

Οπτική Φασματοσκοπία

- Ιστορία – σημασία.
- Πληροφορία.
- Γραμμές εκπομπής – παρατήρηση, θεωρία.
- Αρχές λειτουργίας του φασματογράφου.
- Εξαγωγή τελικού φάσματος με τη χρήση του λογισμικού IRAF.

Astronomical Spectroscopy

I. Spectroscopy in Astronomy

- Spectroscopy: measuring **spectrum**, that is, measuring the **distribution of energy** received from celestial objects.
- Information is used to model the object's **physical properties**, such as temperature and mass, and **chemical properties**, such as abundance and molecules formed.
- **Flux per unit wavelength F_λ** : energy received per unit wave-length by *point source*, e.g. stars (Unit: **ergs/sec/cm²/Å**)
- Definition: $F_\lambda(\lambda) \Delta\lambda =$ Energy of light received between wavelength λ and $\lambda + \Delta\lambda$
- Similarly, **flux per unit frequency F_ν** (Units: **ergs/sec/cm²/Hz**) so that $F_\nu(\nu) \Delta\nu =$ Energy of light received between frequency ν and $\nu + \Delta\nu$ (e.g. Jansky 1 Jy = 10^{-26} erg/sec/m²/Hz)

I. Spectroscopy in astronomy

- Conversion: $F_\lambda = (\nu^2/c) F_\nu$
- The total flux observed for the object F is therefore the integral over all frequencies or wavelengths

$$F = \int F_\lambda d\lambda = \int F_\nu d\nu$$

- A **spectrograph** (**spectrometer**) is a device which separate the incoming radiation into its component wavelengths.
- Common wavelength separator: prism, **diffraction grating**, grism (grating + prism)
- **Spectral resolution R** , defined as $R = \lambda/\Delta\lambda$, where λ is the operating wavelength and $\Delta\lambda$ is the smallest wavelength interval that can be resolved

Some history...

- ✧ In 1857 Gustav Kirchoff, working with Robert Bunsen, discovered that the spectral emission or absorption lines are due to the presence of particular elements.
- ✧ In 1867 helium was discovered in the spectrum of the sun and 30 years later it was isolated in the laboratory.
- ✧ In 1913 the new atomic theory was introduced by Niels Bohr.
- ✧ In the early 1930s the [OIII] doublet was identified

Laws of Spectrum Formation

- In 1860s, Kirchoff summarized the production of spectral lines by matter in three **Kirchoff's laws**:
 1. A hot, dense gas or a hot, solid object produces a continuous spectrum with no dark spectral lines (**black-body spectrum**)
 2. A hot, diffuse gas produces bright spectral lines (**emission lines**)
 3. A cold, diffuse gas in front of a source of continuous spectrum produces dark spectral lines (**absorption lines**) in the continuous spectrum.
- * Another statement of Kirchoff's law: The ratio between the powers of emission and the powers of absorption for rays of the same wavelength is constant for all bodies at the same temperature.

II. Spectral lines and atoms

- Every atom, ion, and molecule has a unique spectroscopic signature which depends on the **electron orbital structure**.
- Atoms in distant universe behave the same way as those on Earth! Therefore, we can understand the physics of celestial objects by understanding atoms in the laboratory.
- From quantum mechanics, we know that in atoms, **energy levels are quantized**.
- When electrons move from *high to low energy level*, we have **photon emission**. In contrary, a photon can excite an electron in an atom to move from *low to high energy level*, and there will be **photon absorption**.
- **Ionization** is the process when an electron is removed from an energy level in the atom (**bound**), into a **free state** (continuum).

II. Spectral lines and atoms

- Example: Hydrogen atom

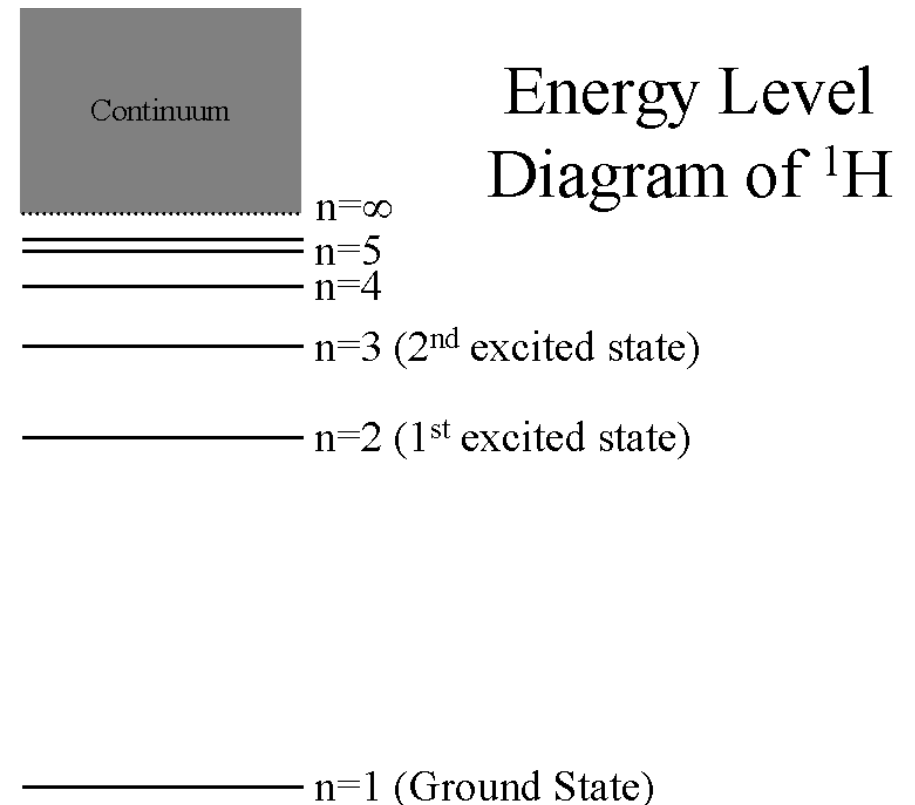
$$E_n = -\mu e^4 / 2\hbar n^2 = -13.6 \text{ eV} / n^2$$

where n = principle quantum number

- **Ground state:** $n = 1$
- **Excited states:** $n = 2, 3, \dots$
- Transition of an electron from the m^{th} to n^{th} energy level will result in a photon of wavelength:

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

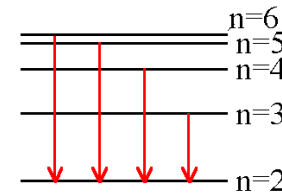
where R_H = Rydberg constant = $1.10 \times 10^7 \text{ m}^{-1}$



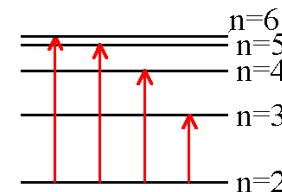
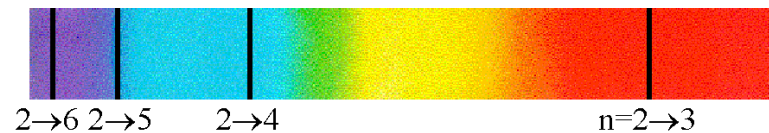
© Professor Richard W. Pogue, Ohio State University

II. Spectral lines and atoms

- **Emission lines:** When an electron jumps from a higher to a lower energy level, a single photon is emitted with exactly the energy difference between the levels.
- **Absorption lines:** When a photon excites an electron to jump from a lower to higher energy level, thus absorbing the photon in the process.

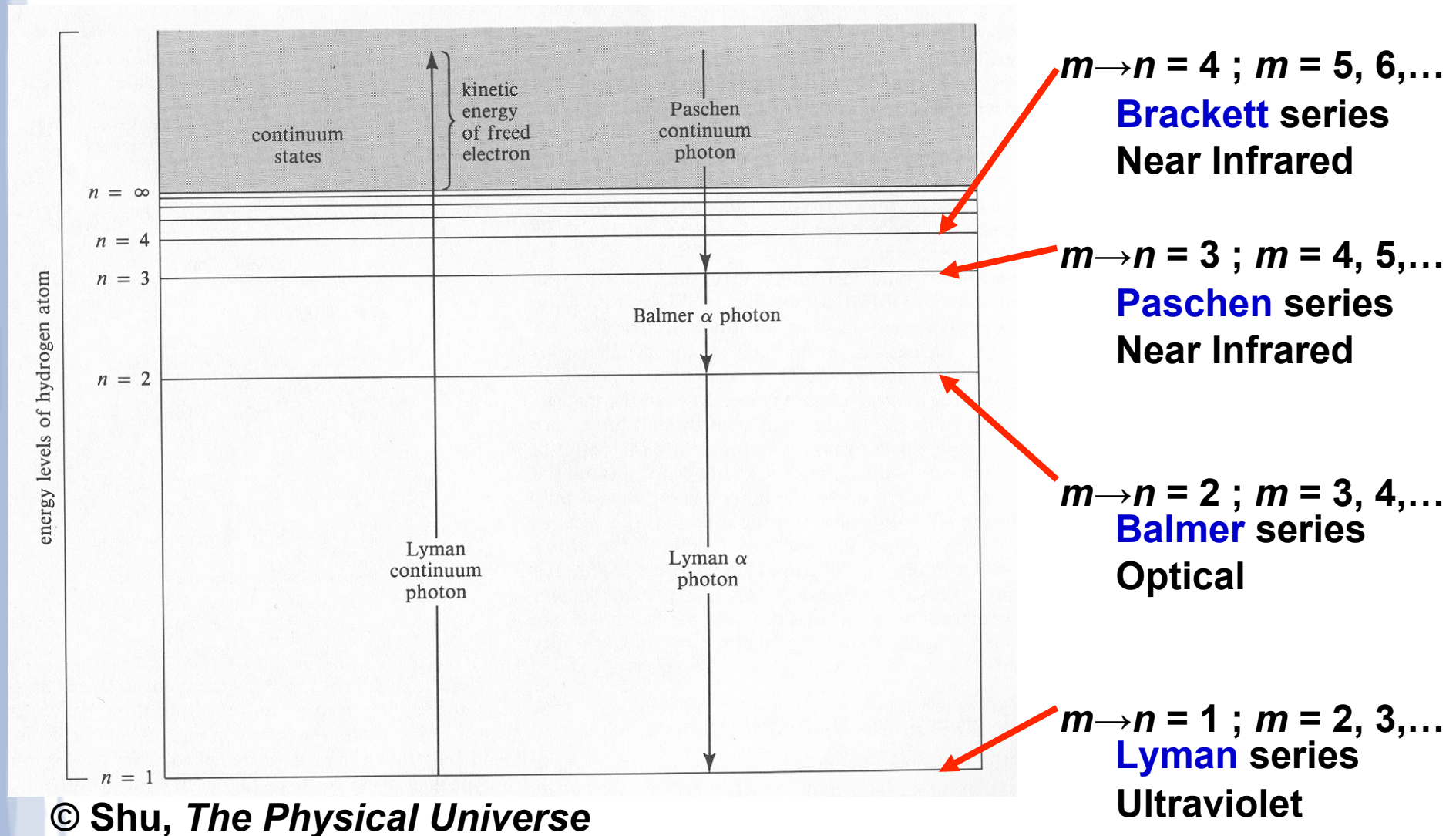


————— n=1 (Ground State)



————— n=1 (Ground State)

II. Spectral lines and atoms

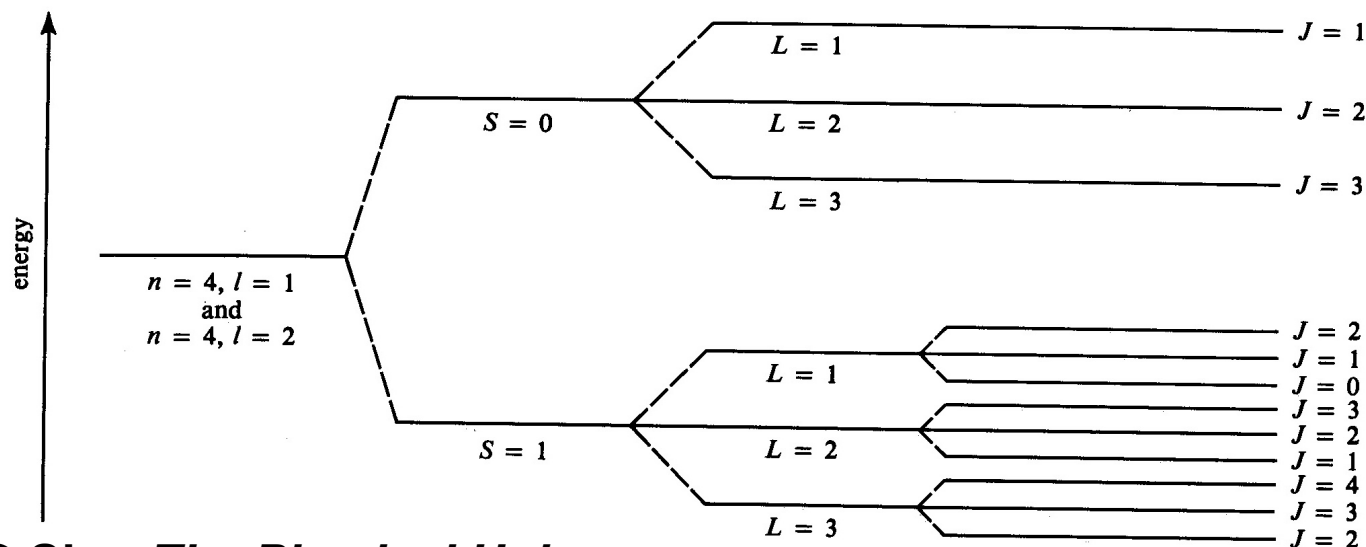


II. Spectral lines and atoms

- For Hydrogen atoms or Hydrogen-like ions (i.e. ions with one electron left), emission line is identified with its series, e.g. Lyman series $\lambda_{2 \rightarrow 1} = 1216 \text{ \AA}$ Lyman α , or Ly α
 $\lambda_{3 \rightarrow 1} = 1026 \text{ \AA}$ Lyman β , or Ly β
 $\lambda_{4 \rightarrow 1} = 972 \text{ \AA}$ Lyman γ , or Ly γ
 $\lambda_{\infty \rightarrow 1} = 912 \text{ \AA}$ Lyman continuum
- Balmer series is the only series of Hydrogen emission line observed in the optical. Therefore, $\lambda_{3 \rightarrow 2}$ Balmer α 6563Å is also called **Hydrogen α , or H α** , $\lambda_{4 \rightarrow 2}$ 4861Å is **H β** , etc.
- For all other emission lines, they are identified by the species and its wavelength, e.g. neutral Oxygen O^0 is **O I**, singly ionized Oxygen O^+ is **O II**, O^{2+} is **O III**, etc. E.g. 5577Å emission line of neutron Oxygen is **O I λ 5577Å**

II. Spectral lines and atoms

- Other than the principle quantum number n , there are also orbital angular momentum l and spin angular momentum s .
 - Quantum mechanics: Spin-Orbit LS -coupling ($J=S+L$)
- However, not all transitions possible between every energy level. They have to satisfy a set of **transition rules**.
- Transitions satisfying the rules: **allowed transitions**, e.g. O I λ 5577Å;
 NOT satisfying the rules : **forbidden transitions**, e.g. [O III] λ 5007Å
 (Note the brackets around the species)



II. Spectral lines and atoms

H (1)

The image shows the emission spectrum of hydrogen. It consists of a dark background with a few distinct, bright vertical lines. The most prominent lines are in the visible range, appearing as a violet line, a blue-violet line, a green line, and a red line. There are also some faint lines in the ultraviolet and infrared regions.

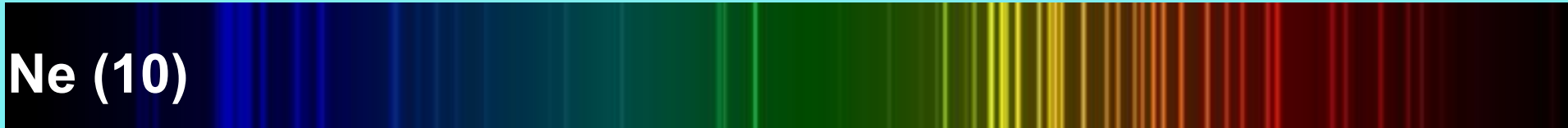
He (2)

The image shows the emission spectrum of helium. It features a dense set of vertical lines across the visible spectrum. The lines are more numerous and closely spaced than those of hydrogen. The colors range from violet to red, with a prominent yellow-green line in the middle.

O (8)

The image shows the emission spectrum of oxygen. It displays a complex pattern of vertical lines, with a particularly dense region in the blue and green parts of the spectrum. The lines are more numerous and varied in intensity compared to the simpler spectra of hydrogen and helium.

Ne (10)

The image shows the emission spectrum of neon. It is characterized by a very dense and complex set of vertical lines, especially in the yellow and orange regions. The lines are numerous and closely packed, creating a rich, multi-colored appearance.

Fe (26)

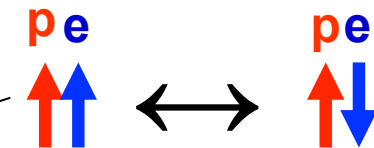
The image shows the emission spectrum of iron. It is the most complex and dense of the spectra shown, with a vast number of vertical lines across the entire visible spectrum. The lines are very closely spaced and vary significantly in intensity, creating a highly detailed and multi-colored pattern.

II. Spectral lines and atoms

Transitions of electrons between different energy levels of atoms or ions is not the only physical process producing spectral lines.

Table 5.1. Examples of discrete transitions

Transition	Energy [eV]	Spectral Region	Example
Hyperfine structure	10^{-5}	Radiofrequencies	21 cm hydrogen line
Spin-orbit coupling	10^{-5}	Radiofrequencies	1 667 MHz transitions of OH molecule
Molecular rotation	10^{-2} – 10^{-4}	Millimetre and infrared	1–0 transition of CO molecule at 2.6 mm
Molecular rotation-vibration	1 – 10^{-1}	Infrared	H ₂ lines near 2 μ m
Atomic fine structure	1 – 10^{-3}	Infrared	Ne II line at 12.8 μ m
Electronic transitions of atoms, molecules and ions	10^{-2} – 10	Ultraviolet, visible, infrared	Lyman, Balmer series, etc. of H; resonance lines of C I, He I; K, L shell electron lines (Fe XV, O VI)
Nuclear transitions	$> 10^4$	X- and γ -rays	¹² C line at 15.11 keV
Annihilations	$\gtrsim 10^4$	γ -rays	Positronium line at 511 keV



IV. Spectrometer (Spectrograph)

Components of a Spectrograph:

- 1. Entrance Aperture:** By using a slit, we usually allow an entrance aperture of size smaller than that of the seeing disk
- 2. Collimator:** Makes light to have same angle of incidence on the dispersing element
- 3. Dispersing Element:** Separate light to different wavelengths, e.g. prism, diffraction grating
- 4. Spectrum Imager:** Focuses spectrum on the recorder
- 5. Image Recorder:** CCD, photographic plate, etc.

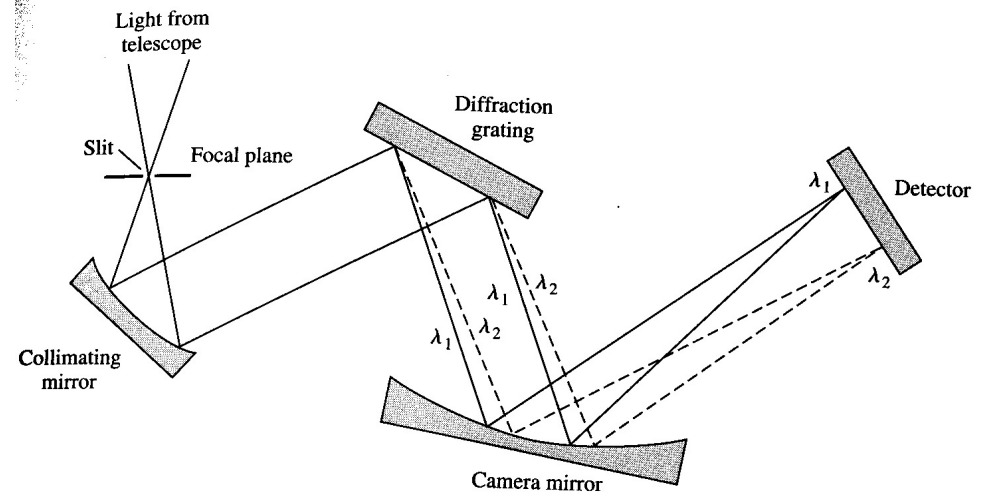
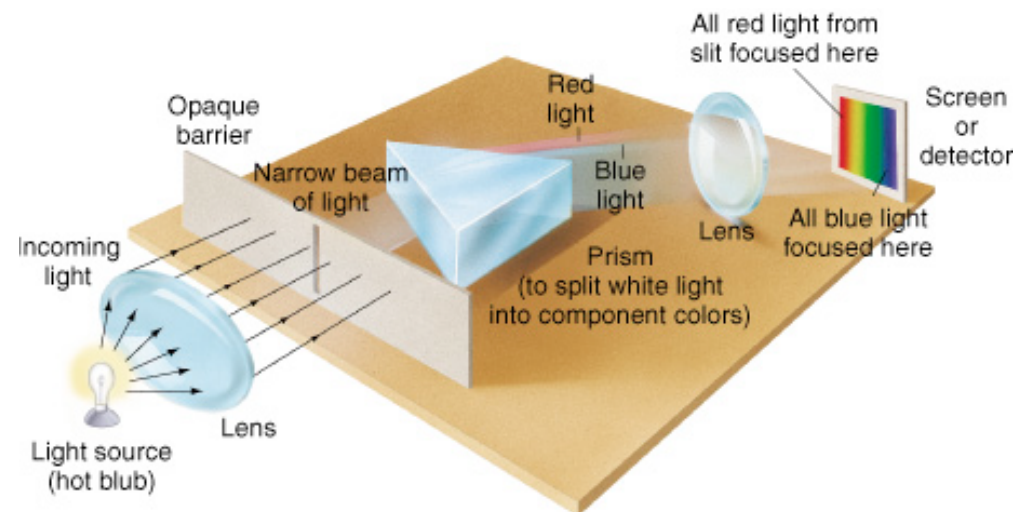
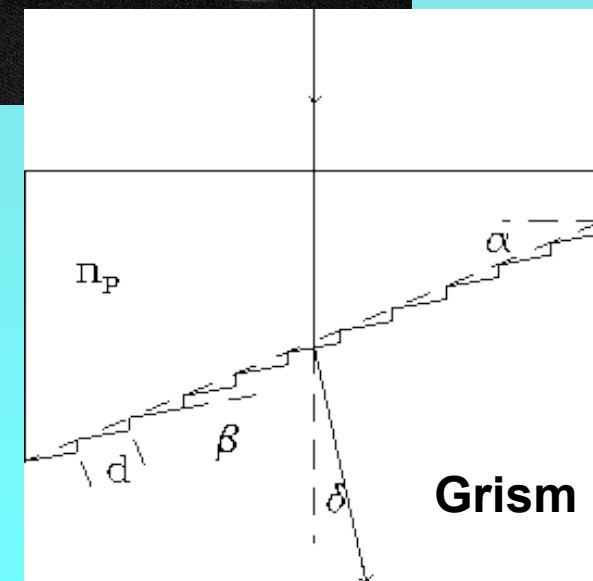


Figure 5.2 Spectrograph



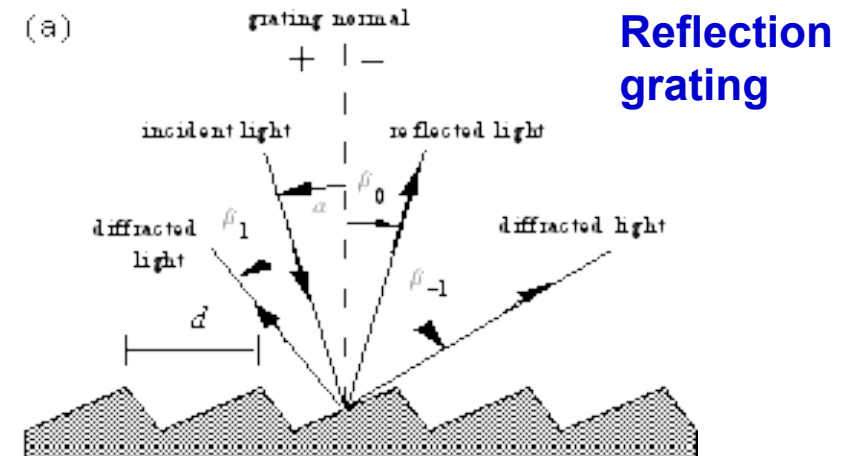
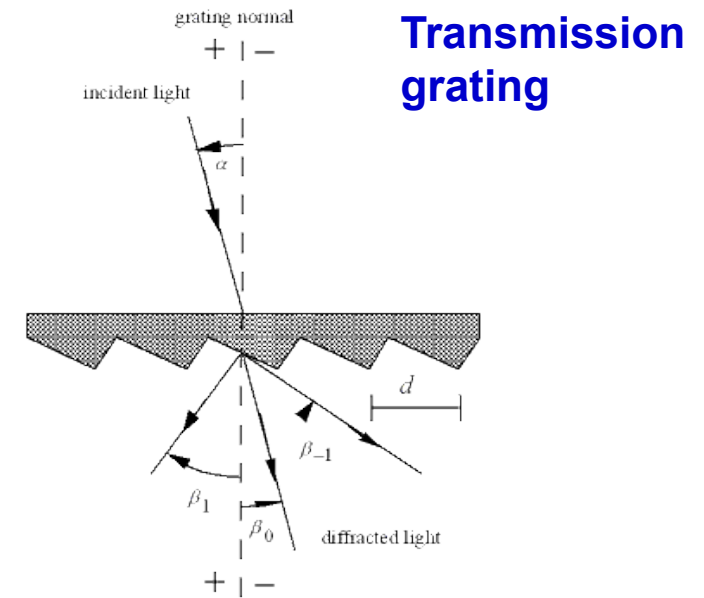
IV. Spectrometer (Spectrograph)

- The most important element of a spectrograph is the dispersing element.
- **Prism**: Based on the different refractive index of glass for different wavelength
- **Objective Prism**: Placed prism near objective lens (no slit), then each image is a spectrum (used in surveys)
- **Grism**: A prism mounted with a transmission diffraction grating. Used for near-IR spectroscopy ($R \sim 500$)



Diffraction Grating

- A diffraction grating is a collection of **equally spaced reflecting or transmitting elements** separated by a distance comparable to the light's wavelength.
- **Advantages:** High throughput, high resolution achieved.
- A **transmission grating** consists of grating superimposed on a transparent surface.
- A **reflection grating** consists of grating superimposed on a reflective surface (most commonly used dispersion element for modern astronomy)
- Incident light will be diffracted and the transmitted light or the reflected light will show **maxima or minima** because of **constructive or destructive interference**.



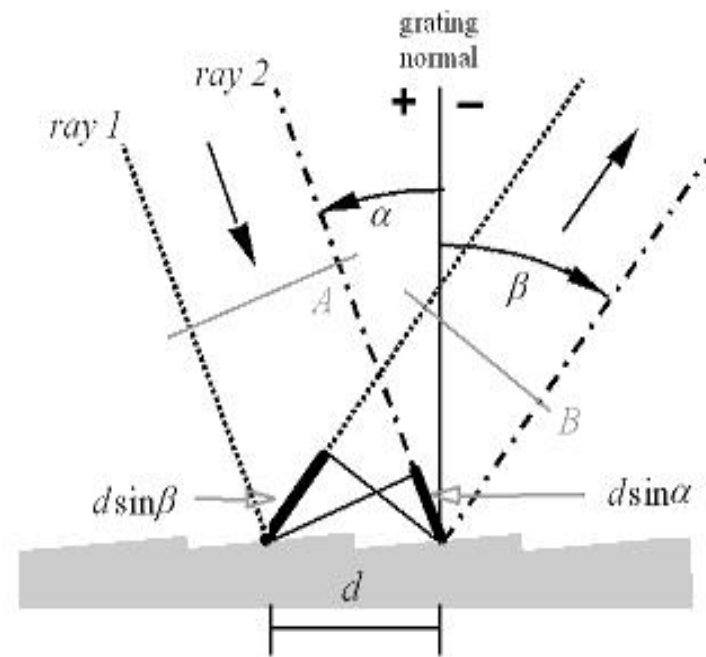
C. Palmer , *Diffraction Grating Handbook*

History of diffraction grating

- ★ The first diffraction grating was made by an American astronomer, David Rittenhouse, in 1785, who reported constructing a half-inch wide grating with fifty-three apertures. He developed this prototype no further, and there is no evidence that he tried to use it for serious scientific experiments.
- ★ In 1821 Joseph von Fraunhofer began his work on diffraction gratings. Fraunhofer's persistence resulted in gratings of sufficient quality to enable him to measure the absorption lines of the solar spectrum, now generally referred to as the Fraunhofer lines. He also derived the equations that govern the dispersive behavior of gratings. Fraunhofer was interested only in making gratings for his own experiments, and upon his death, his equipment disappeared.
- ★ By 1850, F.A. Nobert, a Prussian instrument maker, began to supply scientists with gratings superior to Fraunhofer's.
- ★ About 1870 L.M. Rutherfurd, a New York lawyer with an avid interest in astronomy, became interested in gratings. Rutherfurd developed gratings that surpassed even the most powerful prisms. He made very few gratings, though, and their uses were limited.
- ★ Tremendous strides however were made by H.A. Rowland, professor of physics at the Johns Hopkins University. Rowland's work established the grating as the primary optical element of spectroscopic technology. He continued to rule gratings until his death in 1901.

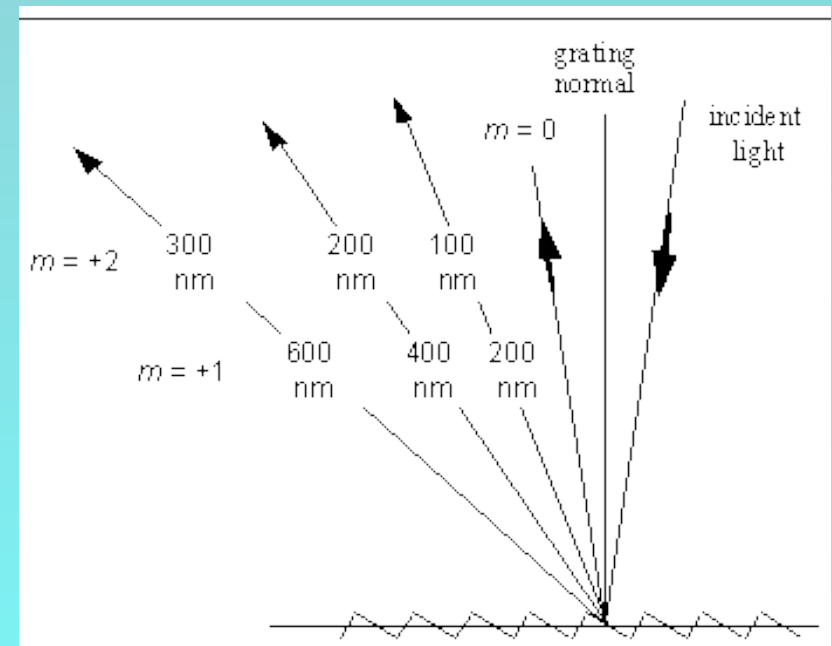
V. Diffraction Grating

- Consider a pair of apertures for a transmission grating (principle the same for reflection grating) with incident angle α and diffracted angle β , for light of wavelength λ , we get **constructive interference** if optical path difference is an integer multiple λ . **Grating Equation:** $d (\sin\alpha + \sin\beta) = m\lambda$, where $m = 0, \pm 1, \pm 2, \dots$, m_{max} is called the **order of interference**.
- *Maxima for different wavelengths appear at different angles θ .*
- m_{max} is determined by $m_{max}\lambda/d < 2$
- If $m=0$, then $\beta = -\alpha$



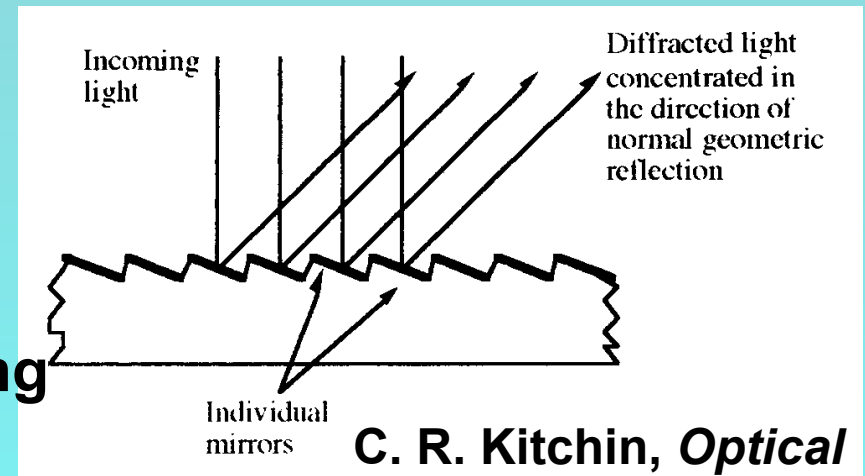
V. Diffraction Grating

- Disadvantage: **Overlap of spectrum of different orders**, i.e. if light of wavelength λ is diffracted in order m , then light of wavelength $\lambda/2$ will be diffracted in order $2m$.
- Solution: 1. Use detectors sensitive at desired wavelengths; 2. Use filters to block out some wavelengths
- **Spectral resolving power (resolution) of a diffraction grating:**
 $R = \lambda/\Delta\lambda = mN$
- Typical N for a grating: $\sim 20,000$;
Typical m used: 1, 2, *occasionally* 3
- **Spectral range** for m order: $D = \lambda/m$



Blazing of Reflection Grating

- A major problem of using grating to produce spectra is that incoming light is split into many orders, thus spectrum formed from a single order will contain less than 10% of incoming light.
- “**Blazing**” the grating: Tilt the diffraction elements so that the direction of normal geometric reflection coincides with the chosen order of diffraction
- Can concentrate ~90% of incoming light into the chosen spectrum
- Most gratings used are reflection gratings because 1. they are **easier to produce** than transmission grating; 2. they are **easier to blaze**.



Angular dispersion

The angular spread D of a spectrum of order m between the wavelength λ and $\lambda + \delta\lambda$ can be obtained by differentiating the grating equation, assuming the incidence angle α to be constant. The change D in diffraction angle per unit wavelength is therefore

$$D = d\beta/d\lambda = m/d\cos\beta$$

The quantity D is called the angular dispersion.

The quantity m/d can NOT be chosen independently of other parameters.

$$D = (\sin\alpha + \sin\beta) / (\lambda\cos\beta)$$

Considering the Littrow configuration ($\alpha = \beta$), in which case reduces to

$$D = 2\tan\beta/\lambda$$

When $|\beta|$ increases from 10° to 63° , the angular dispersion increases by a factor of ten, regardless of the spectral order or wavelength under consideration. Once the diffraction angle β has been determined, the choice must be made whether a fine-pitch grating (small d) should be used in a low diffraction order, or a coarse-pitch grating (large d) such as an echelle grating should be used in a high order.

The fine-pitched grating, though, will provide a larger free spectral range

FREE SPECTRAL RANGE

The range of wavelengths in a given spectral order for which superposition of light from adjacent orders does not occur is called the free spectral range $F\lambda$. It can be calculated directly from its definition: in order m , the wavelength of light that diffracts along the direction of I in order $m+1$ is $I + D|$, where

$$M\lambda = d(\sin\alpha + \sin\beta)$$

$$\lambda + \delta\lambda = \lambda * (m+1)/m$$

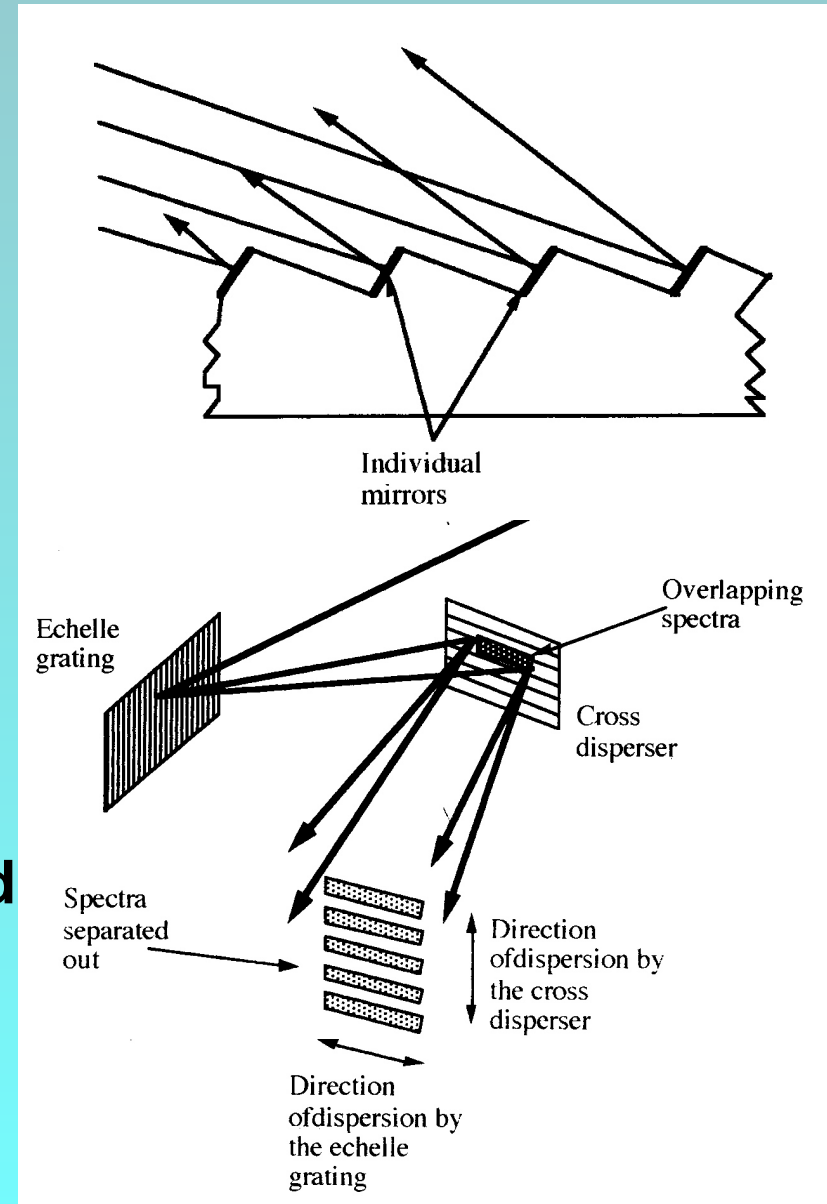
from which

$$F\lambda = \delta\lambda = \lambda/m$$

The concept of free spectral range applies to all gratings capable of operation in more than one diffraction order, but it is particularly important in the case of echelles, because they operate in high orders with correspondingly short free spectral ranges.

Echelle Grating

- To increase spectral resolution R of spectrum, we can increase N (limited by grating production) or increase m (echelle grating)
- To use higher m , need large (close to 90°) α and β in grating equation.
- $R \sim 200,000$ for an echelle grating
- However, spectral range for each order is very small and there will be severe overlapping of orders.
- Need to be separated by a second disperser (Cross Disperser) acting perpendicular to the echelle grating dispersion direction.



VI. Doppler Effect

- Wavelength of waves approaching or leaving us will change due to the Doppler effect

- For sound:

$$\lambda_{obs} = \lambda_{source} \left(\frac{v \pm v_s}{v \mp v_o} \right)$$

- For light:

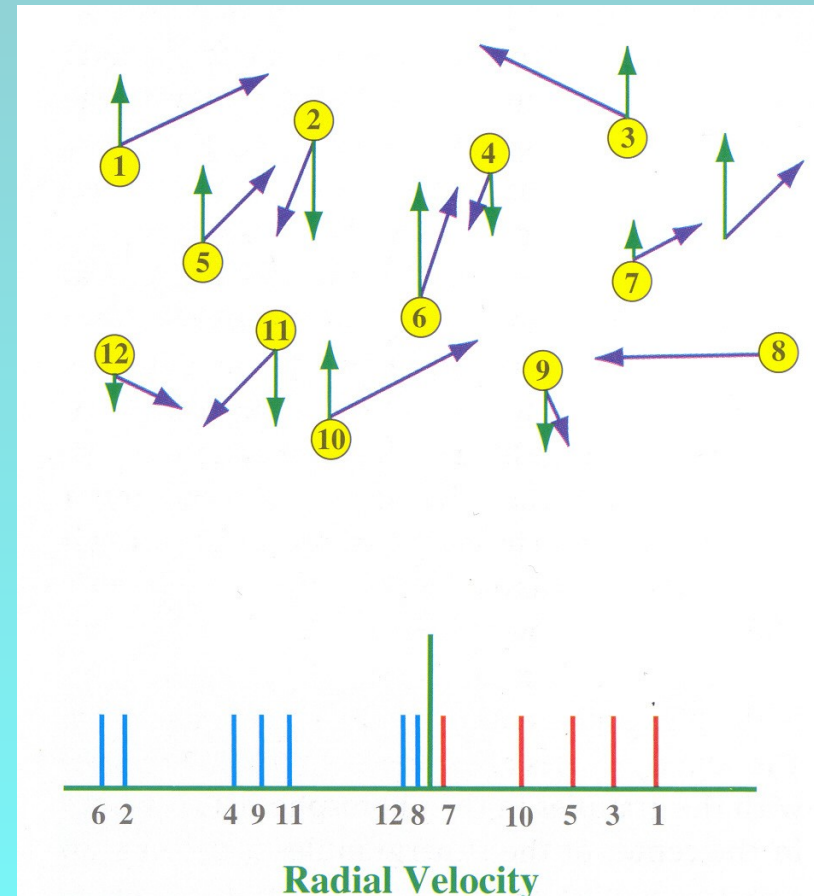
$$\lambda_{obs} = \lambda_{source} \left(\frac{1 + v/c}{1 - v/c} \right)^{1/2}$$

where $v > 0$ if the object is moving away from us

- For $v \ll c$, $\lambda_{obs} = \lambda_{source} (1 + v/c)$
- Since the universe is expanding, for almost all astronomical objects, $\lambda_{obs} > \lambda_{source}$. Therefore, light will shift to the **red** end of spectrum (**cosmological redshift, $z = \lambda_{obs}/\lambda_{source} - 1$**)

VII Doppler Broadening

- We can study the **line profiles** in data with high spectral resolution.
- Photons from the same transition should have the same wavelength.
- However, random motions of gas and ions in a gas can lead to different doppler effects observed.
- **Doppler broadening:** Broadening of emission/absorption lines due to thermal motions.



M.L. Kutner, *Astronomy: A Physical Perspective*

Estimation of Doppler Broadening

- For an ideal gas at temperature T , thermal energy = $3/2kT$, where $k = 1.38 \times 10^{-16}$ erg/K (Boltzmann constant)

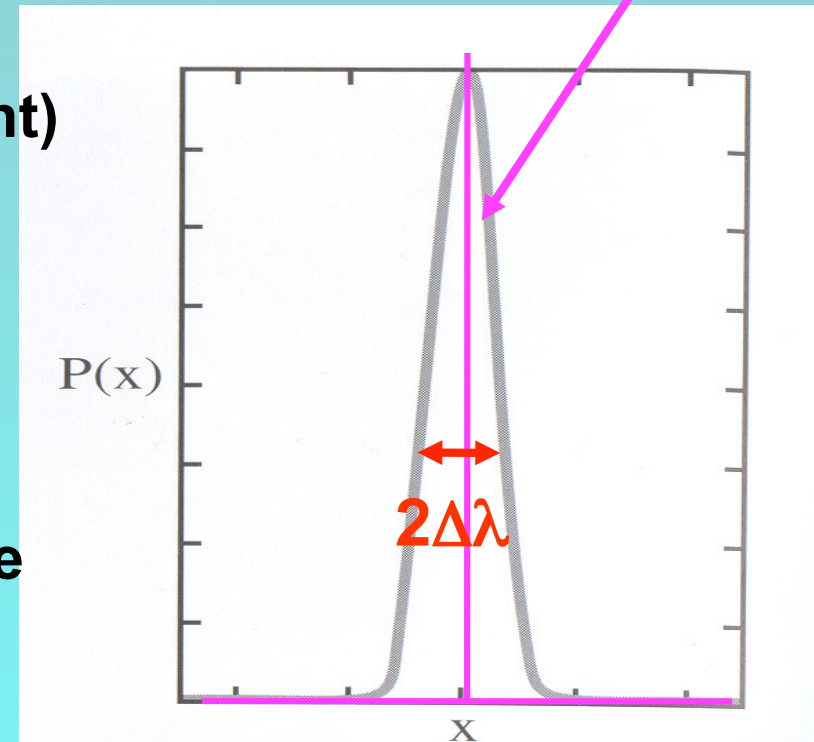
$$1/2 m v_{rms}^2 = 3/2 kT$$

$$\Rightarrow v_{rms} = \sqrt{3kT/m}$$

- Line broadening: $\Delta\lambda/\lambda = v_{rms}/c$.
- Actual line broadening observed is **smaller** than our estimation because only radial velocity component is observed.
- Actual broadening:

$$\Delta\lambda/\lambda = \sqrt{2 \ln 2} kT/mc^2$$

No broadening



M.L. Kutner, *Astronomy: A Physical Perspective*

VIII CCD Spectroscopy

Steps for doing astronomical spectroscopy with CCD data:

1. Center the object within slit and take spectrum.
2. Reduce CCD frames with bias, dark, and flat (cf. Chapter 4)
3. Extract spectrum of object
4. Take a spectrum of the **standard lamp for wavelength calibration**
5. Correct for **Earth's atmospheric extinction and interstellar extinction** (cf. Chapter 5)
6. Flux calibration with standard stars
7. Remove sky lines.