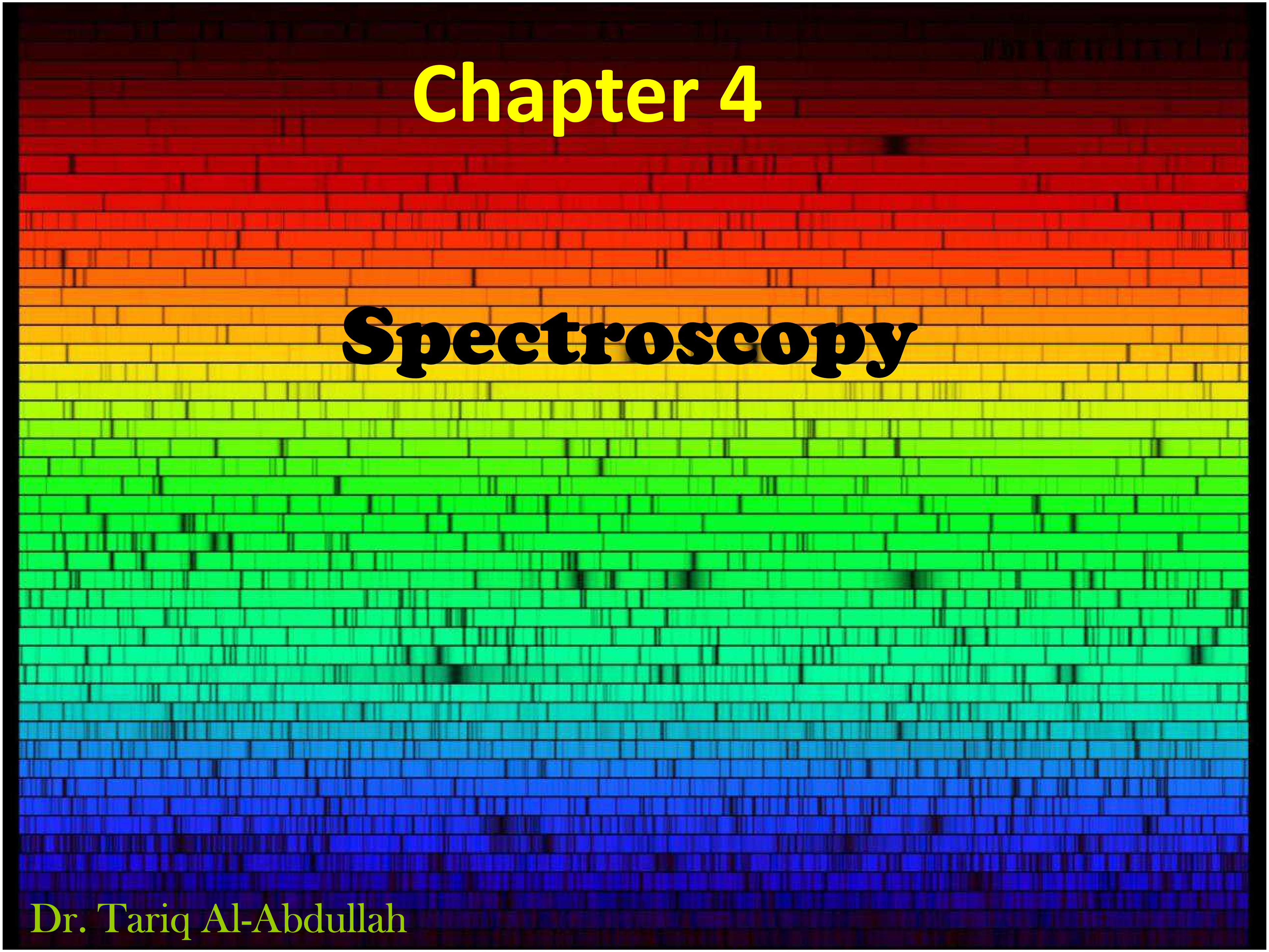


Chapter 4

Spectroscopy

Dr. Tariq Al-Abdullah

Learning Goals:

4.1 Spectral Lines

4.2 Atoms and Radiation

4.3 Formation of the Spectral Lines

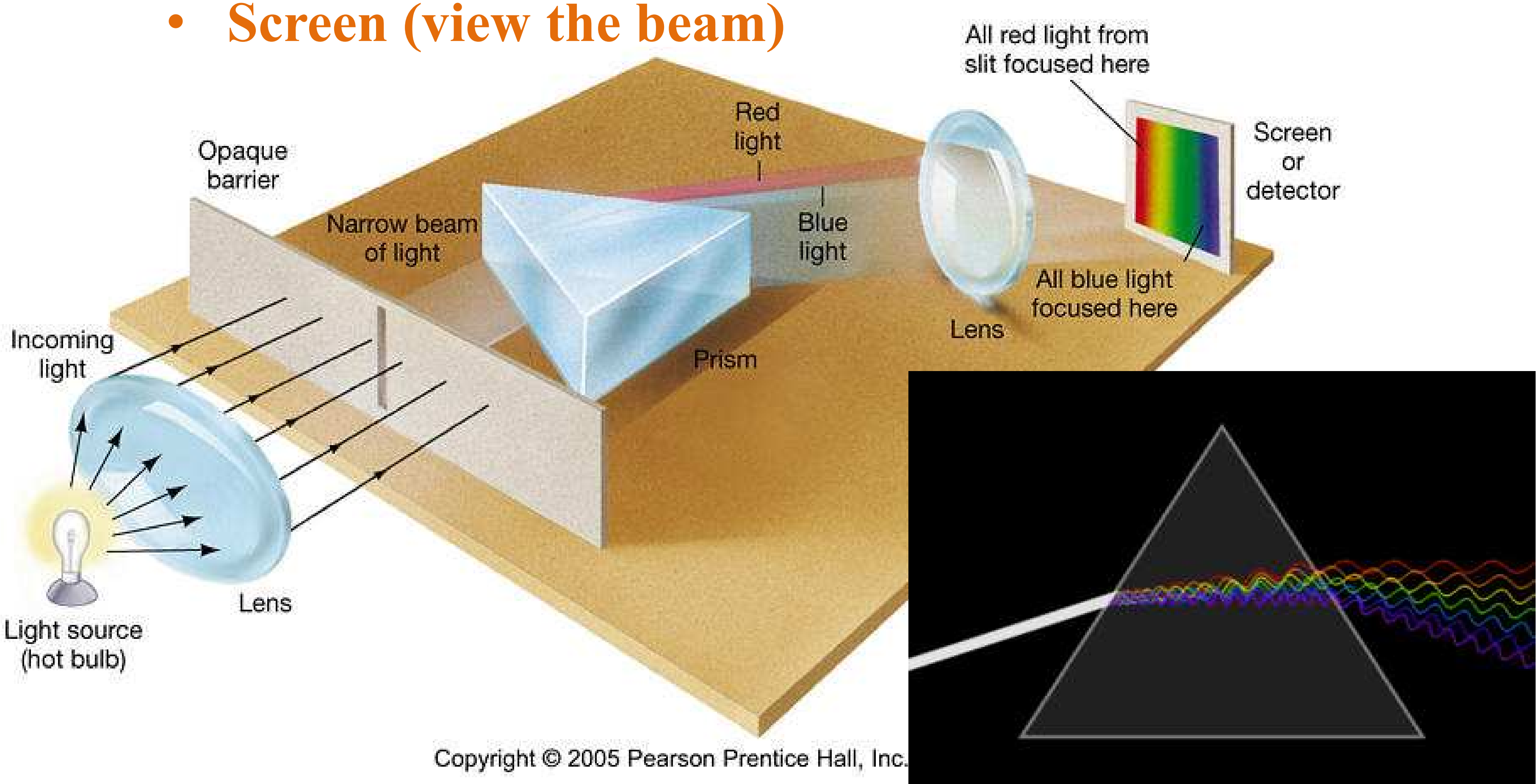
4.4 Molecules

4.5 Spectral Line Analysis

4.1 Spectral Lines

A spectroscope: an instrument to analyze radiation.

- **Slit (define a beam),**
- **Prism (split the beam into components),**
- **Screen (view the beam)**

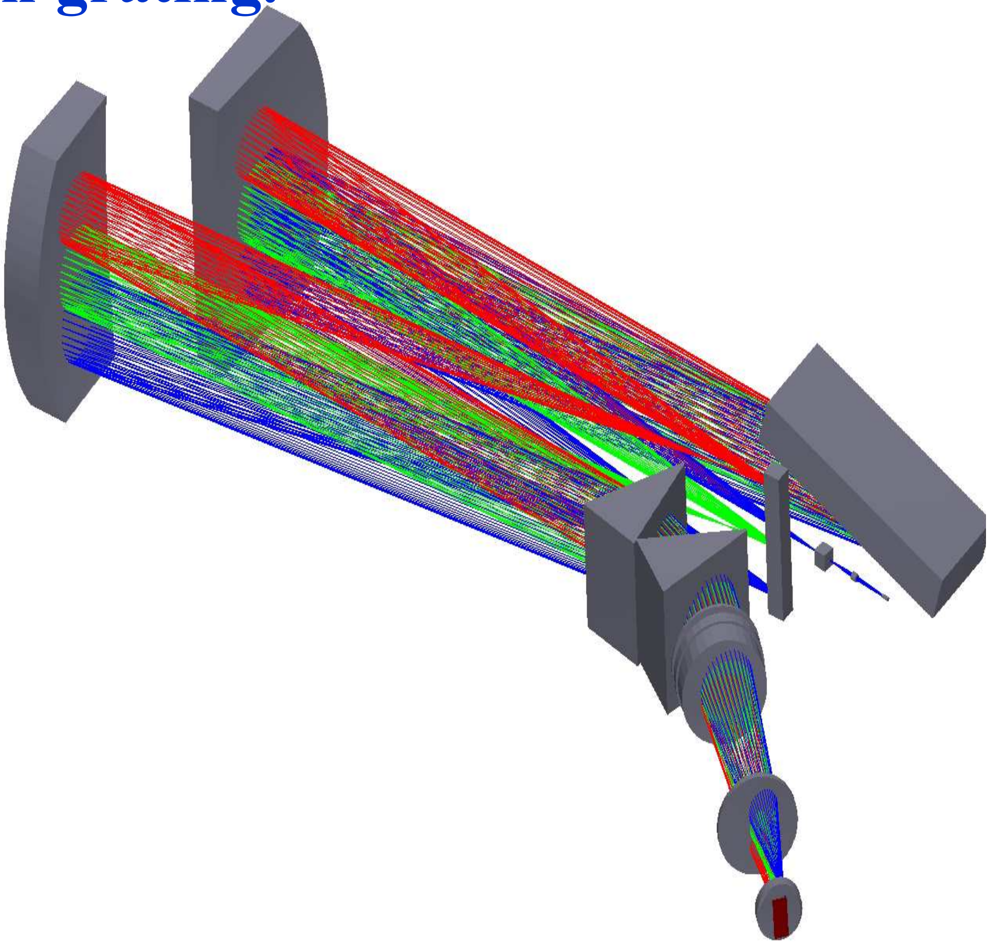


4.1 Spectral Lines

Spectrographs/spectrometers are more complicated:

telescope, dispersing device, detector.

- **Prism replaced by Diffraction grating.**
- **Rainbow**

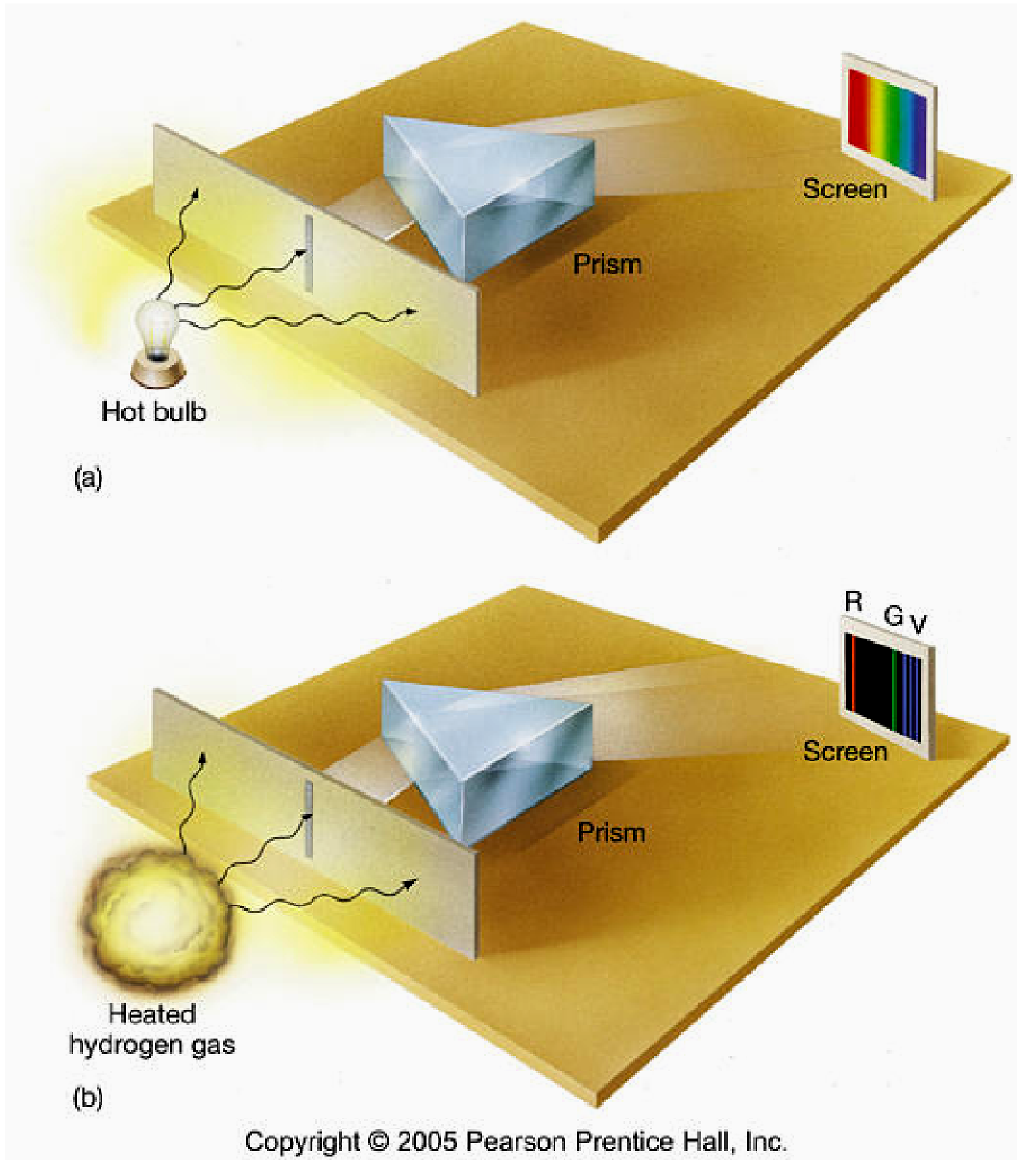


4.1 Spectral Lines

Emission Lines: Single frequencies emitted by particular atoms

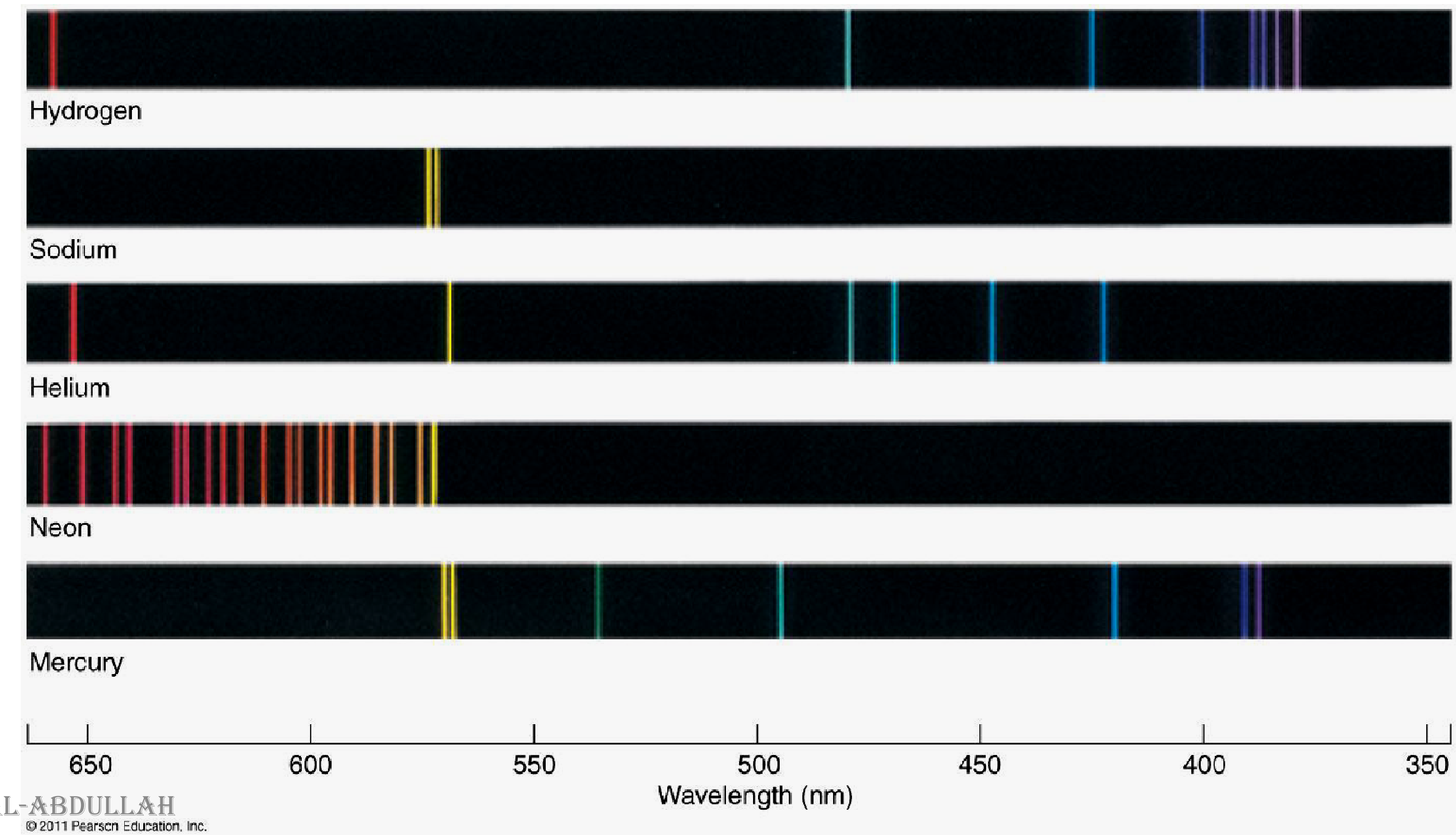
Continuous Spectra

Emission Spectra



4.1 Spectral Lines

❖**Elemental Emission:** Fingerprint of substance under investigation.
→ Detect the presence of particular atom or molecule.
→ Emission Spectrum of several atoms are below;



4.1 Spectral Lines

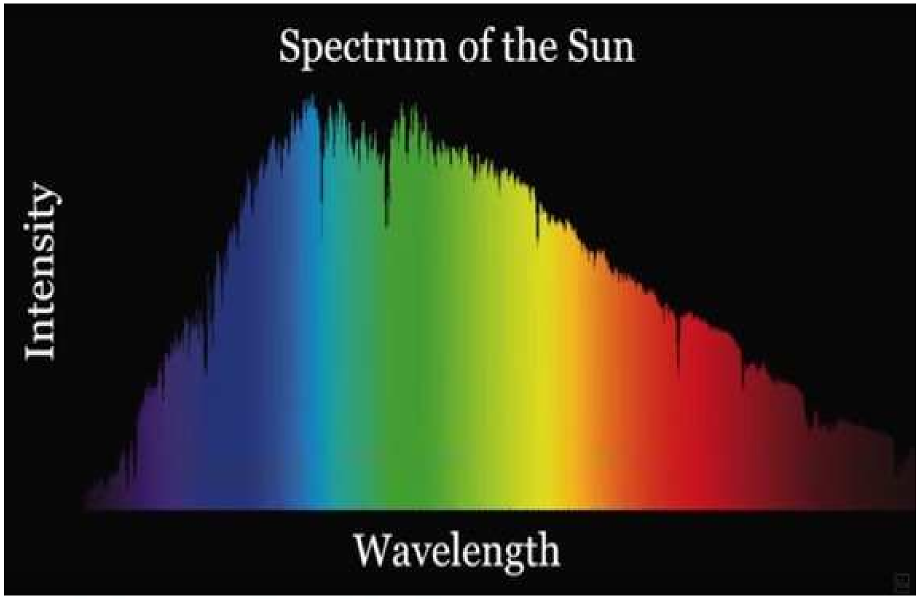
❖Solar Spectrum is not continuous

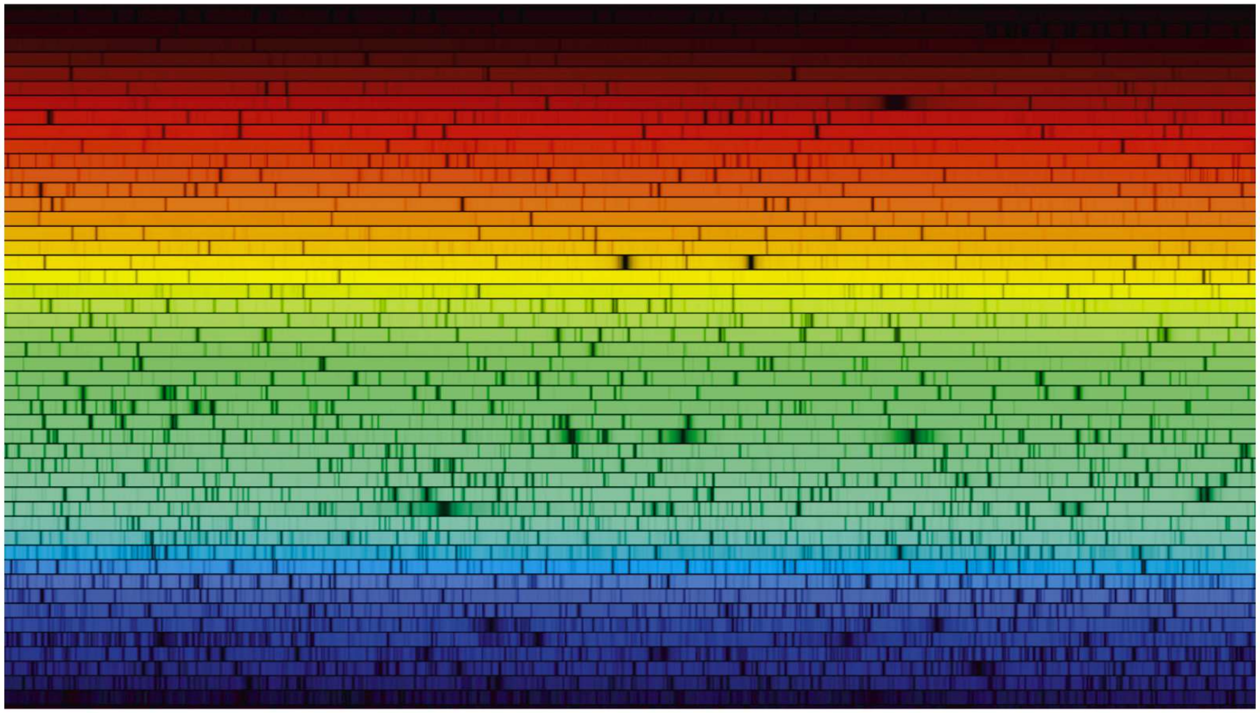
❖ It is interrupted by a large number of narrow dark lines.

❖ Absorption lines by gasses in the Sun's or Earth's atmosphere .

❖ Noticed by William Wollaston 1802

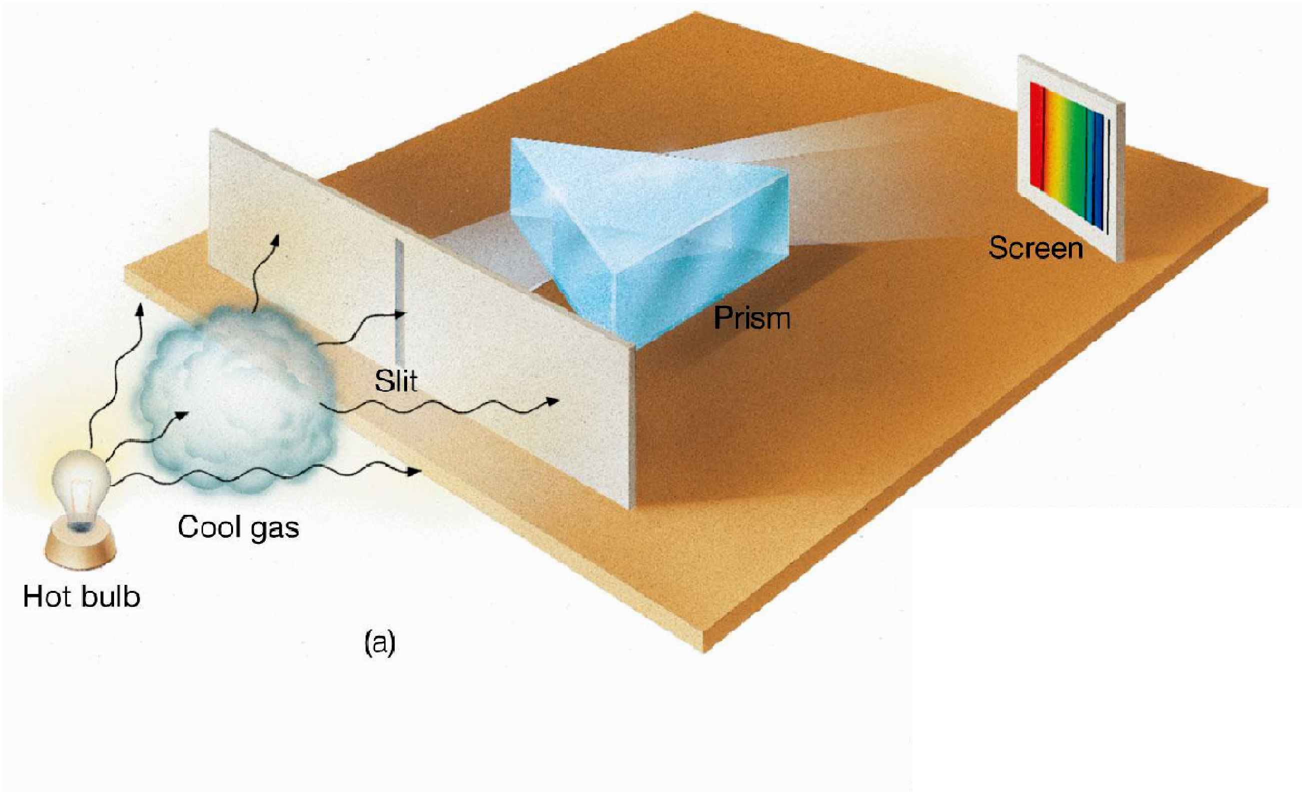
❖ Fraunhofer saw over 600 lines.





4.1 Spectral Lines

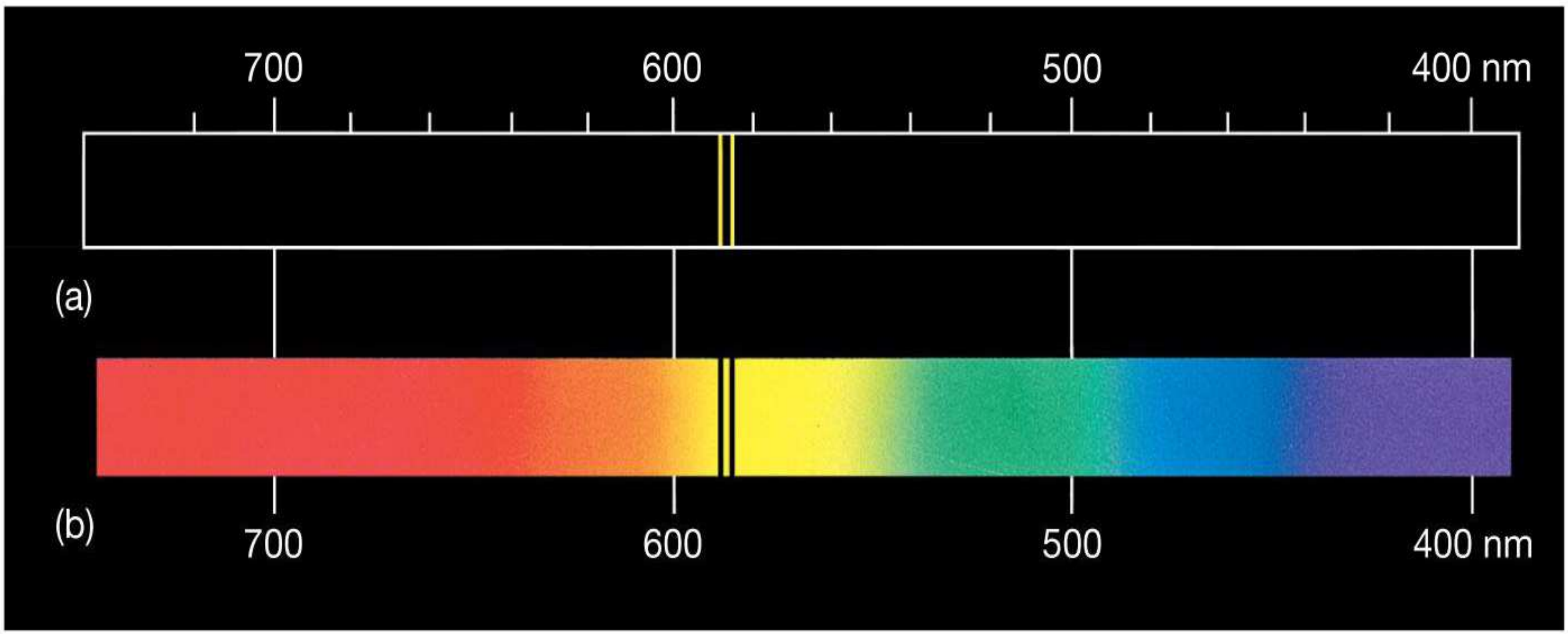
- Absorption lines could be produced in the laboratory by passing a beam through a cool gas
- Atoms of the gas will absorb the same frequencies they emit



4.1 Spectral Lines

An absorption spectrum can also be used to identify elements.

These are the emission and absorption spectra of sodium, wavelength at 589.0 nm

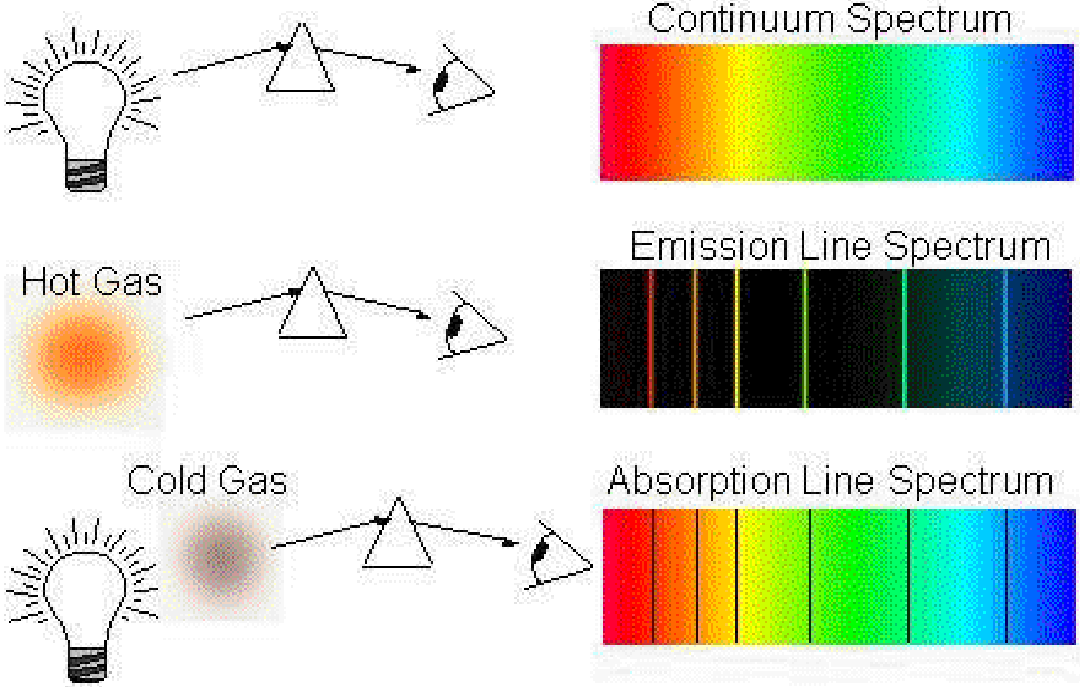


4.1 Spectral Lines

Spectroscopy: **Analysis of the ways in which matter emits or absorbs radiation**

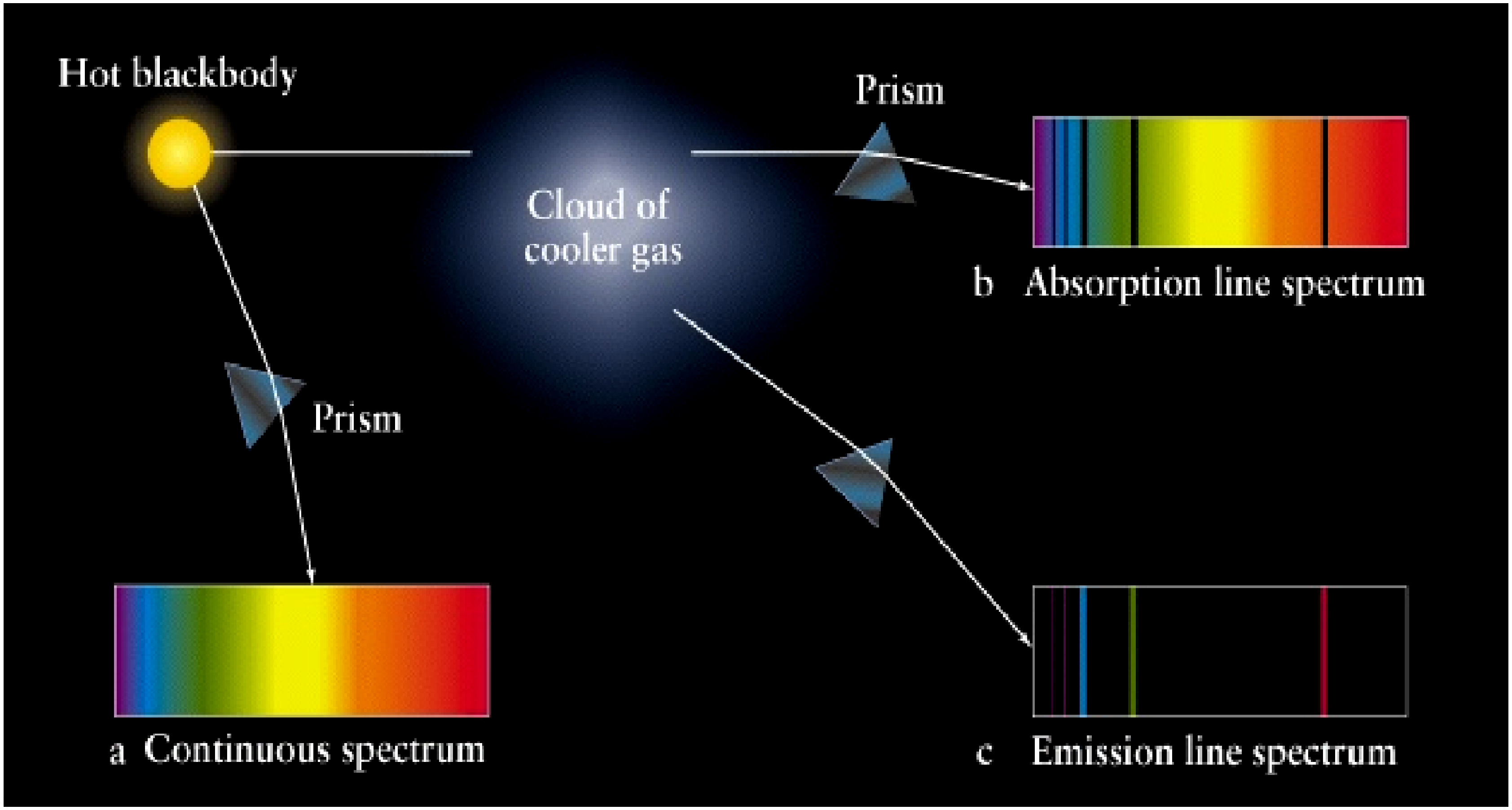
Kirchhoff's laws:

1. **Luminous solid, liquid, or dense gas produces continuous spectrum**
2. **Low-density hot gas produces emission spectrum**
3. **Continuous spectrum incident on cool, thin gas produces absorption spectrum**



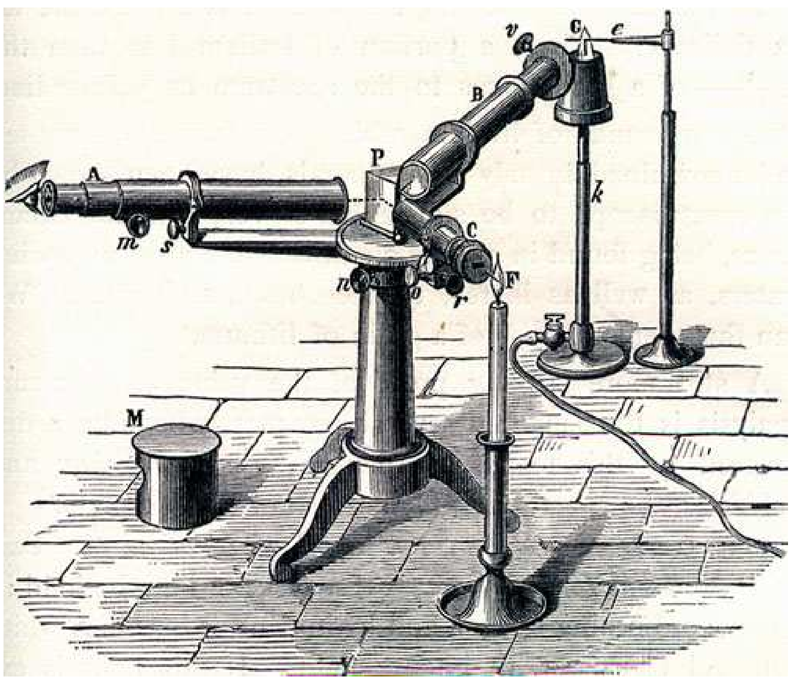
4.1 Spectral Lines

Kirchhoff's laws illustrated



Astronomical Applications

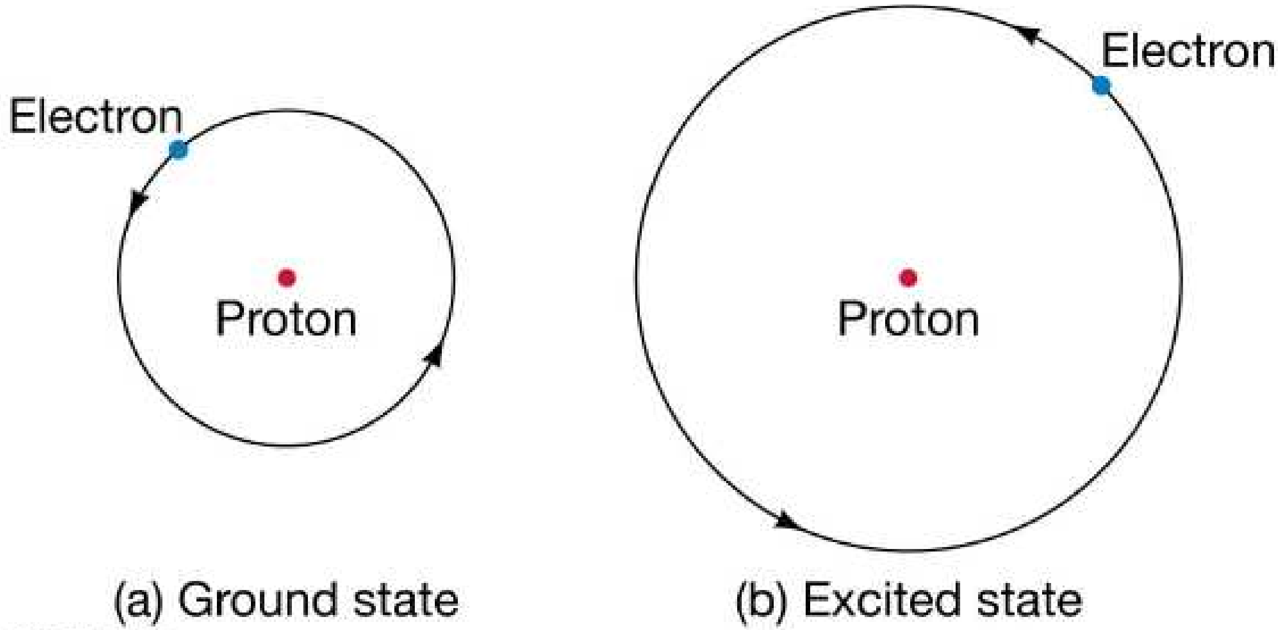
- All lines in light could be attributed to chemical elements.
- Fraunhofer's lines in sunlight are associated with Fe.
- He was discovered in 1868 from the solar spectrum.
- in 1895 He was discovered on the Earth.



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

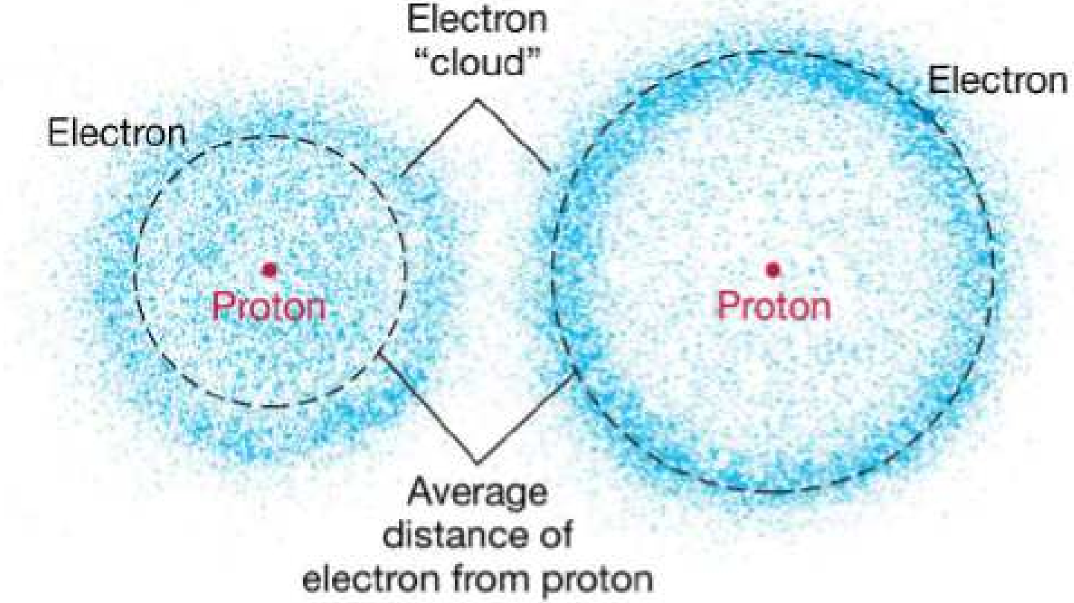
Bohr model had certain allowed orbits for electron



4.2 Atoms and Radiation

Emission energies correspond to energy differences between allowed levels

Modern model has **electron "cloud"** rather than orbit



(a) Ground state (b) Excited state

4.2 Atoms and Radiation

- The atom is in excited state when an electron occupies an orbit with greater-than-normal distance from the nucleus.
- Excited state with the lowest energy: First Excited State.
- Excitations are due to absorption of EM-waves, particle collision, ….
- In 10^{-8} s, excited atom return s to its ground state.

4.2 Atoms and Radiation

- Electrons absorb only specific amount of energy to move to any excited state.
- So they emit radiation precisely corresponded to the energy difference between two orbitals.
- Emitted radiations are called PHOTONS.
- Photons represent the particle behavior of light.

$$(\text{Photon energy}) \ \alpha \ (\text{radiation frequency})$$

- The constant of proportionality is known as Planck's constant.

$$E = hf, \qquad h = 6.626\times10^{-34} \ \text{J.s.}$$

- This relation completes the connection between atomic structure and atomic spectra.
- Wave and particle behaviors of light is still confusing!!!!

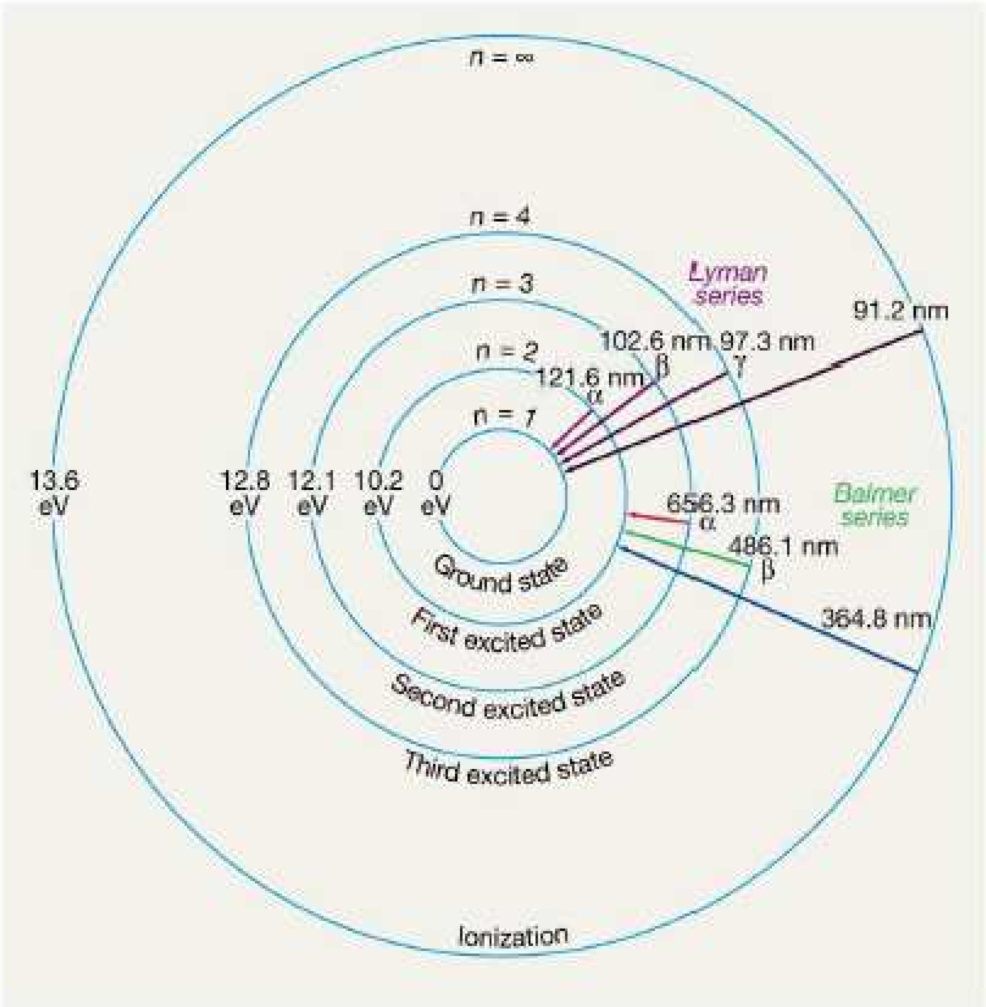
More Precisely 4-1: The Hydrogen Atom

Energy levels of the hydrogen atom, showing two series of emission lines:

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



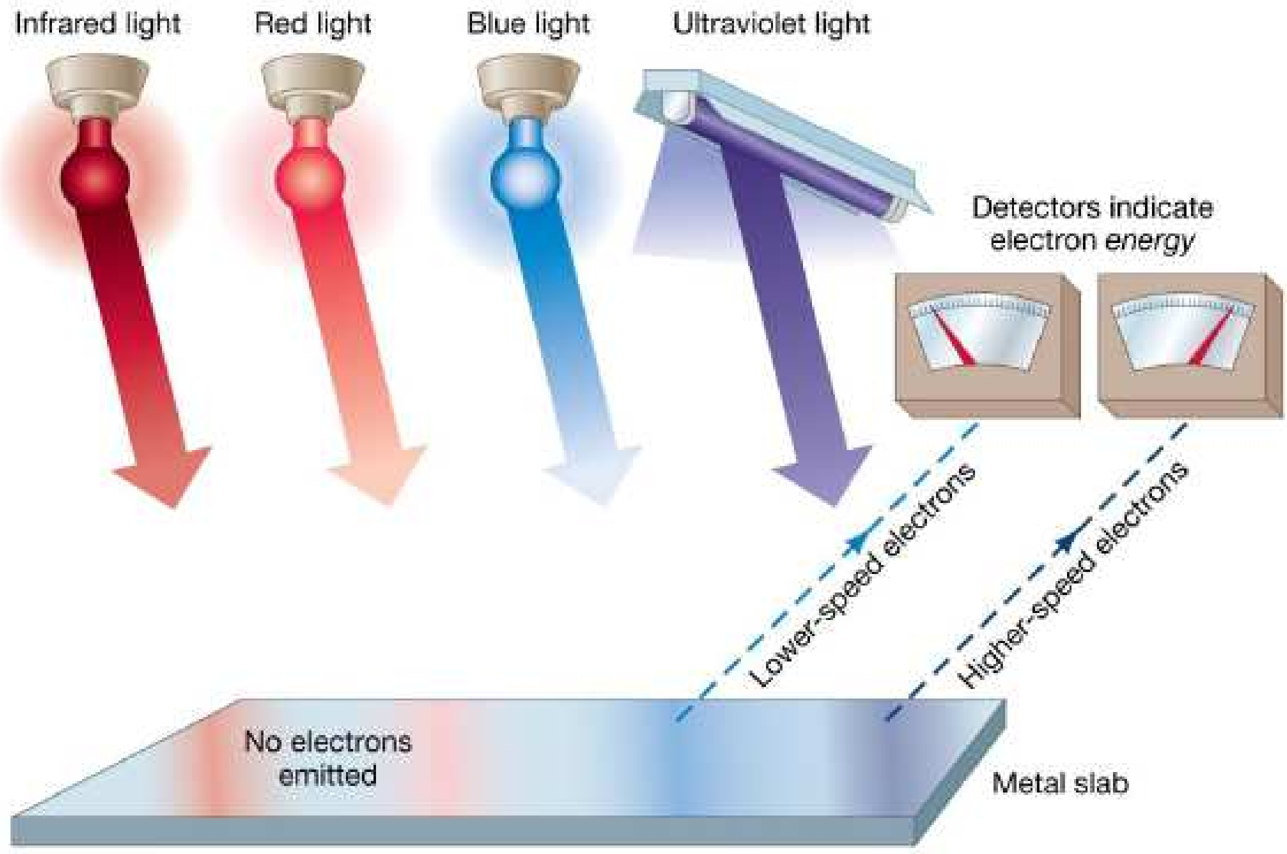
Discovery 4-1: The Photoelectric Effect

The photoelectric effect:

- When light shines on metal, electrons can be emitted
- **Frequency** must be higher than minimum, characteristic of material
- **Increased frequency**—more energetic electrons
- **Increased intensity**—more electrons, same energy

Discovery 4-1: The Photoelectric Effect

Photoelectric effect can only be understood if light behaves like particles



4.3 The Formation of Spectral Lines

- **Quantum Mechanics is our guide to internal structure of atoms.**
- **The spectrum of H consists EM radiations from UV to Radio**
- **Emissions may occur through Direct (to ground state) or Cascade (One orbital at a time) decays.**
- **Rydberg Formula:**

$$\frac{1}{\lambda} = RZ^2\left(\frac{1}{n'^2} - \frac{1}{n^2}\right),$$

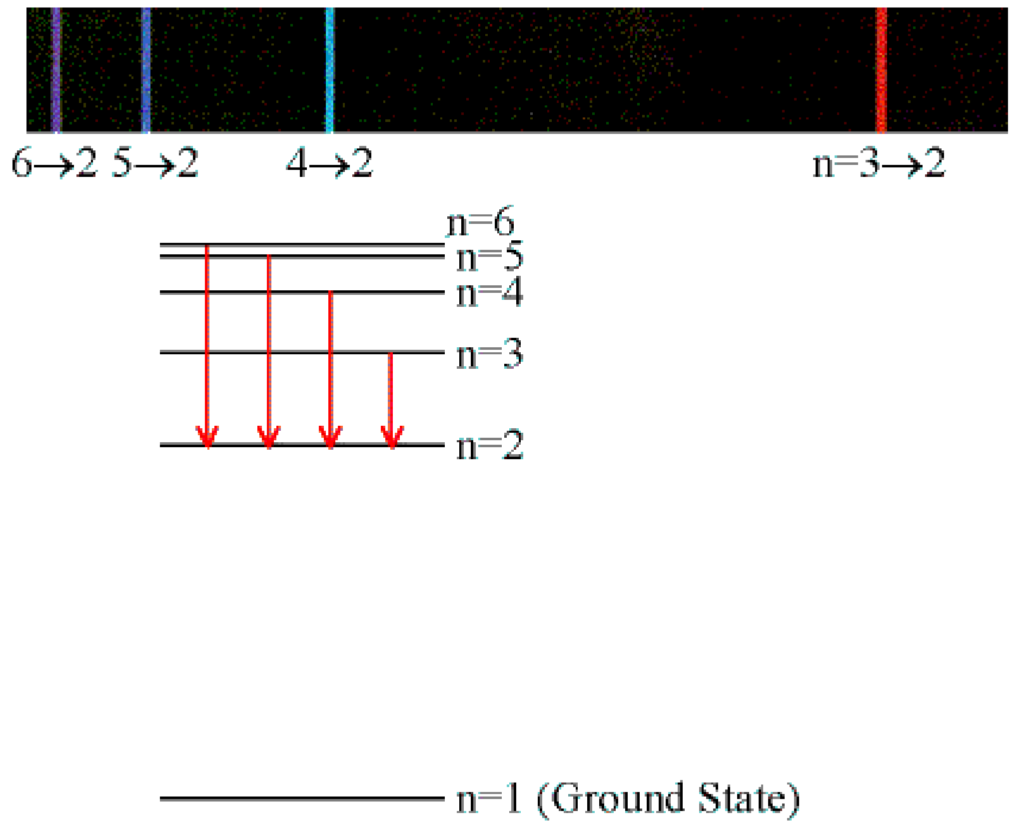
$$R = 1.097373 \times 10^7 \ \text{m}^{-1}$$

$$n = 6 \ \rightarrow \ n' = 2 \Rightarrow 410 \ \text{nm}$$

$$n = 5 \ \rightarrow \ n' = 2 \Rightarrow 434 \ \text{nm}$$

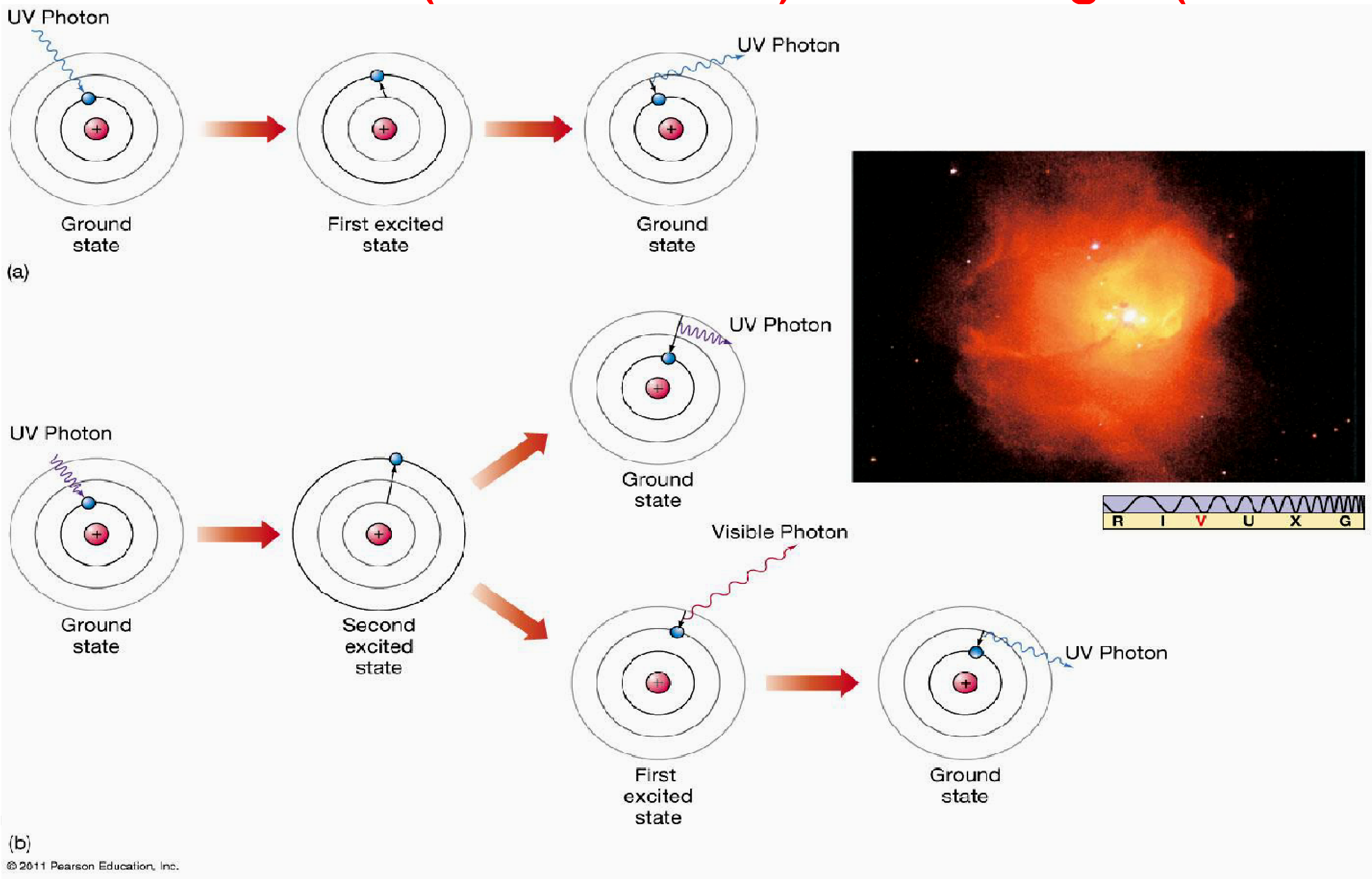
$$n = 4 \ \rightarrow \ n' = 2 \Rightarrow 486 \ \text{nm}$$

$$n = 3 \ \rightarrow \ n' = 2 \Rightarrow 656 \ \text{nm}$$



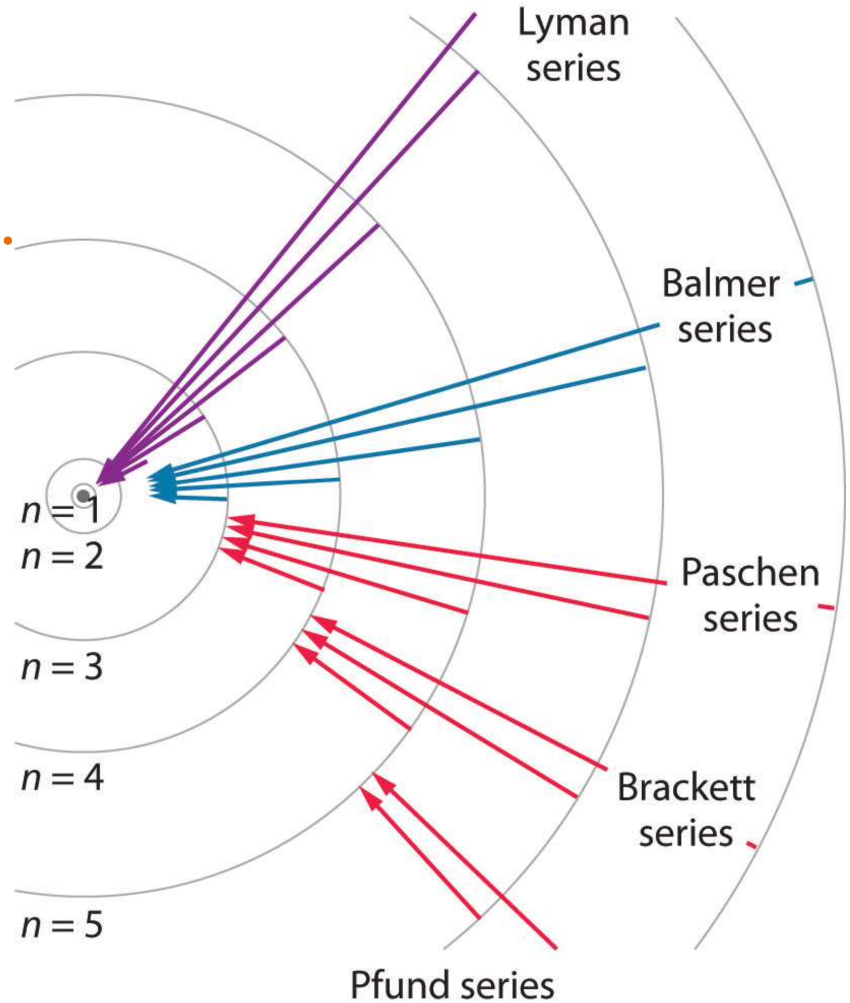
4.3 The Formation of Spectral Lines

- Excitation to 1st excited state ➔ Direct to g.s → UV (121.6 nm)
- Excitation to higher excited state (2nd)
  - ➔ Direct to g.s (UV @102.6 nm) OR
  - ➔ Cascade: 2nd to 1st (Red 656.3 nm) then 1st to g.s. (UV 121.6nm)



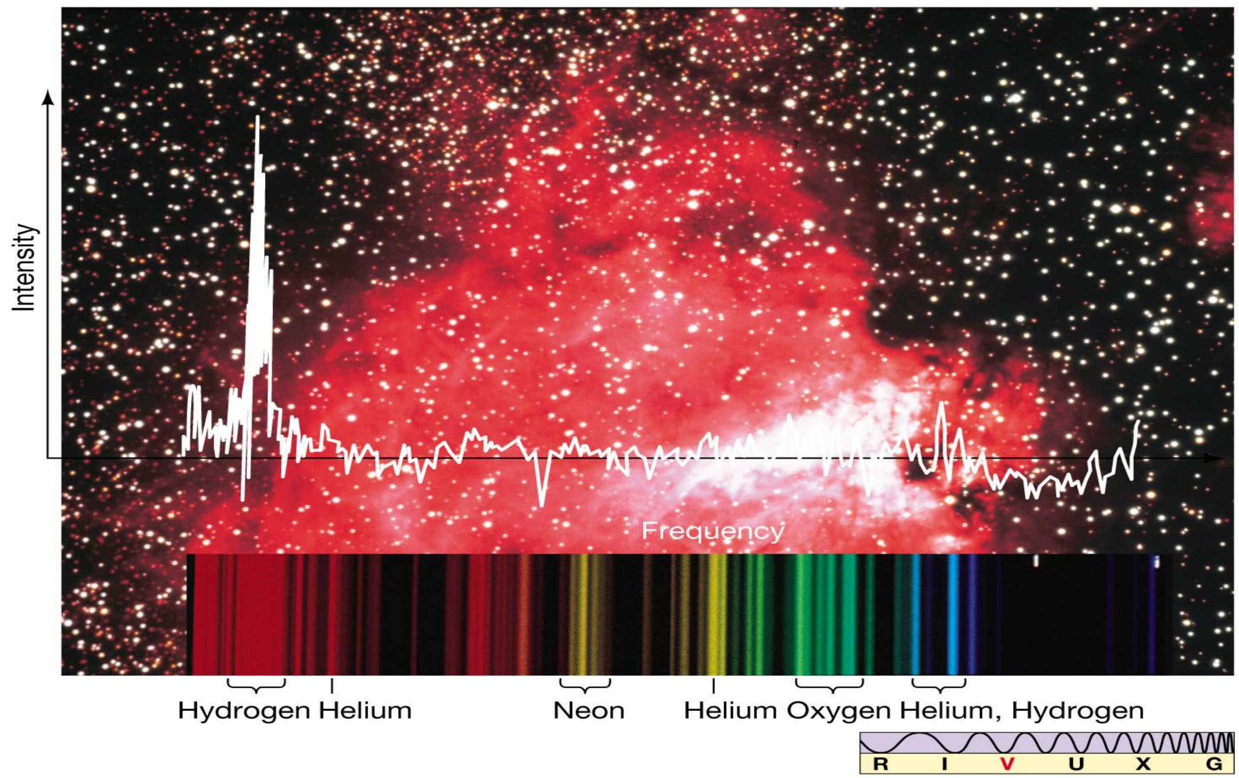
4.3 The Formation of Spectral Lines

- Absorption of additional energy can boost the electron to higher orbitals within the atom.
- Heating H ➔ Several Excited states.
  - ➔ Ending @ g.s. produce UV photons.
  - ➔ Ending to 1st produce lines near the visible spectrum
  - ➔ Ending in higher excited states produce IR & Radio spectral lines.



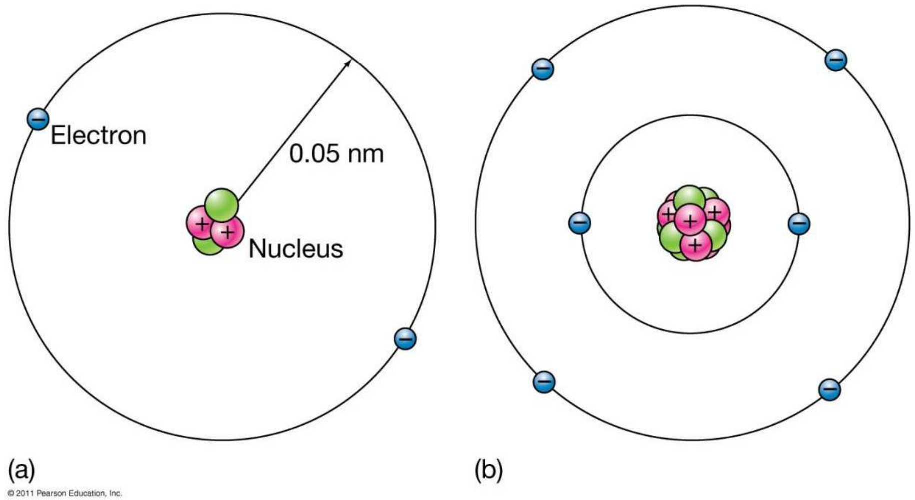
Kirchoff's Laws Explained

- A beam of continuous radiation shines through a cloud of hydrogen gas. Not all photons interact with the gas.
- No interactions or absorption ➔ pass through.
- Continuous Spectra: Excitations in many different atoms.
- Spectral Lines characterize the atoms in the gas not the source.
- Nebula ➔ red light ➔ H atom

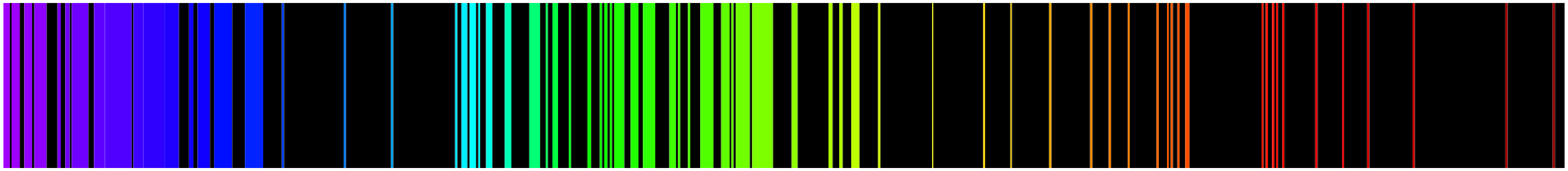


More Complex Spectra

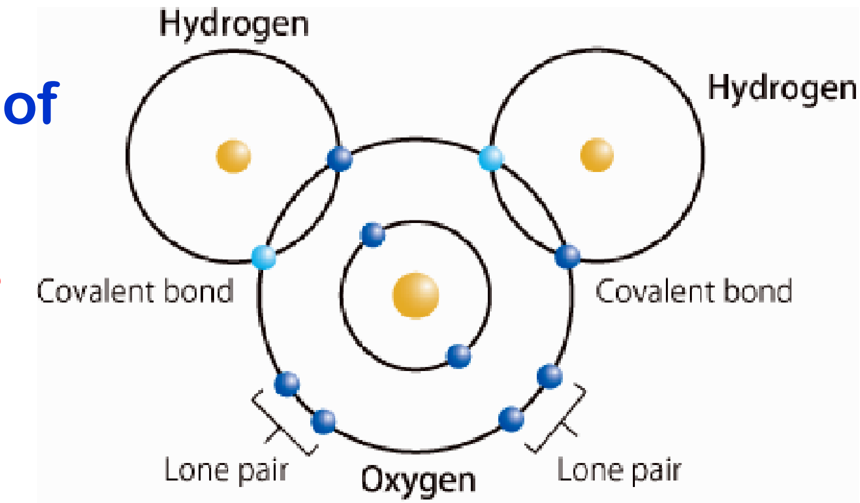
- He-atom is the second simplest element.
- More complex atoms contain more protons → more orbits.
- Fe – atom: 26 protons and 26 electrons→ enormous transitions
- Ionization changes energy levels → new spectra
- The power of spectroscopy determine the clouds composition.



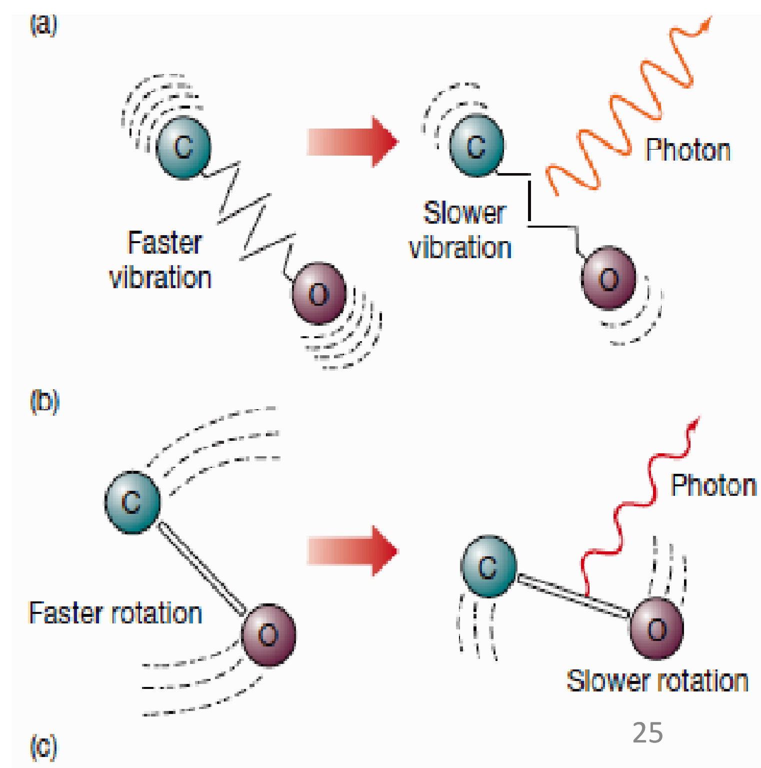
- 800 Fraunhofer lines for Iron (Fe)

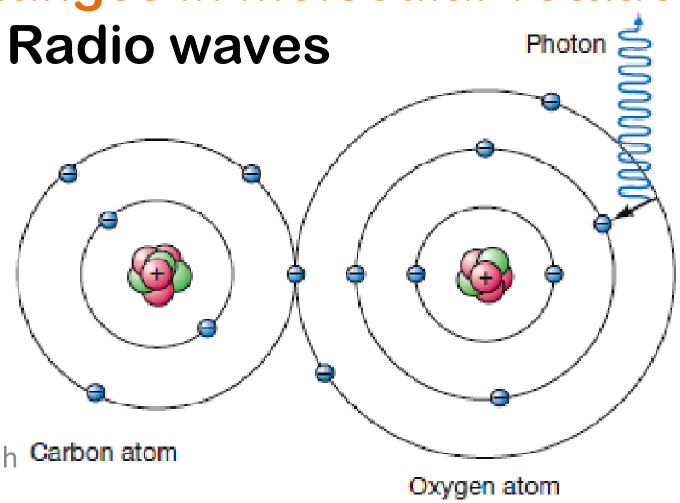


4.4 Molecules



- A molecule: a tightly bound group of atoms held together
- Molecules are complex ➔ ➔ more complex spectrum
- Molecular radiation are due to:
  a) Electron transition within molecules
     ➔ visible and UV lines
  b) Changes in molecular vibrations
     ➔ IR lines
  c) Changes in molecular rotation
     ➔ Radio waves



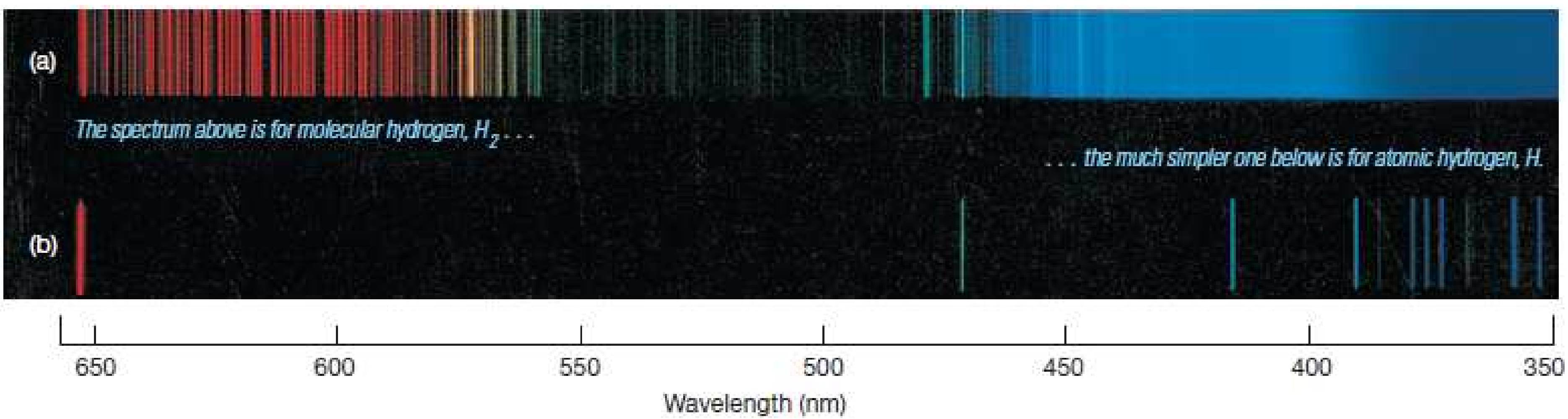


4.4 Molecules

Vibration

Rotational

(a) H-Molecule **(b) H-Atom**



4.5 Spectral-Line Analysis

Information that can be gleaned from spectral lines:

- **Chemical composition**
- **Temperature**
- **Radial velocity**

Spectral-Line Analysis

- **A Spectroscopic Thermometer:**

•Heat → Fully ionized atoms→ Free electrons→ Continuous radiation.

- **Stellar surface→ Cooler→ Bound electrons→ Spectrum.**
- **The strength of the spectral line depend on the number of atoms & the Temperature of the gas containing the atoms.**
- **Low Temperature ➔ Lyman series, absorption lines in the ultraviolet spectrum.➔ no visible H-atom lines. No excited states.**

•The sun has a weak visible line in comparison with other stars.

•Higher Temp. → atoms move faster → more energy become available.➔ excited states ➔ Balmer lines.

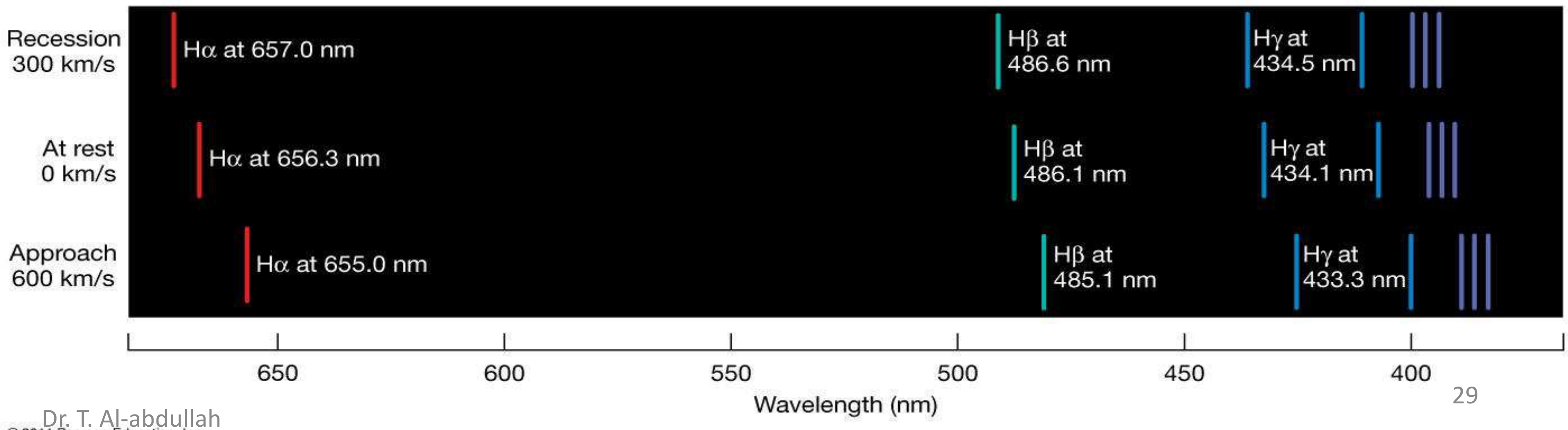
4.5 Spectral Line Analysis

- **Measurement of Radial Velocity**
- **Lines Displaced from their usual locations**
- **Redshifted or blueshifted due to Doppler effec**

→ **How fast is the source?**

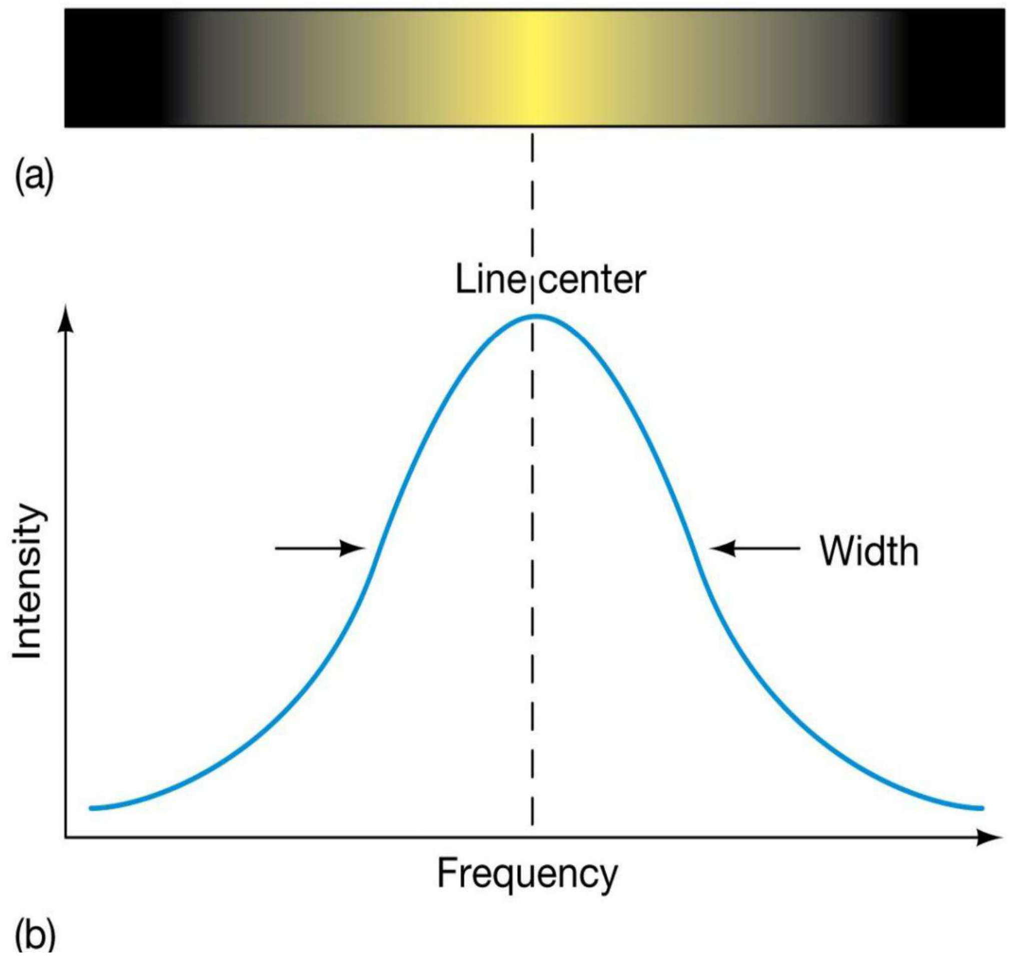
$$\frac{\Delta\lambda}{\lambda}\times c = \frac{-1.0\text{ nm}}{486.1\text{ nm}}\times c = -620\text{ km/s}$$

➔ Galaxy is approaching



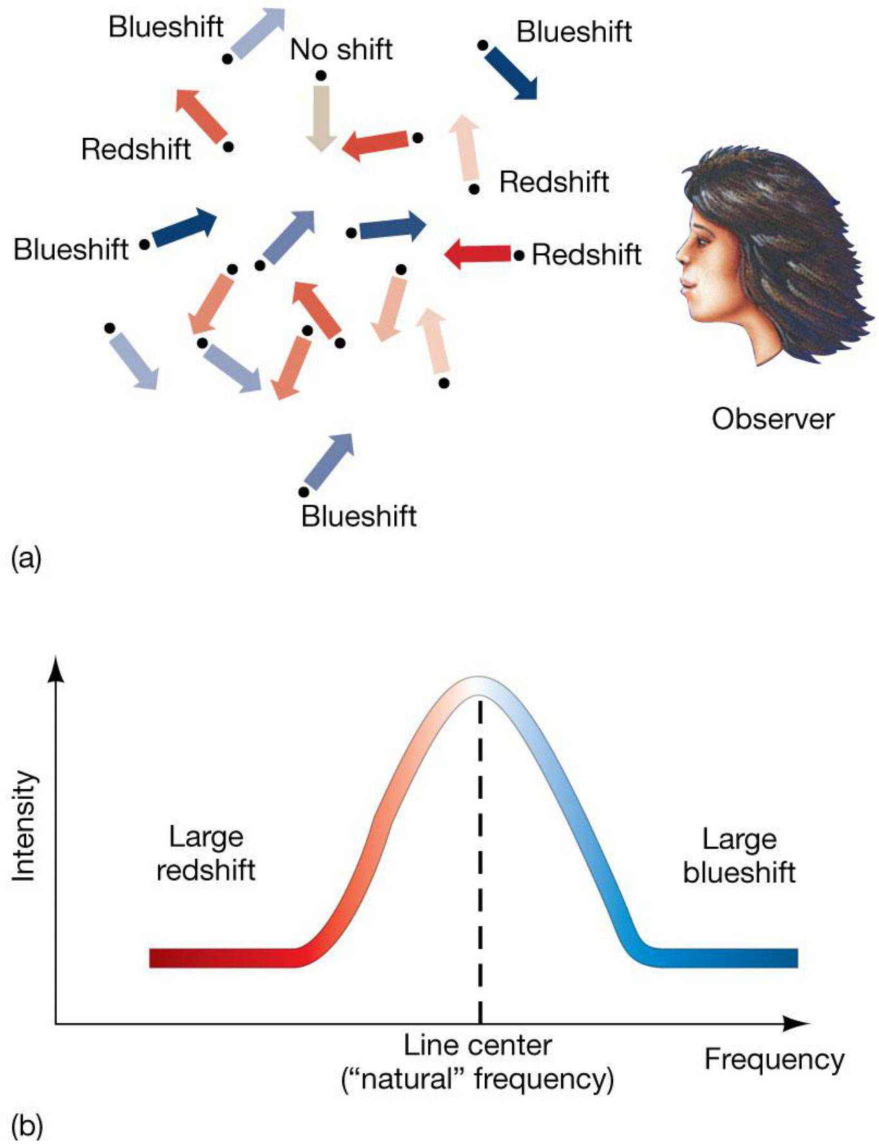
4.5 Spectral-Line Analysis

Line broadening can be due to a variety of causes



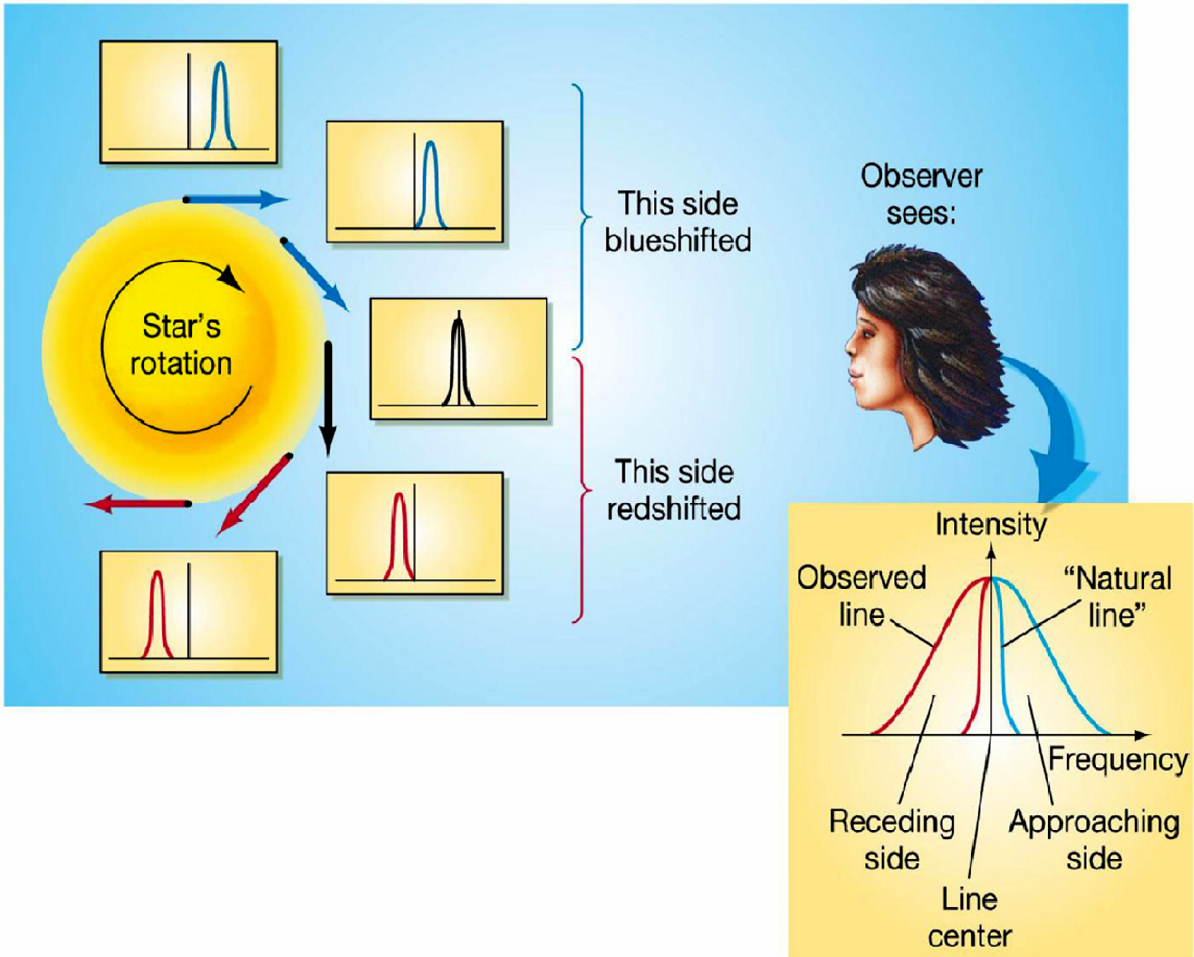
4.5 Spectral-Line Analysis

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



4.5 Spectral Line Analysis

- **Magnetic fields can broaden spectral lines by *Zeeman Effect*.**
- **Presence of B-field may split spectral lines → blurring effect.**

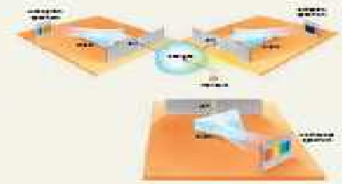
4.5 Spectral-Line Analysis

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

SUMMARY

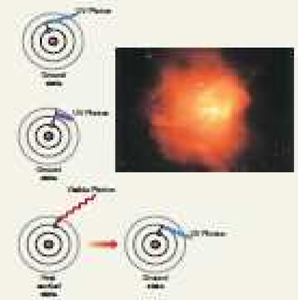
1 A **spectroscope** (p. 80) is a device for splitting a beam of radiation into its component frequencies for detailed study. Many hot objects emit a **continuous spectrum** (p. 80) of radiation, containing light of all wavelengths. A hot gas may instead produce an **emission spectrum** (p. 81), consisting of only a few well-defined **emission lines** (p. 80) of specific frequencies, or colors. Passing a continuous beam of radiation through cool gas will produce **absorption lines** (p. 82) at precisely the same frequencies as would be present in the gas's emission spectrum.



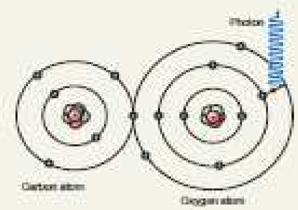
2 **Kirchhoff's laws** (p. 83) describe the relationships among these different types of spectra. The emission and absorption lines produced by each element are unique—they provide a "fingerprint" of that element. The study of the spectral lines produced by different substances is called **spectroscopy** (p. 83). Spectroscopic studies of the Fraunhofer lines in the solar spectrum yield detailed information about the Sun's composition.

3 **Atoms** (p. 84) are made up of negatively charged electrons orbiting a positively charged **nucleus** (p. 84) consisting of positively charged protons and electrically neutral **neutrons** (p. 90). The number of protons in the nucleus determines the particular **element** (p. 90) the atom represents. In the **Bohr model** (p. 84), a hydrogen atom has a minimum energy **ground state** (p. 84) representing its "normal" condition. When the electron has a higher than normal energy, the atom is in an **excited state** (p. 85). For any given atom, only certain, well-defined energies are possible. In the modern view, the electron is envisaged as being spread out in a "cloud" around the nucleus, but still with a sharply defined energy.

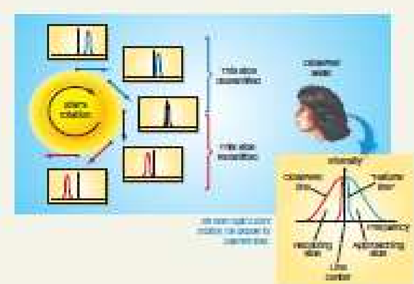
4 Electromagnetic radiation exhibits both wave and particle properties. Particles of radiation are called **photons** (p. 85). In order to explain the **photoelectric effect** (p. 88), Einstein found that the energy of a photon must be directly proportional to the photon's frequency.



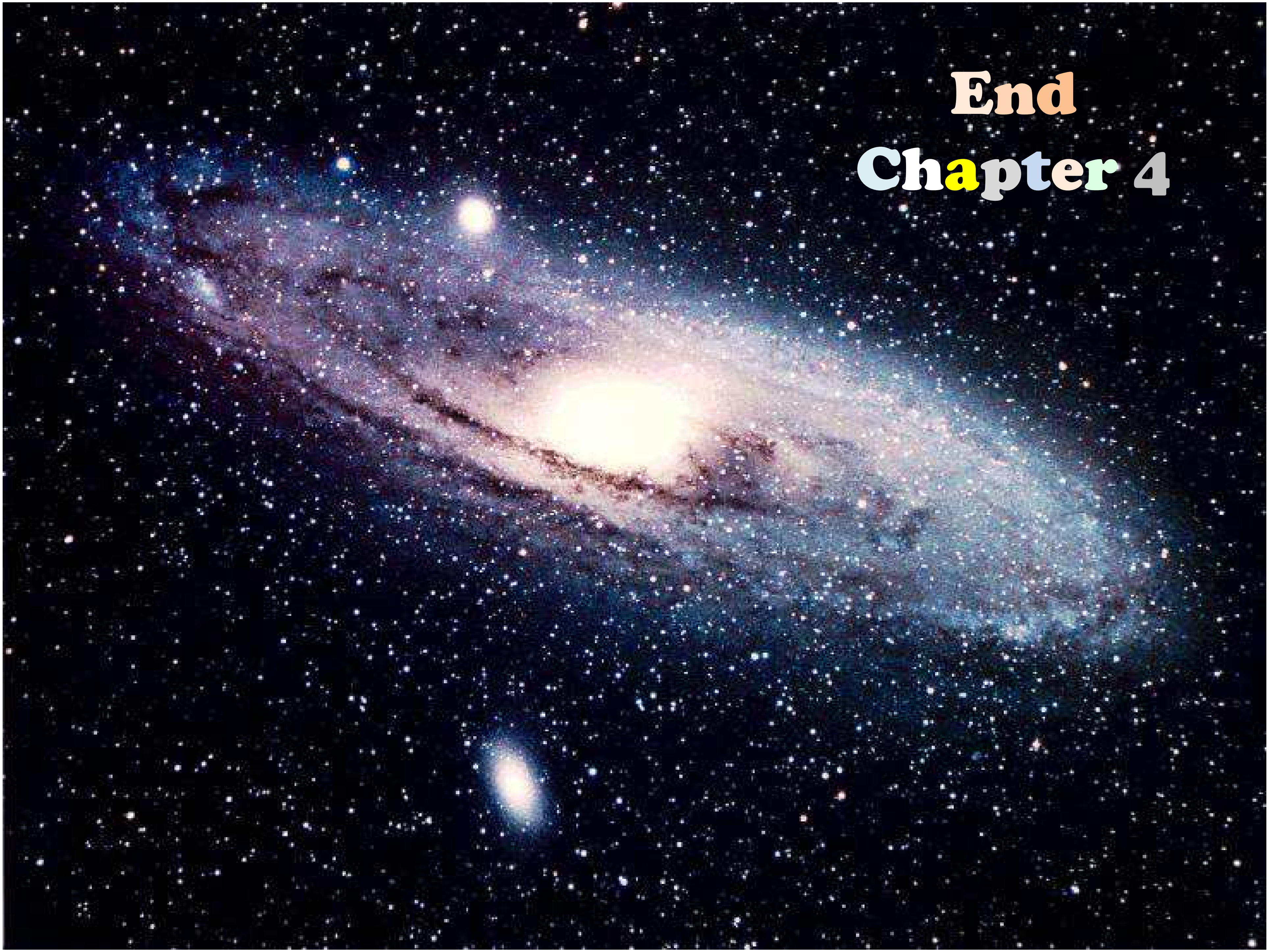
5 As electrons move between energy levels within an atom, the difference in energy between the states is emitted or absorbed in the form of photons. Because the energy levels have definite energies, the photons also have definite energies, and hence colors, that are characteristic of the type of atom involved.



6 **Molecules** (p. 91) are groups of two or more atoms bound together by electromagnetic forces. Like atoms, molecules exist in energy states that obey rules similar to those governing the internal structure of atoms. When a molecule makes a transition between energy states, it emits or absorbs a characteristic spectrum of radiation that identifies it uniquely.



7 Astronomers apply the laws of spectroscopy to analyze radiation from beyond Earth. Several physical mechanisms can broaden spectral lines. The most important is the Doppler effect, which occurs because stars are hot, or rotating, or turbulent, so their atoms are in constant motion.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Chapter 4