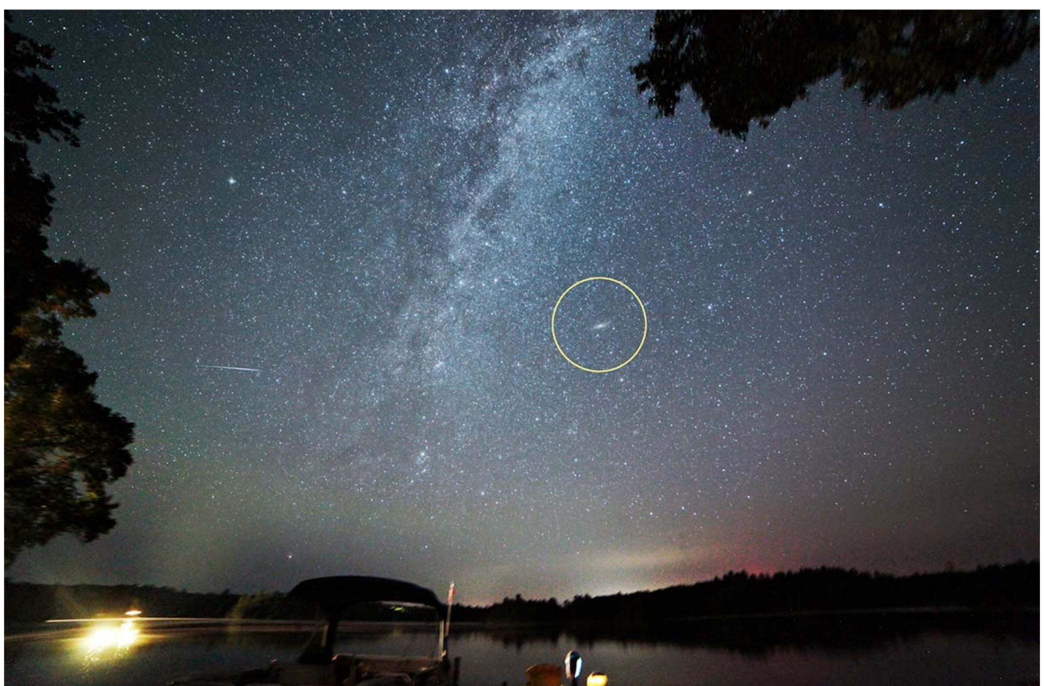
$$l = \theta d = \frac{3 \times 3600}{206265} \times 0.78 \times 10^{6} \times 3.1 \times 10^{16}$$

$$= 1.2 \times 10^{21} \text{ m}$$

$$= \frac{1.2 \times 10^{21}}{3.1 \times 10^{16}} = 4.1 \times 10^{4} \text{ pc} = 41 \text{ kpc}$$



https://astrobackyard.com/andromeda-galaxy/

Interstellar Gas

- Interstellar Medium
- Ionized gas
- Atomic gas
- Molecular gas

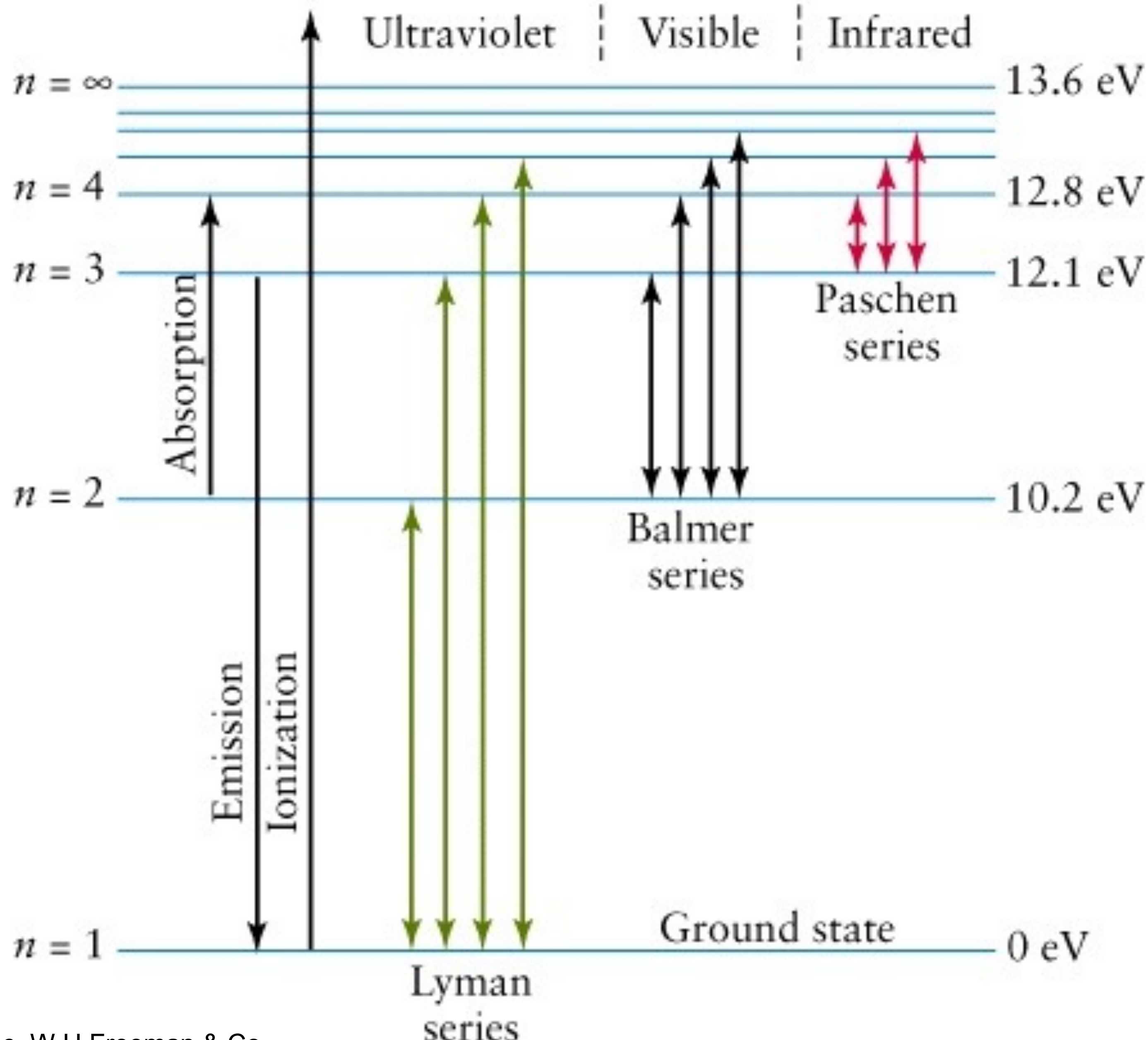
Interstellar Medium

- The space between stars in spiral and irregular galaxies is not empty but contains gas and dust at very low density
- A typical average number density is about 10^6 m^{-3} or 1 particle per cubic centimetre
- However, the interstellar gas exists in a vast range of temperatures and densities

Gemini Observatory

Ionized Gas

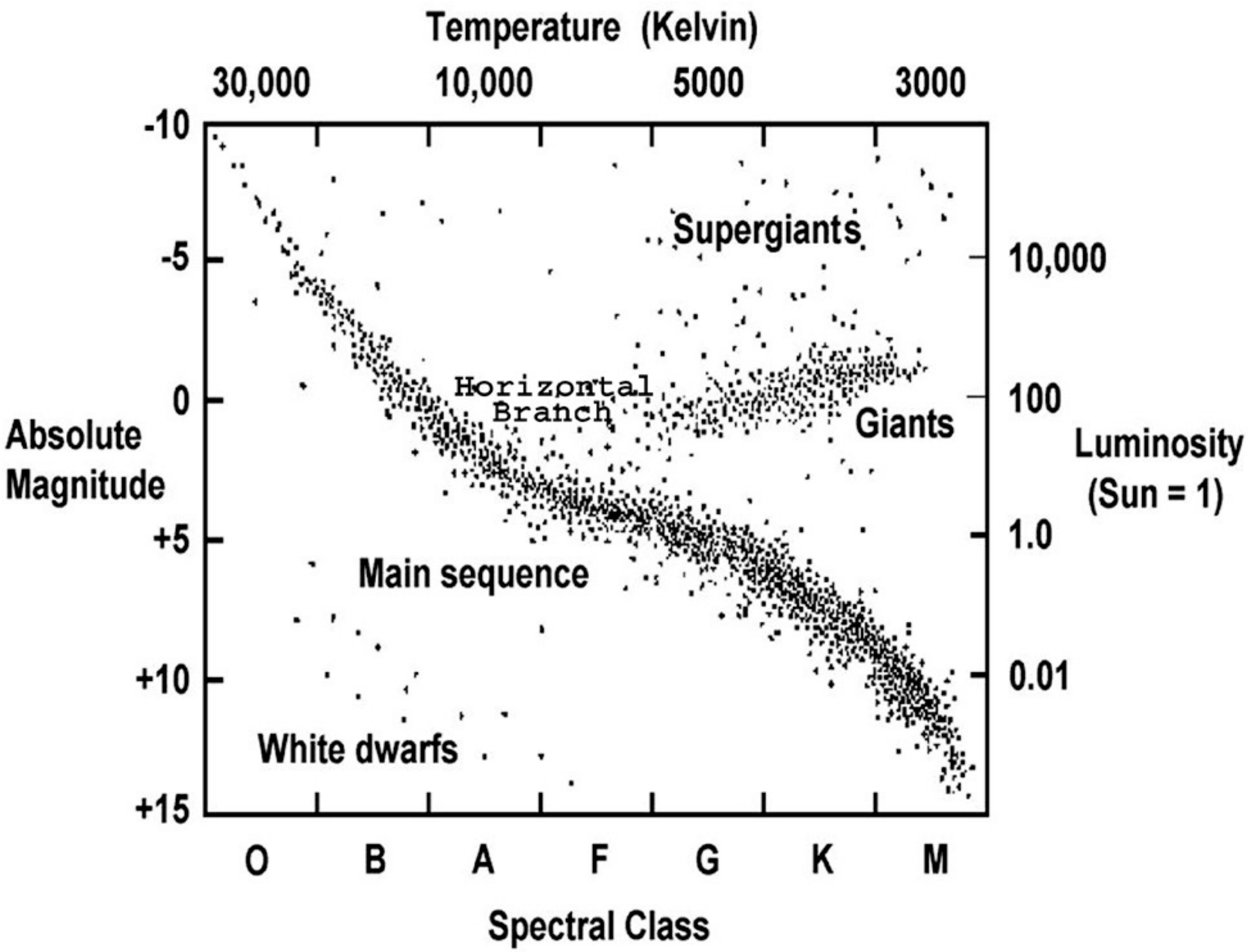
- When interstellar gas exists near hot stars it becomes ionized
- Hydrogen (by far the most abundant element) is ionized by photons with energy > 13.6 eV or with a wavelength shorter than 91.2 nm (far ultra-violet)


Ultraviolet
Visible
Infrared
n = ∞
13.6 eV
n = 4
12.8 eV
n = 3
12.1 eV
Paschen
series
Absorption
n = 2
10.2 eV
Balmer
series
Emission
Ionization
Ground state
n = 1
0 eV
Lyman
series

Class example

- What temperature star would emit most of its photons at 91.2 nm?

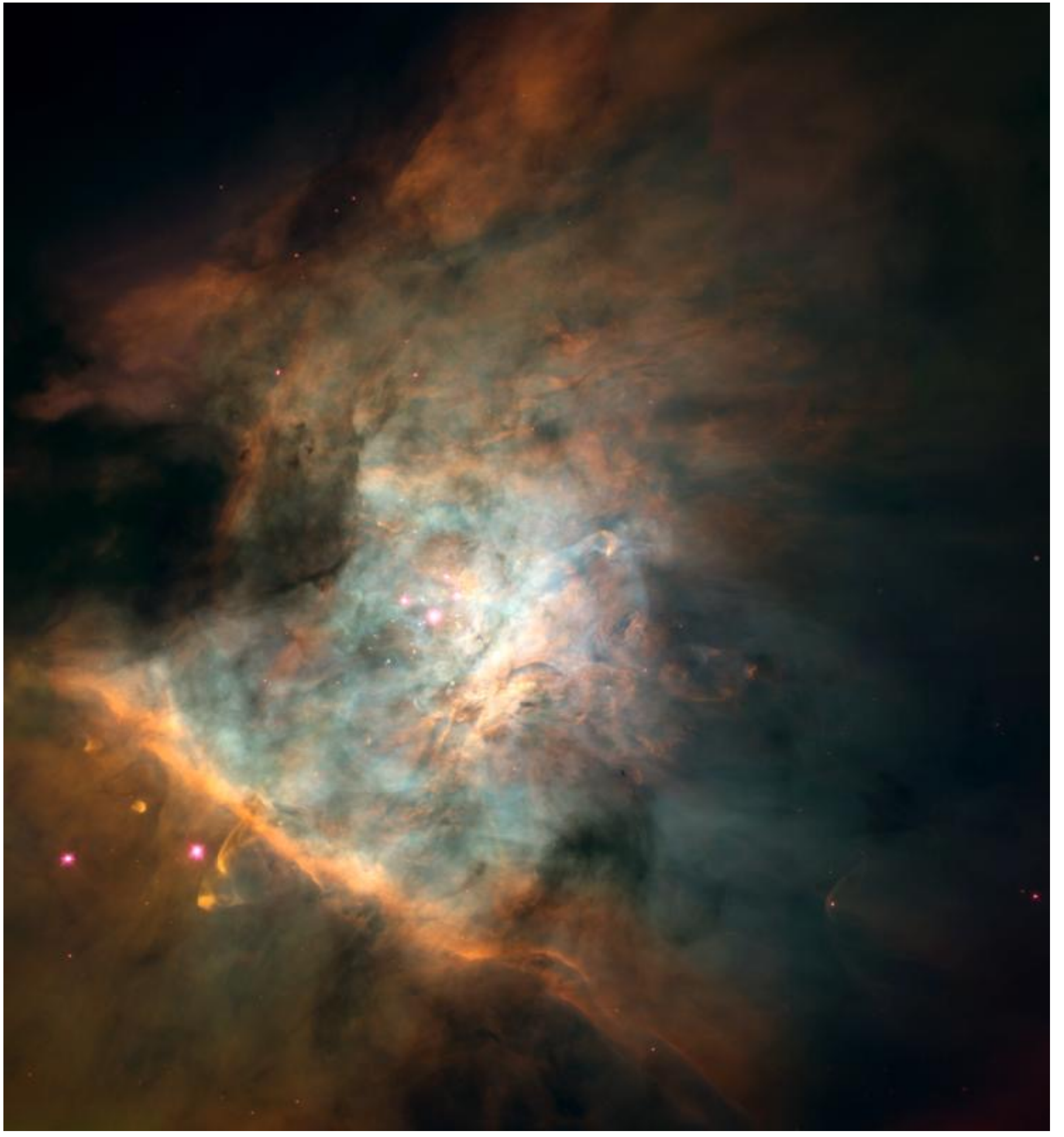
$$T = \frac{3\times10^{-3}}{91.2\times10^{-9}} = 33\,000\ \mathrm{K}$$



https://chandra.harvard.edu/edu/formal/variable_stars/bg_info.html

H II Regions

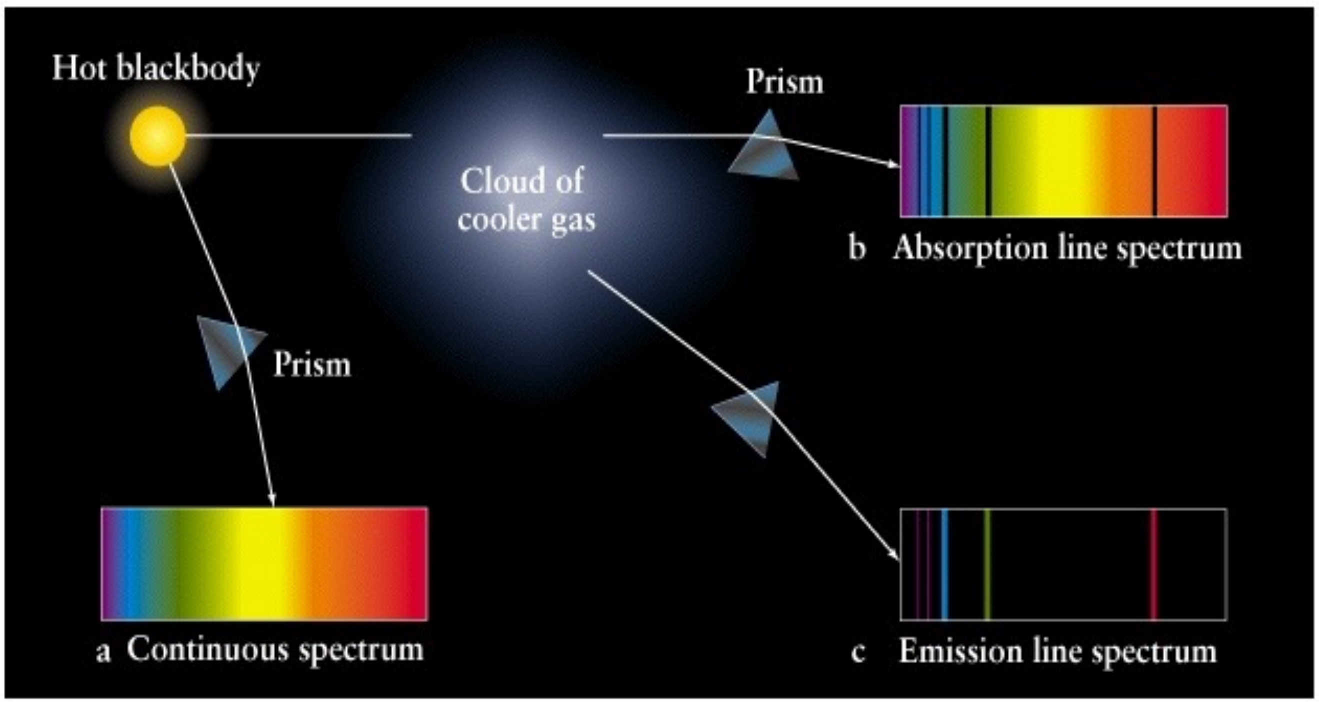
- Massive main sequence stars have T>30 000 K
- Young stars are also still surrounded by dense (10^{10} m^{-3}) gas
- gives rise to ionized nebulae called H II regions
- The gas is hot T~ 10 000 K and fluoresces



Credit: NASA and C.R. O'Dell (Vanderbilt University): HST (Optical)

Emission Line Spectrum

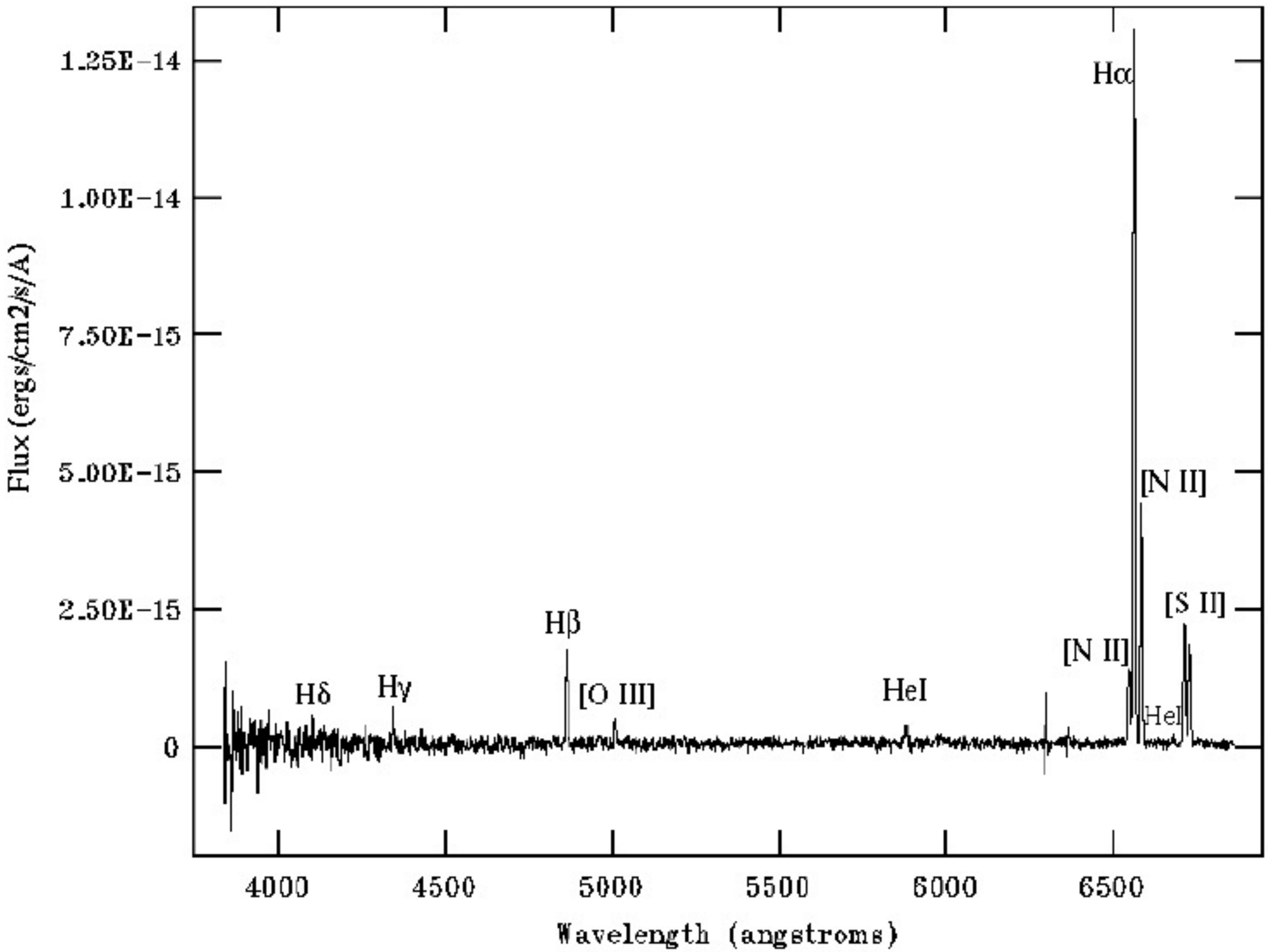
- Arise when hot gas is viewed against a colder background



From Universe Textbook

- Optical spectrum is made up of emission lines
- The strongest being the Hα line
- These result from the recombination of an electron and a proton following photo-ionization

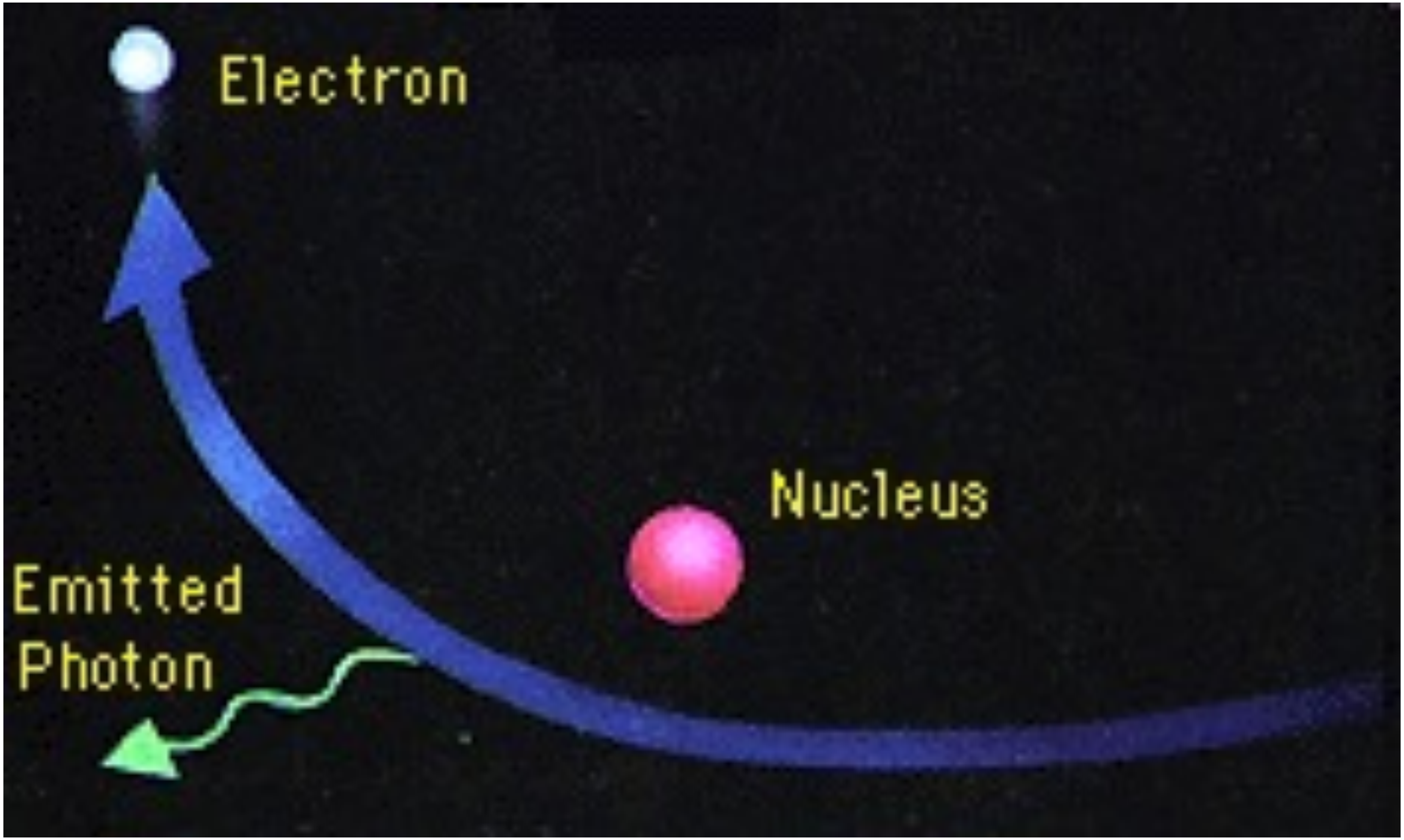
$$\mathrm{H} + h\nu \longleftrightarrow p + e$$



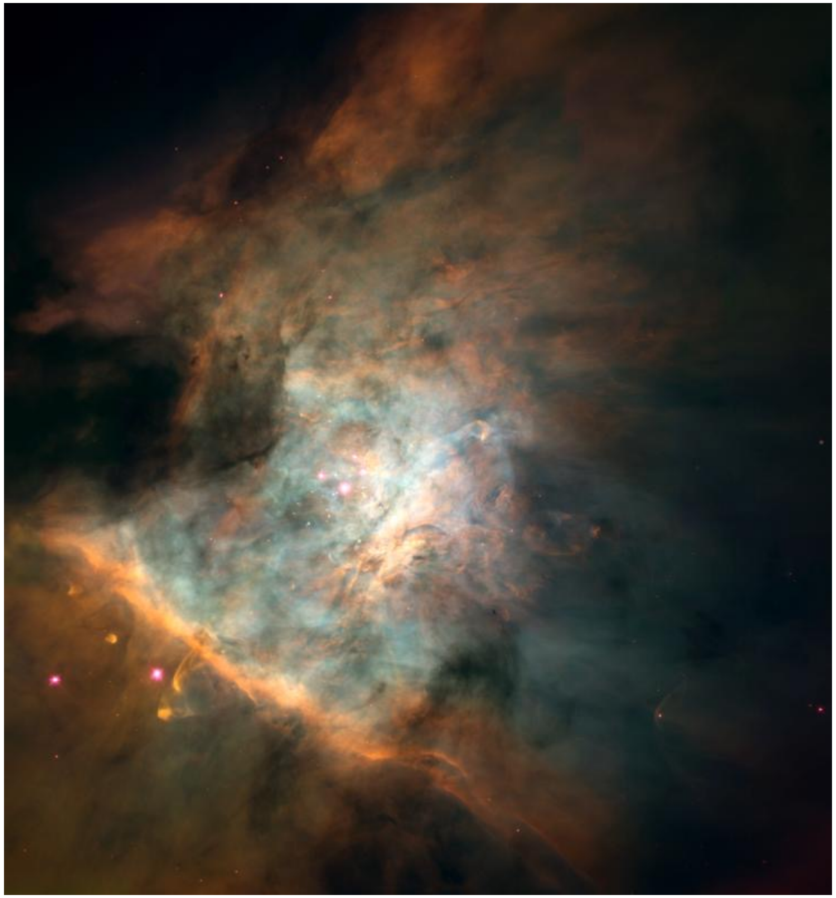
H II Region optical spectrum. S. Temporin & R. Weinberger, A&A 420, 225 (2004), Copyright ESO.

Radio Emission

- H II regions also emit strong radio continuum emission
- Occurs when free electrons are accelerated by ions
- This is called thermal bremsstrahlung
- Strong at cm wavelengths

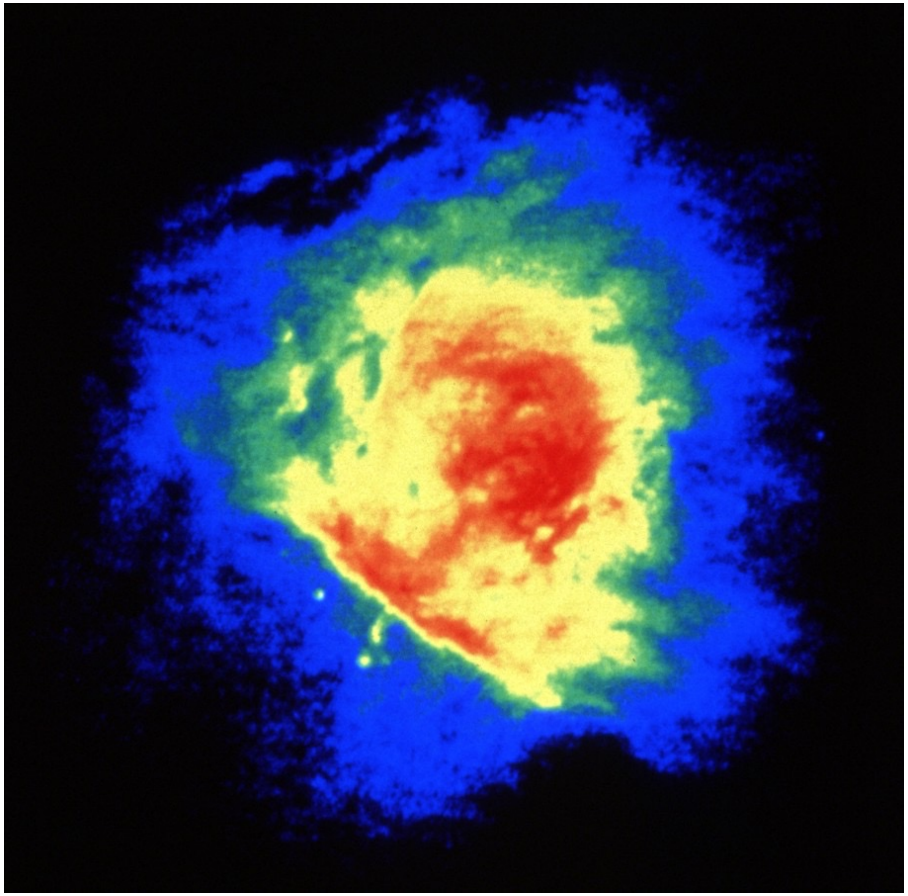


Bremsstrahlung mechansim. NASA Goddard Space Flight Center.



HST (Optical)

Credit: NASA and C.R. O'Dell (Vanderbilt University):

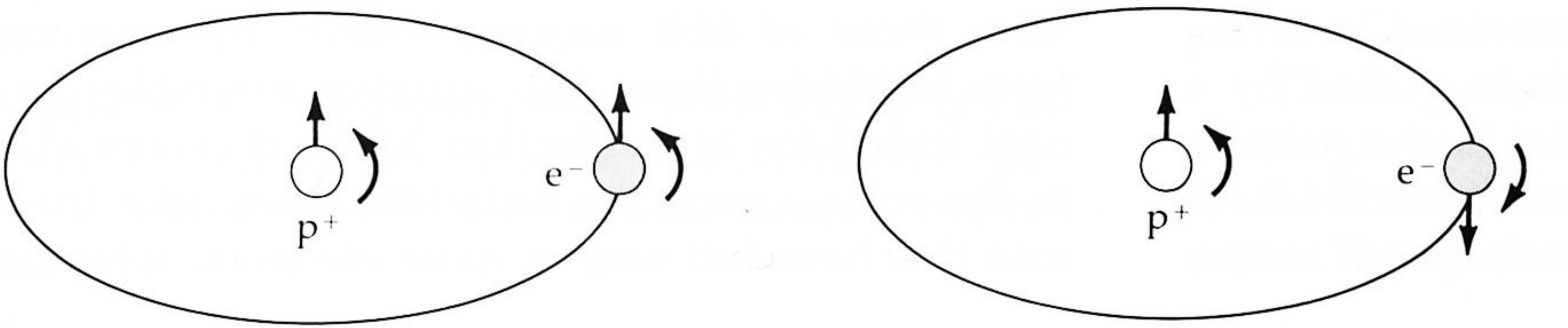


VLA Radio

Image courtesy of NRAO/AUI

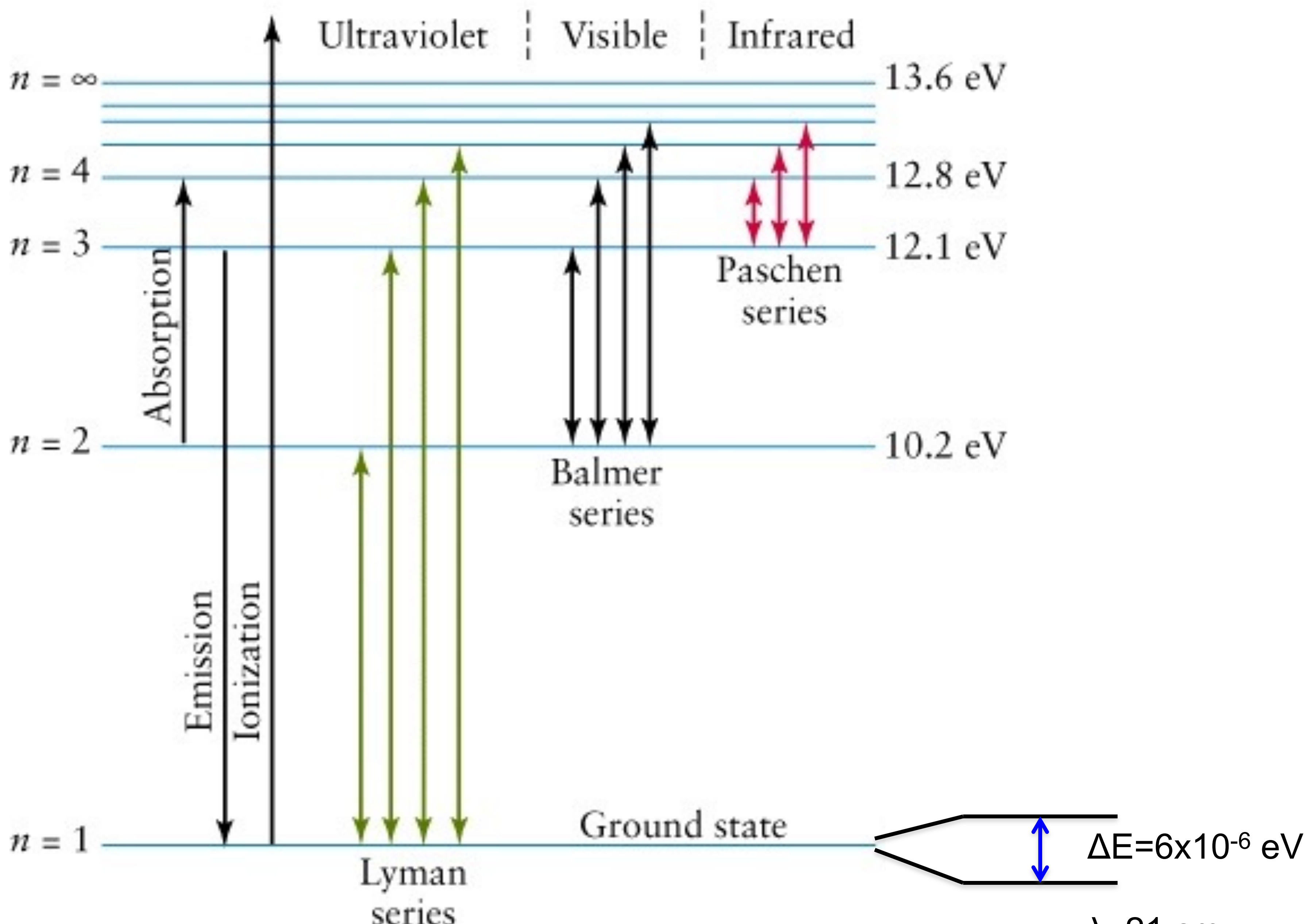
Atomic Gas

- Most of the mass of interstellar gas is in atomic form or H I
- Typical densities of 10^6 m^{-3}
- It is cool (T~100 K) and in the ground state
- Can only emit via a hyperfine transition that occurs at a wavelength of 21 cm in the radio part of the spectrum

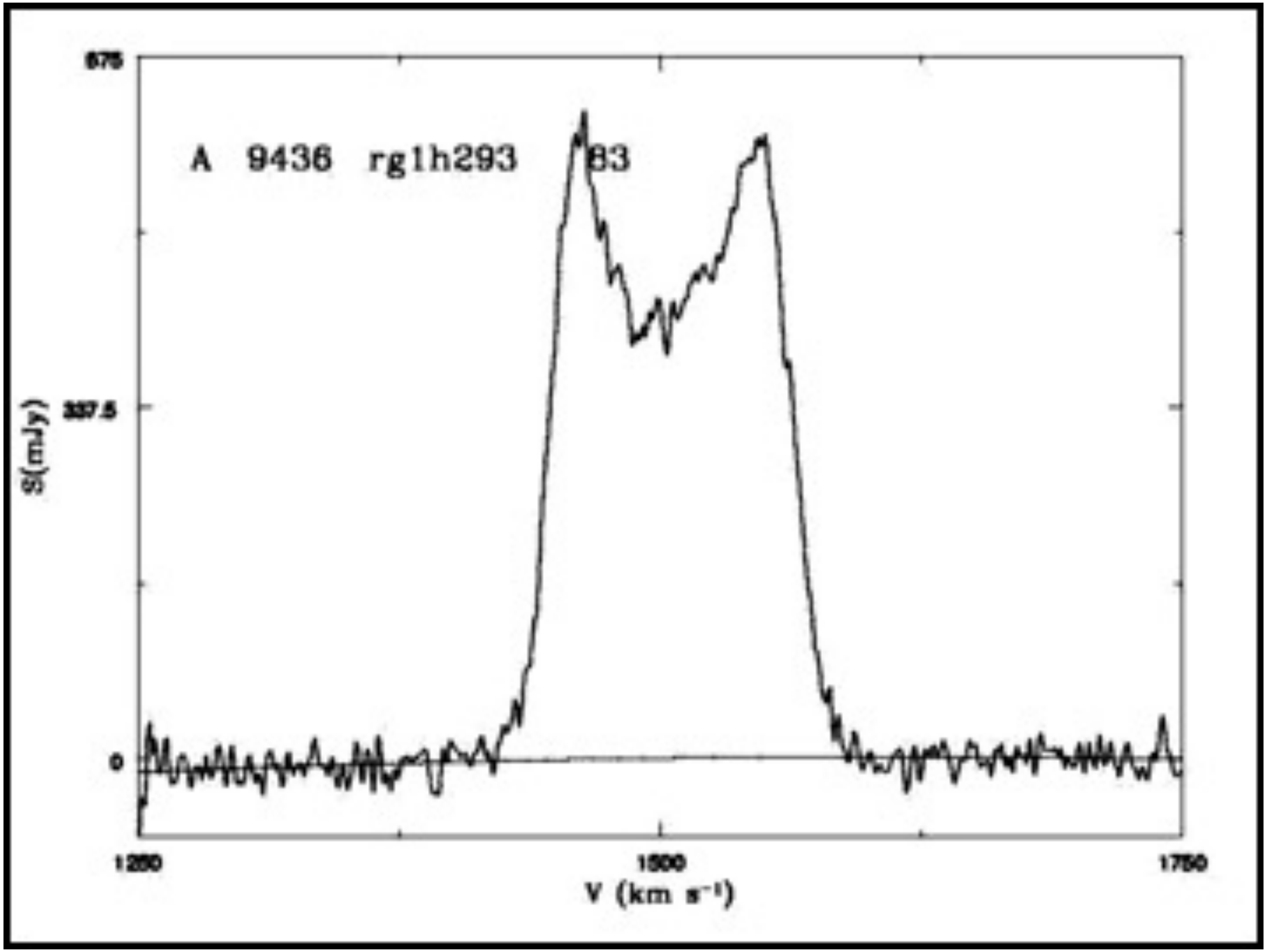


Lower energy state

21 cm Hyperfine transition in atomic hydrogen. Zeilik Fig 15-12



From Universe Textbook



Example H I 21 cm emission line spectrum for a spiral galaxy

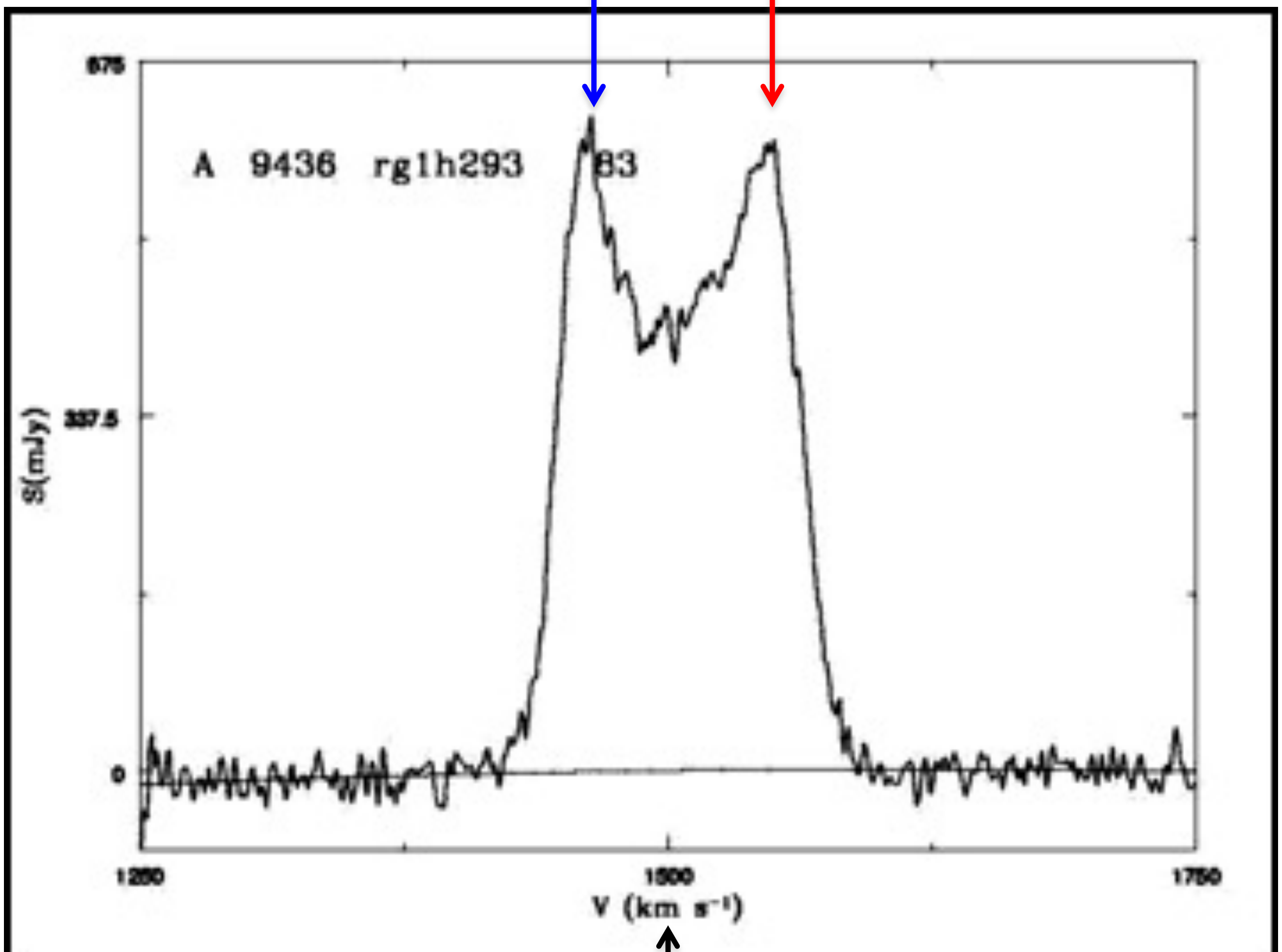
alfalfasurvey.wordpress.com/2009/01/

Class Example

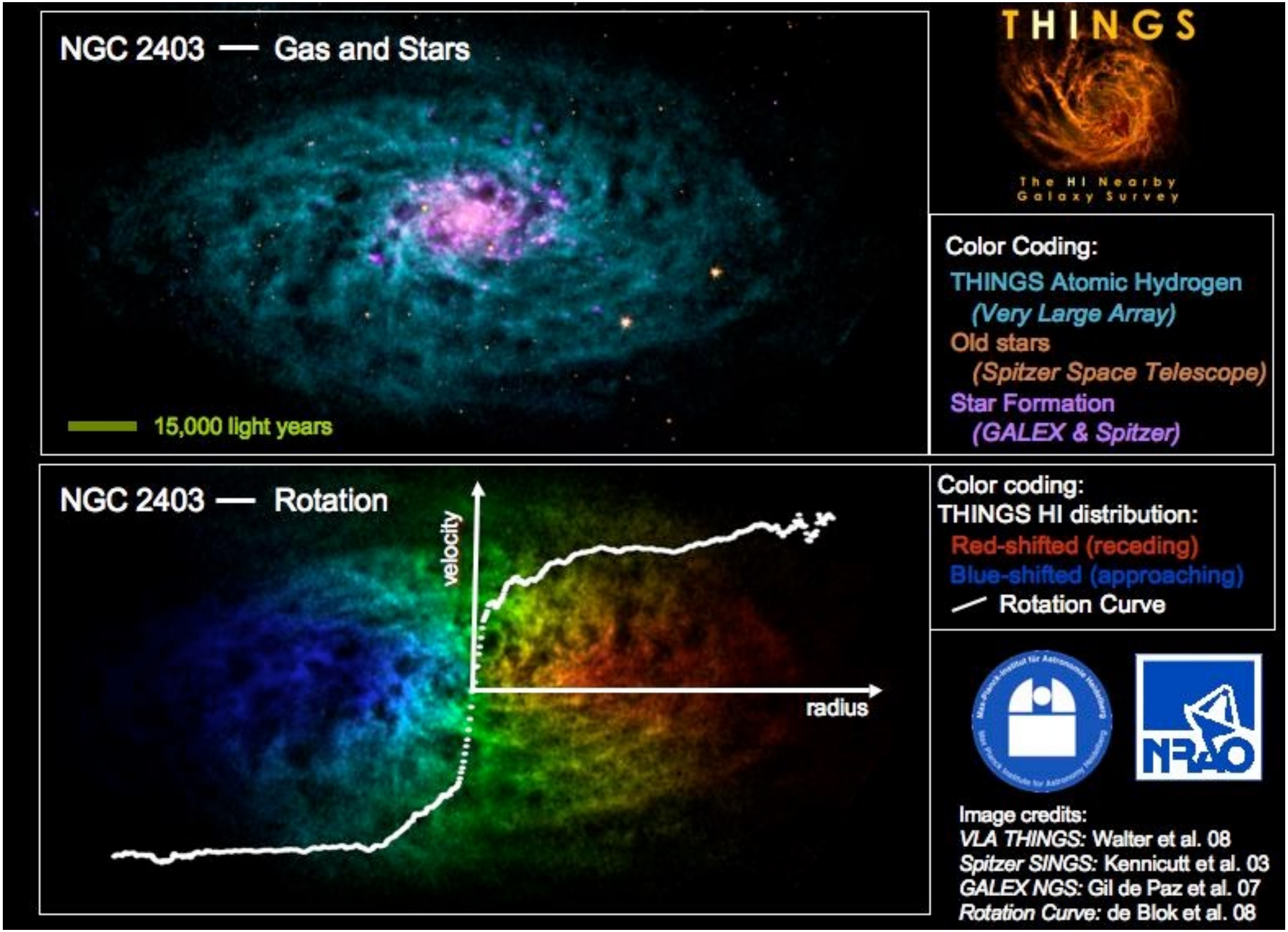
- Why does the H I spectral line have two components and what does the velocity split between them tell us? What does the velocity of the centre of the line tell us?

Blueshifted due to rotation

Redshifted due to rotation



Velocity of the centre of mass of the galaxy

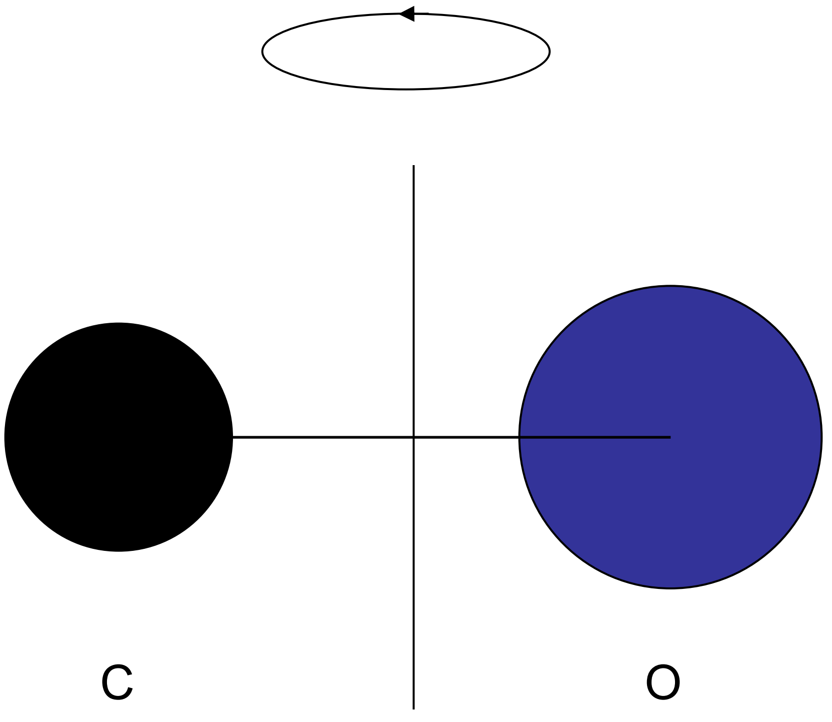

NGC 2403 — Gas and Stars
15,000 light years
THINGS
The HI Nearby Galaxy Survey
Color Coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)
NGC 2403 — Rotation
velocity
radius
Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve
NRAO
Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

Molecular Gas

- In dense (10^{10} m^{-3}), cold ($T<30$ K) regions molecules form from the atomic phase
- Molecular hydrogen (H_2) does not normally emit
- Other trace molecules have to be observed instead, principally carbon monoxide (CO)

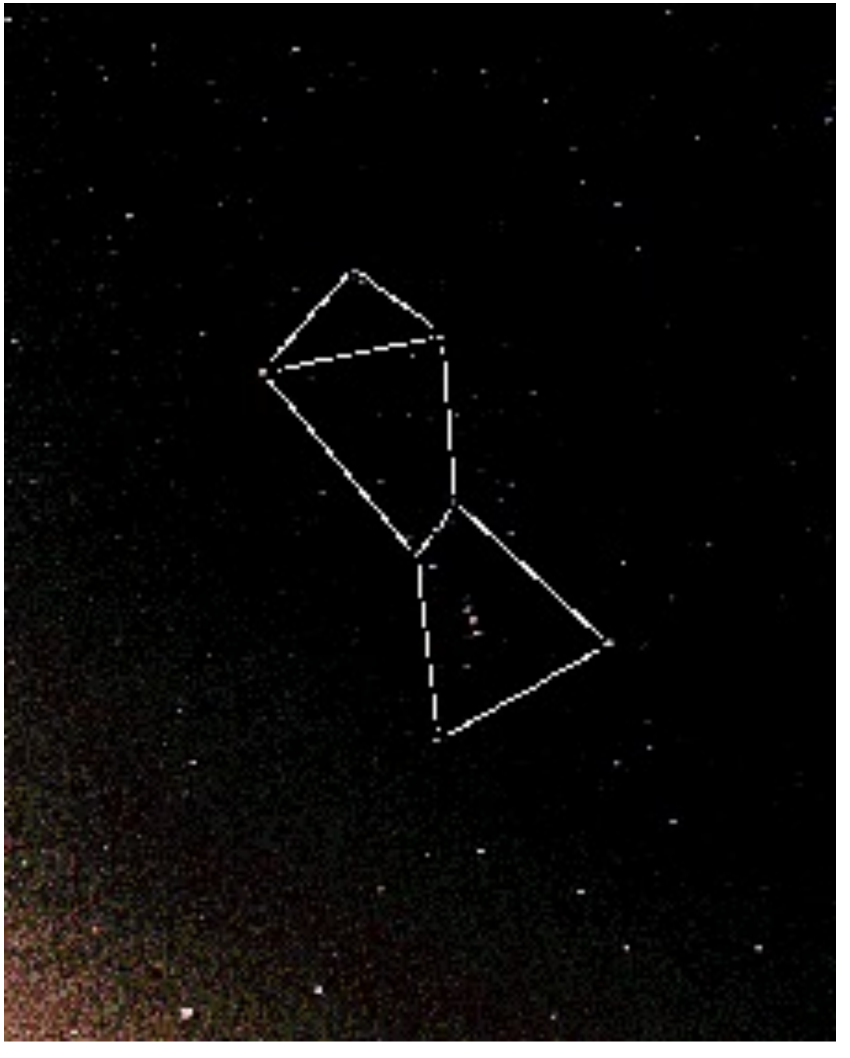
CO Observations

- The CO molecule emits due to rotational transitions excited by collisions
- The ground state transition is at $\lambda \sim 3$ mm
- Many other molecules are observed
- These and H_2 are destroyed (dissociated) by ultra-violet radiation ($\lambda \sim 120$ nm)



Rotational transitions of the CO molecule

- Molecular clouds mapped using CO compared to an optical picture of Orion



Summary

- H II regions arise where massive stars form and are observed mainly in Hα and cm-wave radio continuum
- H I is observed using the 21 cm line and makes up most of the mass of the ISM
- H_2 is traced using mm lines from molecules such as CO and is the material from which stars form

Class Example

- Starting from the ideal gas law, show that the pressure of a gas is proportional to its number density, *n*, in particles per m^{-3} times its temperature, *T.* By taking the typical physical parameters show that H II regions will expand into the molecular clouds that surround them.