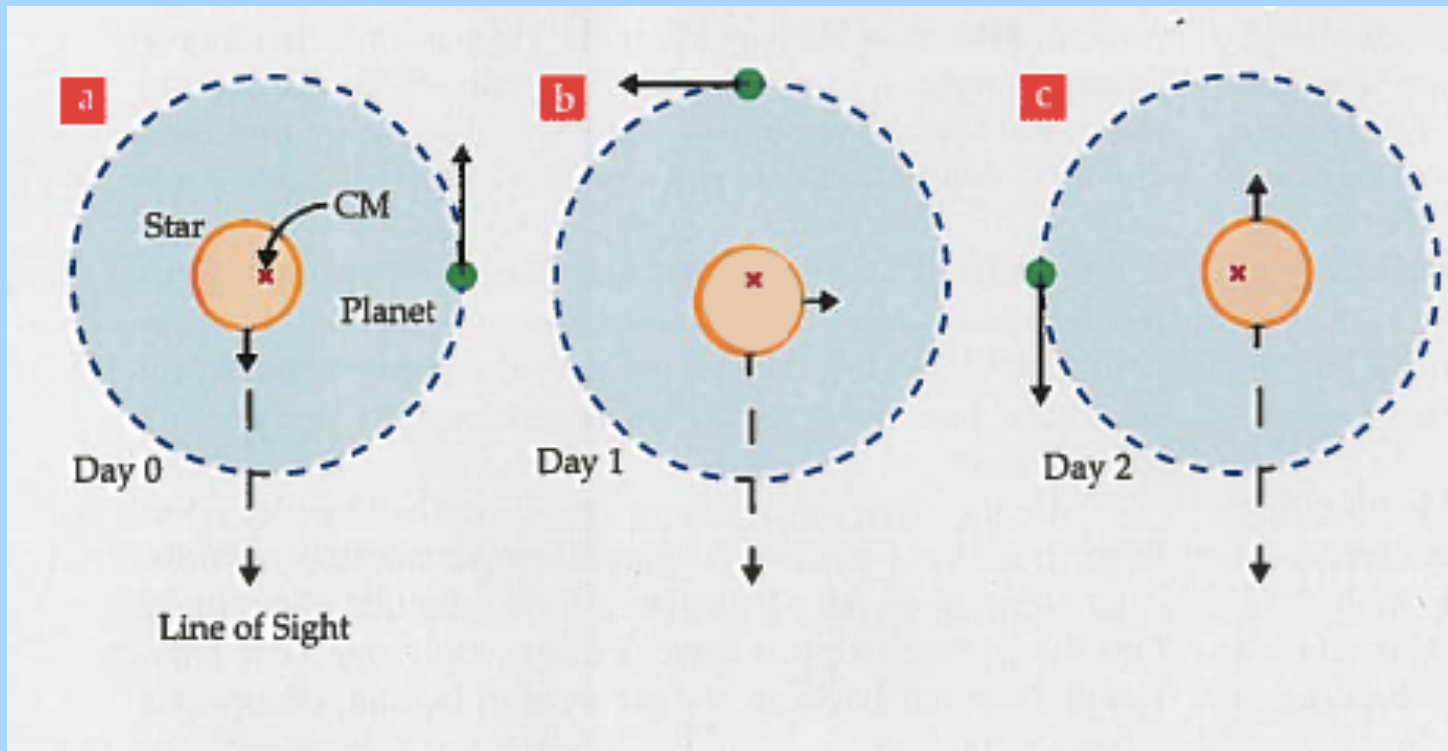
$$V_r = (1/6563) * 300,000 \text{ km/sec} = 46 \text{ km/sec}$$

Similarly, if the red line of hydrogen is observed at 6562 Å, the source of that radiation is moving 46 km/sec towards us.

Redshifts are wavelength shifts toward longer wavelengths. **Blue shifts** are wavelength shifts toward shorter wavelengths.

Except for a small number of nearby galaxies, the Doppler shifts of galaxies are all towards longer wavelengths. Almost all the galaxies in the universe are receding from us.

Very accurate radial velocities of some stars reveal the existence of extra-solar planets.



In October of 1995 the star 51 Pegasi was shown to have a planet more massive than Jupiter, but revolving with a period of only 4 days.

