

## Topics through Chapter 4

**3.5 The Doppler Effect:** this is how we learn about the motions of objects in the universe, discover extraterrestrial planets, black holes at the centers of galaxies, and the expansion of the entire universe.

**4.1 Spectral Lines:** appearance, excess or deficit of energy at *particular* wavelengths. (Don't worry about Kirchoff's laws, and the pictures with little prisms and light bulbs etc.--see notes)

**4.2 Atoms and Radiation:** quantized energy levels of electrons in atoms, and how they interact with radiation.

The hydrogen atom--the simplest, and most important case.

**4.3 The Formation of Spectral Lines:** understanding emission lines and absorption lines

**4.4 Molecules:** not just electronic changes, but vibrational and rotational changes of energy.

**4.5 Spectral-Line Analysis:** Information from spectral lines--abundances, turbulent motions, rotation, ...

## 3.5 The Doppler Effect

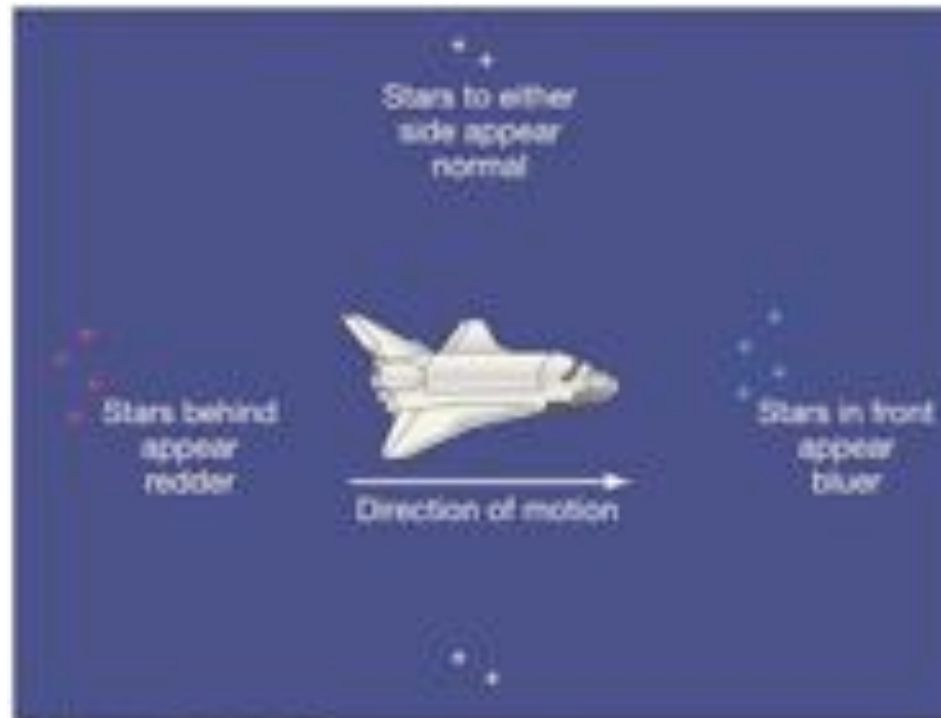
The wavelength (or frequency) of a wave, as measured by an observer, depends on the relative radial speed of the source and observer.

Radial motion means: motion towards or away; along the line of sight.

The Doppler effect involves *only* this component of motion. What we get from measuring it is called the **radial velocity**.

Moving away: wavelengths increase (“**redshift**”)

Moving toward: wavelengths decrease (“**blueshift**”)



## 3.5 The Doppler Effect

Relationship between wavelength and speed:

! *Shift* in compared to “rest (no motion) wavelength” is proportional to *radial velocity*

! So if you know the exact wavelength where some feature in the spectrum *should* be (“true wavelength”), and the wavelength at which it *appears* (“apparent wavelength”), you can obtain the radial velocity.

! This is how we get speeds of cosmic objects, stars, galaxies, even expansion of universe.

Actual formula is:

$$\frac{\text{(apparent)}}{\text{(true)}} = 1 \pm (\text{speed of object/speed of light})$$

where the  $\pm$  sign means it is + if it is moving away from us (redshift, longer wavelength), - if it is moving toward us (blueshift, shorter wavelength)

This applies to *any* wave; and no reason not to use frequency instead of wavelength.

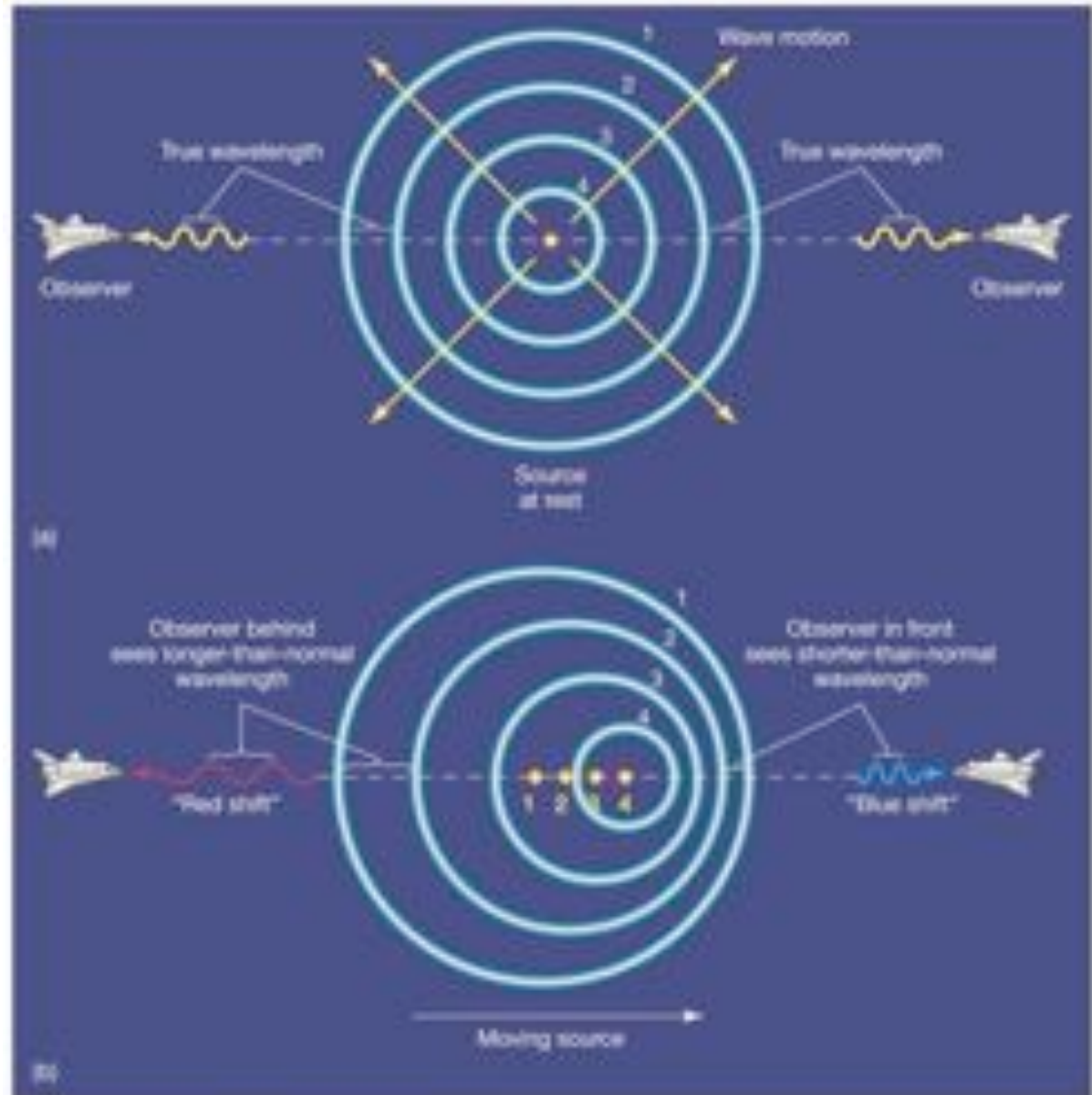
Textbook writes it this way:

$$\begin{aligned} \frac{\text{apparent wavelength}}{\text{true wavelength}} &= \frac{\text{true frequency}}{\text{apparent frequency}} \\ &= 1 + \frac{\text{recession velocity}}{\text{wave speed}} \end{aligned}$$

## 3.5 The Doppler Effect

See textbook for this rather confusing example. In class we'll use a simpler example of water waves in a pond.

Important point: Doppler effect depends only on the *relative motion* of source and observer



## More Precisely 3-3: Measuring Velocities with the Doppler Effect

Example: For a speed of 30 km/s, the Doppler shift is given by

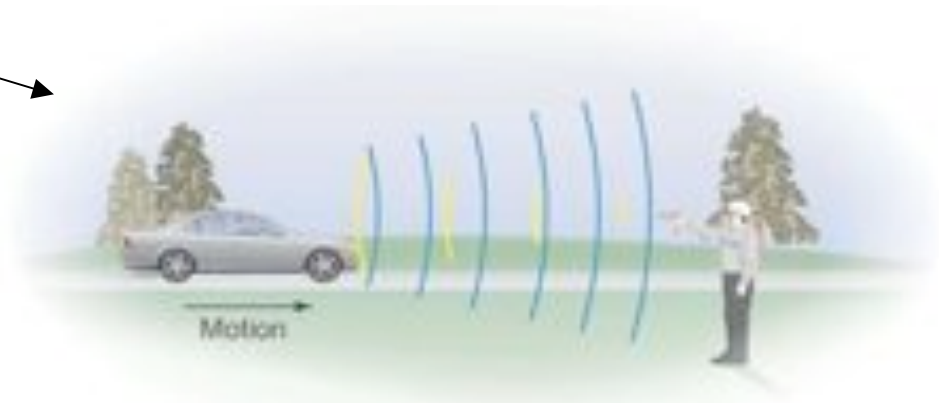
$$\frac{\text{change in wavelength}}{\text{true wavelength}} = \frac{\text{recession velocity}}{\text{wave speed}}$$
$$= \frac{30 \text{ km/s}}{300,000 \text{ km/s}} = 0.01 \text{ percent.}$$

speed of object

speed of light

This may seem small, but it is easily detectable with a radar gun.

It is NOT so easy to detect from the spectrum of an astronomical object, unless you know something about spectral lines.

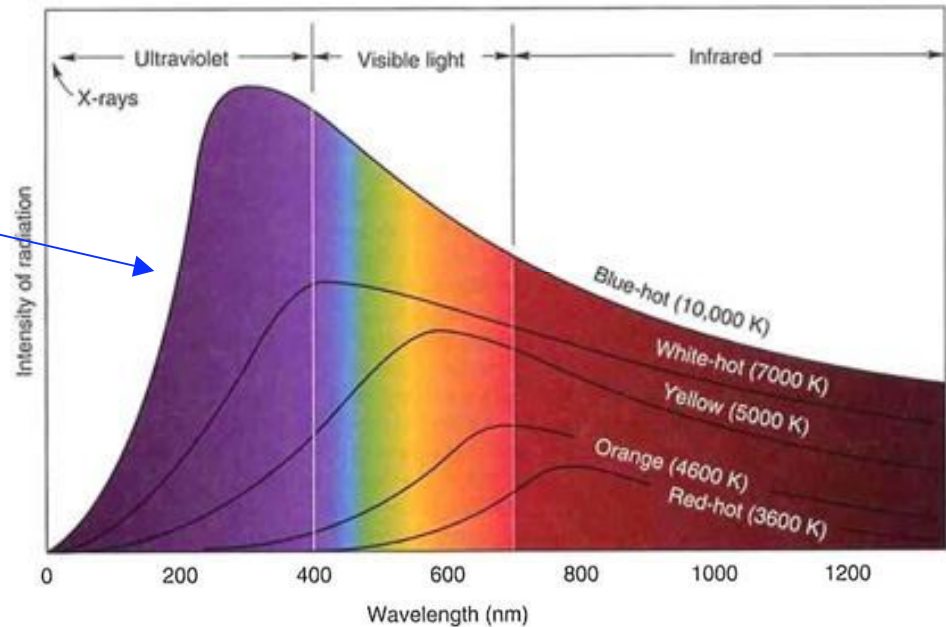


Look at the Doppler shift formula again:

$$\frac{\lambda_{\text{apparent}}}{\lambda_{\text{true}}} = 1 \pm (\text{radial velocity of object} / \text{speed of light})$$

If velocity of object away or toward us is much less than the speed of light (true for almost all objects in the universe), the apparent wavelength will be only slightly different from the “laboratory” or “rest” wavelength.

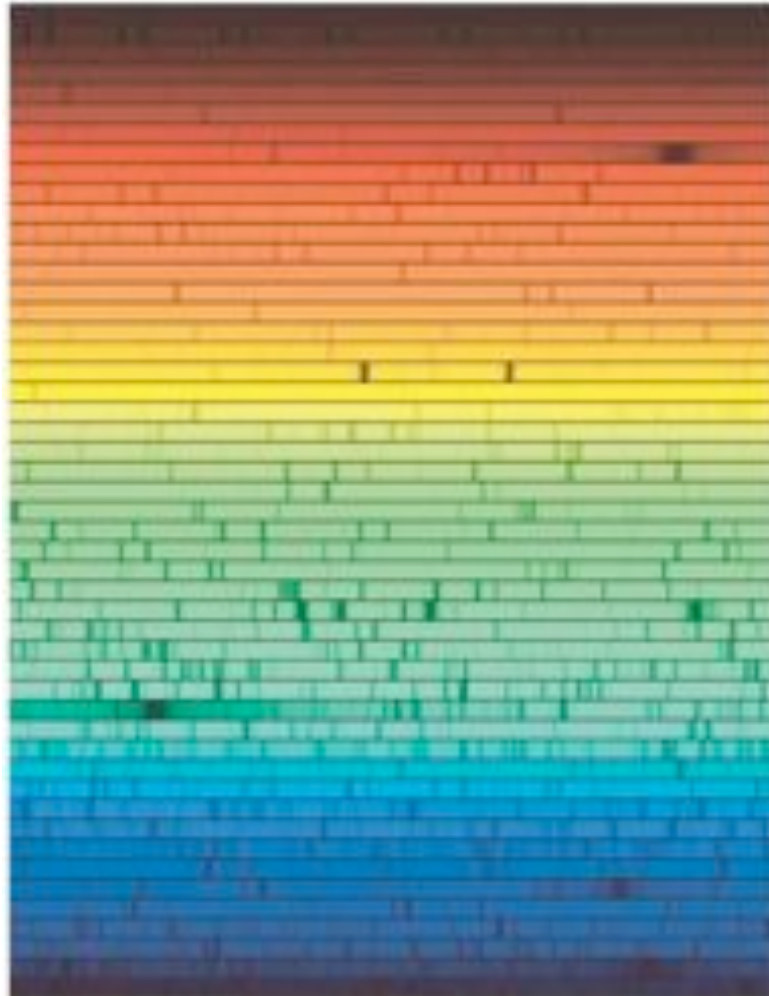
For most objects in the universe, this relative shift is so tiny, that we **can't detect it using the “shift” of the whole *continuous* spectrum.** But we can use places in the spectrum whose wavelengths are precisely known by the presence of *spectral lines* (the subject of Chapter 4)



# Chapter 4

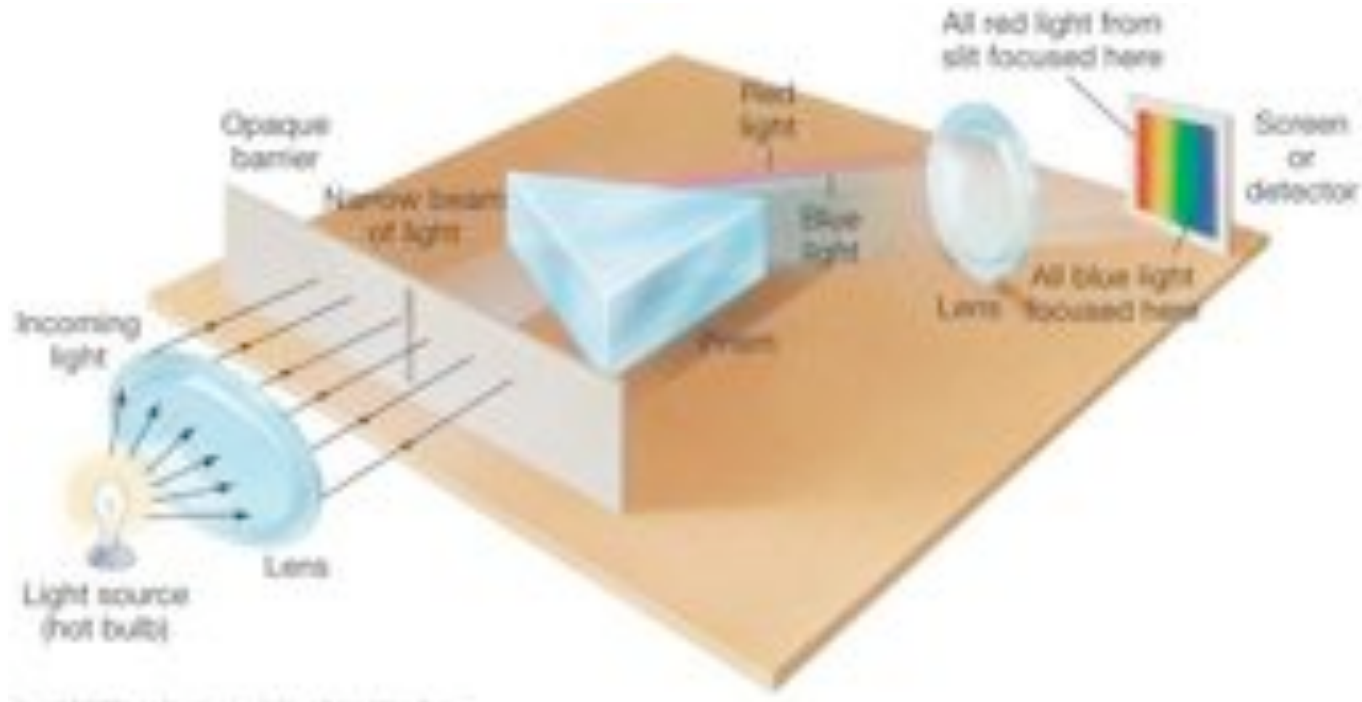
## Spectroscopy

*Don't worry if you can't understand what this pretty picture represents, unless it is the day before the next exam.  
A more important question is why the authors insist on showing this form of spectra without adequately explaining!*



## 4.1 Spectral Lines

**Spectroscope: Splits light into component colors (wavelengths, frequencies)**



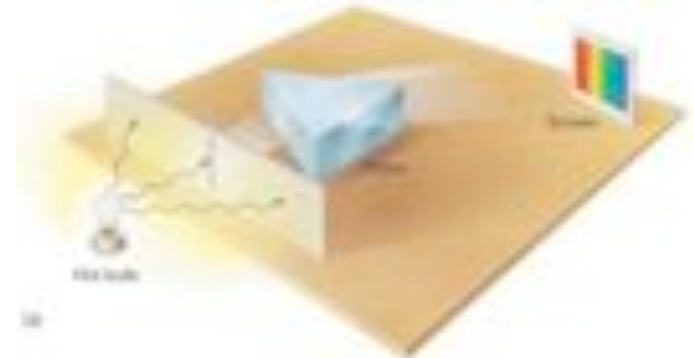
*Most of this illustration is completely unnecessary! The only important point is that light from any object can be spread out into a “rainbow” of wavelengths. A **spectrum** is a picture of how much light is at each wavelength. This illustration is showing a **continuous** spectrum.*



# 4.1 Spectral “Lines”

## Continuous spectrum:

Continuous range of frequencies emitted by an object (something like the “black bodies” we discussed in ch.3)



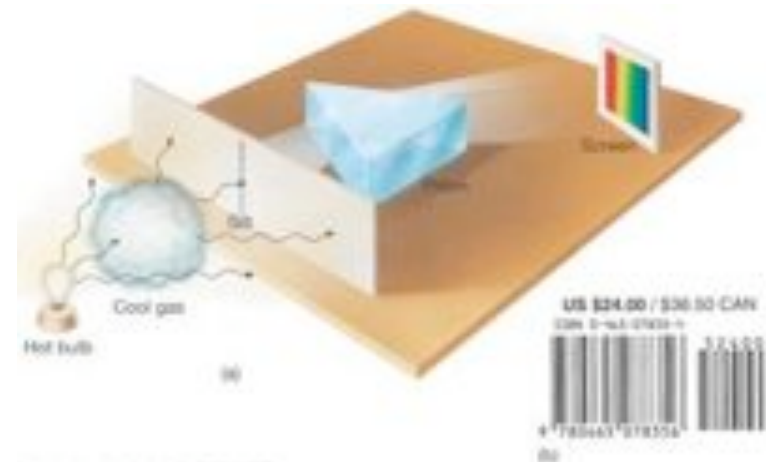
## Emission lines:

Single frequencies emitted by particular atoms in a hot gas



## Absorption lines:

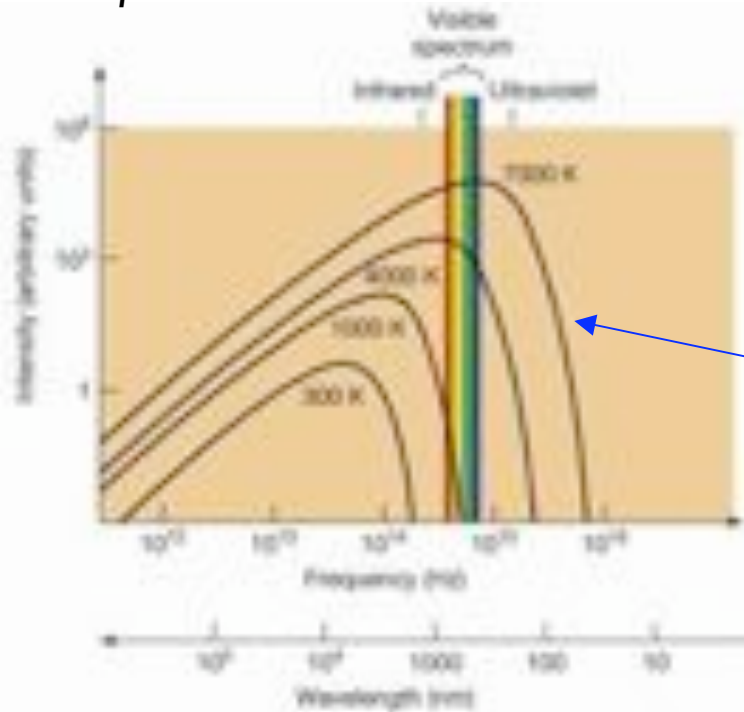
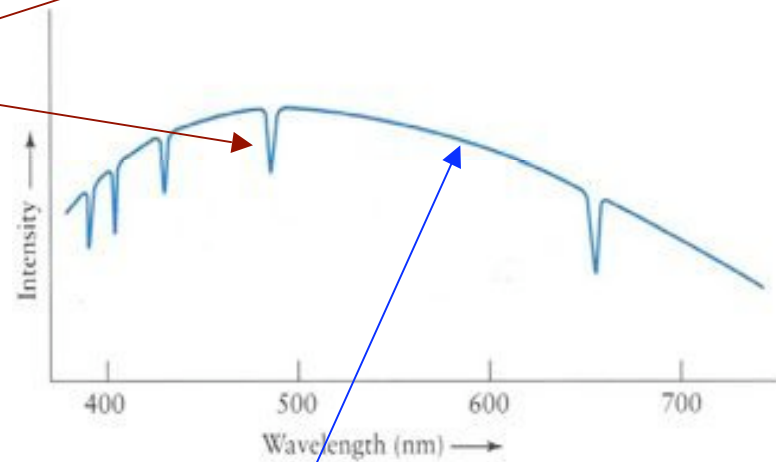
If a continuous spectrum passes through a cool gas, atoms of the gas will absorb the same frequencies they emit



## Spectral lines

Spectral lines—very narrow, well-defined (in wavelength) wavelength/frequency regions in the spectrum where excess photon energy appears (emission lines) or else where photons are missing (absorption lines).

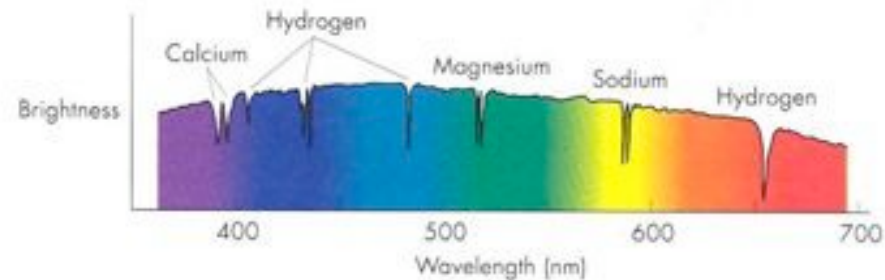
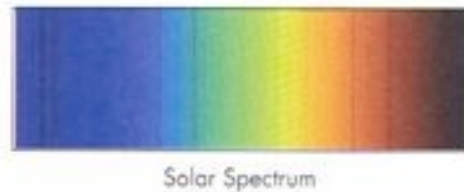
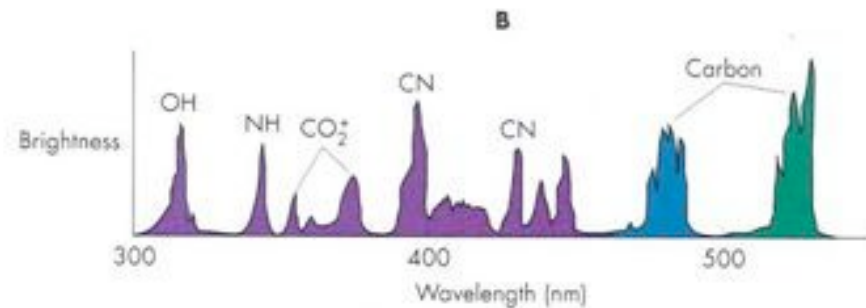
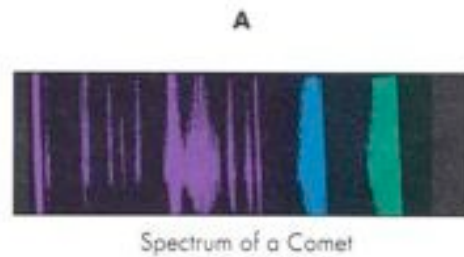
Cartoon view of *absorption lines*, both in the spectrum as a graph (below), and in the recorded spectrum (top), the band of colors—*this is just how the spectra are gathered—pay no attention to the rectangular shape!*



Often these lines are superimposed on a smooth, “continuous” spectrum, which is the near-blackbody emission of a heated object that we have been discussing so far (ch. 3, Wien, Stefan-Boltzmann).

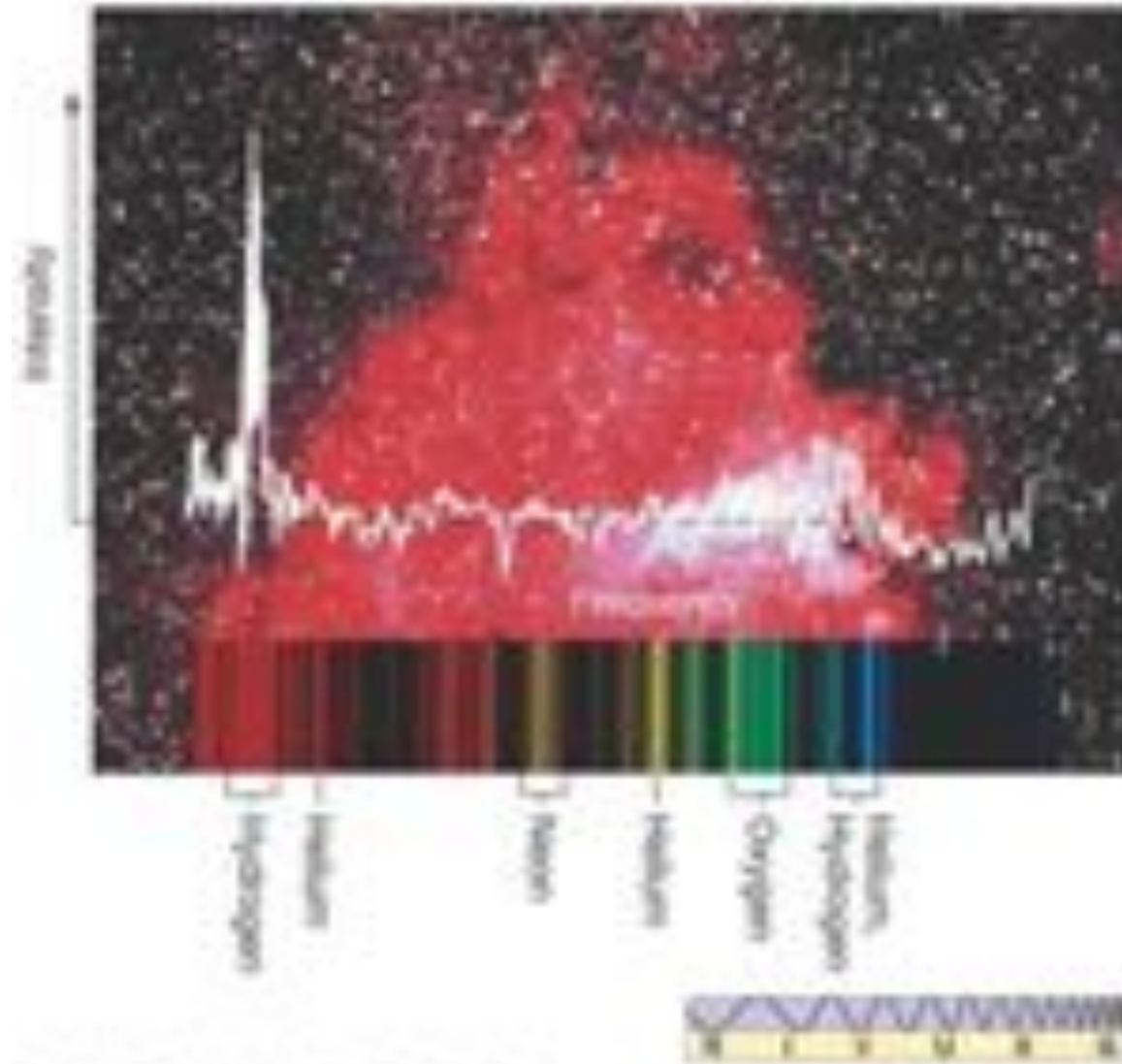
## Spectral of real astronomical objects

Here are spectra of two real astronomical objects, a comet (top) and star (bottom). By the time you take the next exam, you should be able to explain why these look so different.



The wavelengths, shapes, and strengths of these “spectral lines” are the keys to understanding many of the physical properties of planets, stars and galaxies.

**Spectra are not black rectangles with vertical lines.  
They are a recording of how many photons per second are being  
emitted as a function of wavelength**

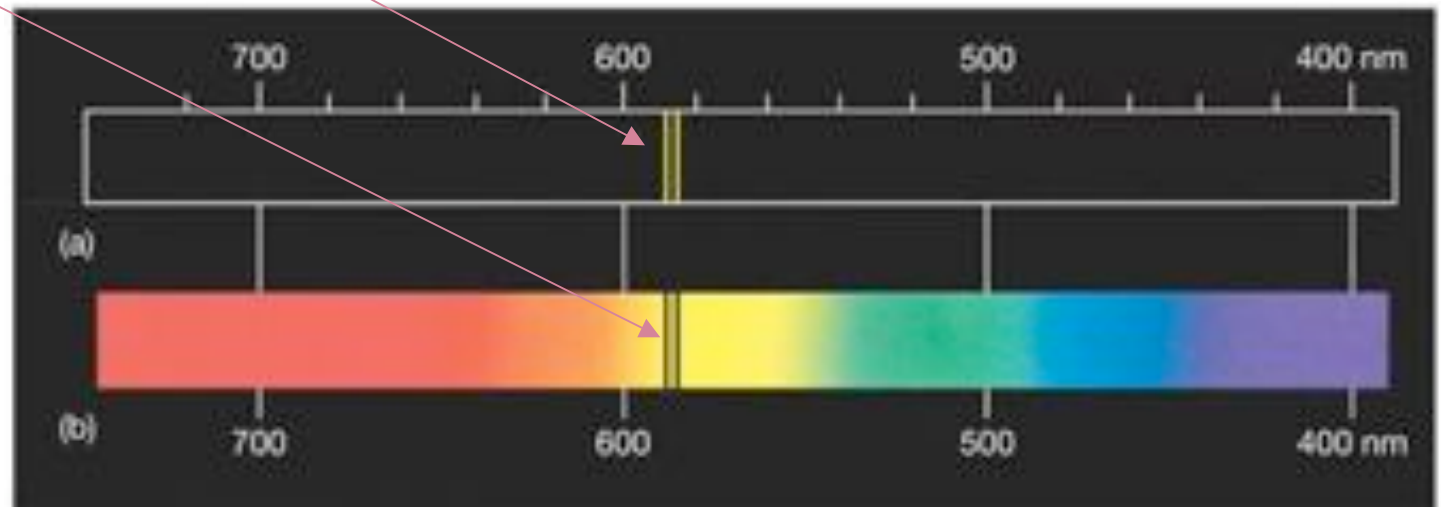
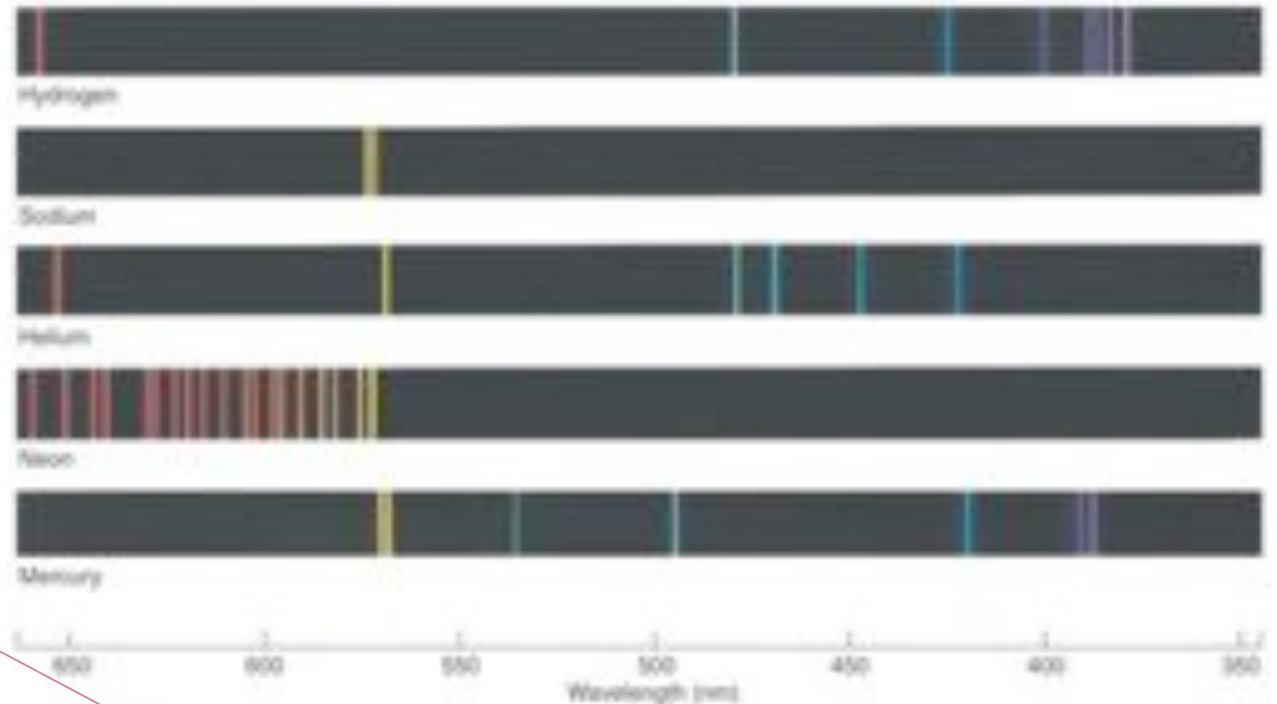


## 4.1 Spectral Lines

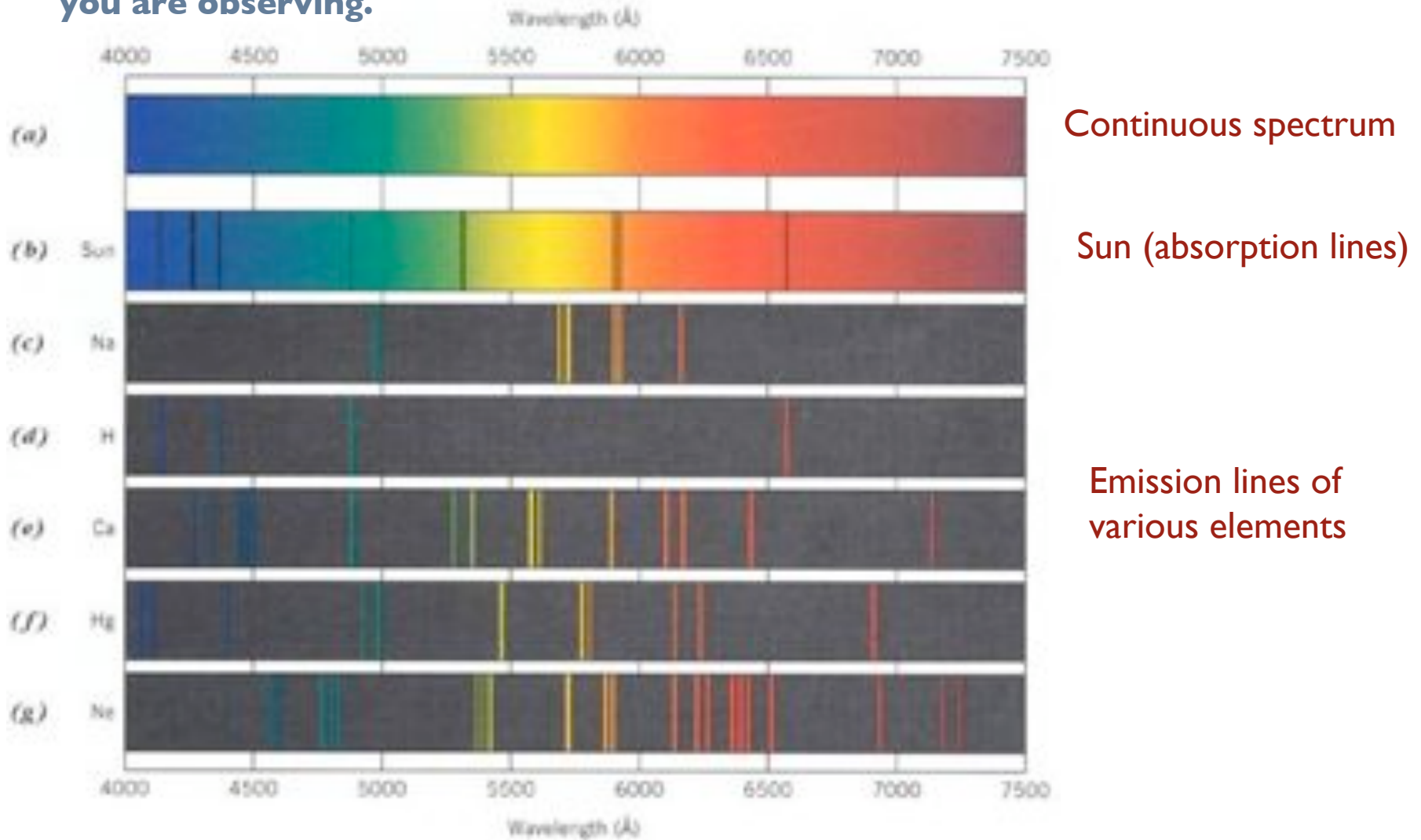
**Emission spectrum  
can be used to  
identify elements**

**An absorption  
spectrum can also be  
used to identify  
elements.**

**These are the emission  
and absorption spectra  
of sodium:**



Here is the Sun's spectrum, along with a blackbody of the sun's temperature (top--why are there no lines?), and the spectra of individual elements as observed in the laboratory. Each spectral line is a “chemical fingerprint” telling you which elements, and how much of each element, is contained in the object you are observing.

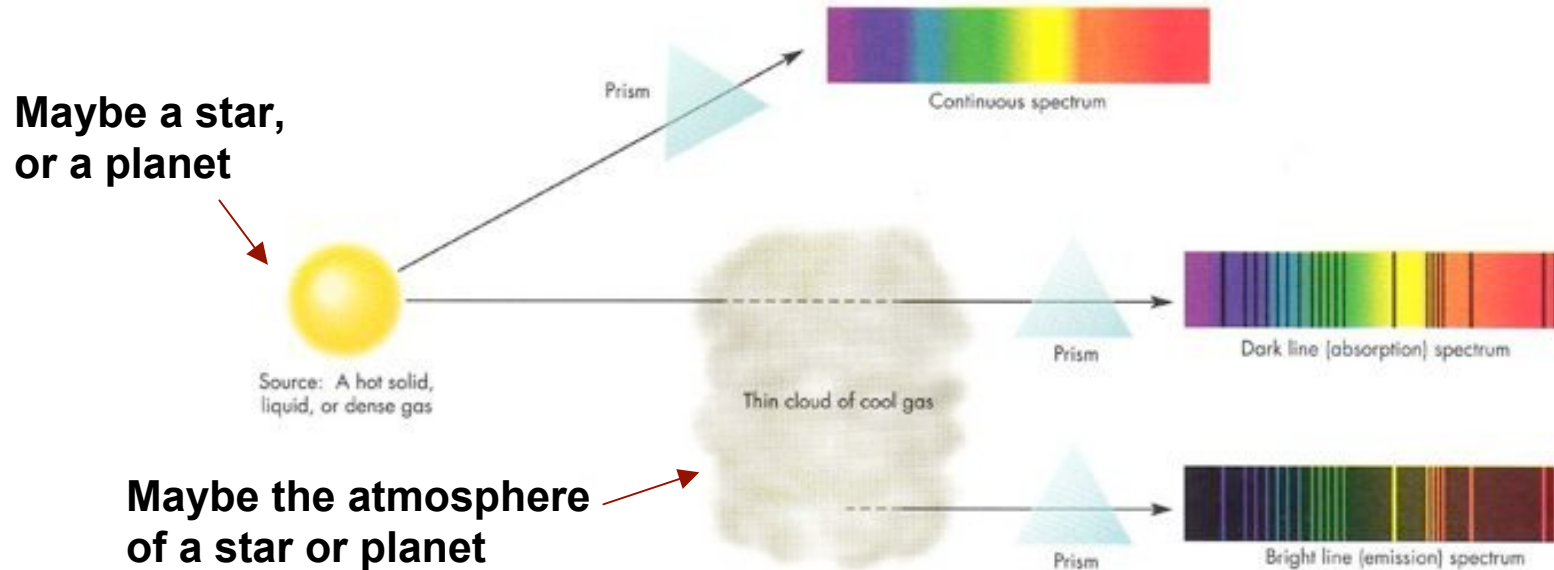


**Kirchoff's laws: don't memorize them. Instead, come back to this illustration later and find if you understand enough to explain them**

“Kirchoff's laws” are usually presented with prisms and striped colorful “spectra.”

This is confusing, and they aren't even “laws” at all!

Just note that “prism” is supposed to represent an instrument, called a “spectrometer.”



If the light from the hot “star” or blackbody doesn't pass through any low-density gas, then the spectrum is featureless--it is a “continuous spectrum.” (top)

If that continuous spectrum passes through a cloud of gas that is cooler than the source, the cloud can absorb particular wavelengths, and you get an absorption spectrum (middle)

But if the gas is hot, say at least a few thousand degrees, it will emit spectral lines on its own (bottom), i.e. emission lines.

How does this occur? The answer lies in the structure of atoms.

*Next :*

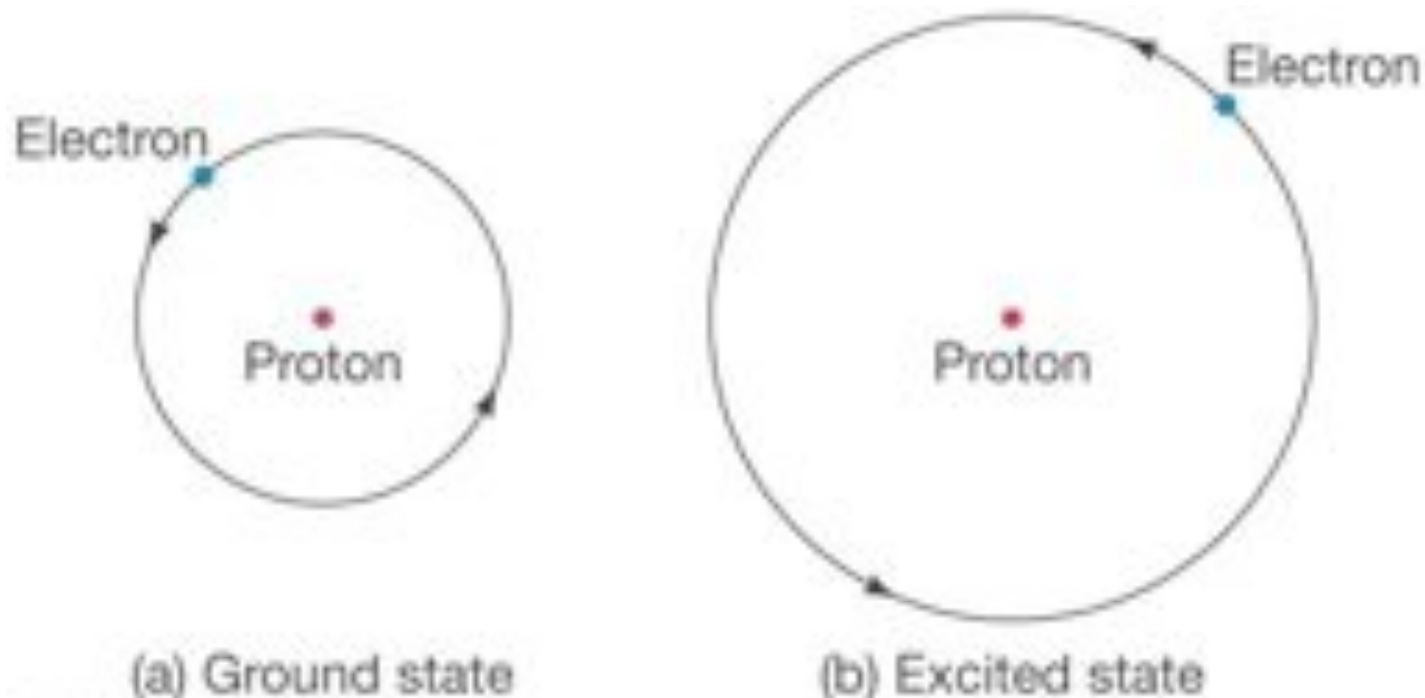
Energy levels of electrons in atoms



## 4.2 Atoms and Radiation

Existence of spectral lines required new model of atom, so that only certain amounts of energy could be emitted or absorbed

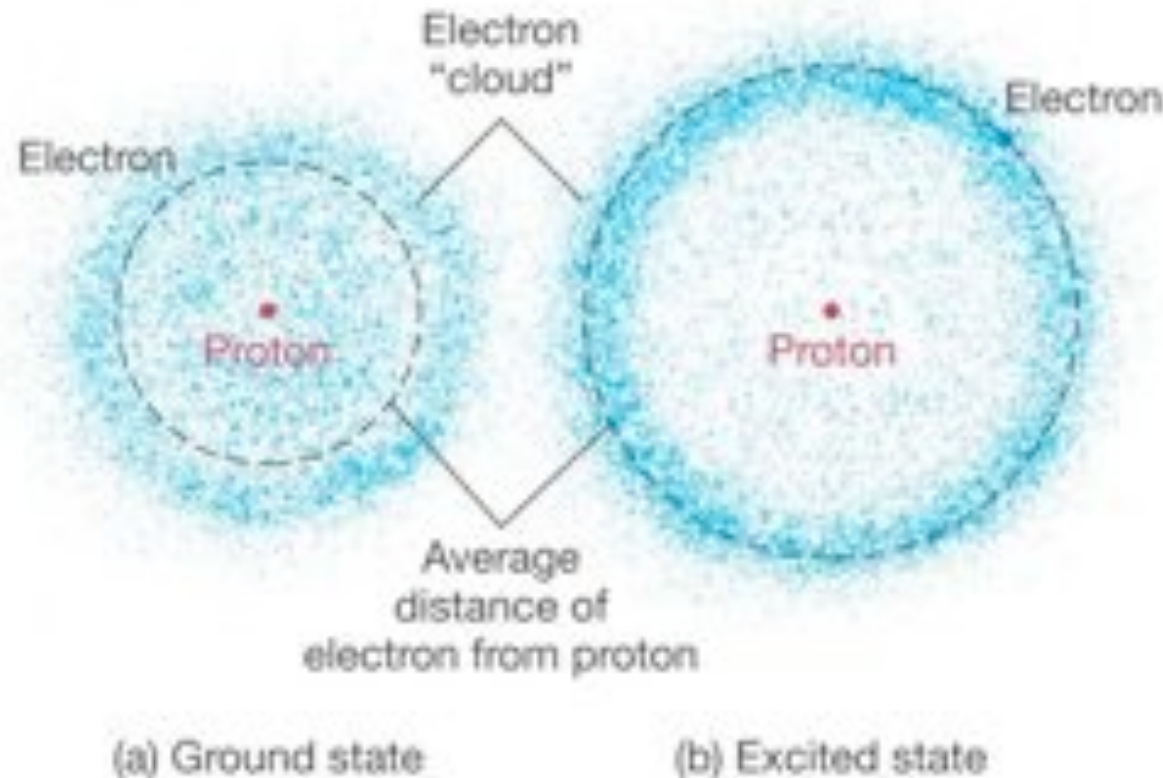
Bohr model had certain allowed orbits for electron



## 4.2 Atoms and Radiation

Emission energies correspond to energy differences between allowed levels

Modern model has electron “cloud” rather than orbit

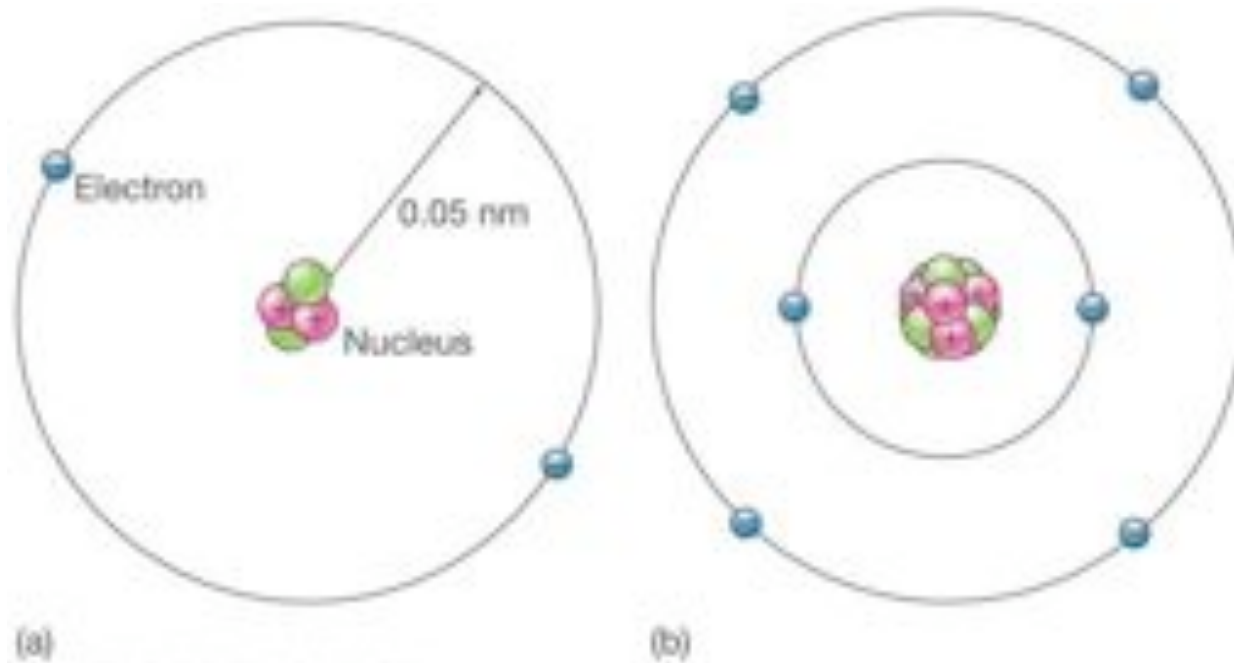


## 4.3 The Formation of Spectral Lines

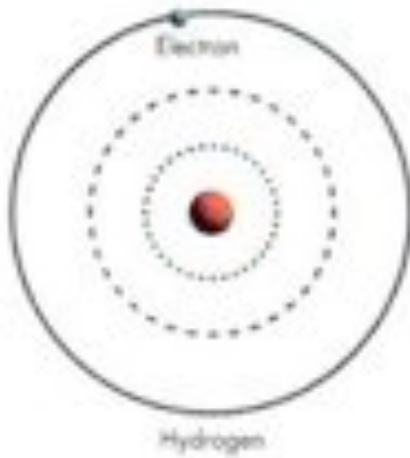
Absorption spectrum: Created when atoms absorb photons of right energy for excitation

Multielectron atoms: Much more complicated spectra, many more possible states

Ionization changes energy levels



# Energy levels in H and He



## Electron Distances and Energy Levels

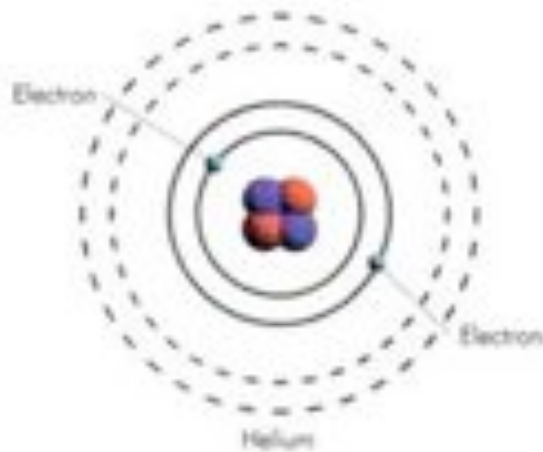
▲ The electron in a hydrogen atom can exist only at certain distances from the nucleus. Each of the possible electron distances corresponds to a different energy level.



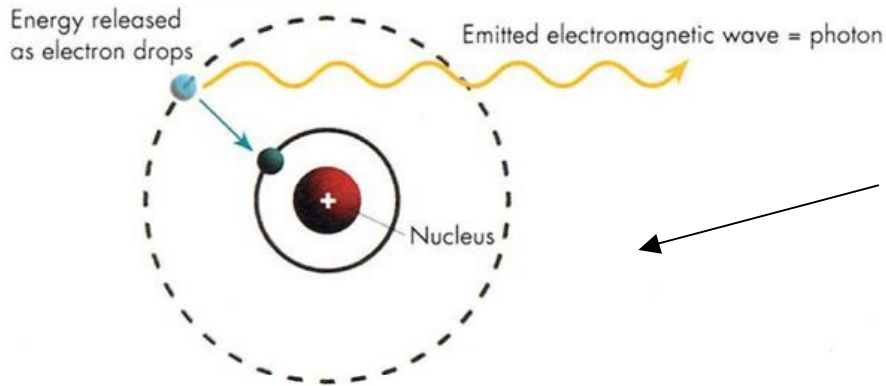
▲ Possible distances of the electron in a hydrogen atom



■ Energy levels for the hydrogen atom

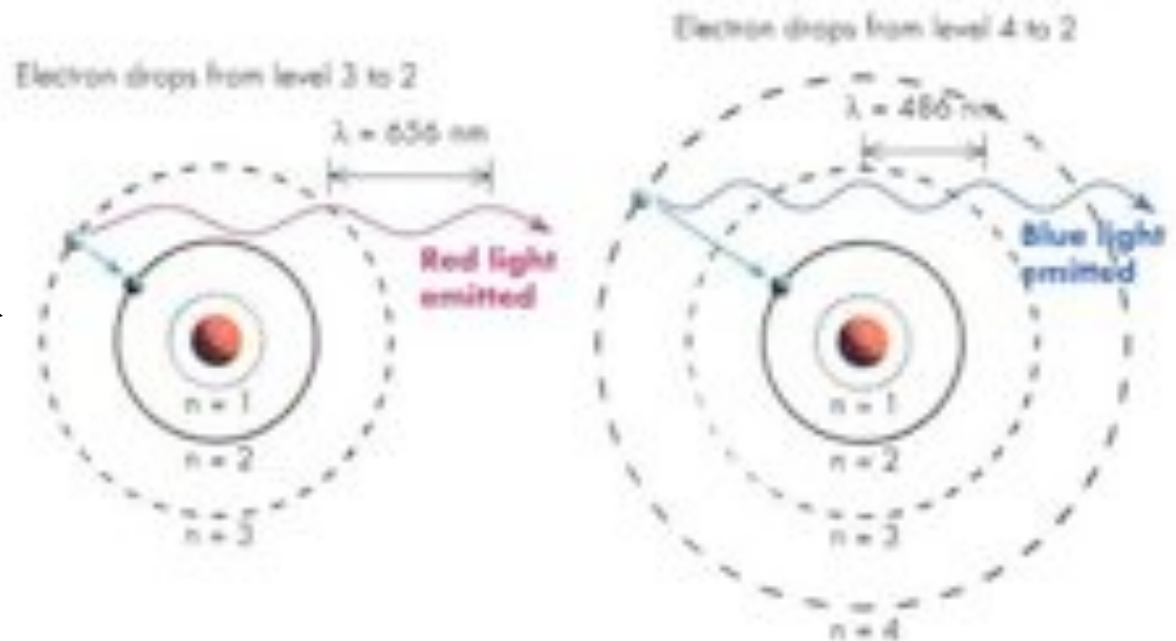


# Spectral lines = electronic transitions



Energy is released when an electron drops from an upper to a lower orbit, causing the atom to emit electromagnetic radiation.

The light emitted has a wavelength corresponding to the energy difference between the two electron energy levels.



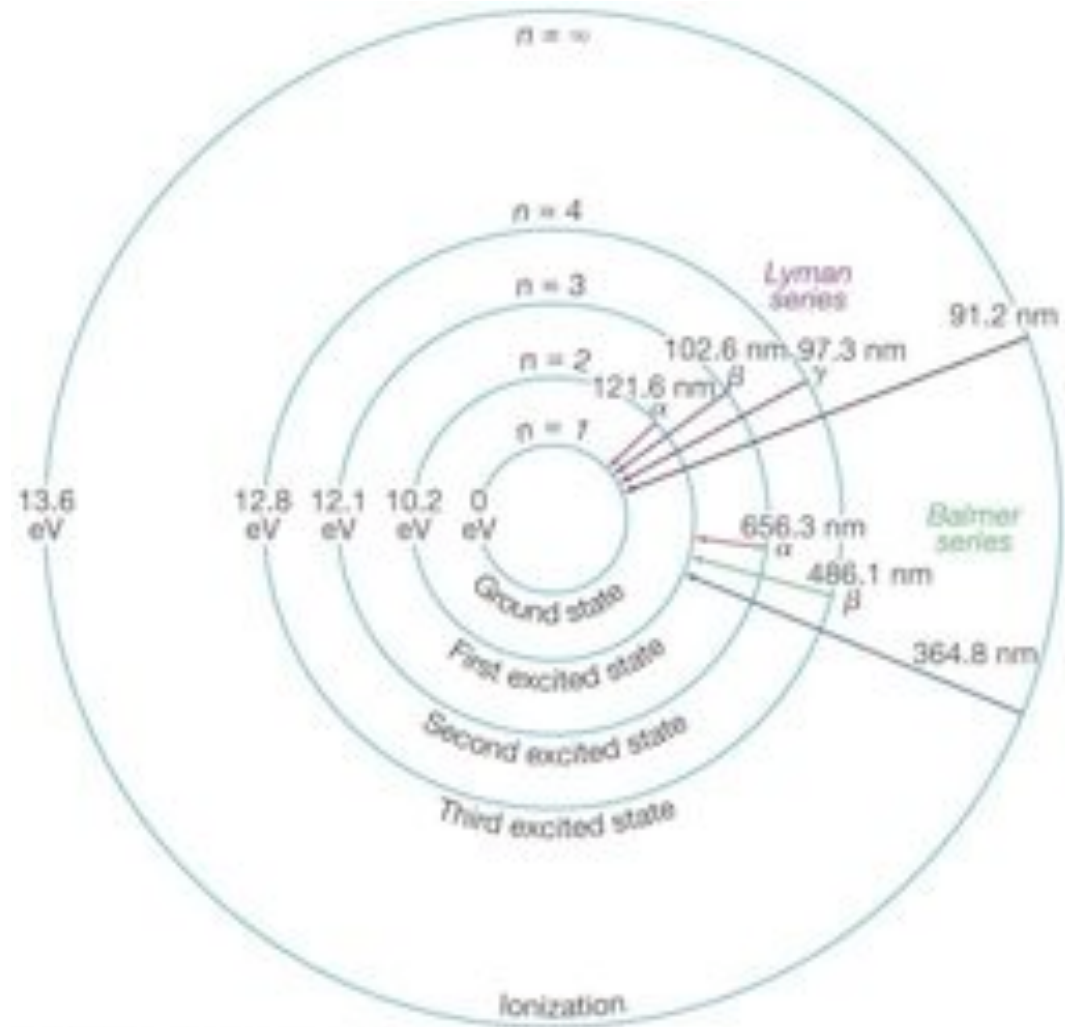
## Spectral lines of hydrogen

**Energy levels of the hydrogen atom, showing two series of emission lines: Lyman and Balmer**

The energies of the electrons in each orbit are given by:

$$E_n = 13.6 \left( 1 - \frac{1}{n^2} \right) \text{ eV}$$

The emission lines correspond to the energy differences

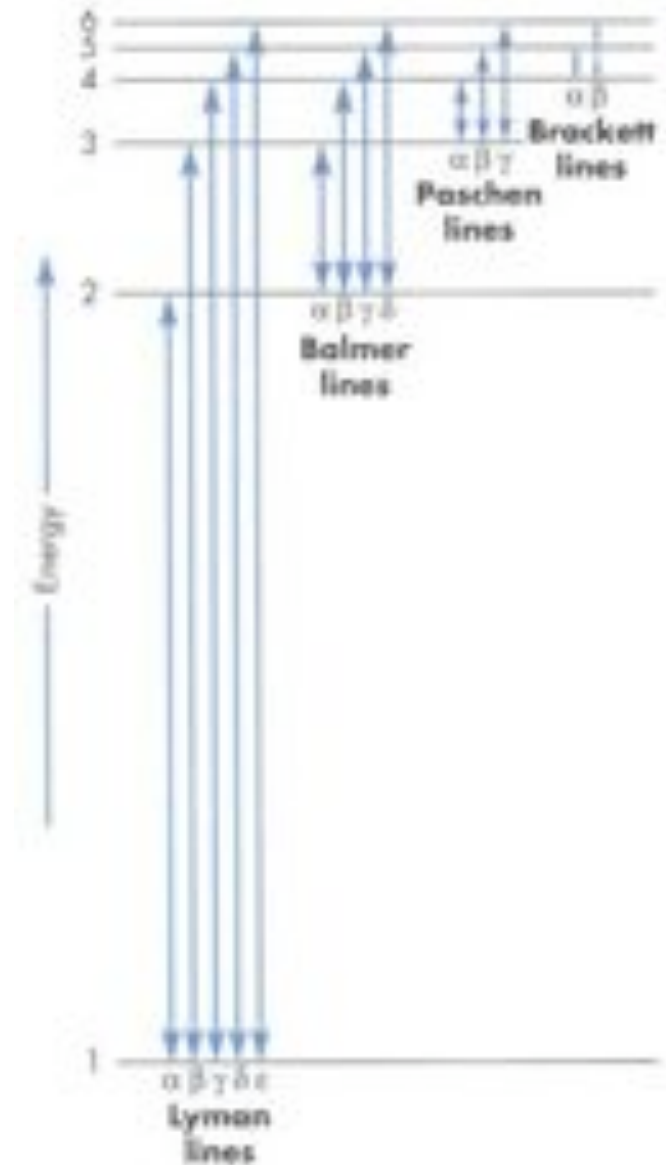


## 4.3 The Formation of Spectral Lines

Absorption of energy (either by a collision, or by absorbing a photon) can boost an electron to the second (or higher) excited state

Two ways to decay:

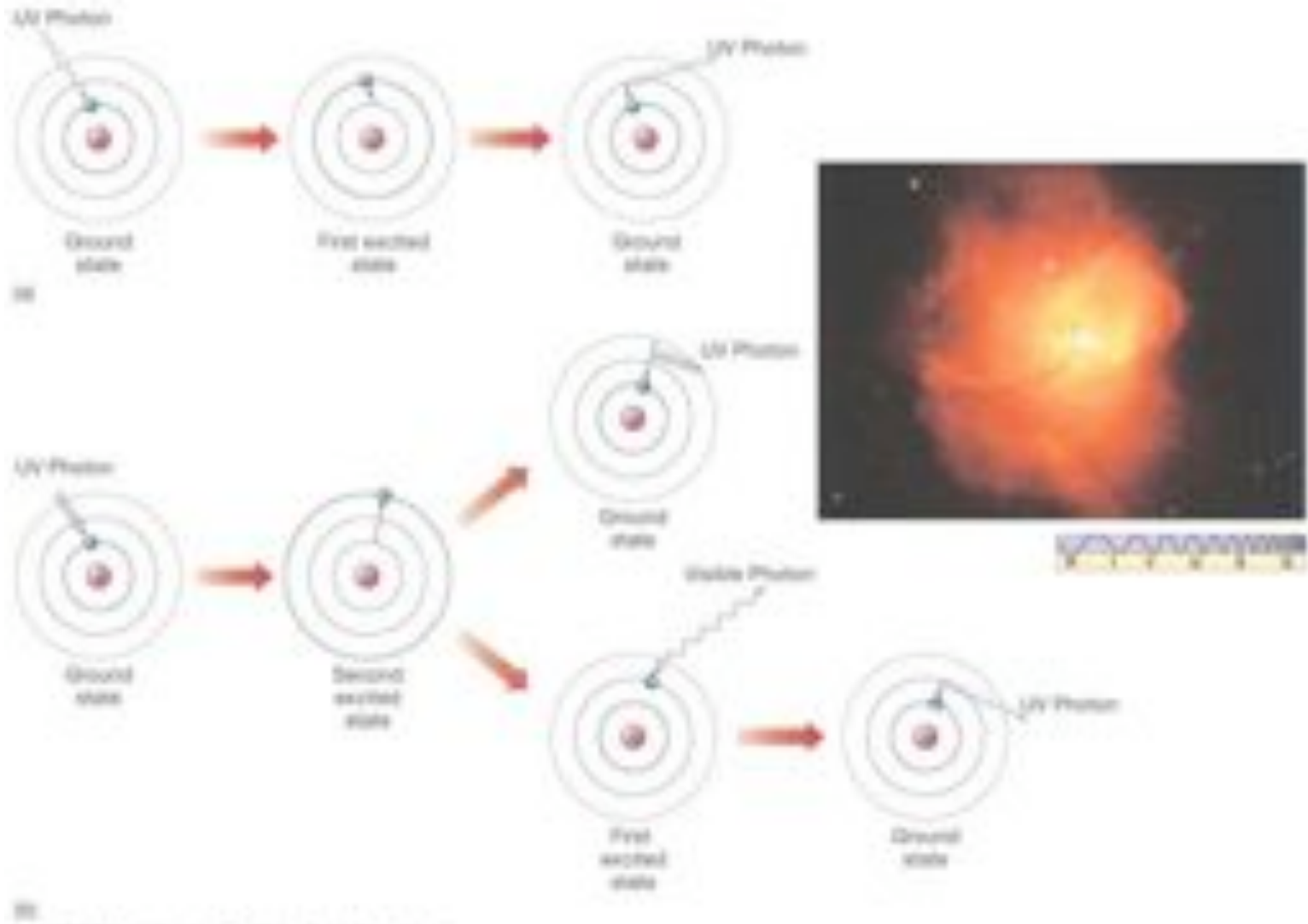
1. To ground state
2. Cascade one orbital at a time



# 4.3 The Formation of Spectral Lines

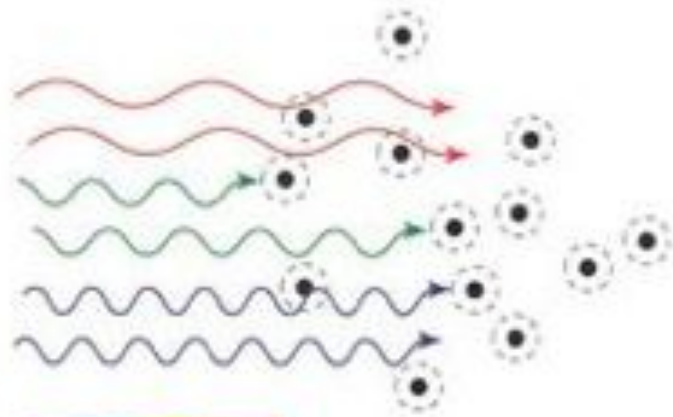
**(a) Direct decay**

**(b) Cascade**

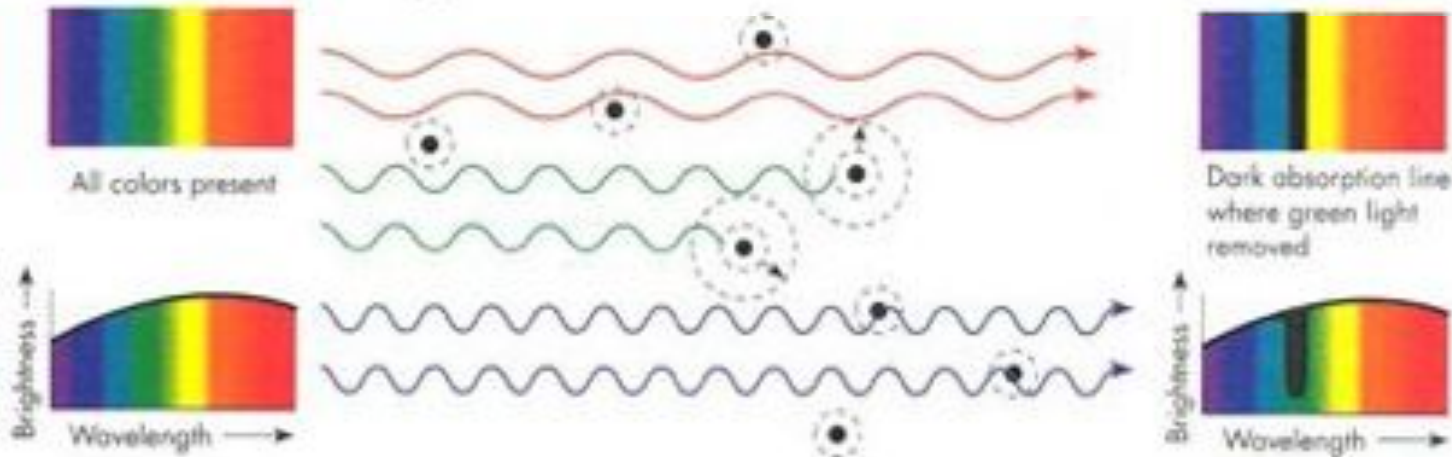




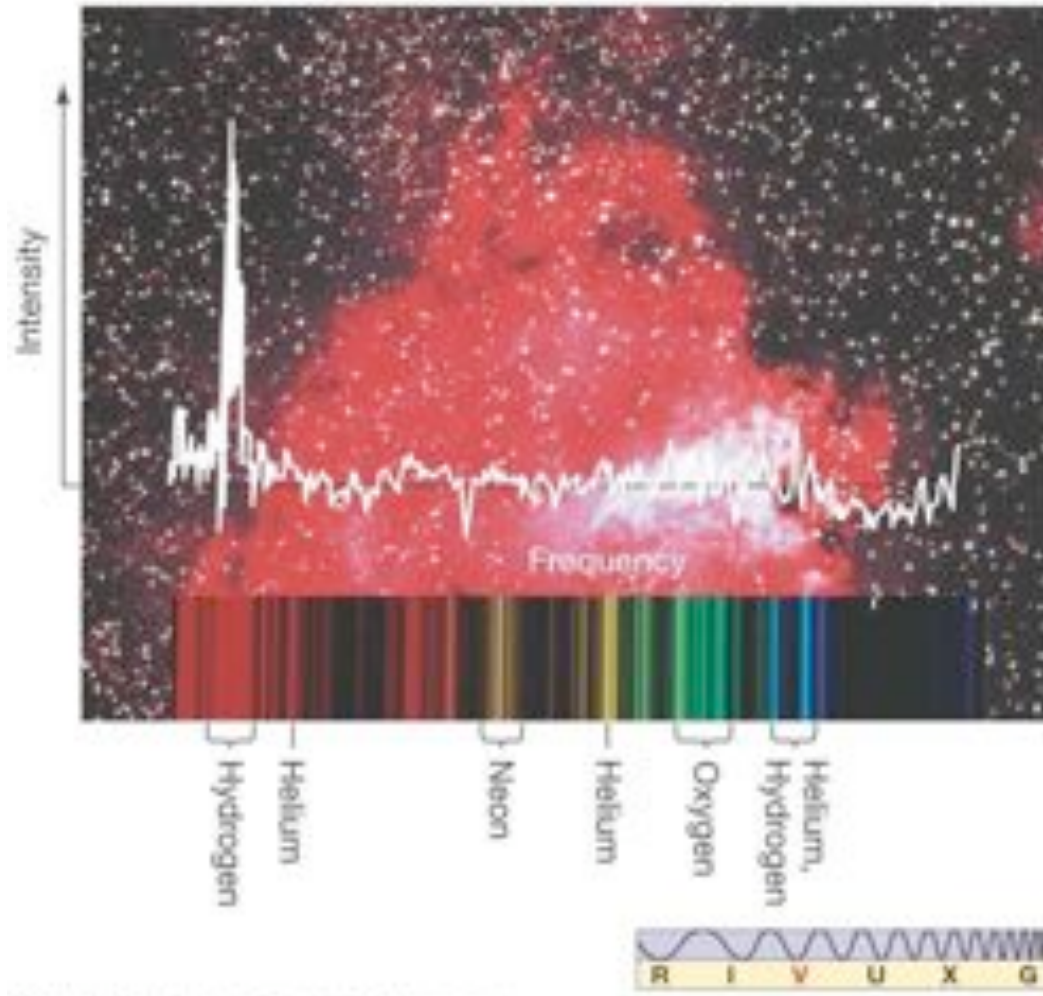
# Absorption of light as it passes through an atmosphere



An atom can absorb light, using the light's energy to lift an electron from a lower to a higher orbit. To be absorbed, the energy of the light's photons must equal the energy difference between the atom's electron orbits. In this example, the green light's energy matches the energy difference, but the red and blue light's energy does not. Therefore only the green is absorbed.



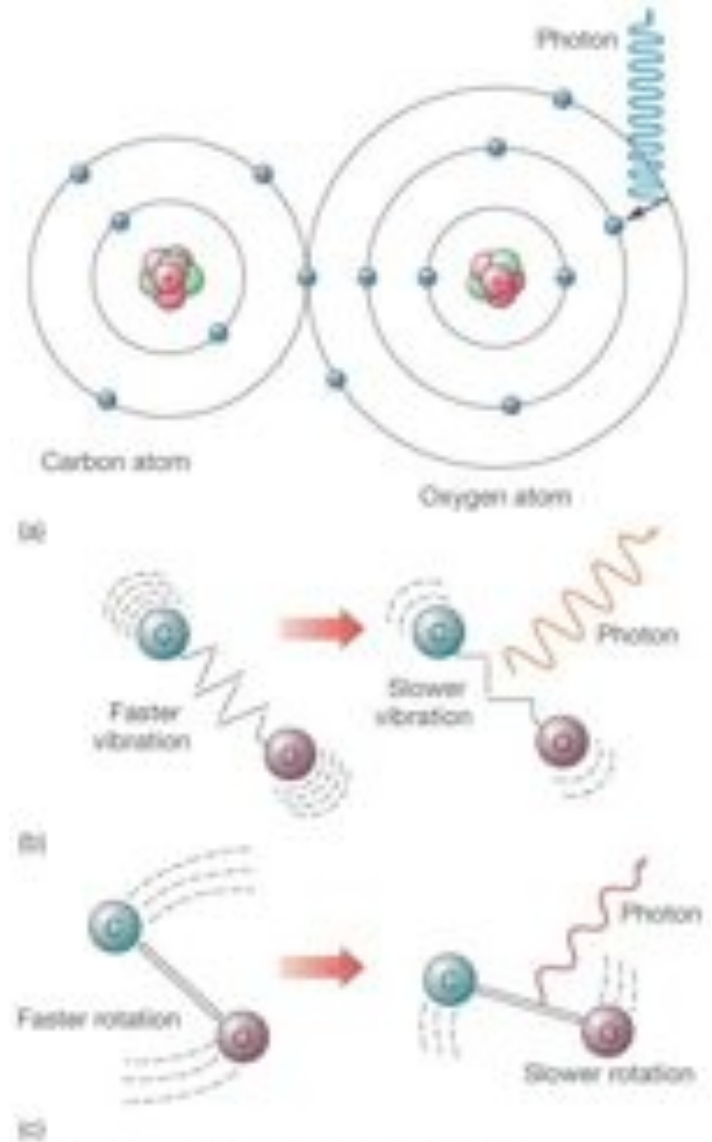
Emission lines can be used to identify atoms



## 4.4 Molecules

Molecules can vibrate and rotate, besides having energy levels

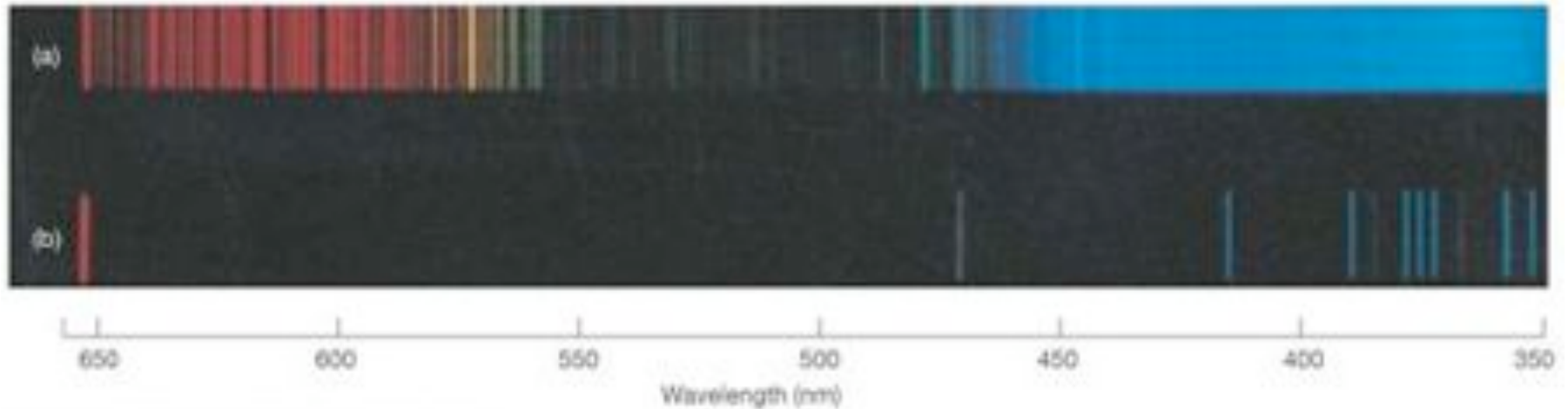
- Electron transitions produce visible and ultraviolet lines
- Vibrational transitions produce infrared lines
- Rotational transitions produce radio-wave lines



## 4.4 Molecules

Molecular spectra are much more complex than atomic spectra, even for hydrogen:

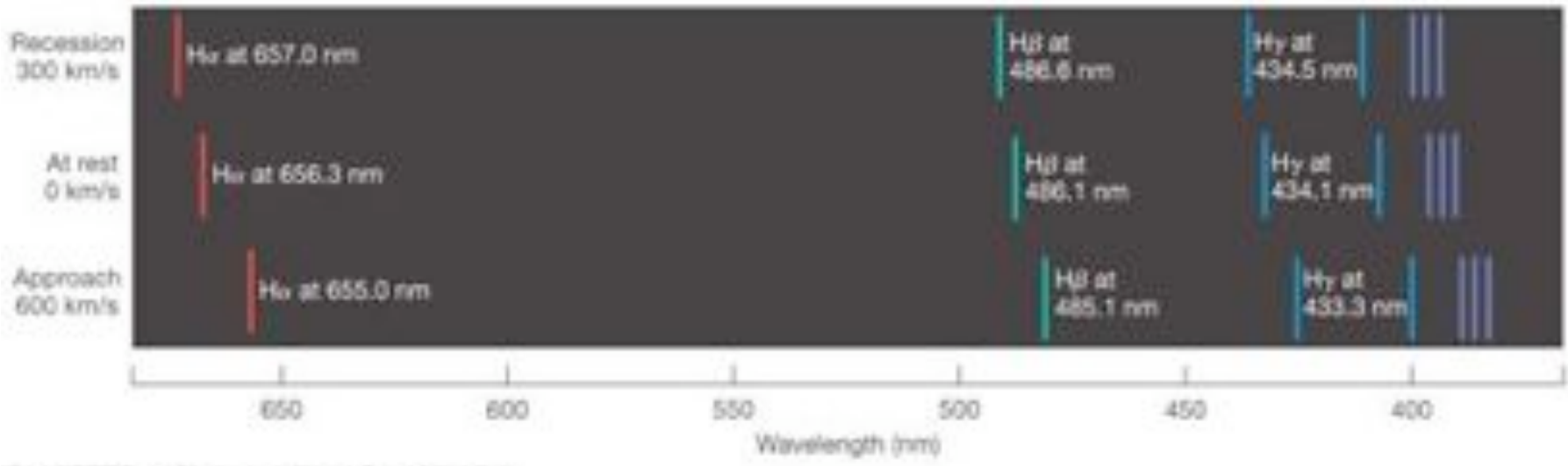
(a) Molecular hydrogen (b) Atomic hydrogen



## 4.5 Spectral-Line Analysis

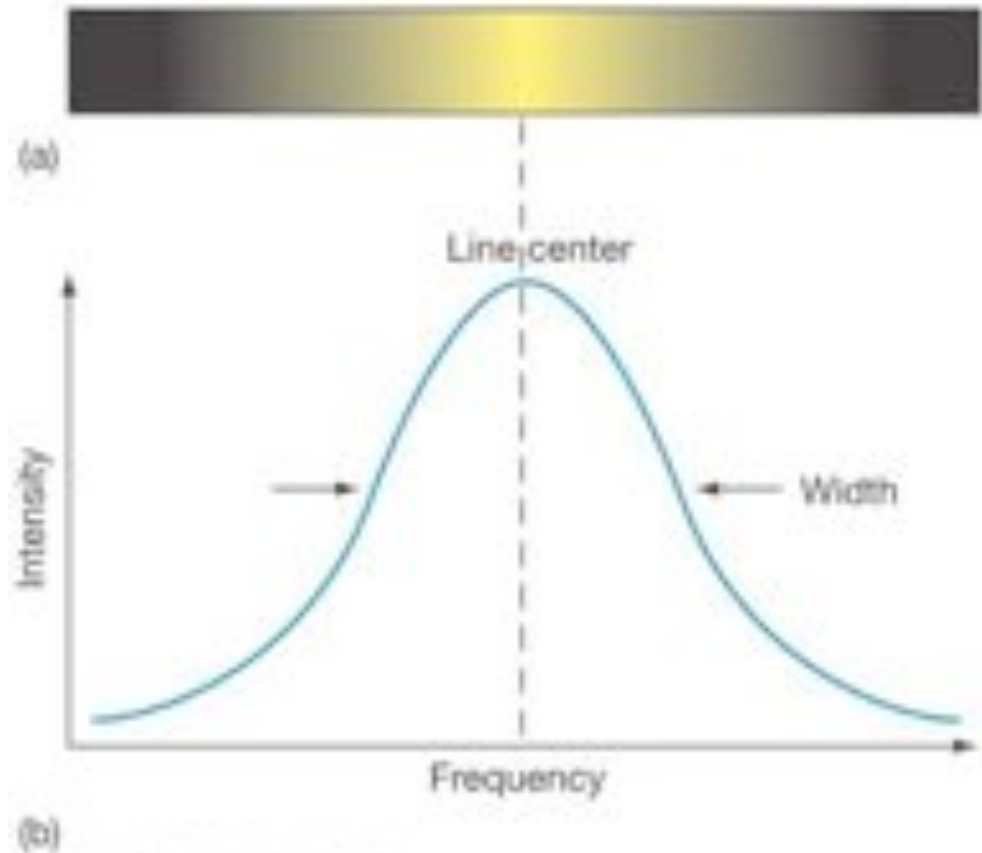
Information that can be gleaned from spectral lines:

- Chemical composition
- Temperature
- Radial velocity



## 4.5 Spectral-Line Analysis

**Line broadening can be due to a variety of causes**



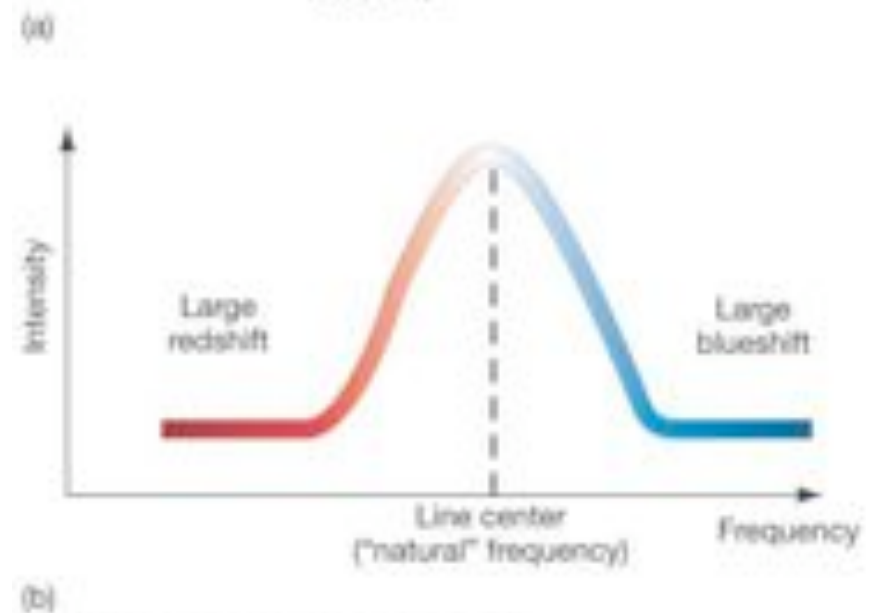
## 4.5 Spectral-Line Analysis

**TABLE 4.1** Spectral Information Derived from Starlight

Observed Spectral Characteristic	Information Provided
Peak frequency or wavelength (continuous spectra only)	Temperature (Wien's law)
Lines present	Composition, temperature
Line intensities	Composition, temperature
Line width	Temperature, turbulence, rotation speed, density, magnetic field
Doppler shift	Line-of-sight velocity

## 4.5 Spectral-Line Analysis

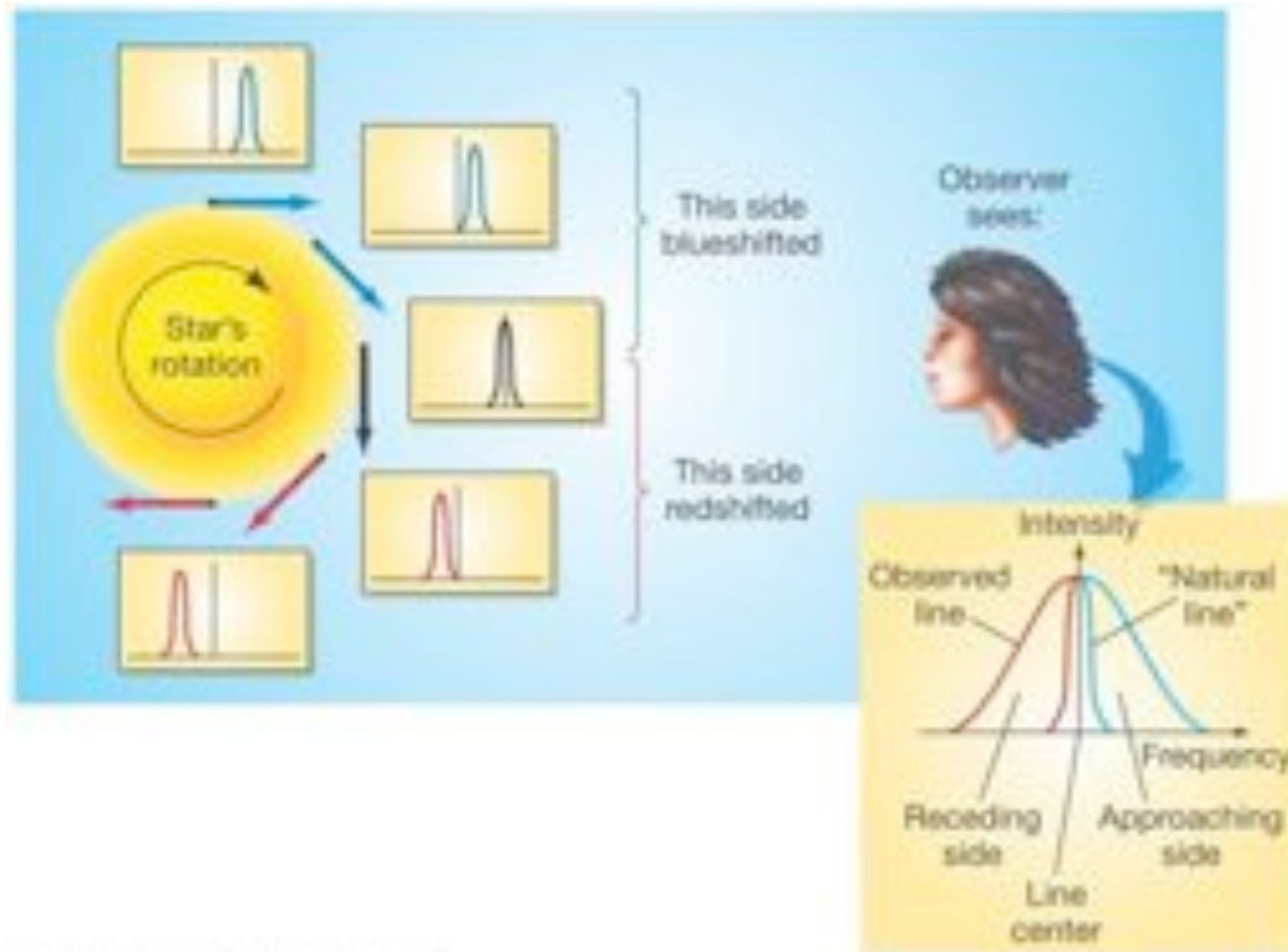
The Doppler shift may cause thermal broadening of spectral lines





## 4.5 Spectral-Line Analysis

**Rotation will also cause broadening of spectral lines through the Doppler effect**



## Summary of Chapter 4

- Spectroscope (spectrometer) splits light beam into component frequencies/wavelengths
- Continuous spectrum is emitted by solid, liquid, and dense gas
- Hot gas has characteristic emission spectrum
- Continuous spectrum incident on cool, thin gas gives characteristic absorption spectrum

## Summary of Chapter 4 (cont.)

- Spectra can be explained using atomic models, with electrons occupying specific orbitals
- Emission and absorption lines result from transitions between orbitals
- Molecules can also emit and absorb radiation when making transitions between vibrational or rotational states