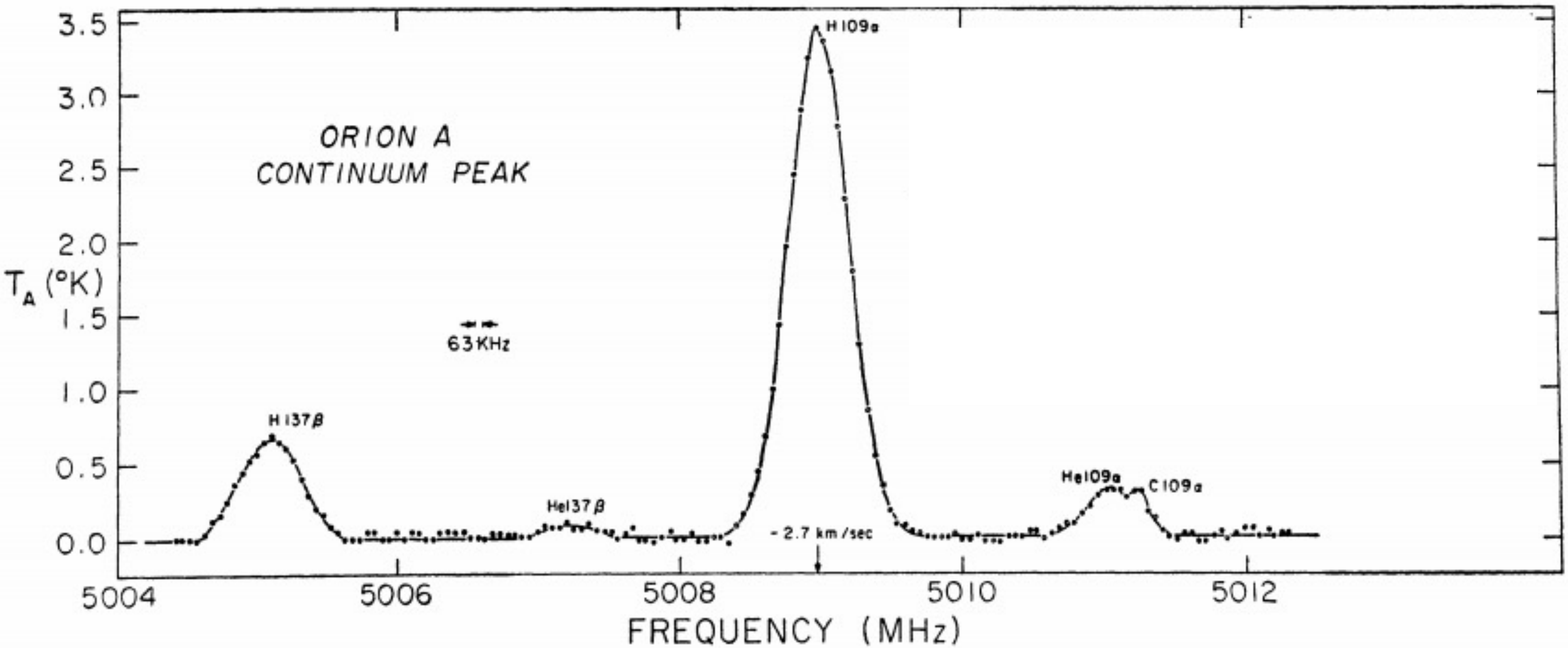
Spectral Lines

- Uses of spectral lines
- Opacity for spectral lines
- Profiles of spectral lines
- Examples of radio spectral lines

Spectral Lines in Radio Astronomy

- Up to now we have mostly discussed processes that give rise to radio continuum emission such as the free-free and synchrotron mechanisms
- There are also examples of spectral line emission (and absorption) in radio astronomy

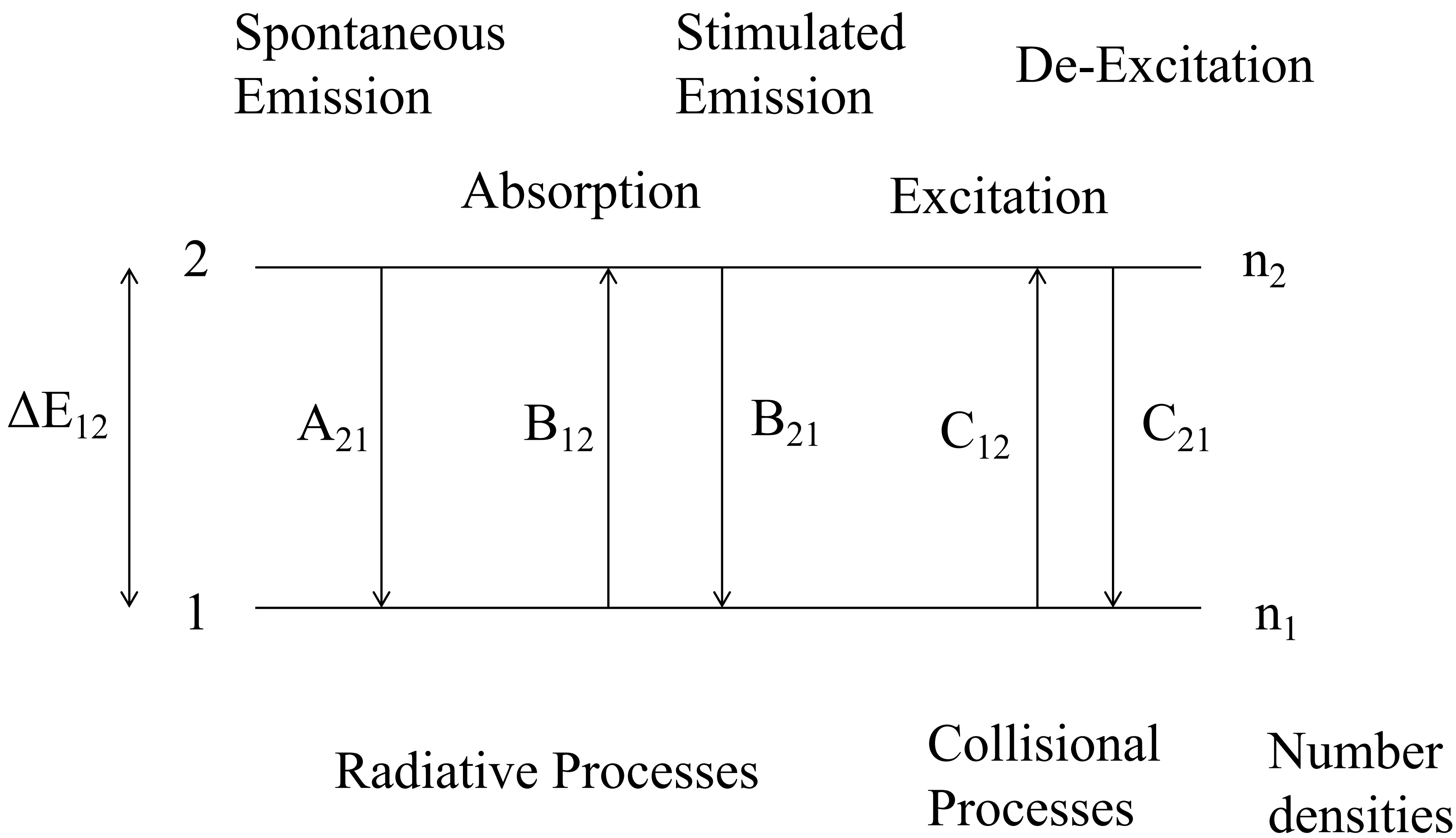


ORION A
CONTINUUM PEAK
H109α
H137β
He137β
He109α
C109α
63 KHz
-2.7 km/sec
T_A (°K)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5004
5006
5008
5010
5012
FREQUENCY (MHz)

Uses of Spectral Lines

- To determine the physical conditions such as density and temperature
- To determine abundances of species
- To probe the kinematics of the region
- To probe the magnetic field strength via the Zeeman effect

Two-level system



Einstein Coefficients

- A_{21} is the probability that a spontaneous radiative decay from level 2 to level 1 per unit time (s^{-1})
- B_{12} is the coefficient for absorption of a photon during excitation from level 1 to level 2 ($m^2\ J^{-1}\ Hz\ st$)
- B_{21} is the coefficient for stimulated emission of a photon from level 2 to level 1

Collision Coefficients

- C_{12} is the collisional excitation coefficient describing the rate of collisional excitations from level 1 to level 2 (m^3s^{-1})
- C_{21} is the collisional de-excitation coefficient describing the rate of collisional de-excitations from level 2 to level 1

Line Optical Depth

- Optical depth τ_ν is defined as

$$d\tau_\nu = \kappa_\nu ds$$

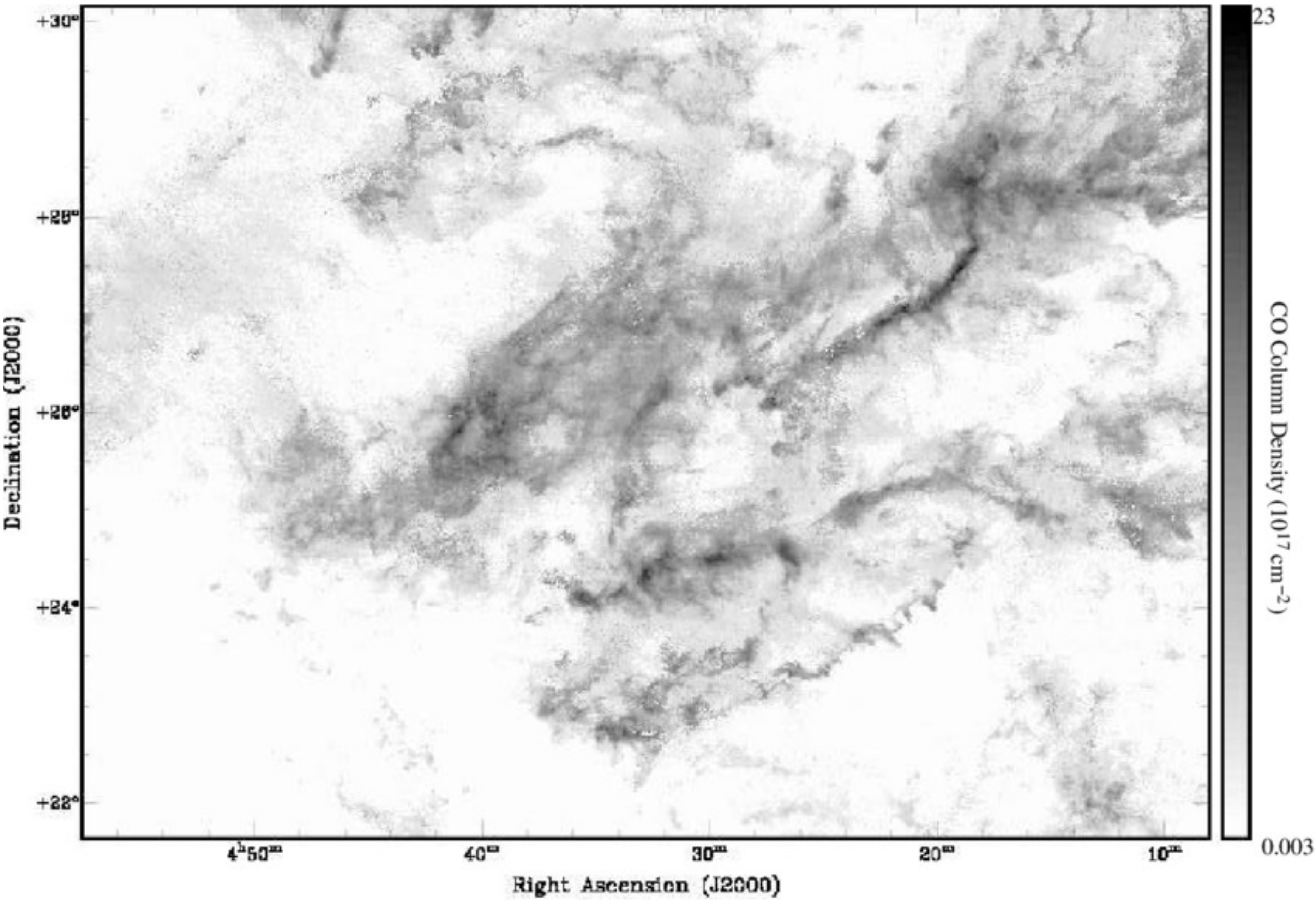
So for a spectral line

$$d\tau_\nu = (n_1 B_{12} - n_2 B_{21}) \frac{h\nu_{12}}{4\pi} \varphi(\nu) ds$$

Column Density

- Note that the line optical depth is (mainly) proportional to n_1
- This will be proportional to the total number density of the species, n
- Hence, $\tau_\nu \propto \int n ds \propto N$

where N is called the column density and has units of m^{-2}



+30°
+28°
+26°
+24°
+22°
Declination (J2000)
4h50m
40m
30m
20m
10m
Right Ascension (J2000)
23
0.003
CO Column Density (10^{17} cm^{-2})

Discussion

- What kind of assumptions would you need to make in order to estimate the number density, n (m^{-3}), from measurements of the column density, N (m^{-2})?

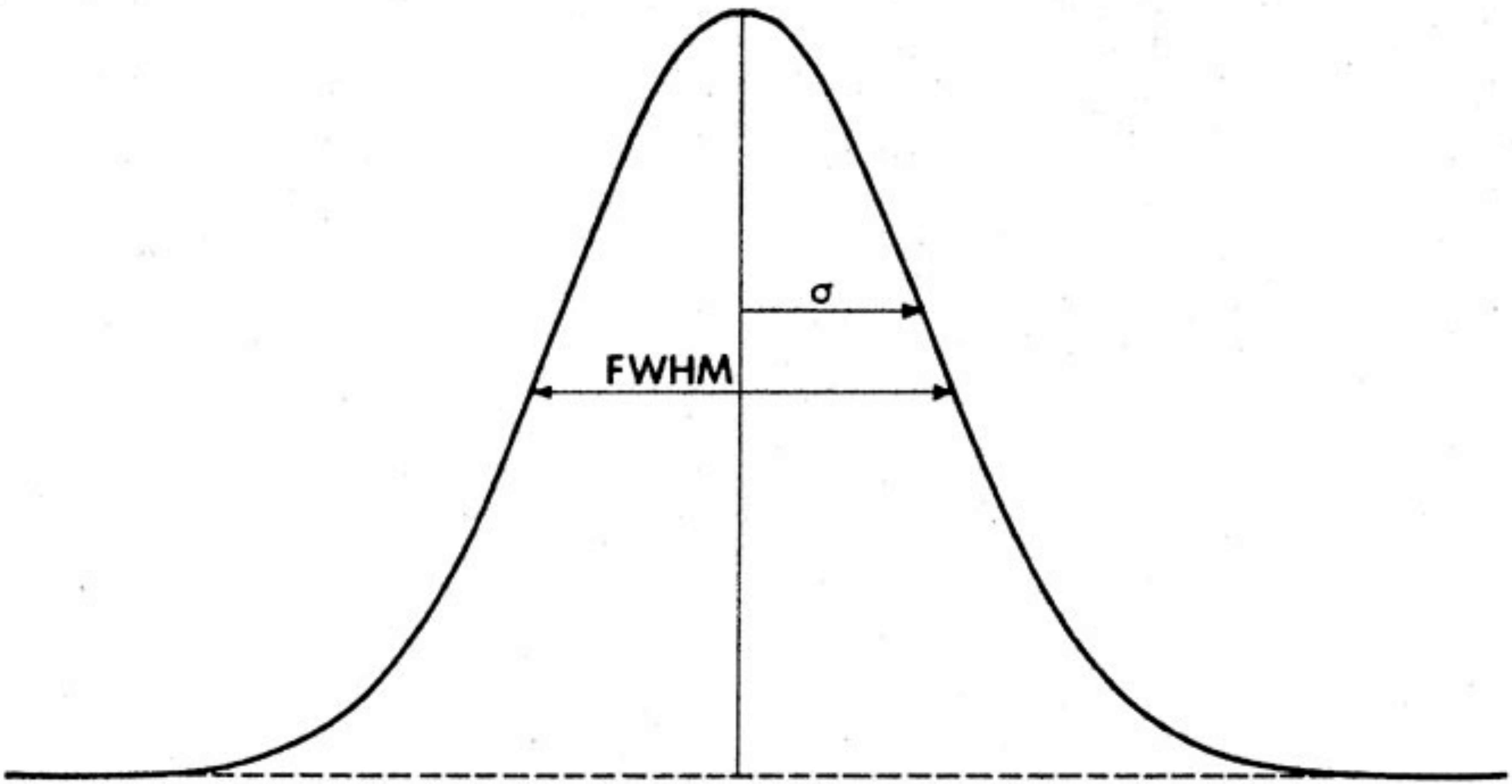
Line Profile

For Doppler broadening by thermal motion of the molecules the frequency profile is Gaussian

$$\varphi(\nu) = \frac{1}{\sqrt{\pi}\Delta\nu_D} \exp - \frac{(\nu - \nu_0)^2}{\Delta\nu_D^2}$$

where the FWHM in velocity of the profile is

$$\Delta \mathrm{v}_{FWHM} = 2\sqrt{\ln 2}\Delta \mathrm{v}_D = 2\sqrt{\ln 2}\frac{\Delta\nu_D}{\nu_0}c = 2\sqrt{\ln 2}\left(\frac{2kT}{m}\right)^{\frac{1}{2}}$$


σ
FWHM

Other Line Profiles

- Very often spectral lines are broader than their purely thermal width
- Usually due to Doppler shifts due to the kinematics of the gas, e.g.
  - Broad gaussian due to turbulence
  - Double-peaked due to rotation or outflow

Negative Optical Depth

- In special circumstances the spectral line optical depth can go negative

$$d\tau_\nu = (n_1 B_{12} - n_2 B_{21}) \frac{h\nu_{12}}{4\pi} \varphi(\nu) ds$$

- This happens if $n_2 > n_1$ – population inversion, and leads to maser amplification of the intensity as e^{τ_ν}

Line Emissivity

- We can write the line emissivity as

$$j_\nu = n_2 A_{21} \frac{h\nu}{4\pi} \varphi(\nu)$$

- Useful for interpreting optically thin line emission to derive column densities

LTE

- In local thermodynamic equilibrium (LTE) each process is balanced by its inverse process, and the local temperature determines the level populations

$$j_\nu = \kappa_\nu B_\nu(T) \quad \text{or} \quad S_\nu = B_\nu(T)$$

- Good in optically thick situations and for continuum radiation like free-free

Non-LTE

- Often LTE is not a good assumption
- Optically thin situations when the radiative rates are no longer determined by the local radiation field
- Need to solve full statistical equilibrium equations to determine level populations which can be characterized by an excitation temperature $T_{ex} \neq T$

Discussion

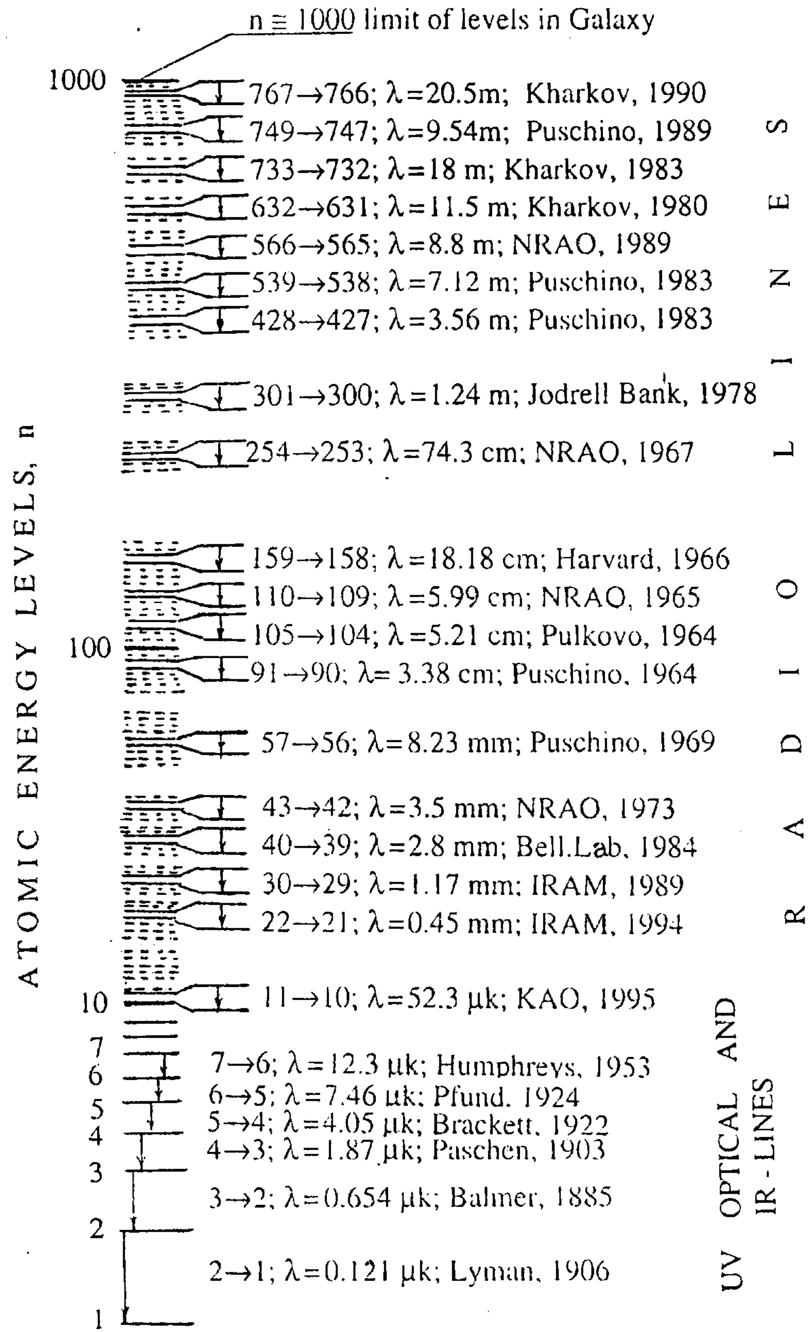
- Which of the following situations do you think LTE would be a good approximation?
  - The photosphere of Sun
  - The corona of the Sun
  - An H II region
  - The Big Bang

Examples of Radio Lines

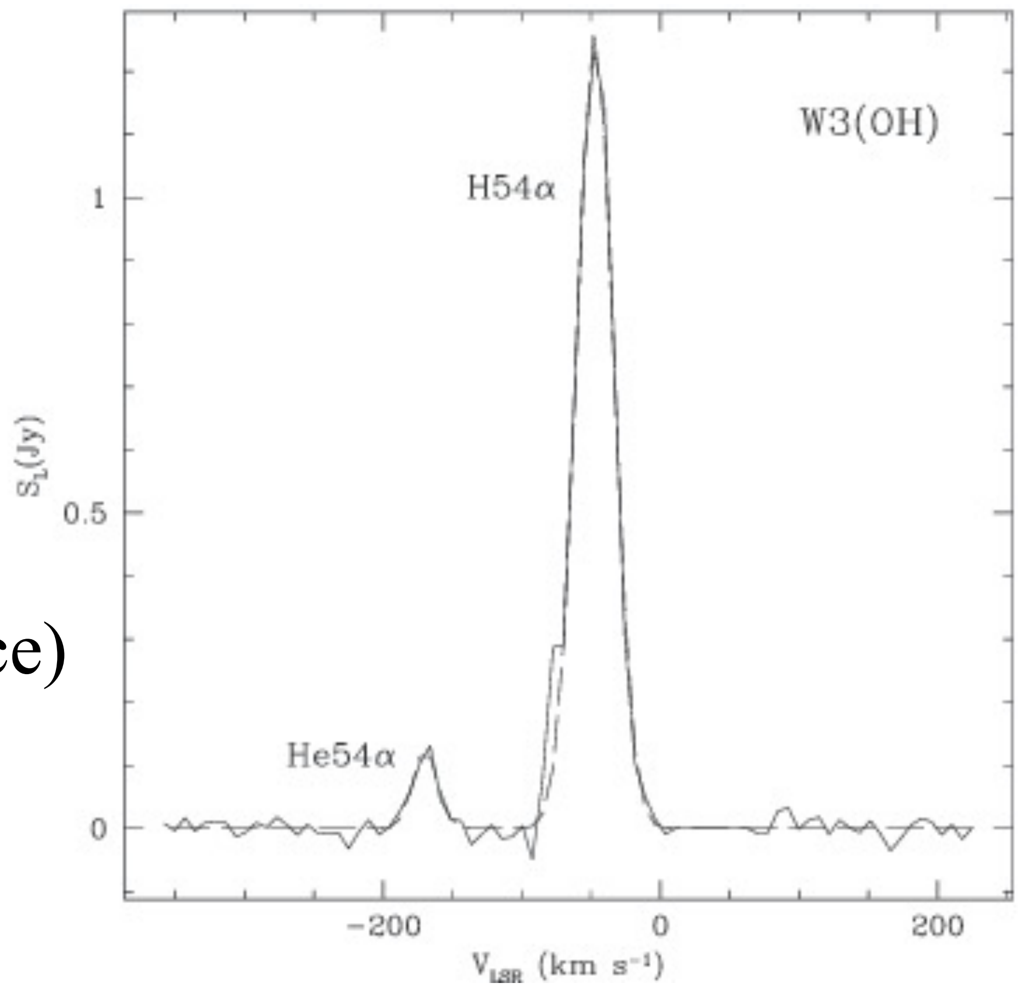
- There are spectral lines right across the radio spectrum
- These can arise from ions, atoms and molecules

Radio Recombination Lines

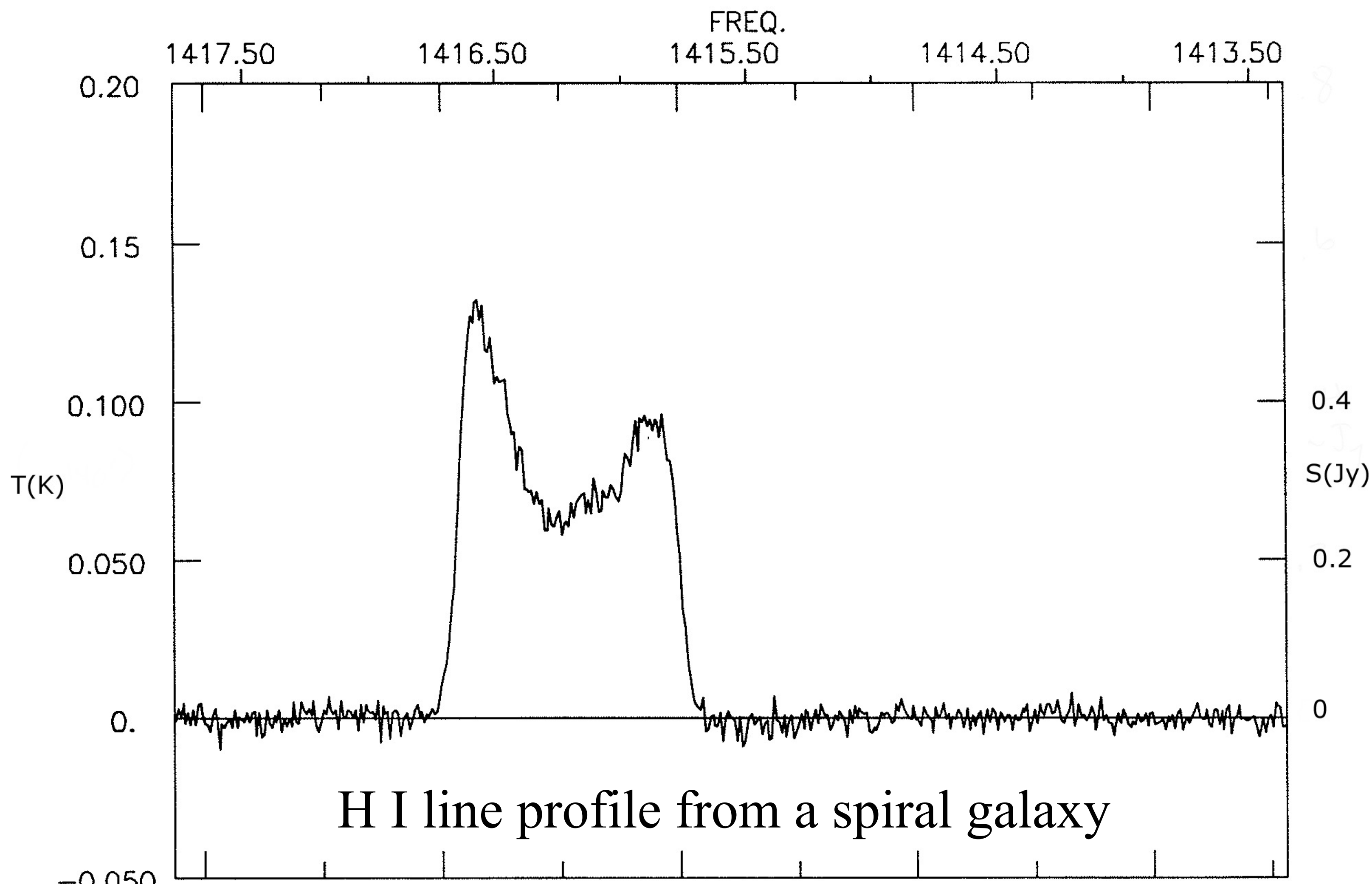
- Photo-ionized gas emits lines from electrons cascading down the high energy levels of hydrogen after recombination of a proton and electron



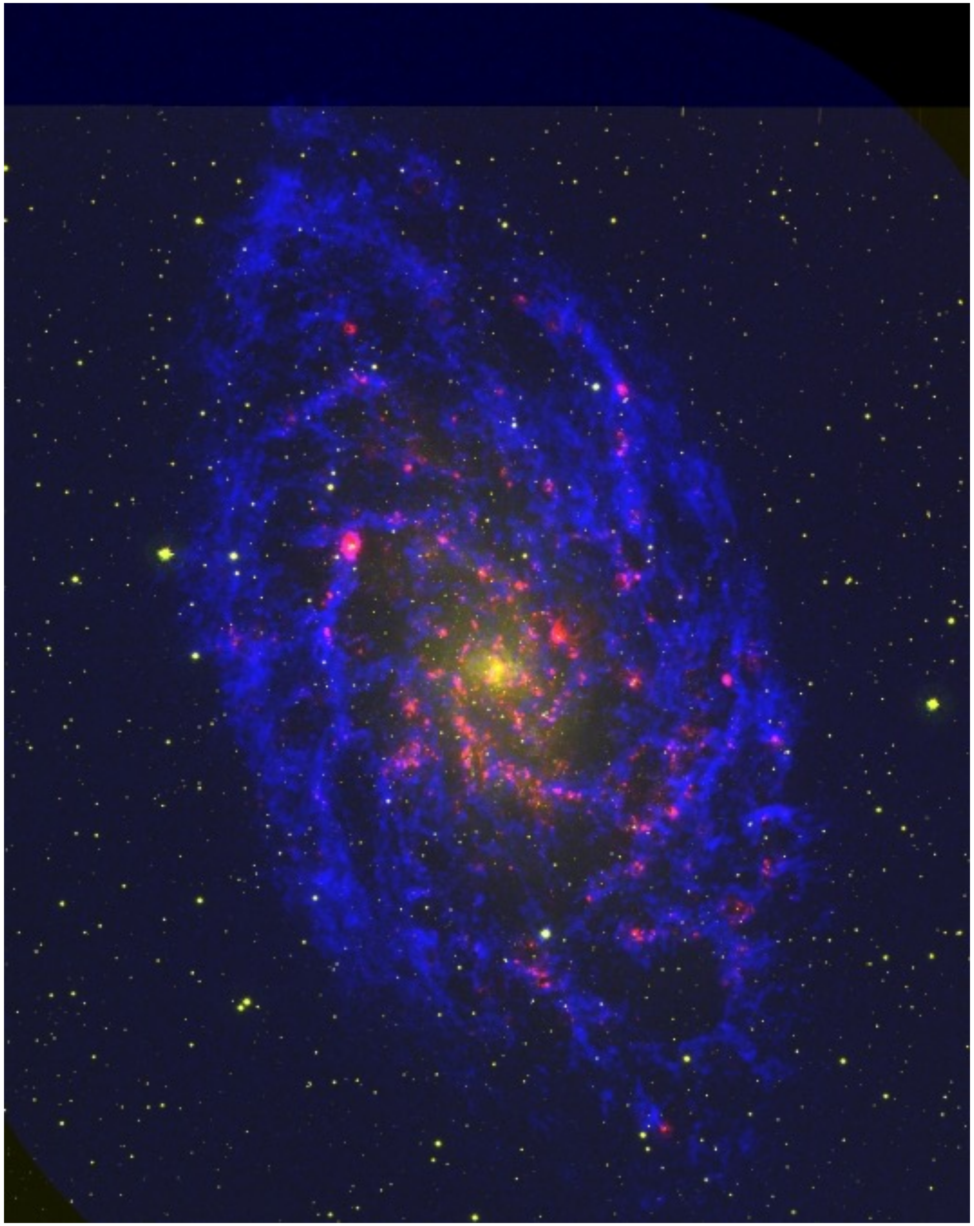
- Can use to diagnose:
  - Temperature
  - Density
  - He abundance
  - Velocity (Distance)
  - Expansion



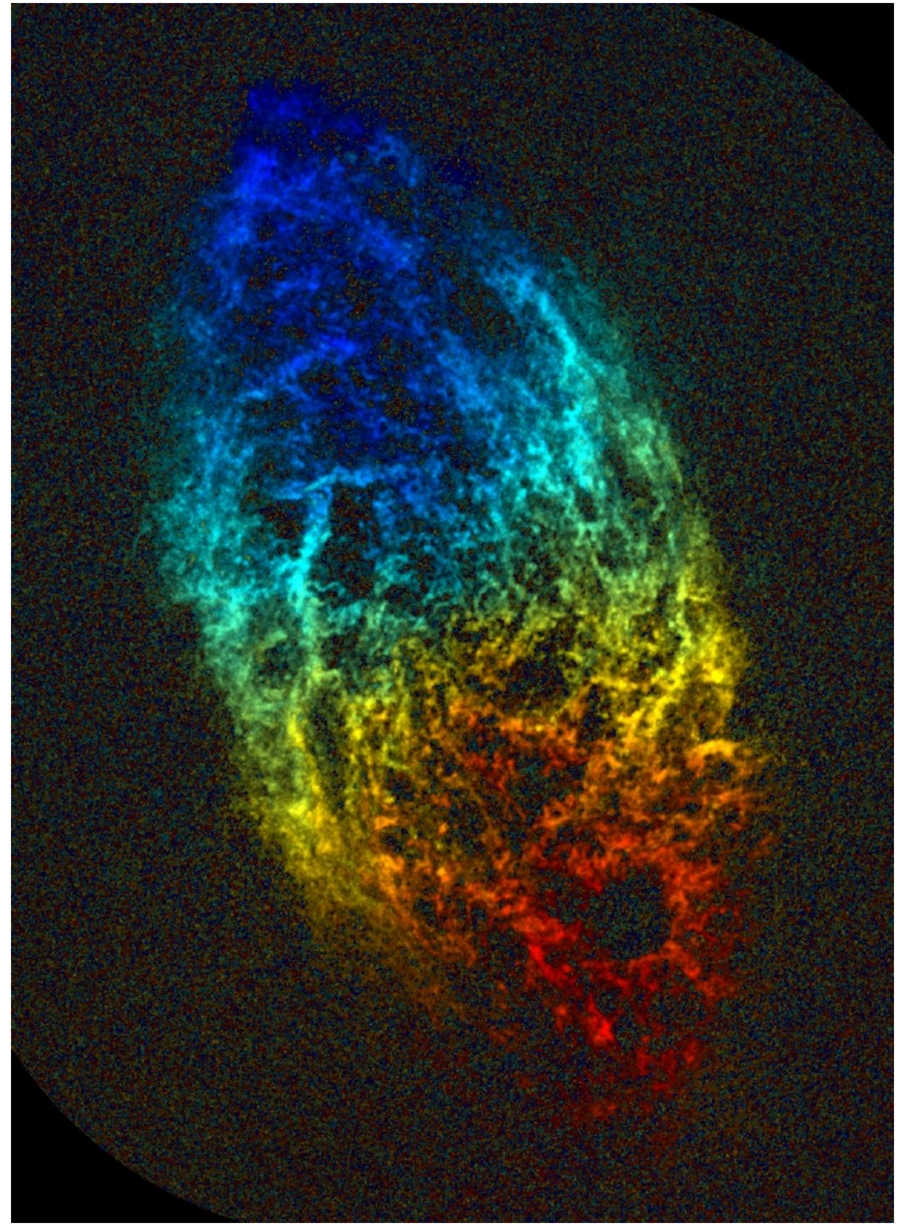
H I 21 cm Line



H I line profile from a spiral galaxy



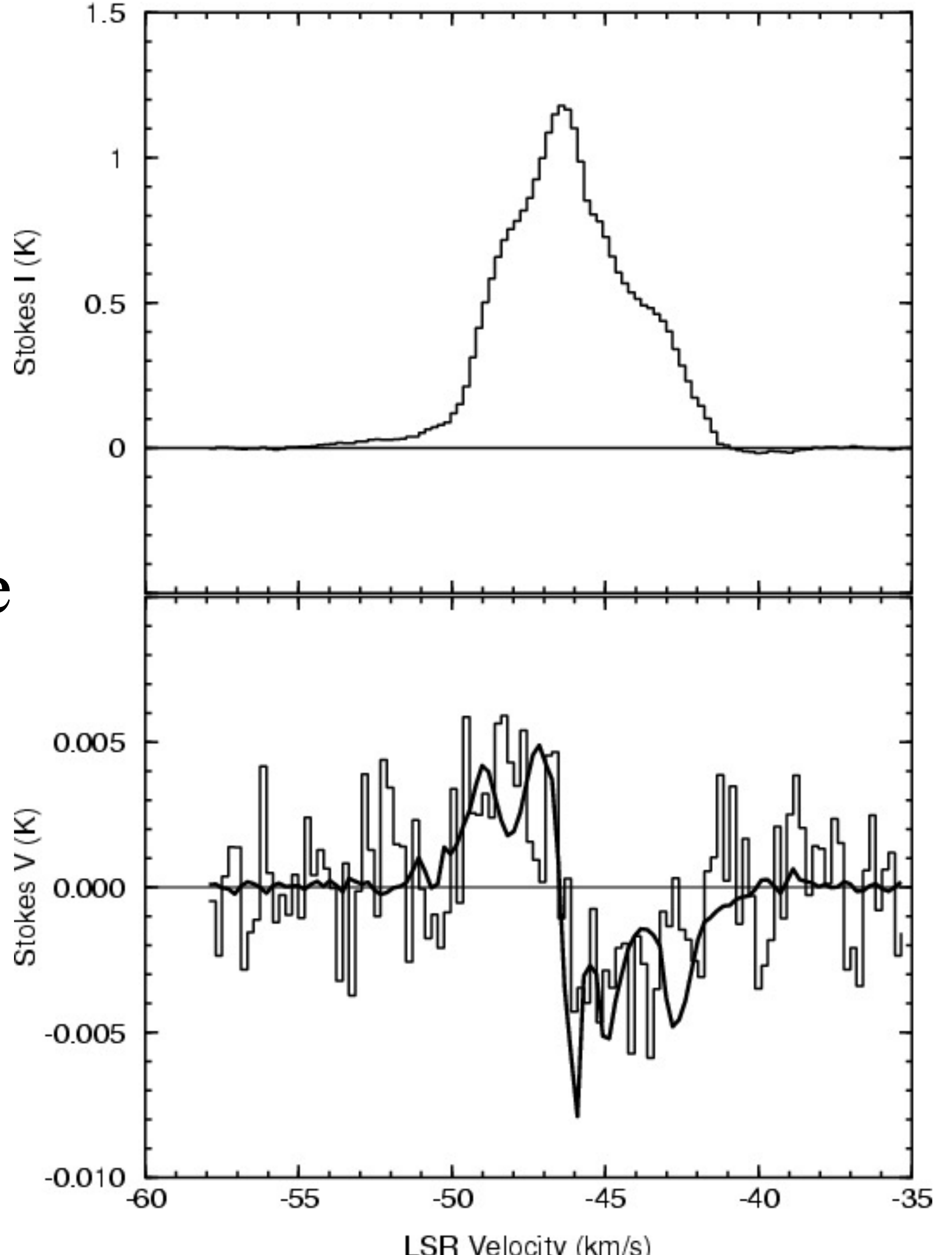
H I (blue) and optical image



Doppler shift (colours) of H I

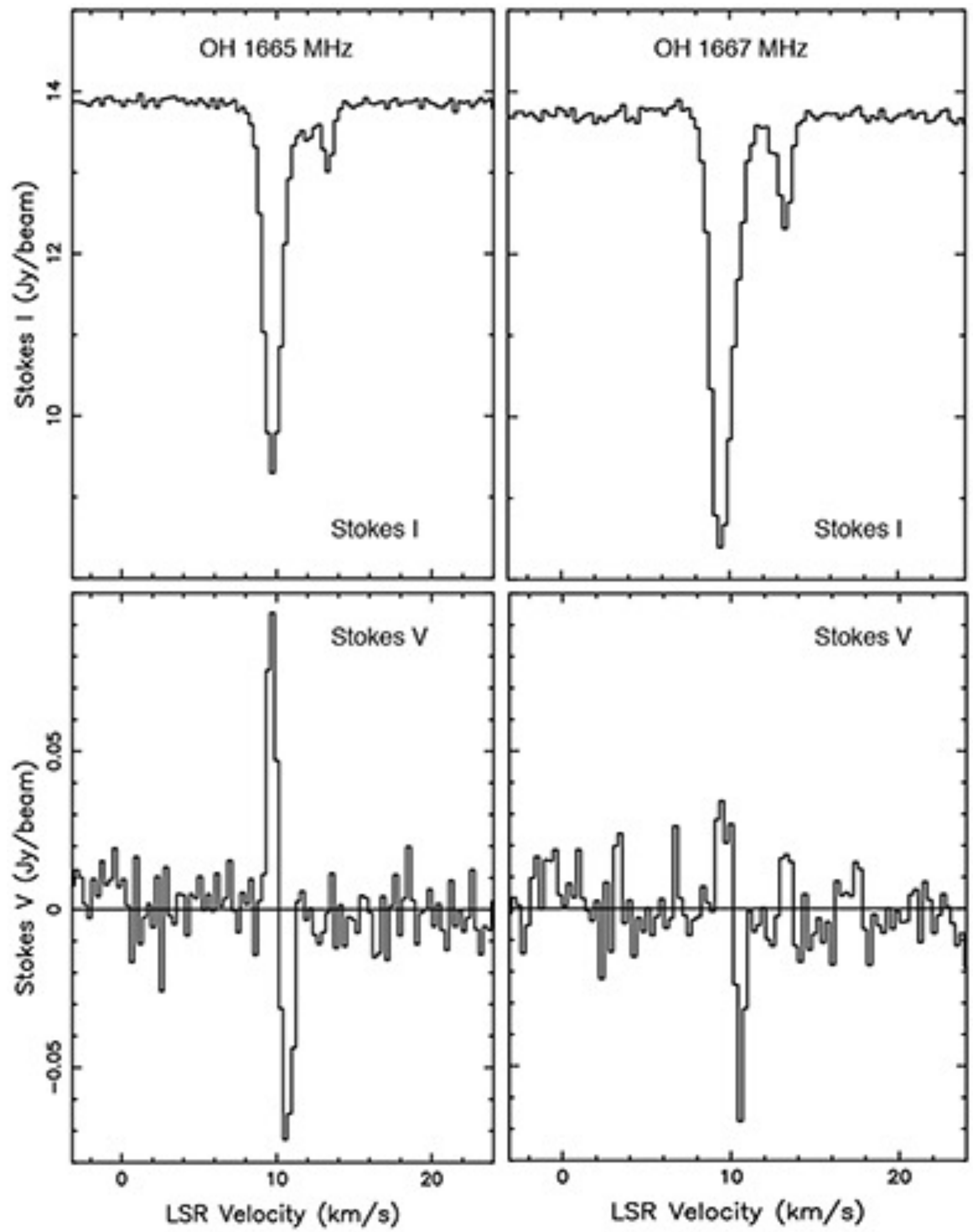
Molecular Emission Lines

- E.g. CN molecule at 113 GHz
- Used to measure magnetic field via Zeeman effect



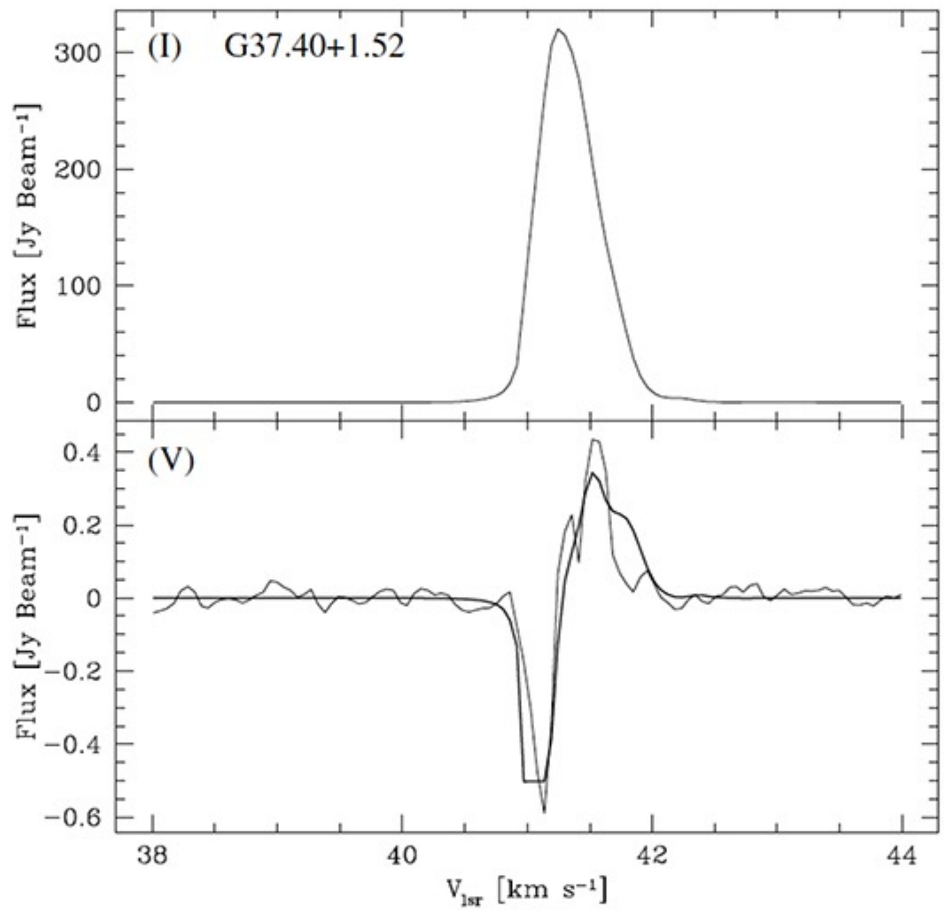
Molecular Absorption Lines

- Lines appear in absorption against a strong background continuum source



Maser Lines

- Several molecules exhibit strong non-thermal maser emission lines



Summary

- Radio spectral lines can be used to determine:
  - Physical conditions
  - Abundances
  - Kinematics
  - Magnetic field