ASTR 400/700: Stellar Astrophysics

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ASTROPHYSICS **: studies the physics of stars, stellar systems and interstellar material.**

LIGHT!!

PHOTOMETRY

Measures the amount of electromagnetic energy received from a celestial object.

$$m = -\log(F_{\lambda})$$

SPECTROSCOPY

Studies the nature of the celestial objects by analyzing the light they produce

SPECTRUM

TELESCOPES

Spectral Lines

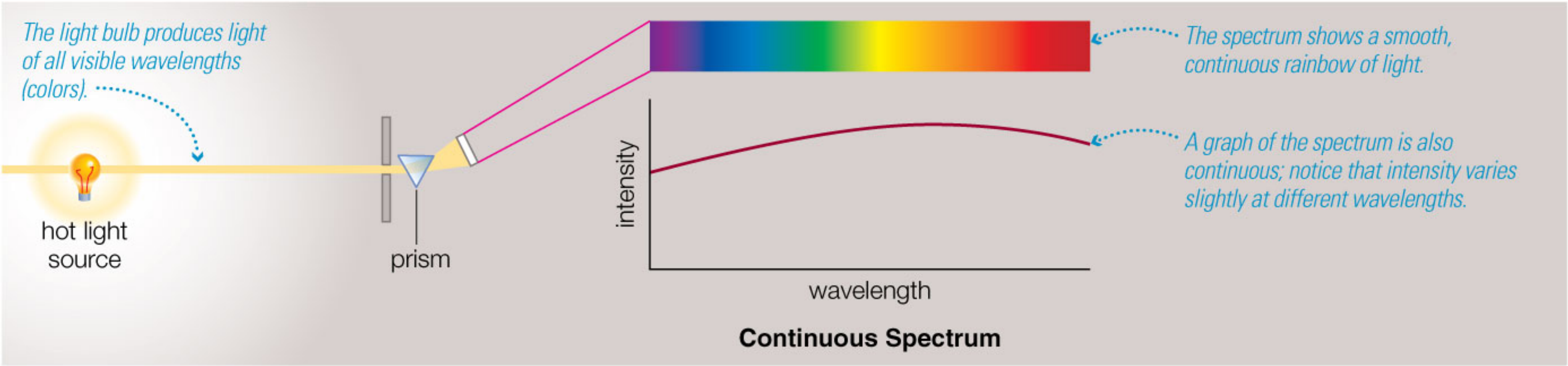
Chapter 5.1

(with bits of 5.2 and 5.3)

How do light and matter interact?

- Emission
- Absorption
- Transmission
  - Transparent objects transmit light.
  - Opaque objects block (absorb) light.
- Reflection or scattering

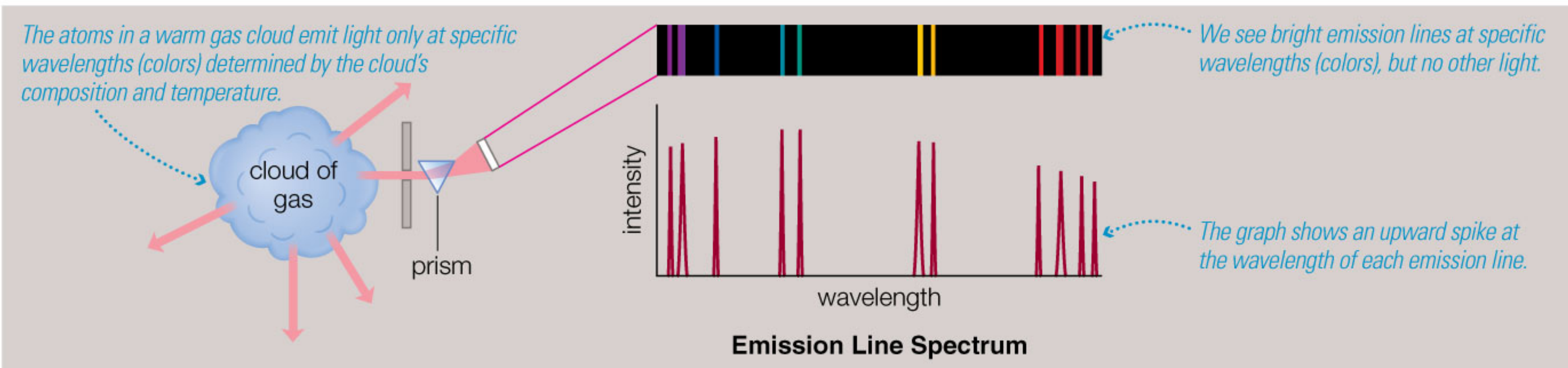
Continuous Spectrum



a

- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption.

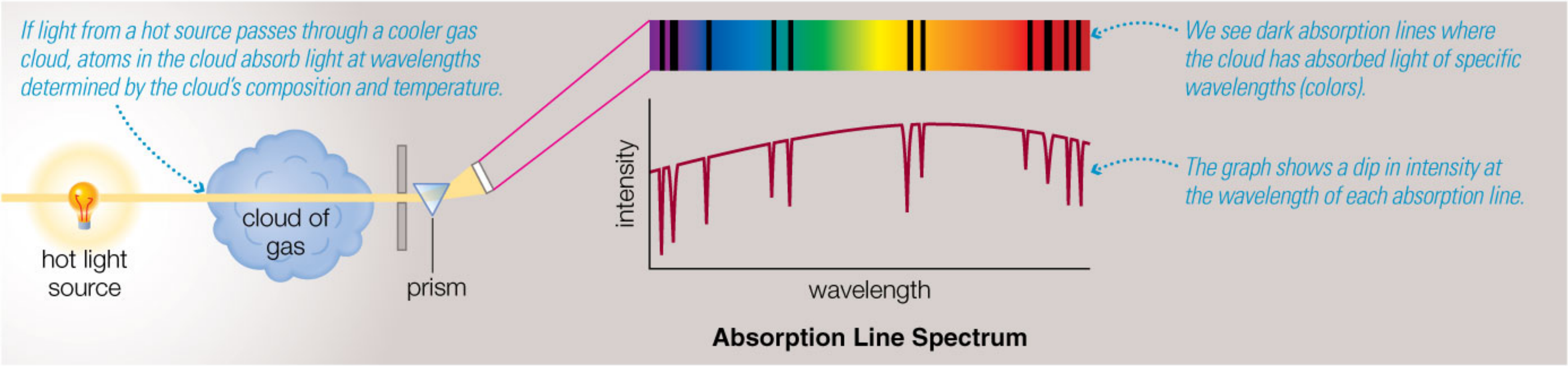
Emission Line Spectrum



b

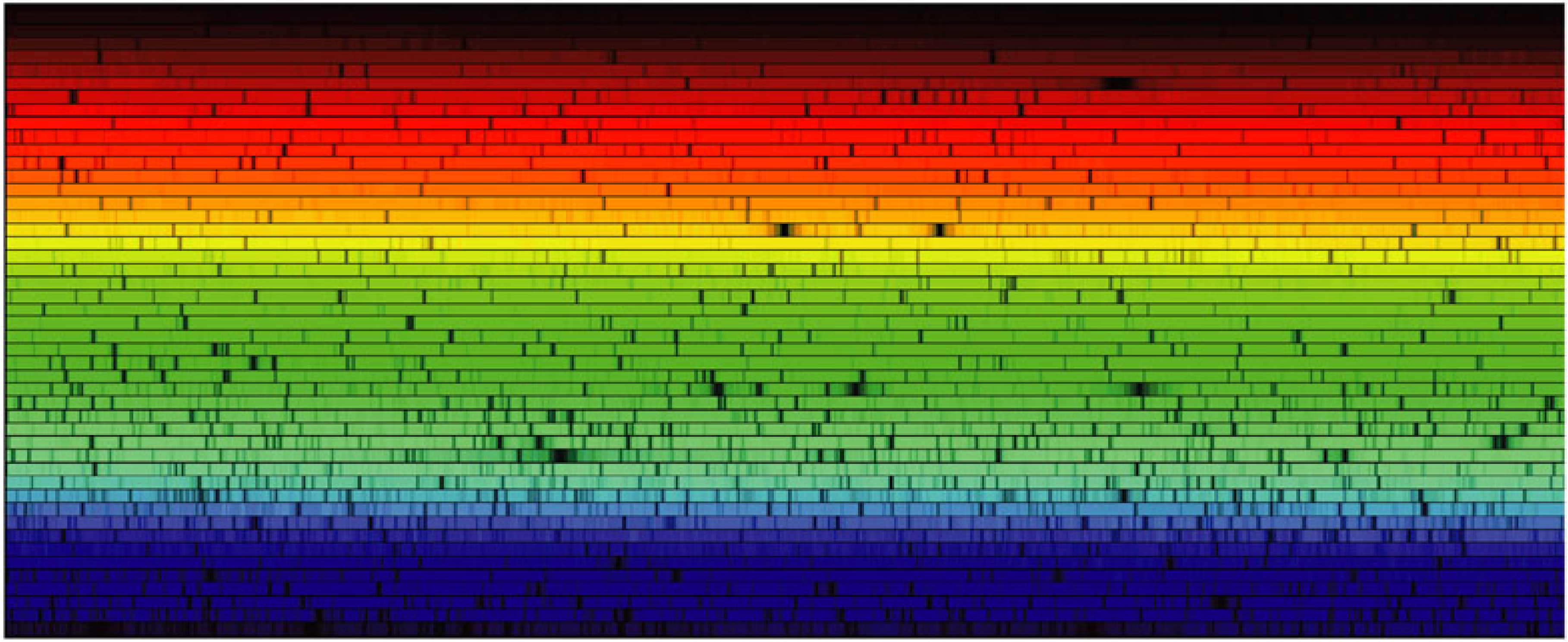
- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines.

Absorption Line Spectrum



c

- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum.



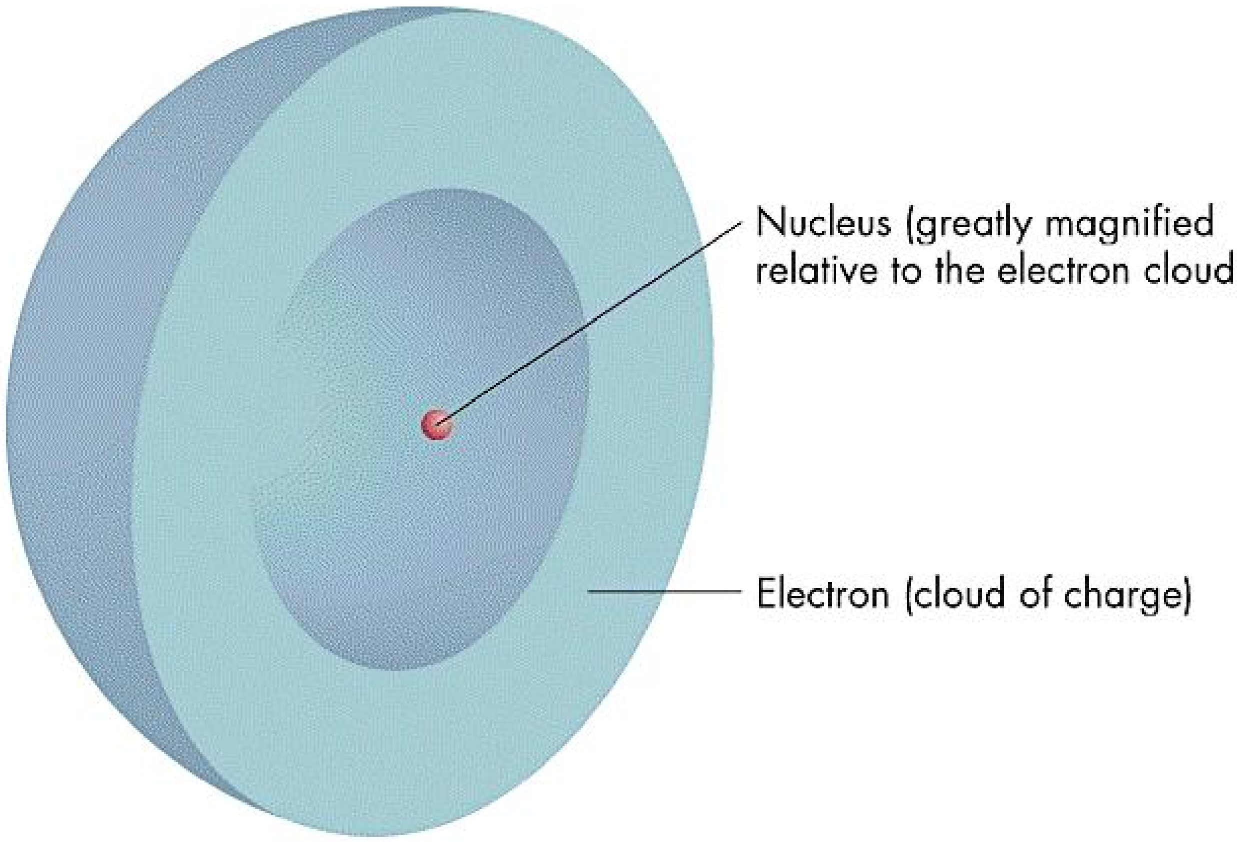
Absorption lines in the Sun’s spectrum (Fraunhofer lines)

Kirchoff’s laws

Chemical Analysis by Spectral Observations (Kirchoff & Bunsen)

- A hot solid, liquid, or dense gas produces a continuous spectrum.
- A thin gas in front of a cooler background produces an emission line spectrum.
- A thin gas in front of a hot source imprints absorption lines on the spectrum. This is mainly what we see from stars.

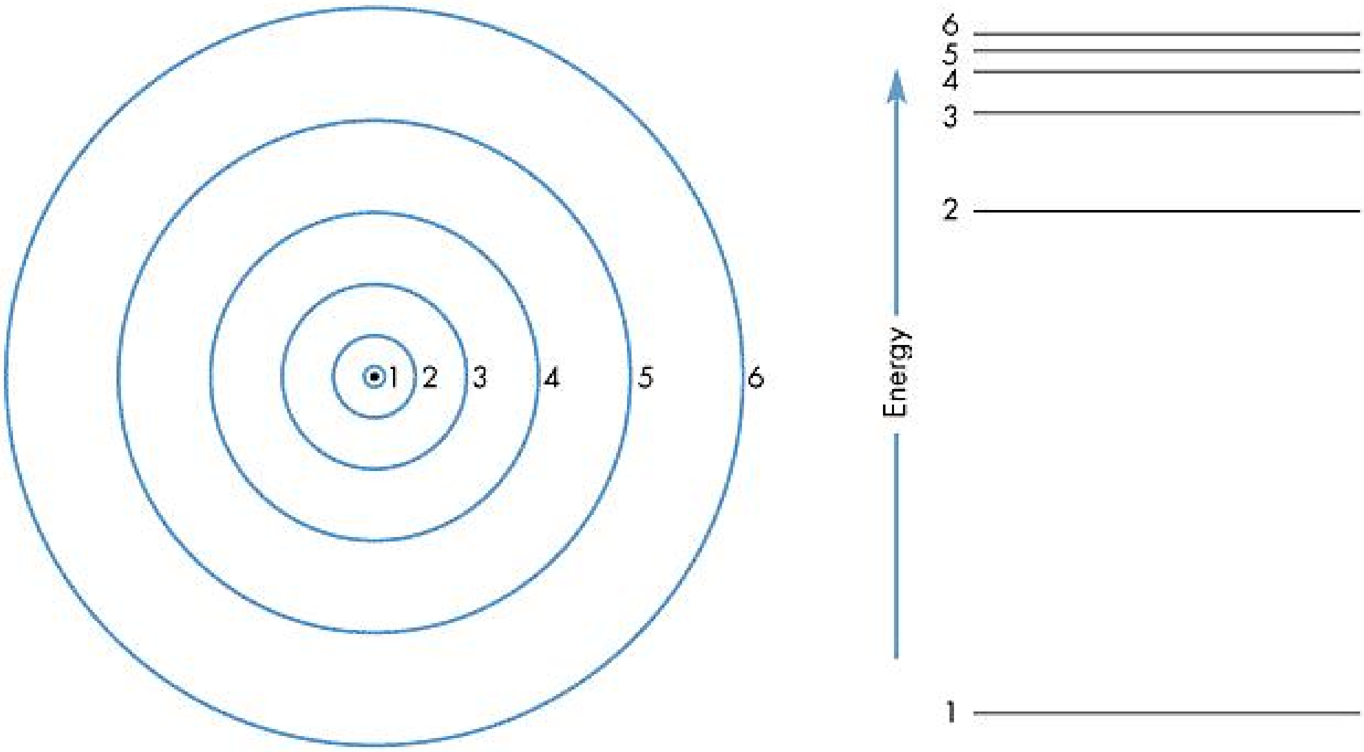
Hydrogen atom



Cross section of a hydrogen atom

Electron orbits around nucleus

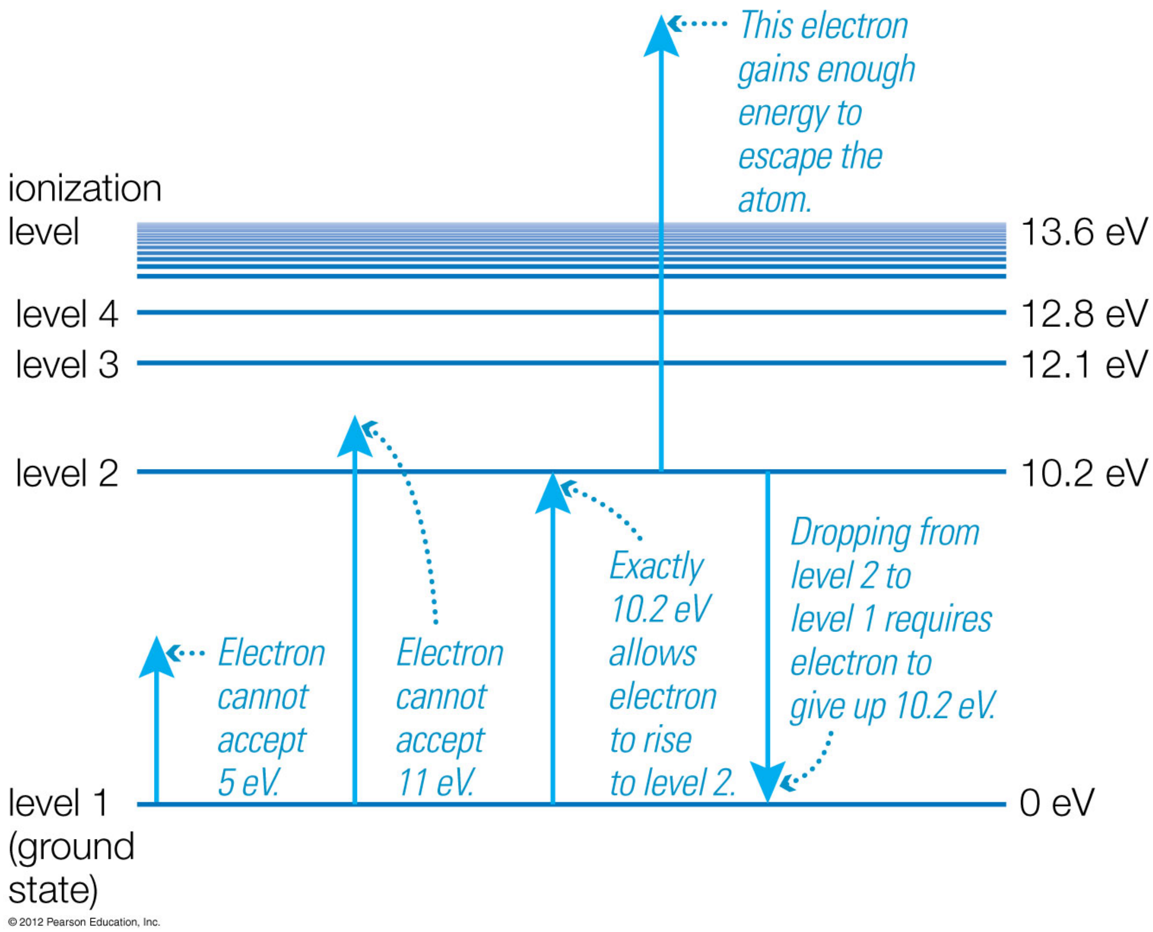
Electron orbits



A Possible distances of the electron in a hydrogen atom **B** Energy levels for the hydrogen atom

From quantum mechanics, only certain orbits are allowed.
Each orbit has a specific energy.

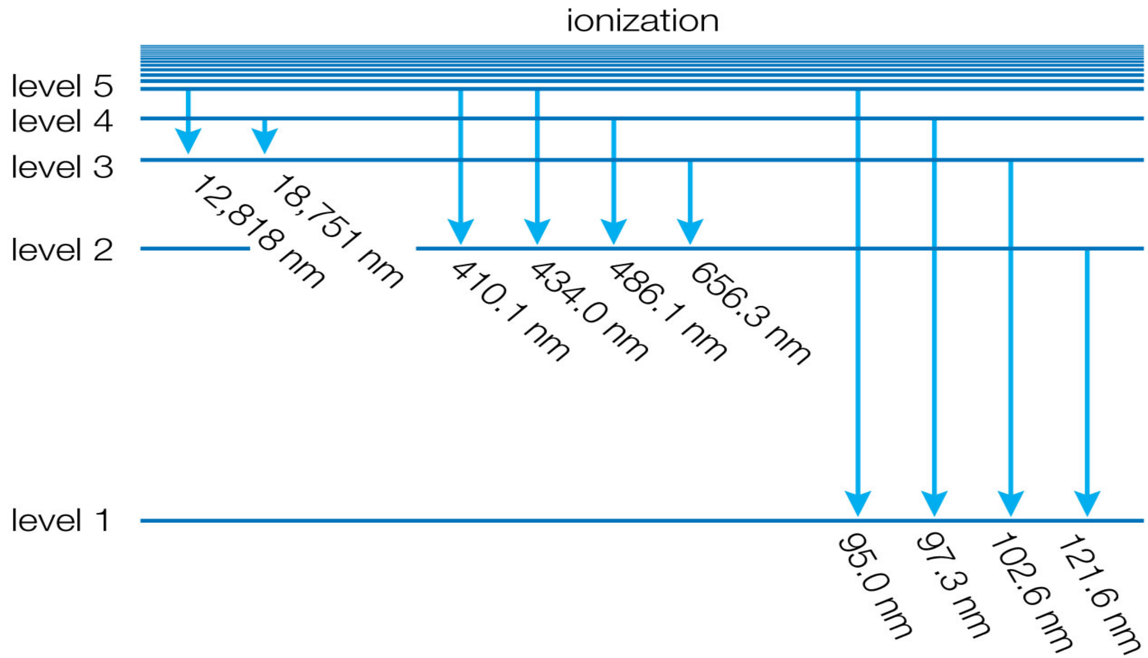
Chemical Fingerprints



Energy levels of hydrogen

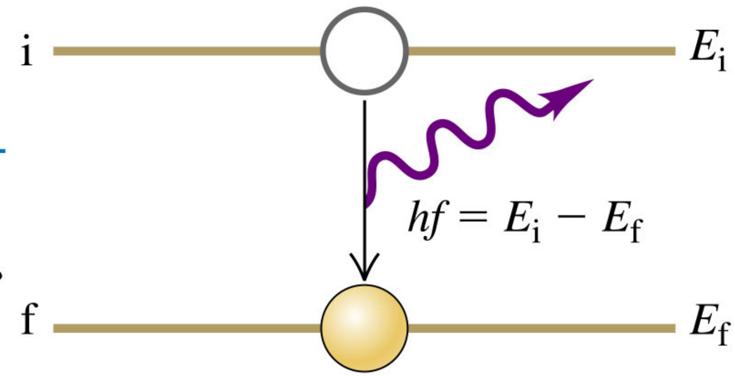
- Each type of atom has a unique set of energy levels.
- Each transition corresponds to a unique photon energy, frequency, and wavelength.

Chemical Fingerprints



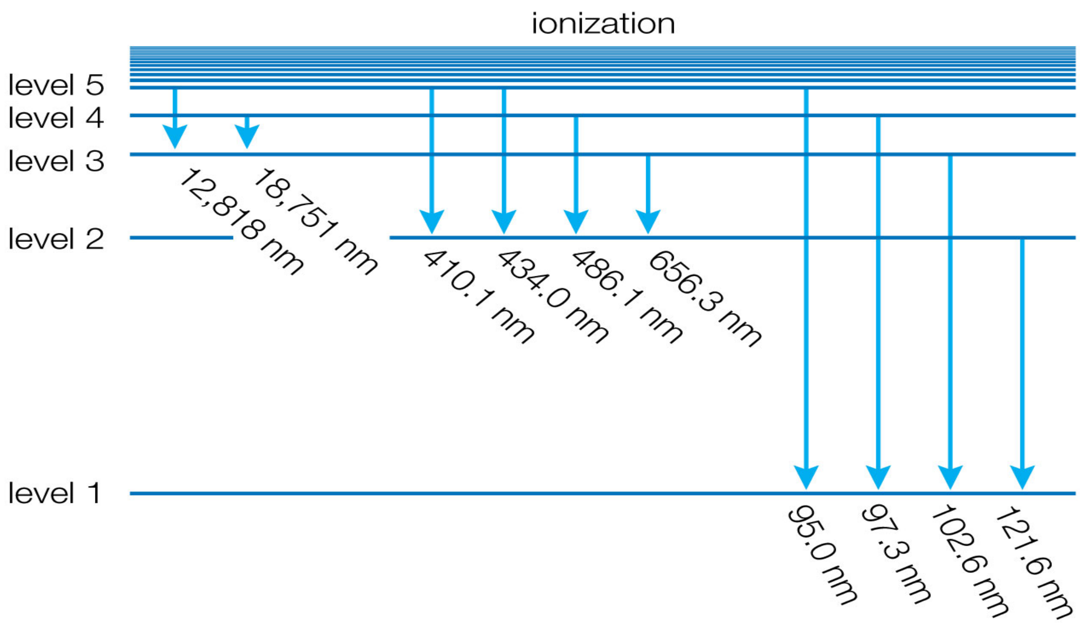
a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.

- Downward transitions produce a unique pattern of emission lines.



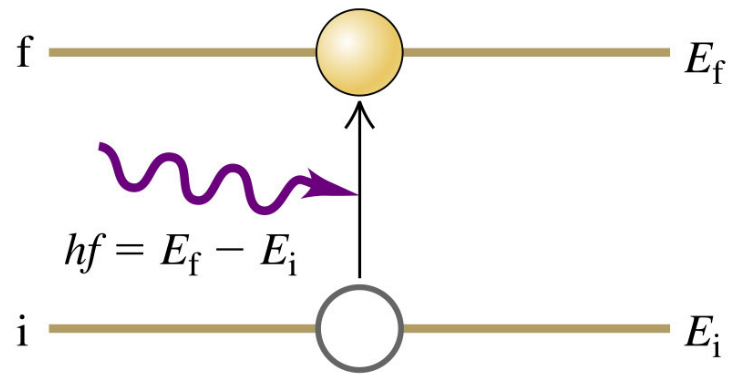
b This spectrum shows emission lines produced by downward transitions between higher levels and level 2 in hydrogen.

Chemical Fingerprints



a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.

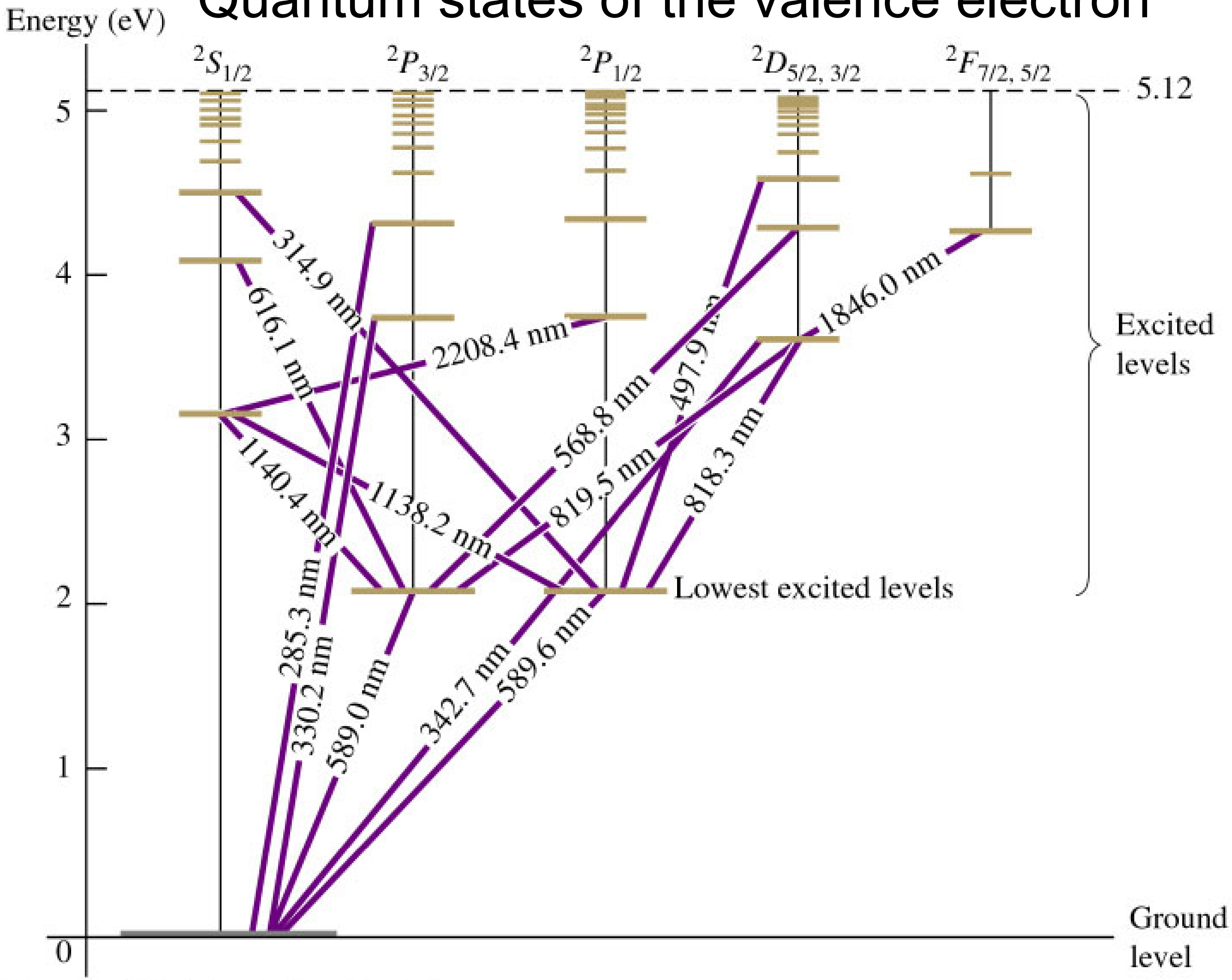
- Because those atoms can absorb photons with those same energies, upward transitions produce a pattern of absorption lines at the same wavelengths.



c This spectrum shows absorption lines produced by upward transitions between level 2 and higher levels in hydrogen.

Energy levels and transitions of the many-electron atom: Sodium

Quantum states of the valence electron



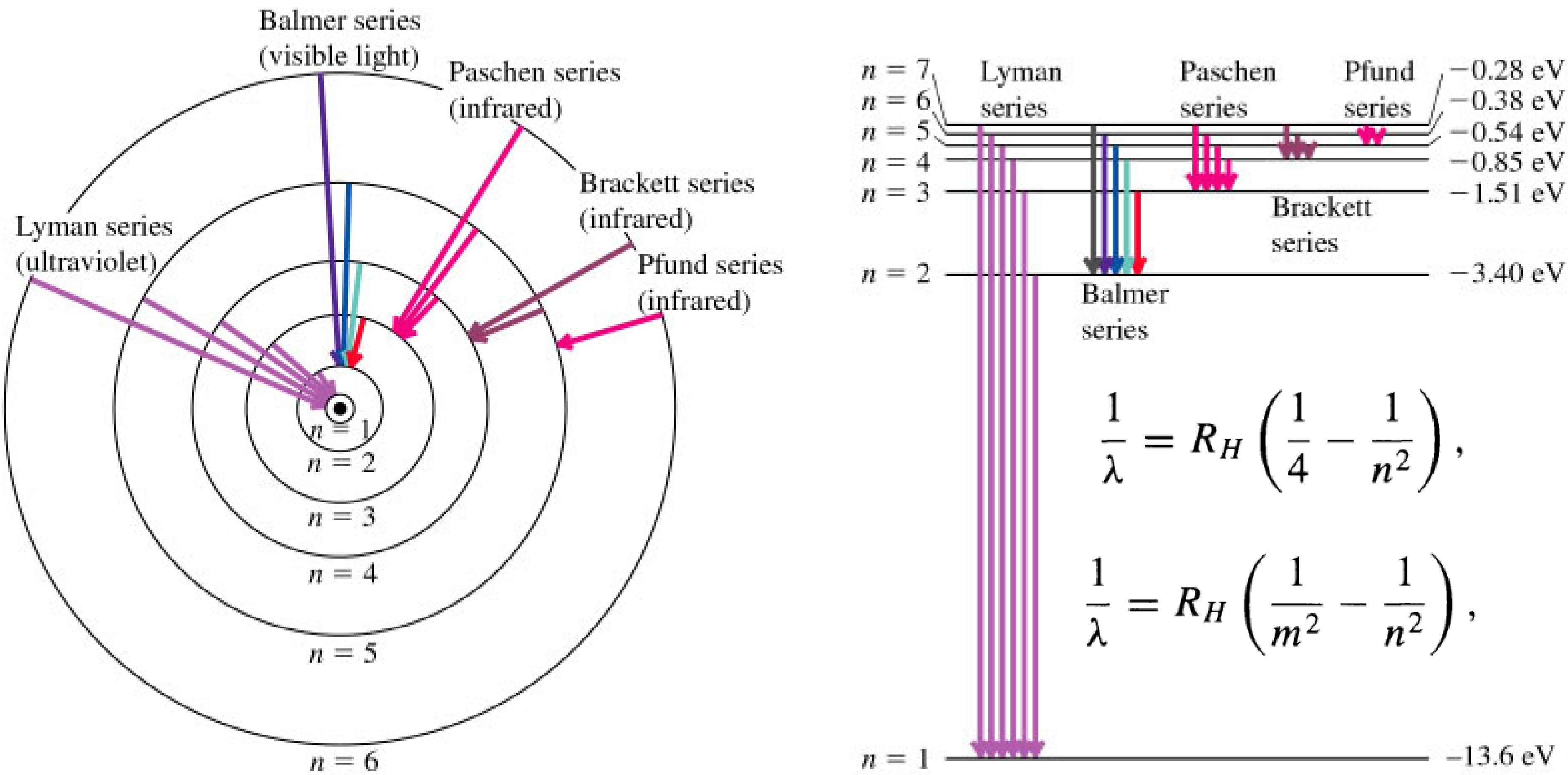
Chemical Fingerprints

- Each type of atom has a unique spectral fingerprint.
- Observing the fingerprints in a spectrum tells us which kinds of atoms are present.

The hydrogen atom

$$E_n = -\frac{hcR}{n^2} \qquad n = 1, 2, 3, 4, \ldots$$

(energy levels of the hydrogen atom)



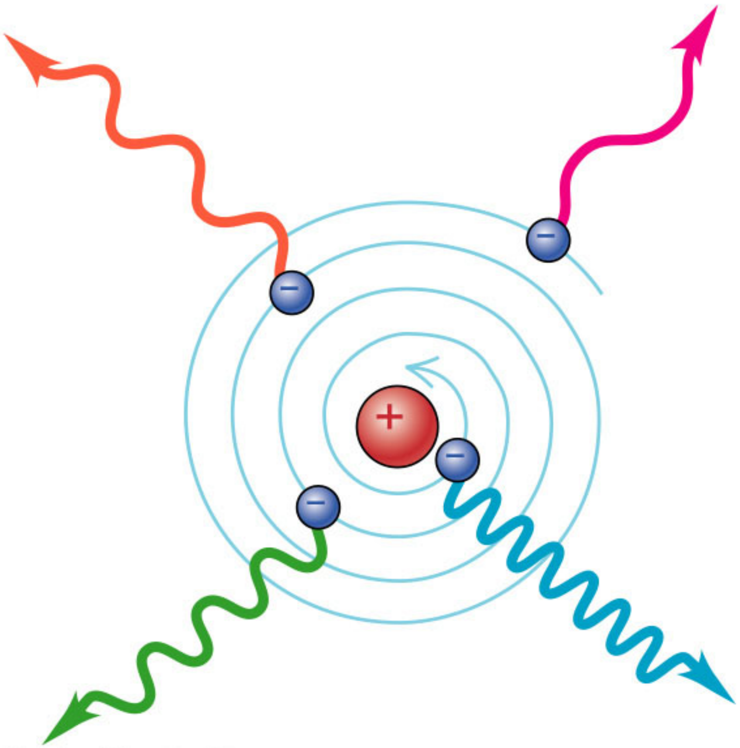
$$\frac{1}{\lambda} = R_H\left(\frac{1}{4} - \frac{1}{n^2}\right),$$

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

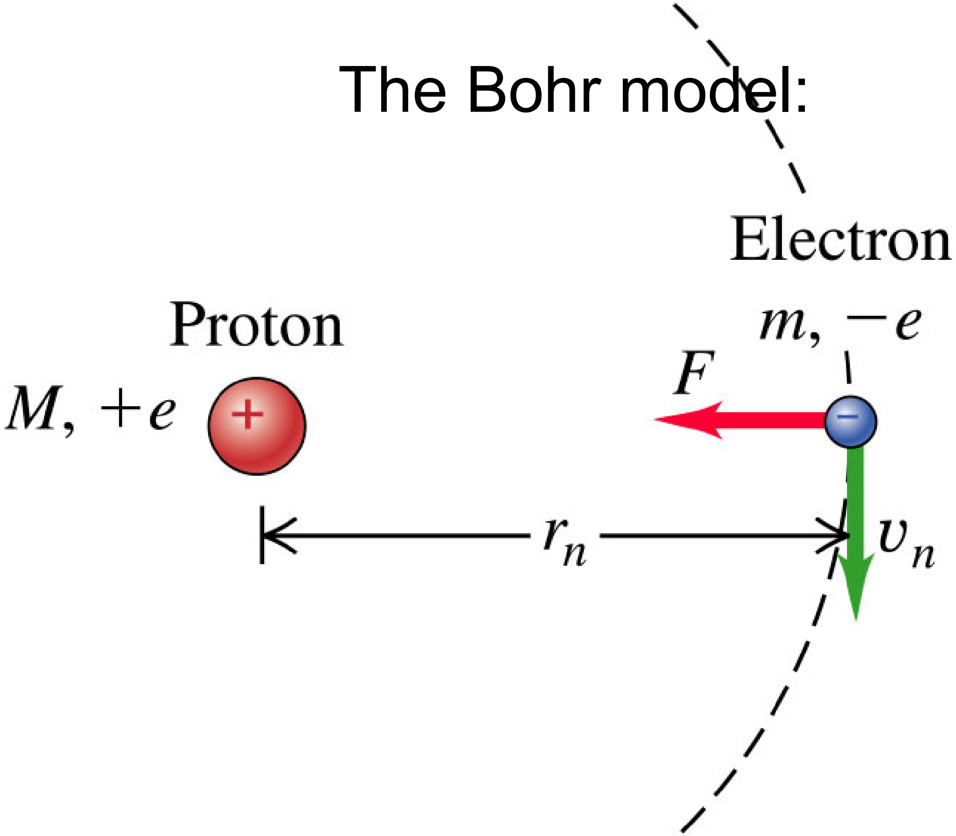
(a) (b)

The Bohr Model

- Classical physics predicts that the electron should spiral into the nucleus
- Cannot explain emission spectra



The Bohr model:



- The e- stays in certain stable orbits, emits no radiation unless it jumps to a lower level
- The angular momentum of the e- is <u>quantized</u>
- The attraction between p and e- provides the centripetal acceleration

n = principal quantum number

$$L_n = mv_n r_n = n\frac{h}{2\pi} \qquad \text{(quantization of angular momentum)}$$

From Coulomb's law, the force between the proton and electron is

$$F = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r^2}$$

Where $q_1 = q_2 = e$ for the hydrogen atom

This is the centripetal force, mv^2 / r

So when the electron is in any energy level n:

$$\boxed{r_n = \frac{4\pi\epsilon_0\hbar^2}{\mu e^2}n^2 = a_0 n^2,}\qquad \boxed{E_n = -\frac{\mu e^4}{32\pi^2\epsilon_0^2\hbar^2}\frac{1}{n^2} = -13.6\,\mathrm{eV}\frac{1}{n^2}.}$$

Bohr radius $a_0 = \varepsilon_0 h^2 / \pi m e^2 = 5.29 \times 10^{-11}$ m

Then the energy of an emitted photon is:

$$\boxed{E_{\text{photon}} = E_{\text{high}} - E_{\text{low}}}$$

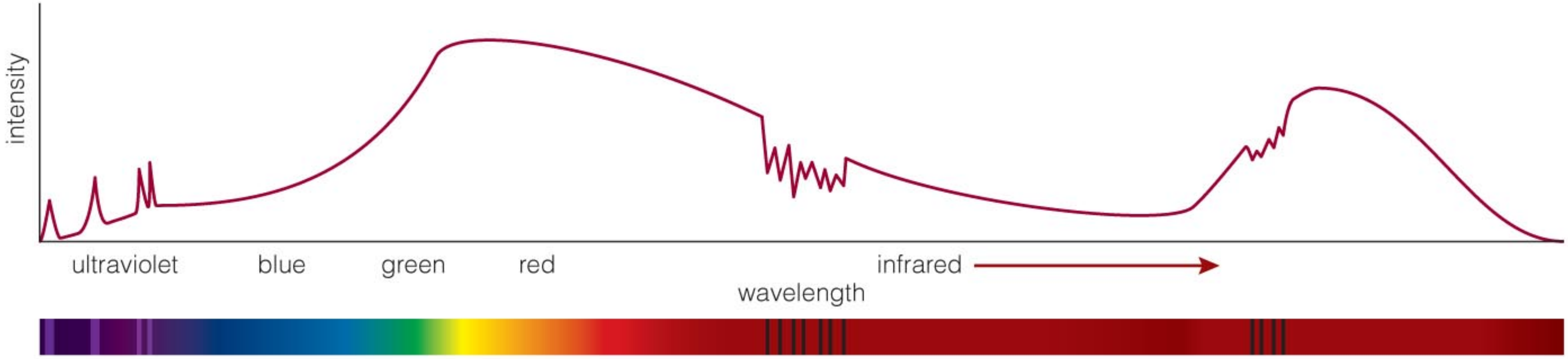
$$\frac{hc}{\lambda} = \left(-\frac{\mu e^4}{32\pi^2\epsilon_0^2\hbar^2}\frac{1}{n_{\text{high}}^2}\right) - \left(-\frac{\mu e^4}{32\pi^2\epsilon_0^2\hbar^2}\frac{1}{n_{\text{low}}^2}\right)$$

$$\frac{1}{\lambda} = \frac{\mu e^4}{64\pi^3\epsilon_0^2\hbar^3 c}\left(\frac{1}{n_{\text{low}}^2} - \frac{1}{n_{\text{high}}^2}\right)$$

Explaining Kirchoff’s laws

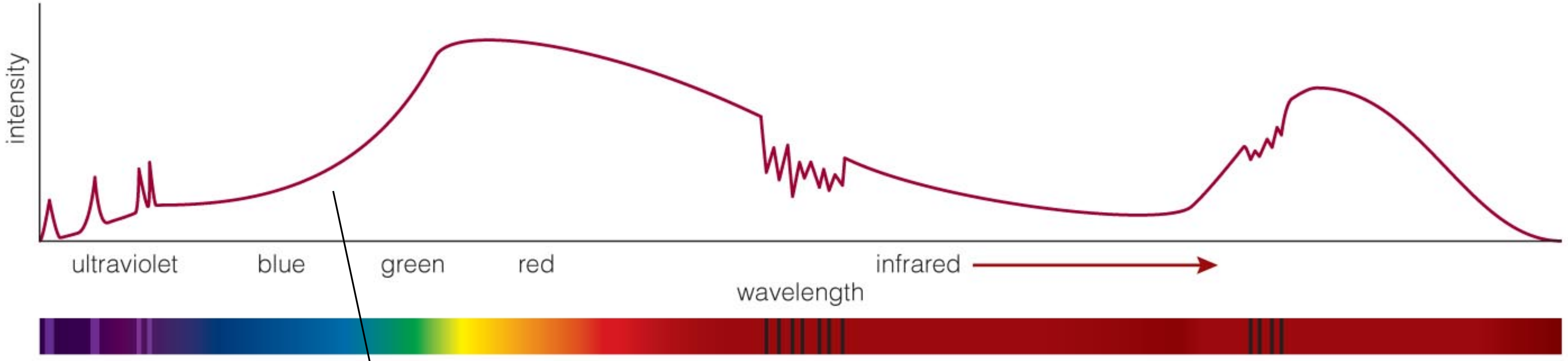
- A hot solid, liquid, or dense gas produces a continuous spectrum. **Blackbody radiation described by the Planck function and Wien's law.**
- A thin gas in front of a cooler background produces an emission line spectrum. **Downward transition of electron producing a single photon.**
- A thin gas in front of a hot source imprints absorption lines on the spectrum. This is mainly what we see from stars. **Upward transition of electron depending on energy of incident photon.**

Interpreting an Actual Spectrum



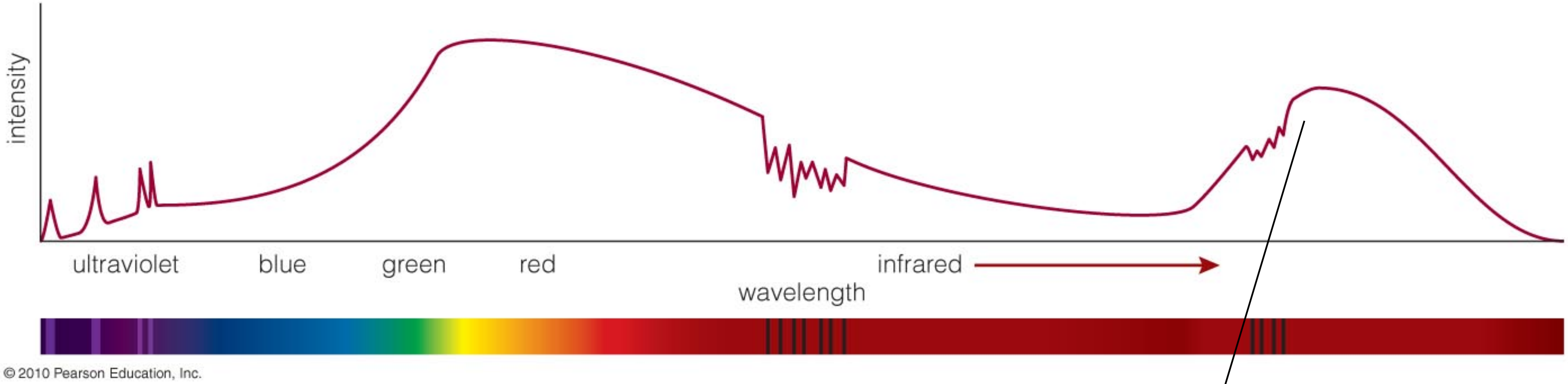
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

Interpreting an Actual Spectrum



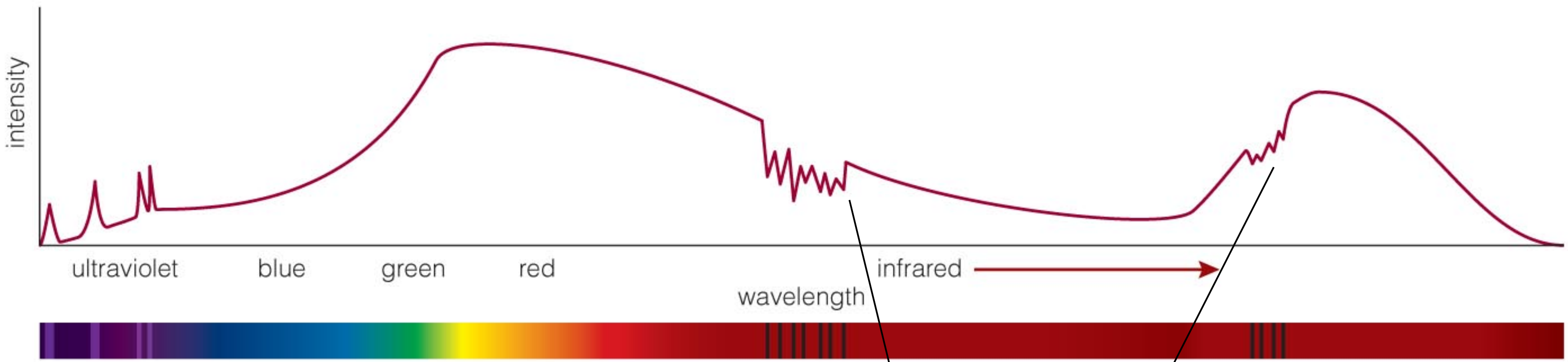
Reflected sunlight: Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed—the object must look red.

Interpreting an Actual Spectrum



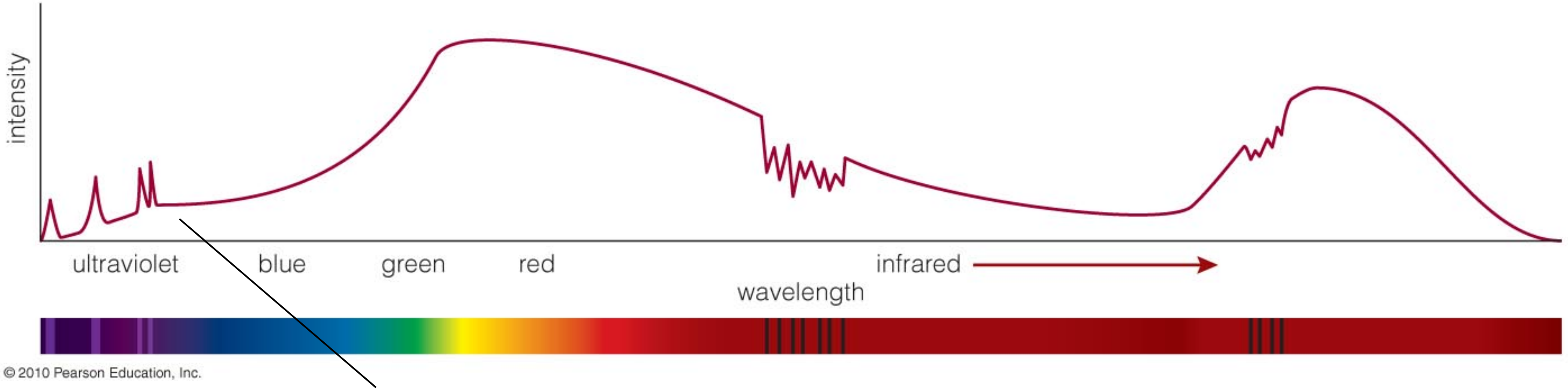
Thermal radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K.

Interpreting an Actual Spectrum



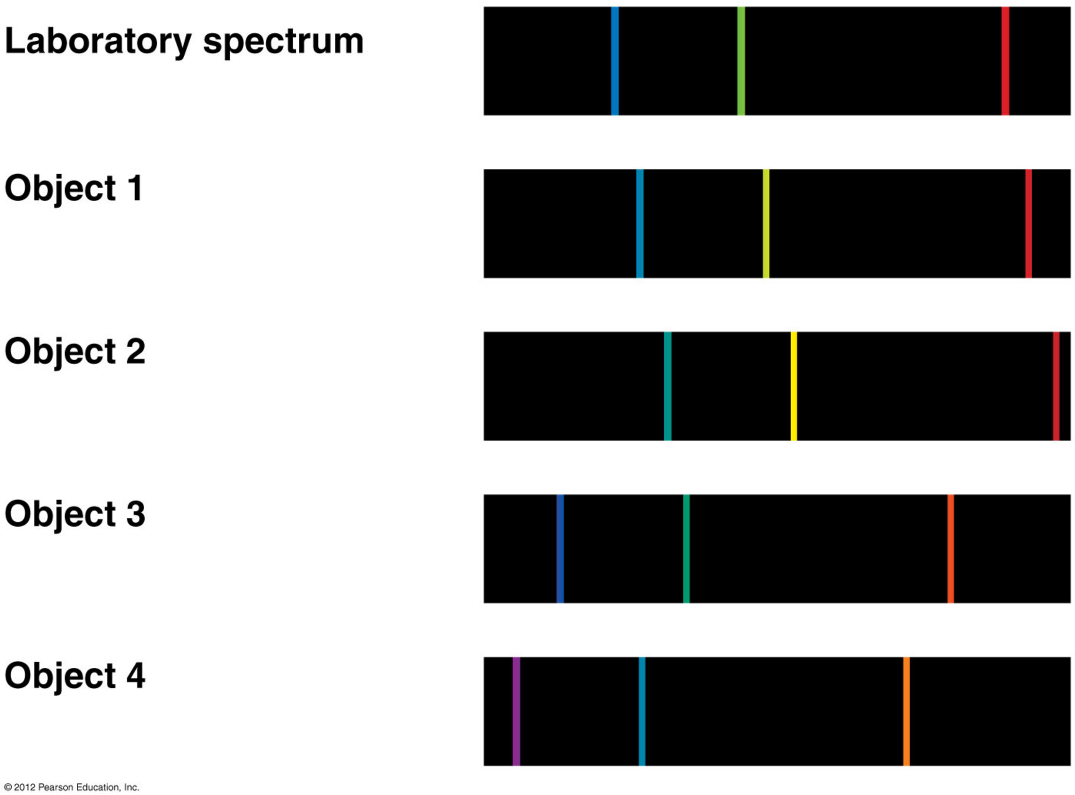
Carbon dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere.

Interpreting an Actual Spectrum



Ultraviolet emission lines:
Indicate a hot upper
atmosphere

Measuring the Shift



Stationary

Moving Away

Away Faster

Moving Toward

Toward Faster

- We generally measure the Doppler effect from shifts in the wavelengths of spectral lines. A **blueshift** means moving towards us. A **redshift** means moving away.

Doppler shift tells us ONLY about the part of an object’s motion toward or away from us.

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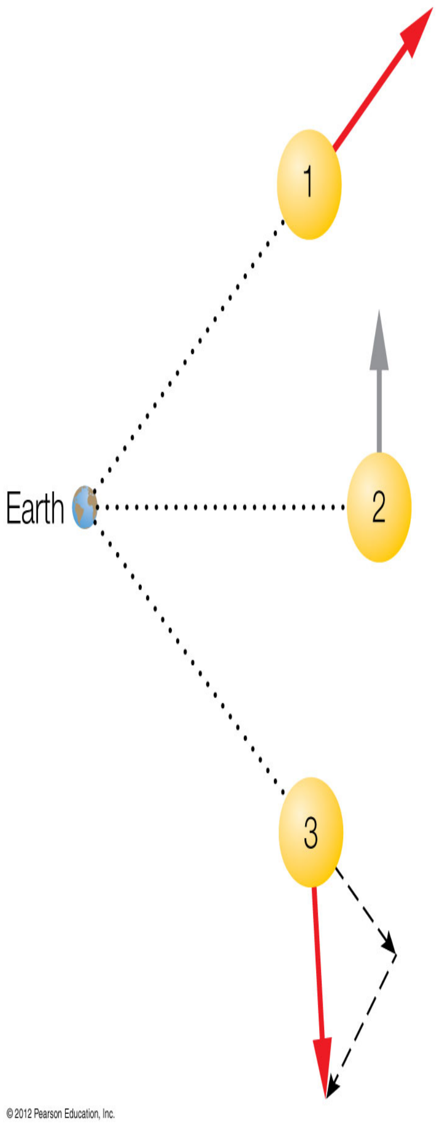


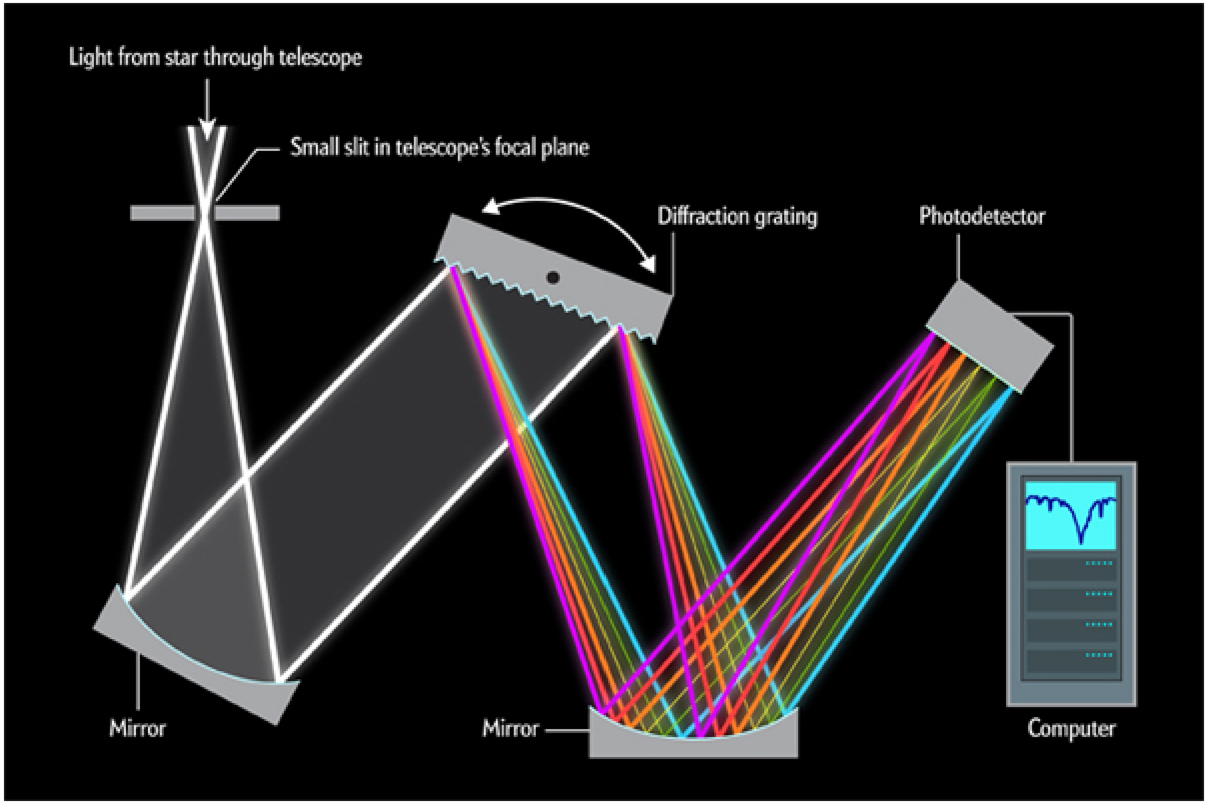
Radial velocity motion

$$\frac{\lambda_{\text{obs}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} = \frac{\Delta\lambda}{\lambda_{\text{rest}}} = \frac{v_r}{c},$$

Transverse (proper) motion

Combined motion

Anatomy of a Spectrograph



- A diffraction grating can consist of a reflection or transmission grating.
- Different wavelengths have their maxima occurring at different angles:

$$d \sin\theta = n\lambda \qquad (n = 0, 1, 2, \ldots),$$

- Resolving power:

$$\Delta\lambda = \frac{\lambda}{nN},$$