Light as a messenger

Spectroscopic Diagnostics in Astronomy

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Contents

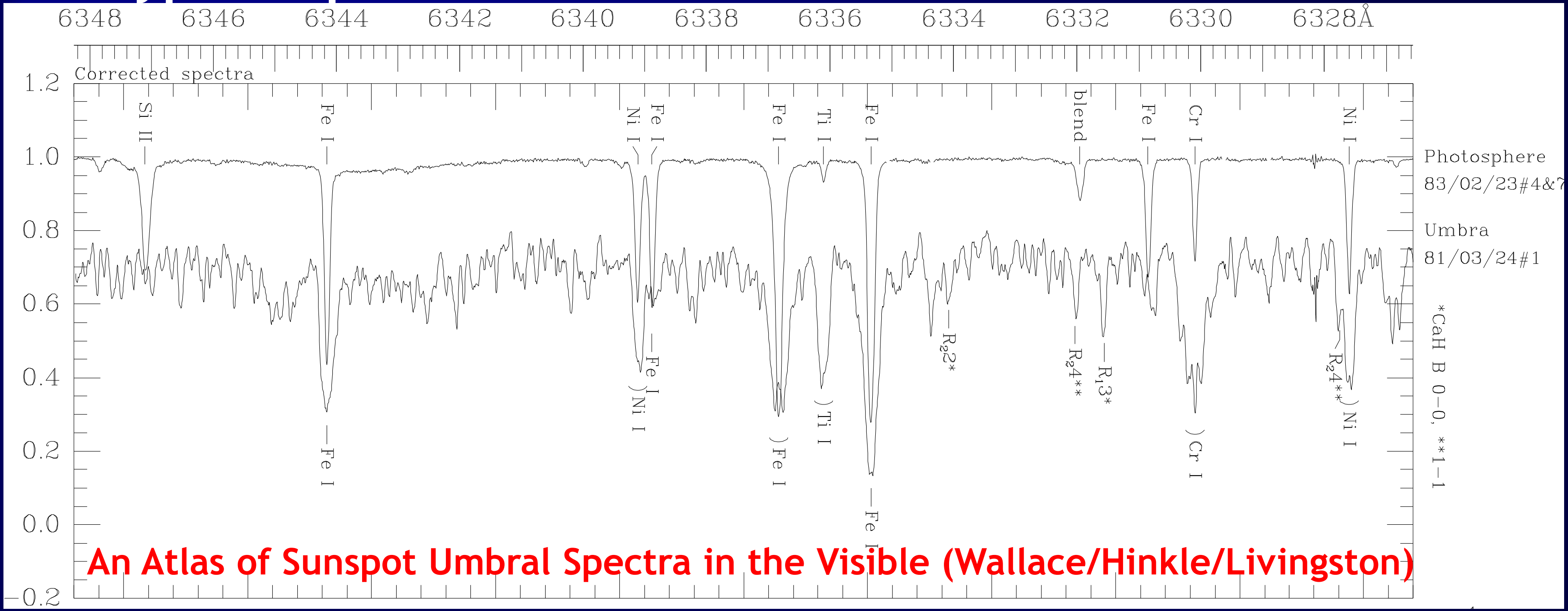
What can we learn from imaging?

Andromeda galaxy

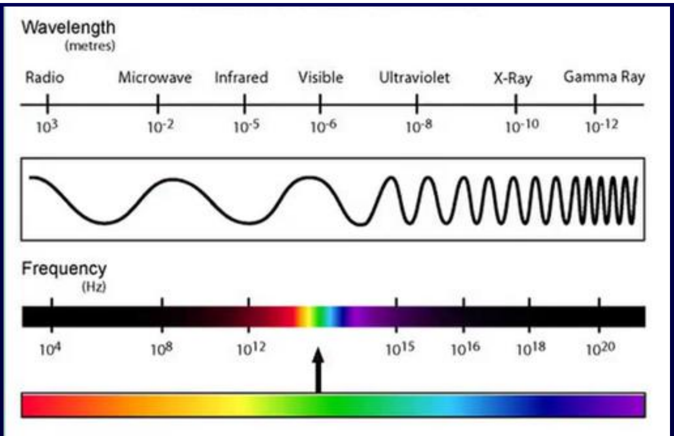
- blue light: regions where hot, young stars have formed, which is mostly out on the edges (in the spiral arms)
- pink and white regions toward the center: older, cooler stars
- dark regions: giant clouds of gas and dust ring the spiral arms

What can we learn from spectroscopy?

A typical spectrum:



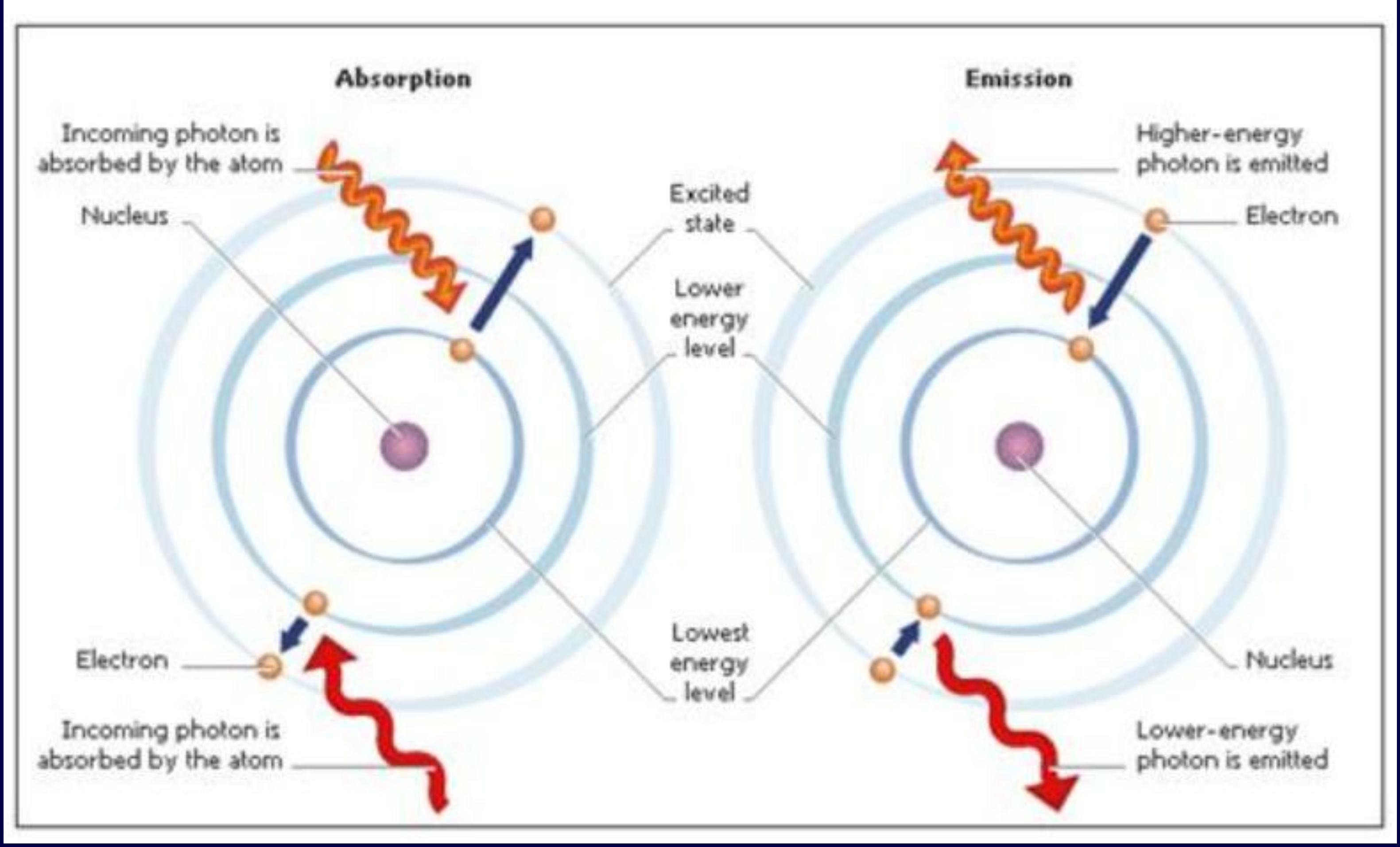
An Atlas of Sunspot Umbral Spectra in the Visible (Wallace/Hinkle/Livingston)



Electromagnetic spectrum

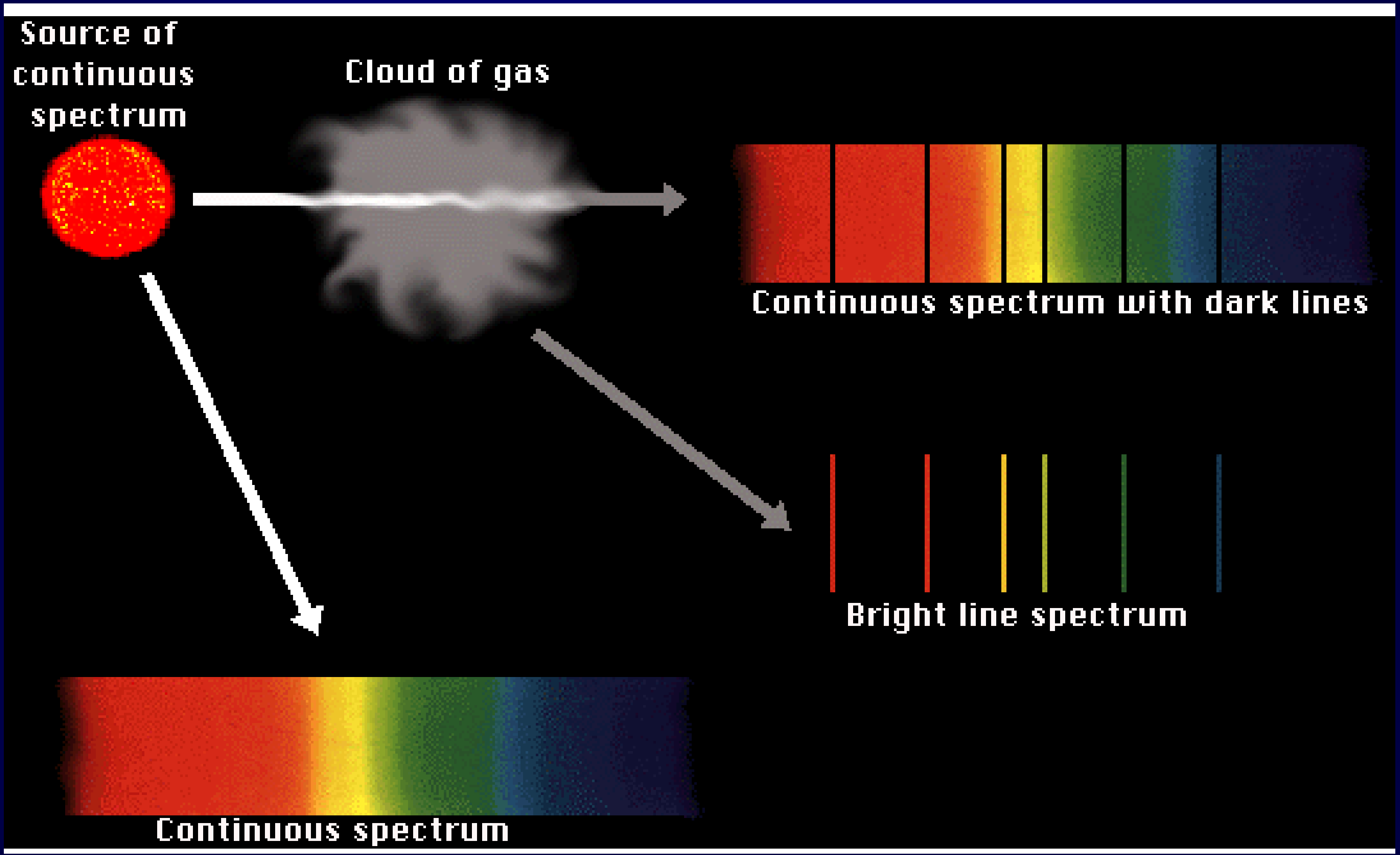
Interaction of Light and Matter

Understanding infinitesimally large
-> understand the infinitesimally small



Atomic Spectroscopy

Different kinds of spectra:



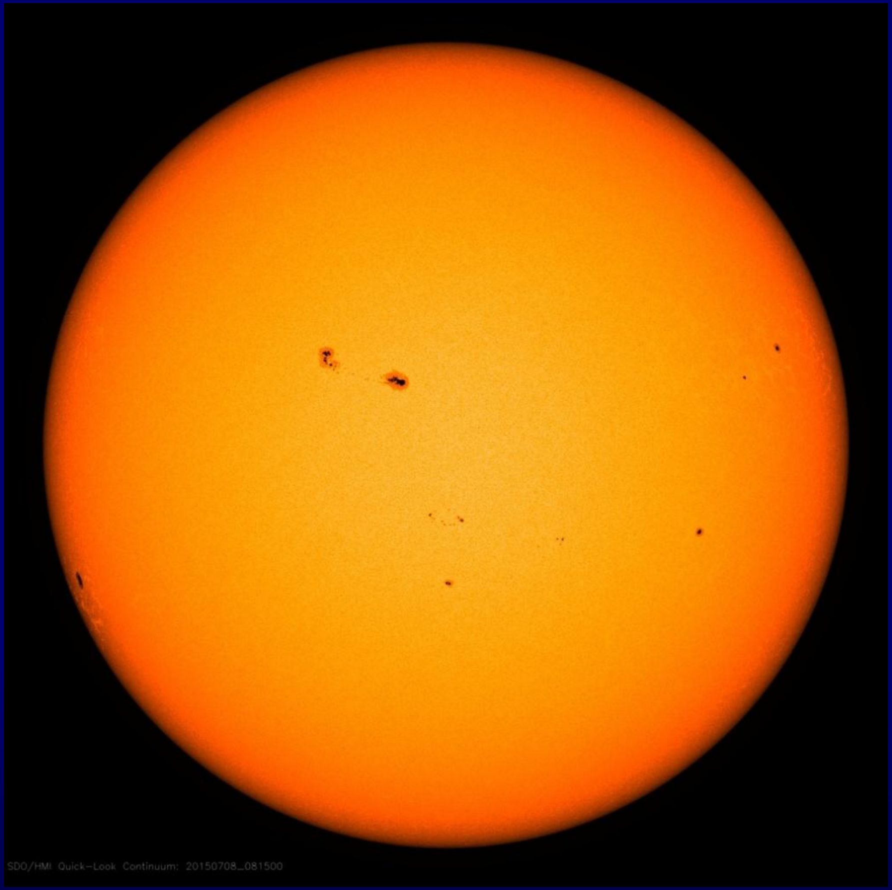
http://www.astro.virginia.edu/class/majewski/astr313/lectures/spectroscopy/spec.html

Different kinds of spectra

- A hot, opaque body produces a continuous spectrum
- A hot, transparent gas produces an emission line spectrum
- A cool, transparent gas produces an absorption line spectrum

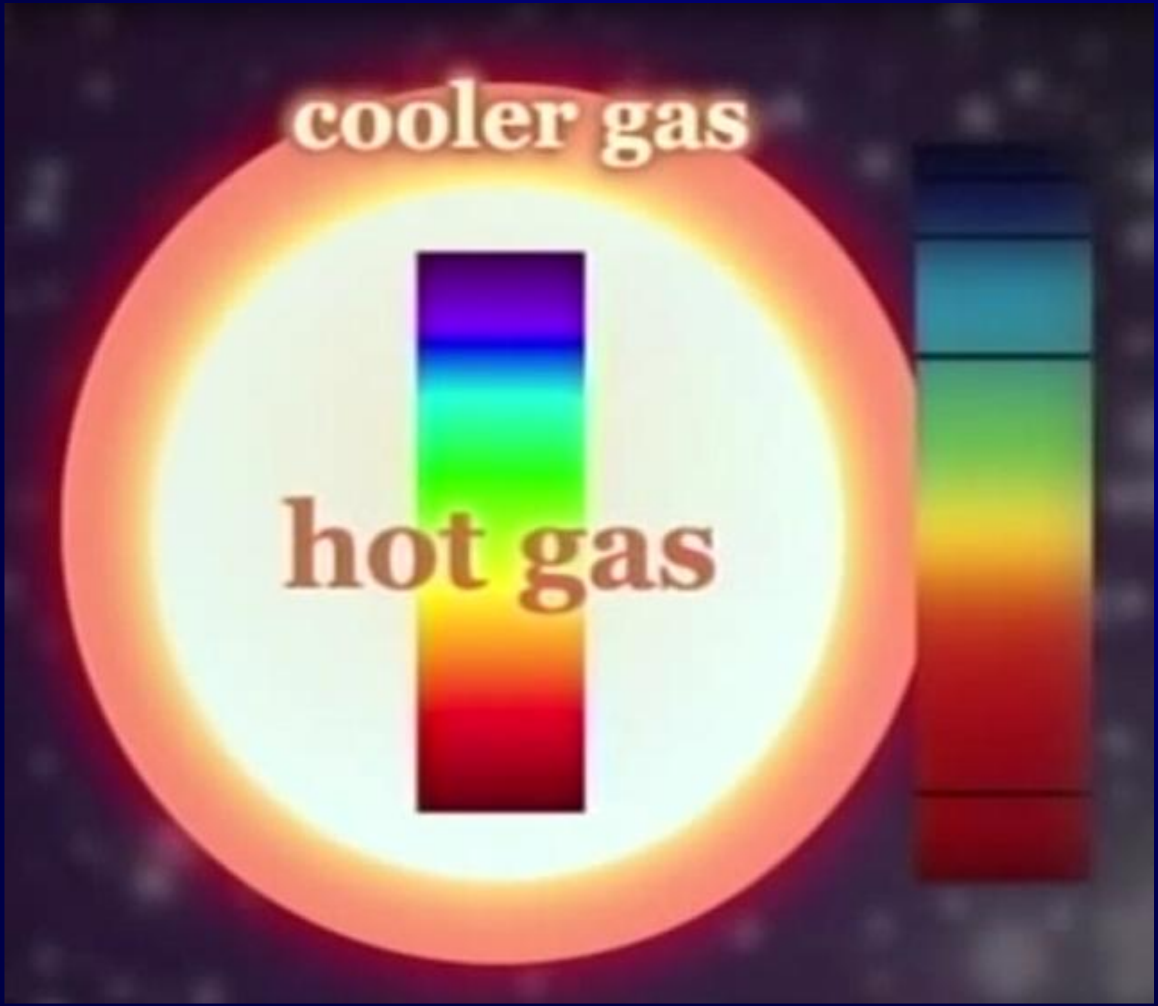
Spectroscopy

Absorption spectrum



Spectroscopy

Absorption spectrum



- Surface of star cooler than gas underneath
- The light from the hot dense gas inside produces continuous spectrum
- The cooler gas above it absorbes specific wavelengths => absorption spectrum

Spectroscopy

- Spectral line diagnostics: deciphering a spectrum leads to information on different solar/stellar atmosphere parameters:
  - **Line width**: temperature and turbulent velocity, stellar wind speeds
  - **Line depth:** temperature and temperature gradient
  - **Wings of strong lines**: gas pressure
  - **Equivalent width**: element abundance, temperature
  - **Splitting of lines** (and polarization): magnetic field

Spectroscopy

- **Doppler shift of line**: (net) flows in LOS direction, rotation rates
- **Line asymmetry**: velocity gradient, v, T inhomogeneities

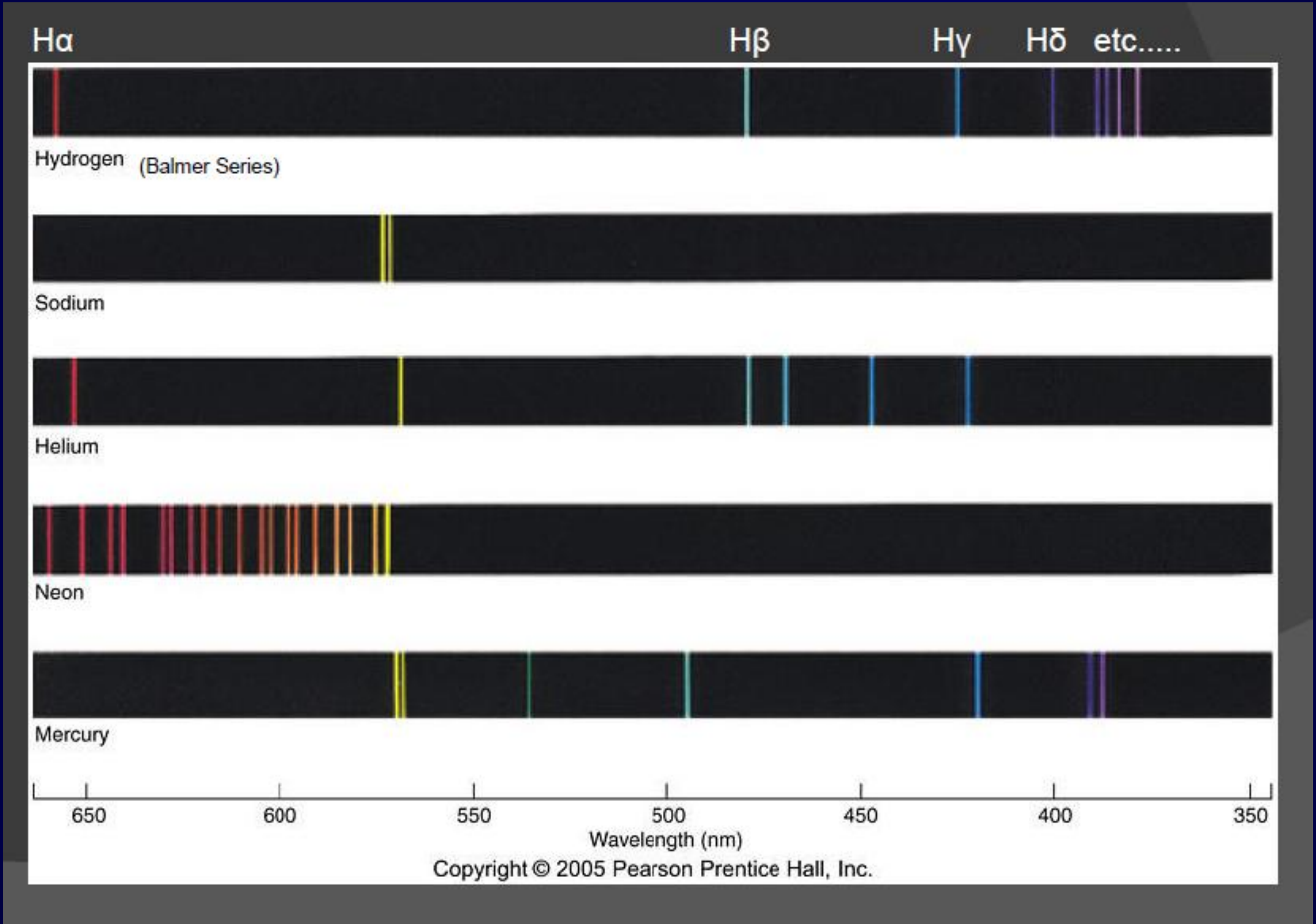
=> Atmospheric temperatures, compositions of stars and planets, planet surface properties (via absorbed and emitted light), stellar ages, chemical evolution of galaxies, etc

Spectroscopy

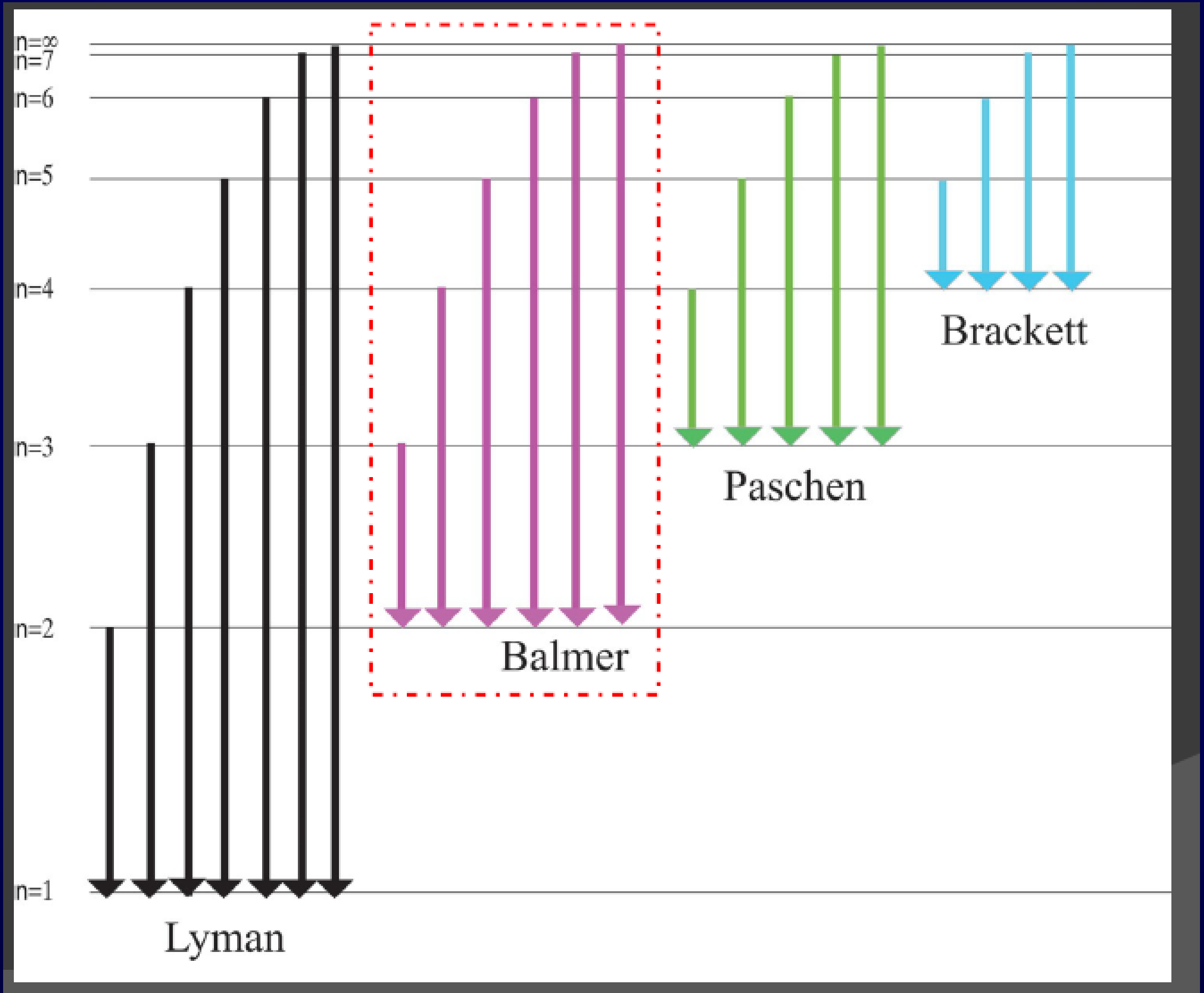
1860s: Systematic attribution of spectra
to chemical elements:

physicist Gustav Kirchhoff (left) & chemist Robert Bunsen (right)

Spectral Fingerprints



Energy Levels of Hydrogen

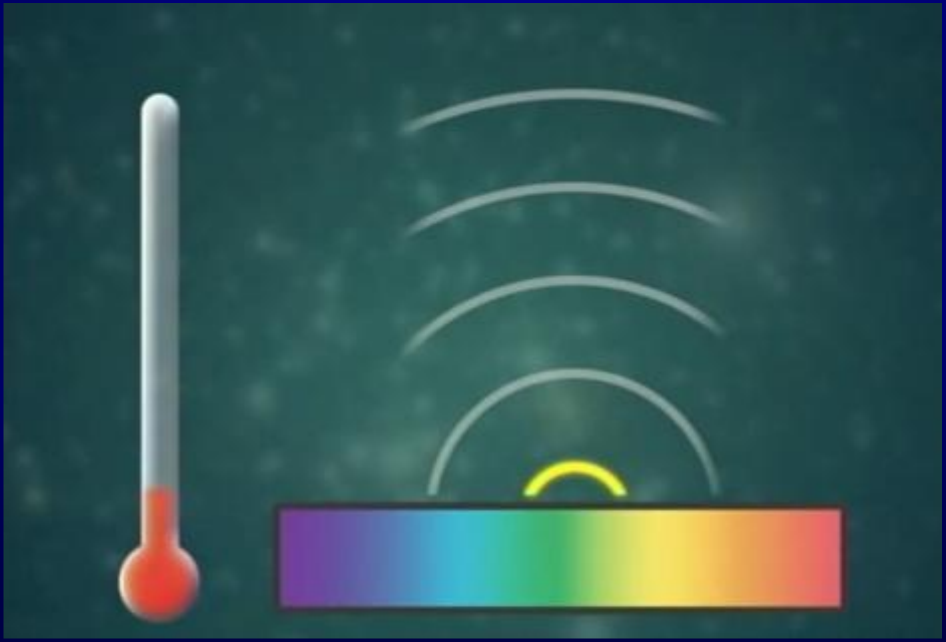


Temperature and Spectral Classification

- Hydrogen: electrons in 2nd level absorb photons to produce Balmer series
- Temperature of gas in star affects spectrum of star

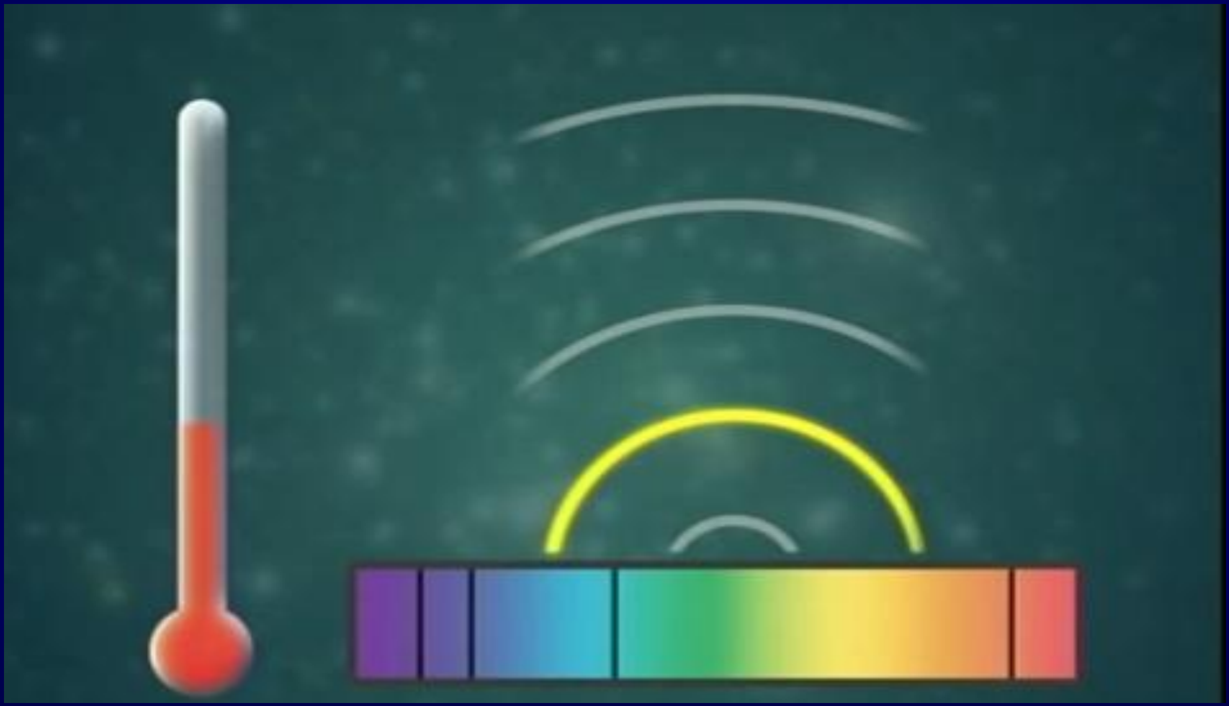
Temperature and Spectral Classification

Star of cool temperature: most electrons lower than 2nd level: weak or invisible Balmer



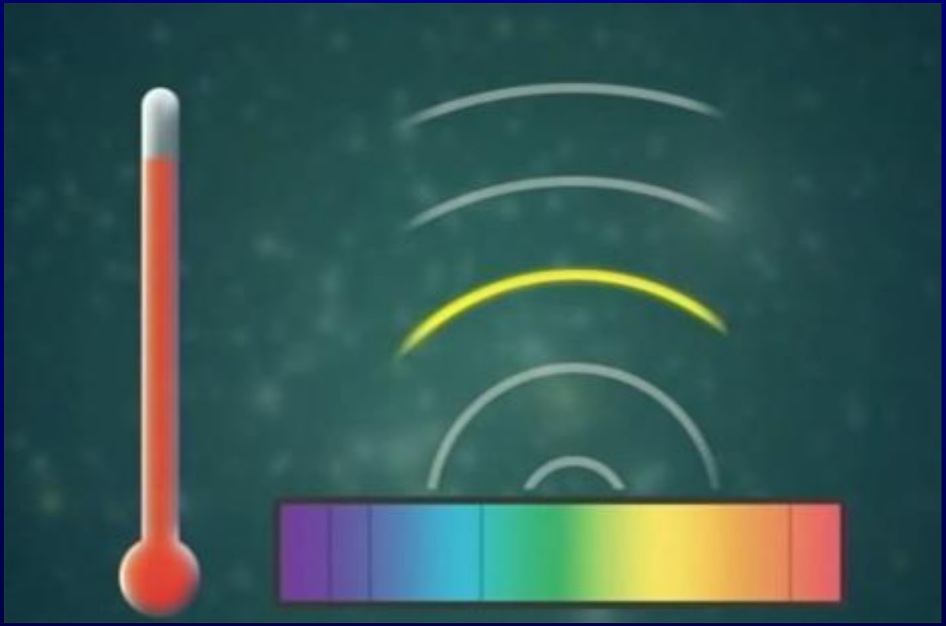
Temperature and Spectral Classification

Star of intermediate temperature: most electrons in 2nd level: strong Balmer

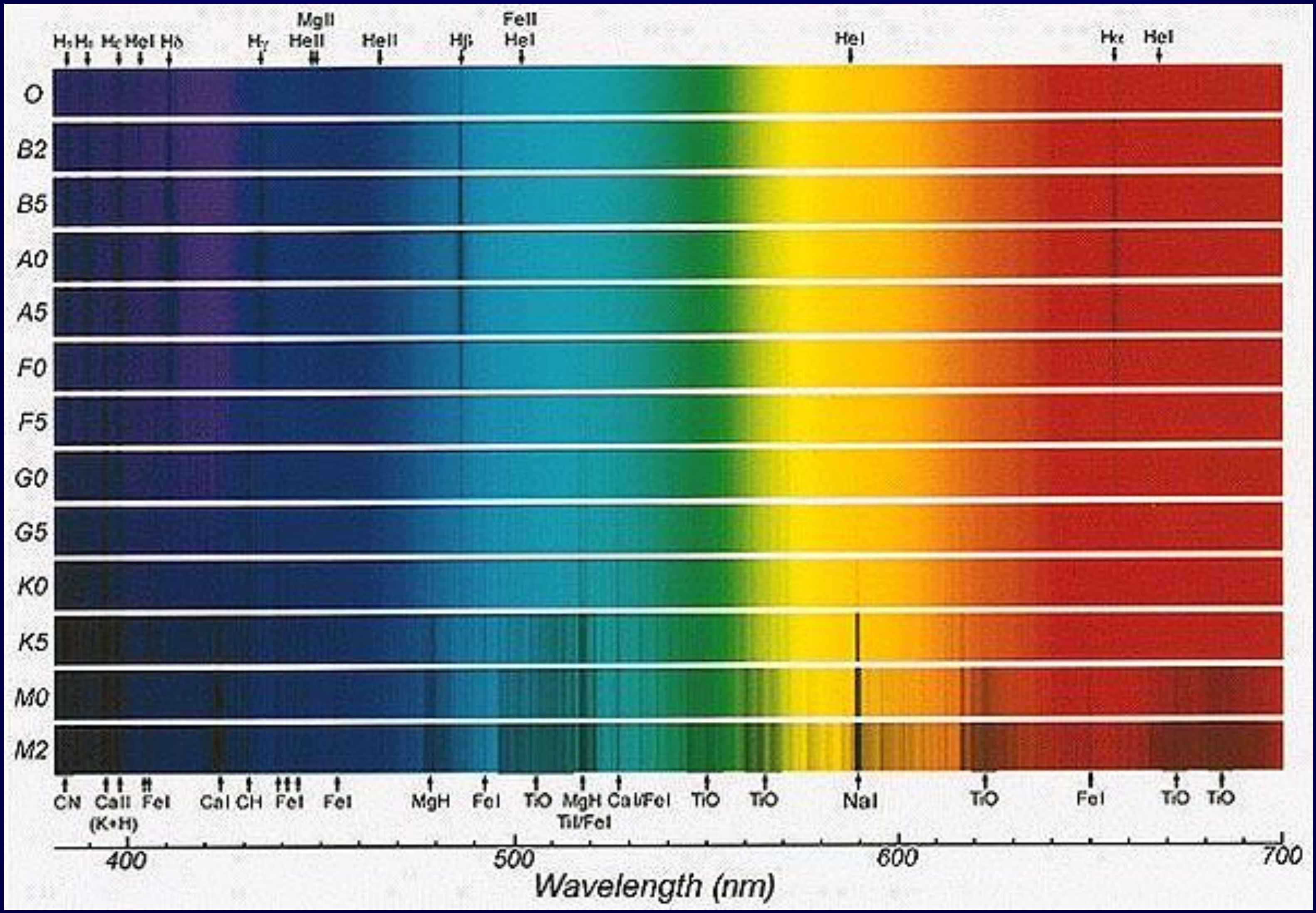


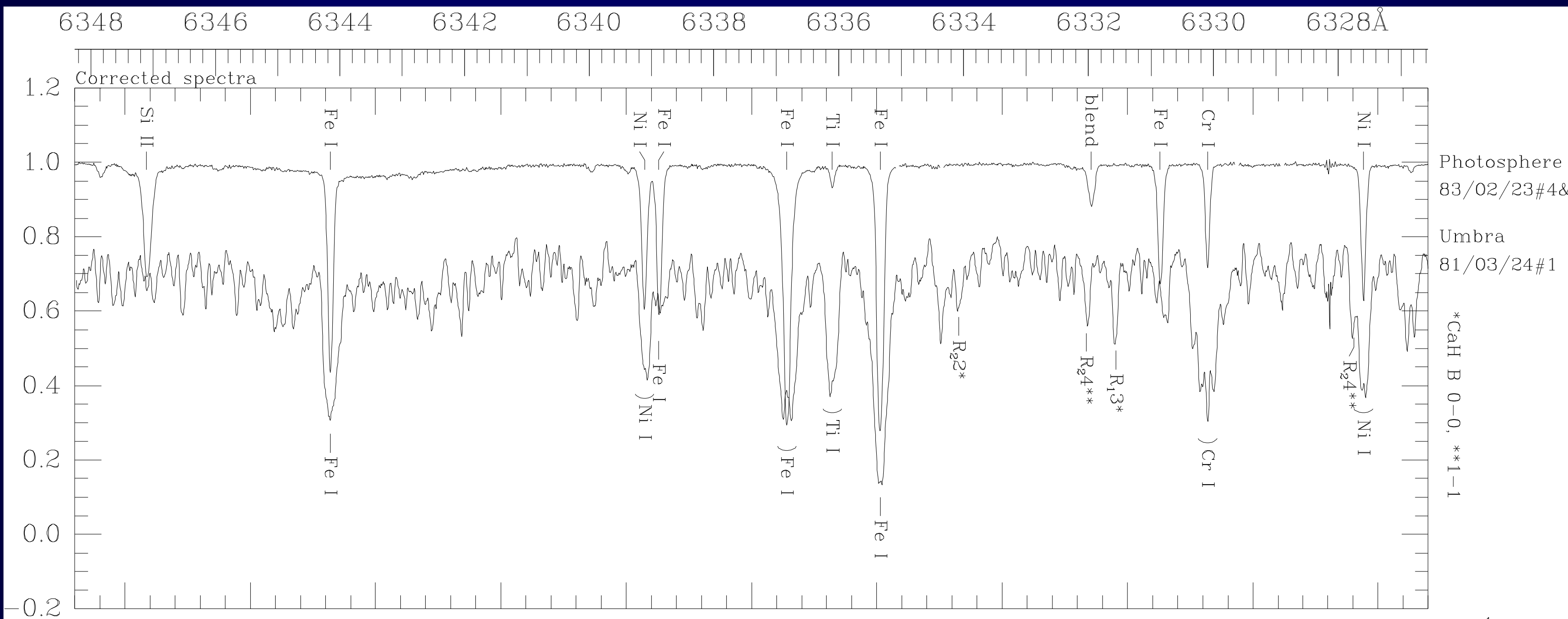
Temperature and Spectral Classification

Star of high temperature: most electrons excited to higher than 2nd level: weak Balmer



Temperature and Spectral Classification

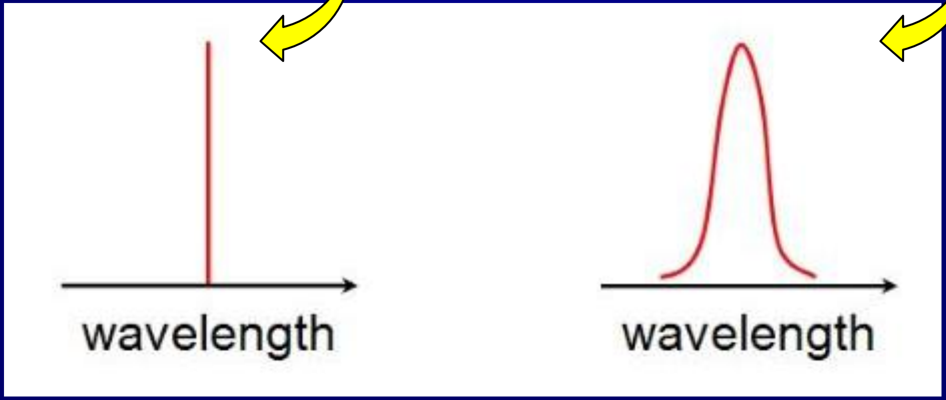




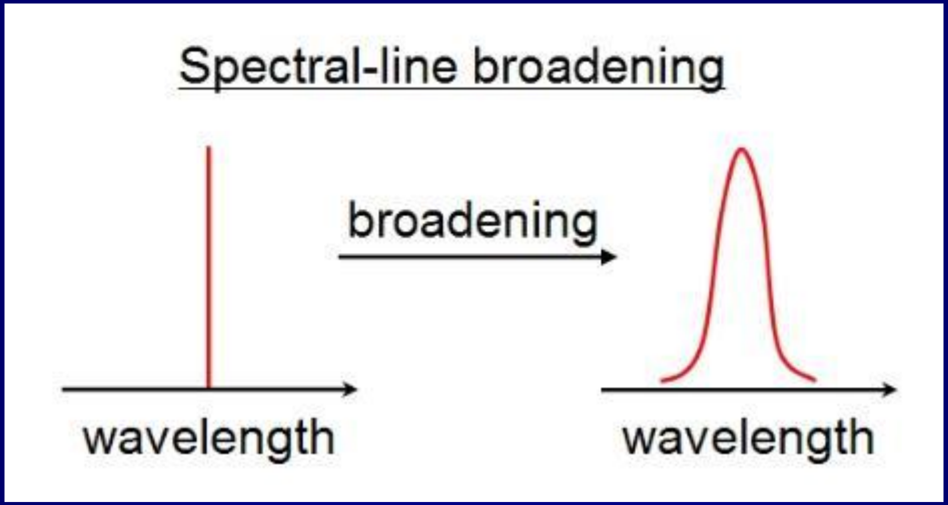
6348
6346
6344
6342
6340
6338
6336
6334
6332
6330
6328Å
Corrected spectra
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
Si II
Fe I
Ni I
Fe I
Ti I
blend
Cr I
$R_2 2^*$
$R_2 4^{**}$
$R_1 3^*$
Photosphere
83/02/23#4&7
Umbra
81/03/24#1
*CaH B 0–0, **1–1

Spectral Line Appearance

Why does a spectral line not look like this but like that ?



Spectral Line Broadening



- Energy levels not infinitely sharp
- Atoms move relative to observer

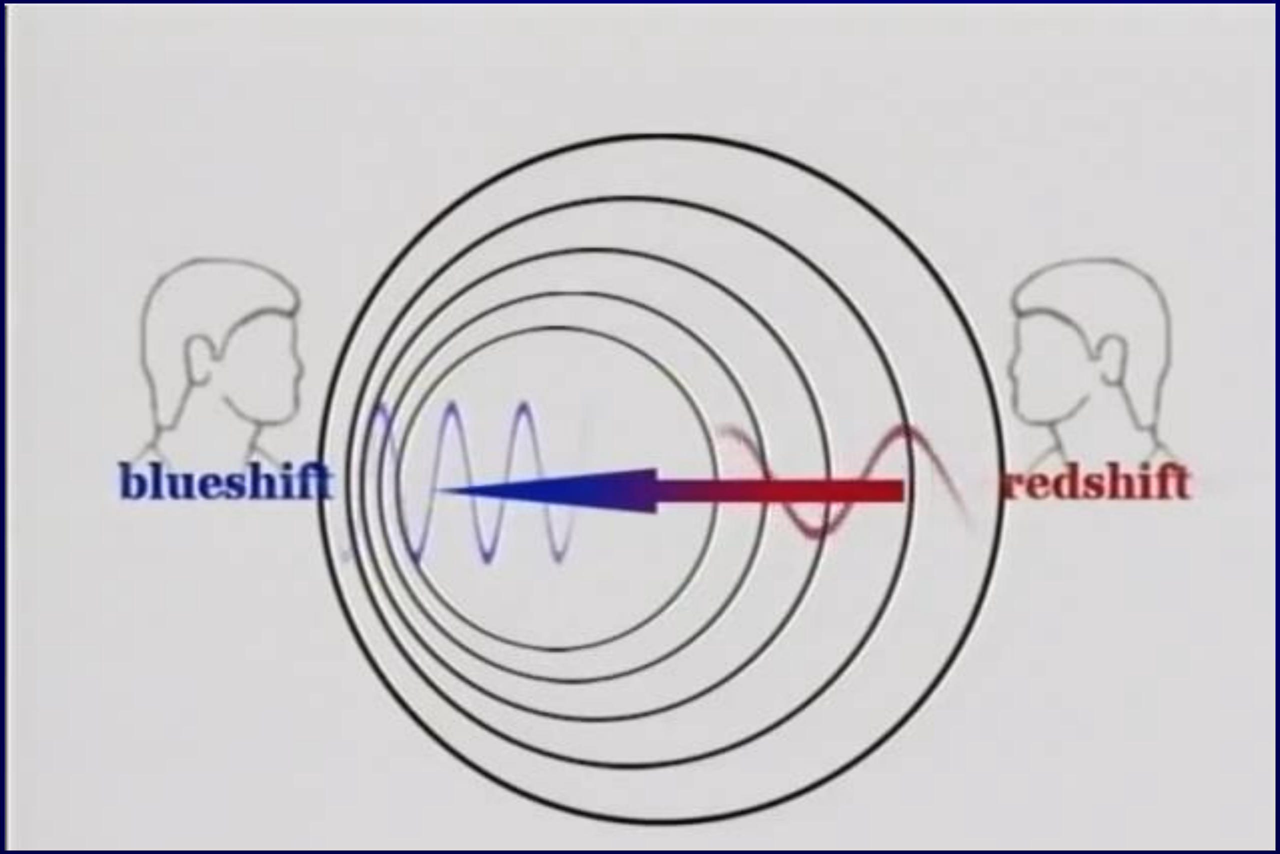
Doppler broadening

Light in Motion with spectroscopy

- Is the object moving away or towards us?
- Is the object spinning?
- Is the object expanding?
- Is the object orbiting another object?

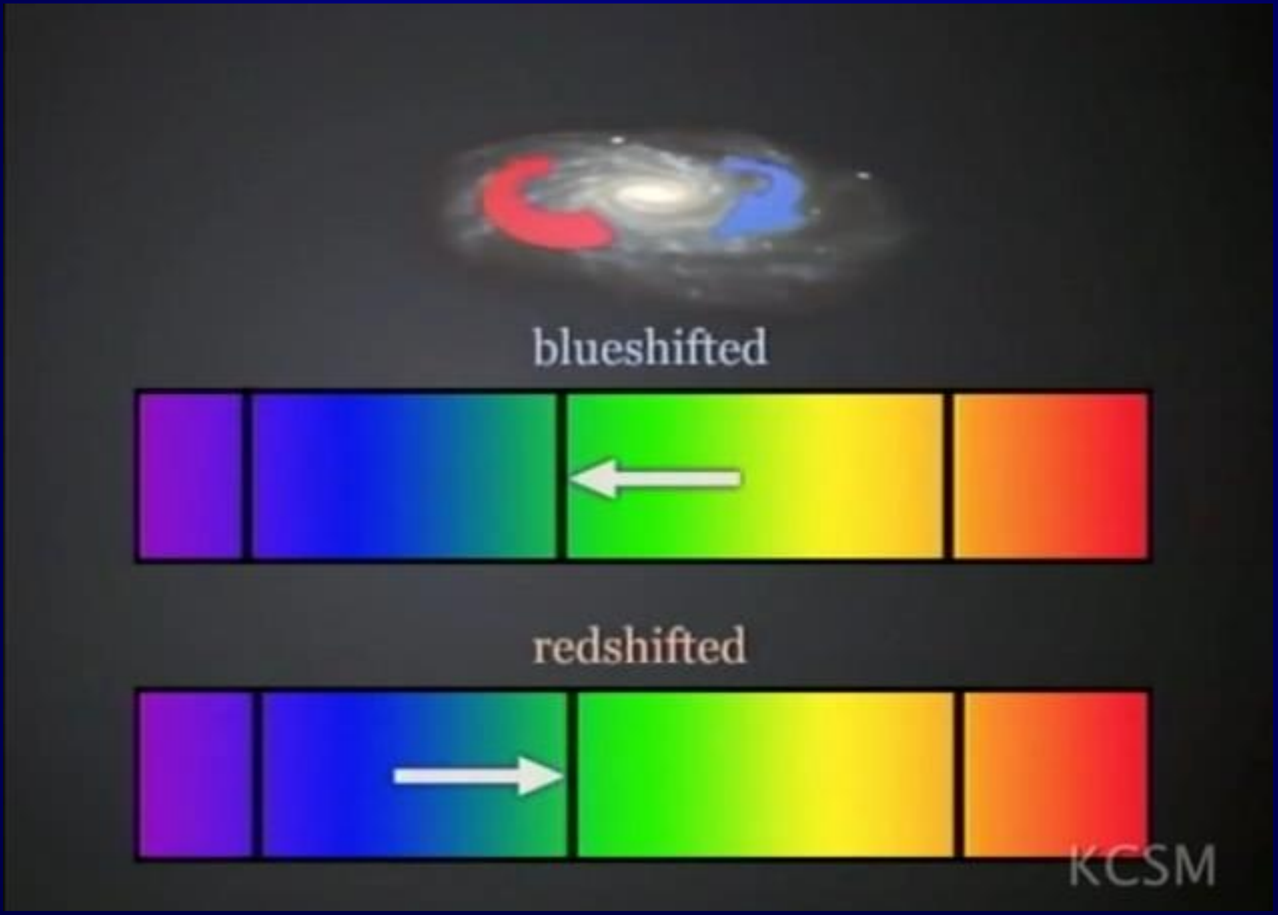
Doppler broadening

Doppler Effect



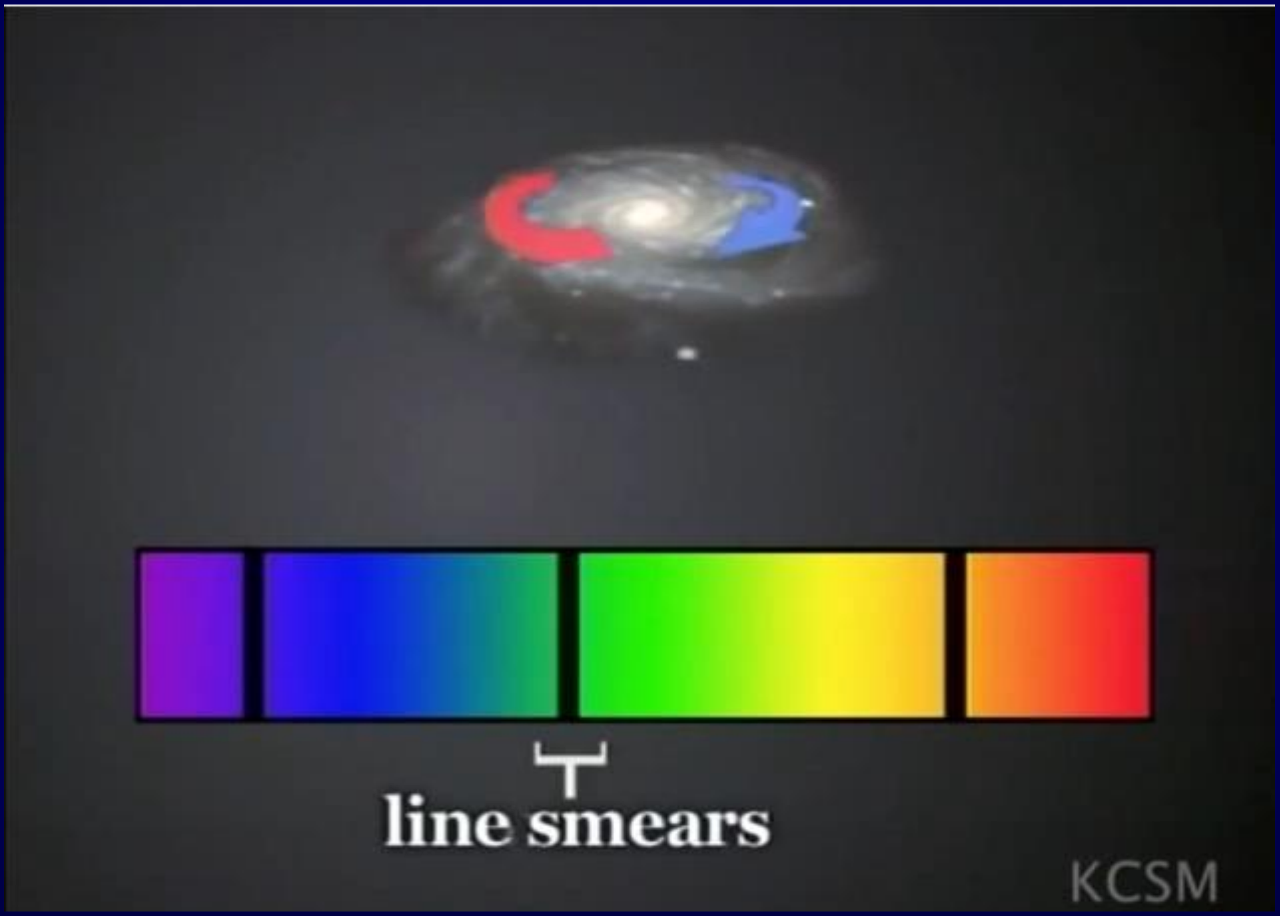
Doppler Broadening

Doppler Effect: Rotating object



Doppler broadening

Doppler Effect: Rotating object



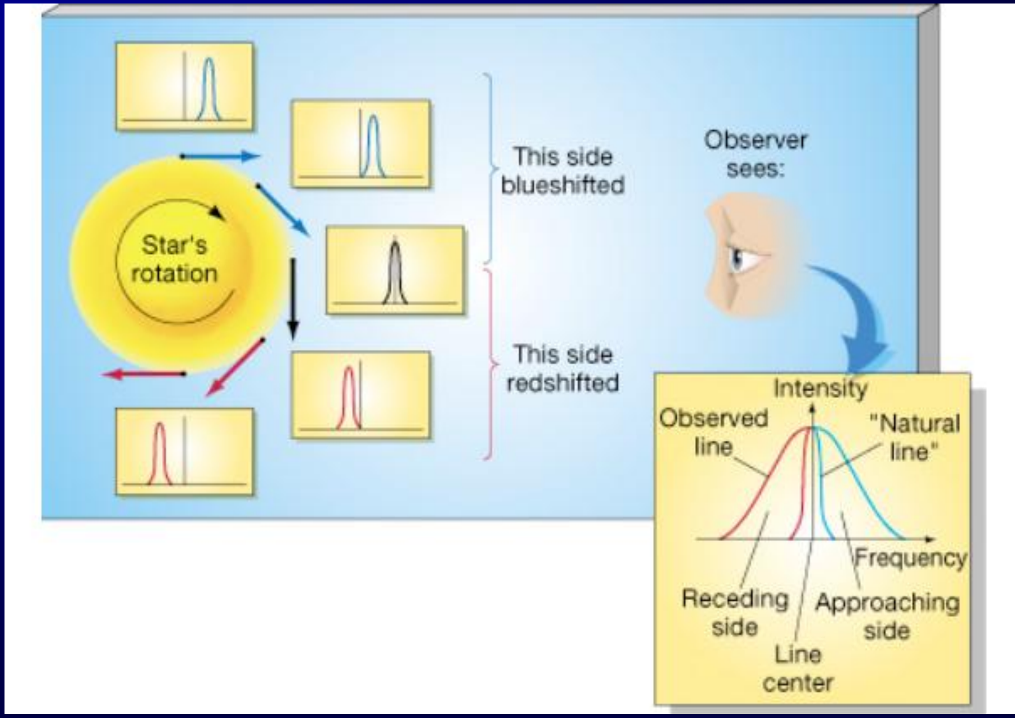
Spectral Line Broadening

Doppler broadening

-> Doppler profile (Gaussian)

moving towards us: blue-shifted

moving away: red-shifted



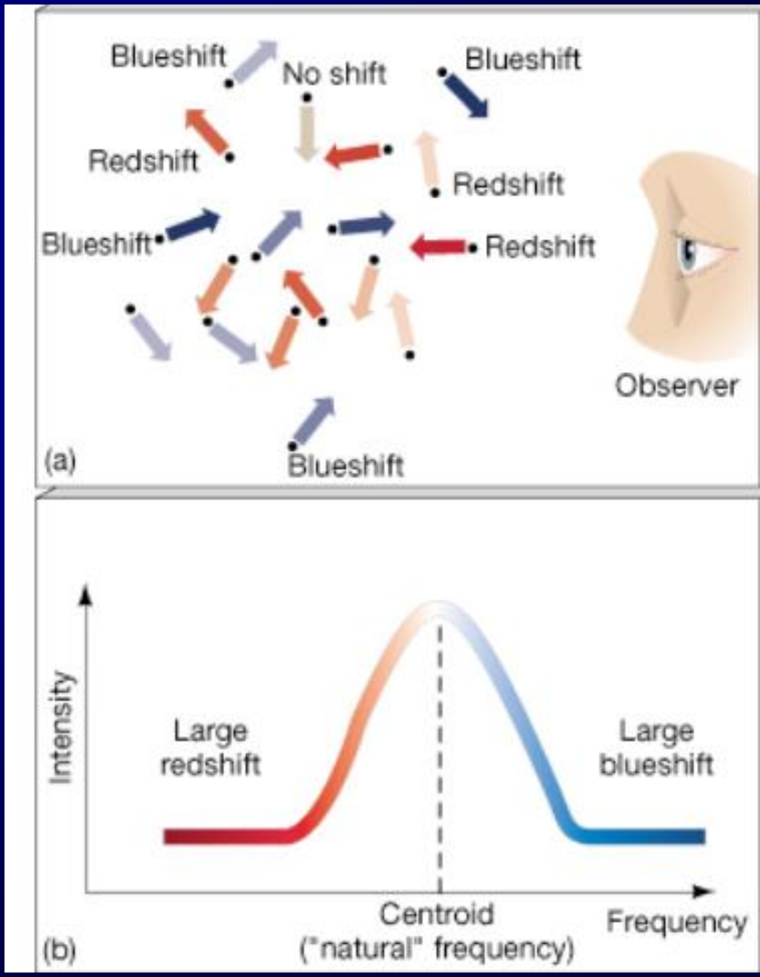
Spectral Line Broadening

Doppler broadening
-> Doppler profile (Gaussian)

Thermal Doppler broadening: atoms/molecules in random thermal motion

This kinetic energy is thermal: the hotter the gas of atoms, the faster they move about on average

=> the more the line is broadened



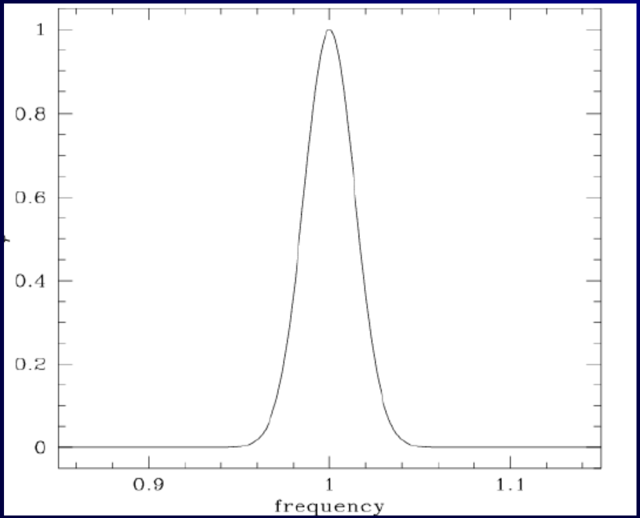
Spectral Line Broadening

Doppler width

$$\Delta\nu_D = \frac{\nu_0}{c}\sqrt{\frac{2kT}{m}}$$

-> Doppler profile (Gaussian)

$$\phi(\nu) = \frac{1}{\Delta\nu_D\sqrt{\pi}} e^{-((\nu-\nu_0)^2/(\Delta\nu_D)^2)}$$



faster decay than Lorentzian

Spectral Line Broadening

Natural (intrinsic) broadening

-> Lorentzian profile

Quantum-mechanical effect: the longer a state exists for, the greater the uncertainty in its energy $\Delta E \Delta t \sim \hbar$

=> all photons emitted by an ensemble of atoms in identical excited states will not all be exactly at the same energy

=> range of possible frequencies cluster around average energy

$$\Delta \nu \sim \frac{\Delta E}{h} \sim \frac{1}{2\pi \Delta t}$$

=> naturally broadened line (in line wings, usually small effect, in low pressure environments, nebula)

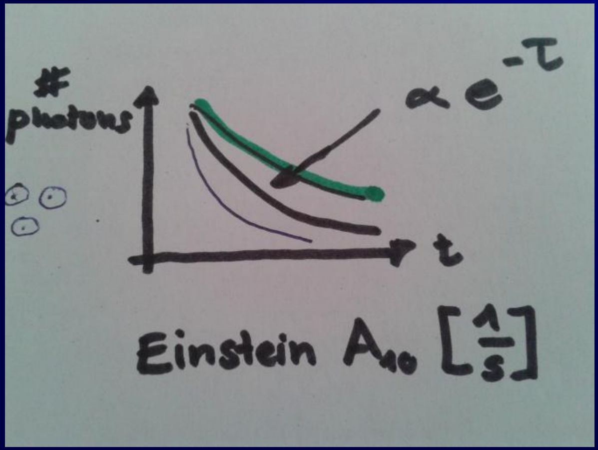
Spectral Line Broadening

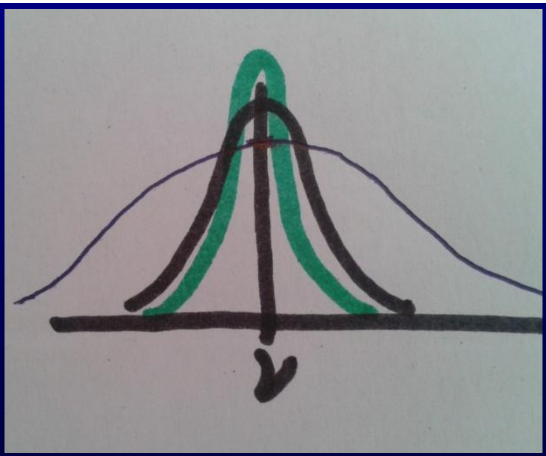
Spontaneous decay of state n to all lower energy states n'

$$\gamma = \sum_{n'} A_{nn'}$$

-> Lorentzian profile

$$\phi(\nu) = \frac{\gamma/4\pi^2}{(\nu-\nu_0)^2 + (\gamma/4\pi)^2}$$



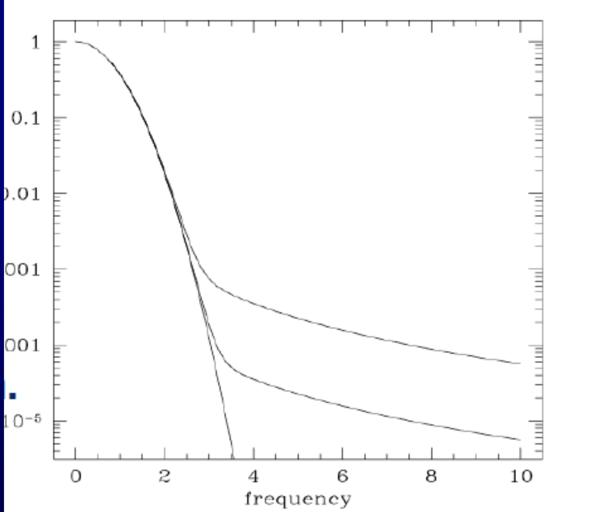


Spectral Line Broadening

Convolution of Lorentzian (natural/ collisional) and Doppler (thermal) broadening

-> Voigt profile (no analytic form)

Curves show the profile as the natural (or collisional) linewidth is increased.



Lorentz profile falls off slower than Doppler

-> core Gaussian, wings Lorentzian

Spectral Line Broadening

Collisional broadening

Collisional (pressure) broadening

Collisions of atoms => exchange of energy (particularly in plasma)

=> change of energy of electrons in excited atoms

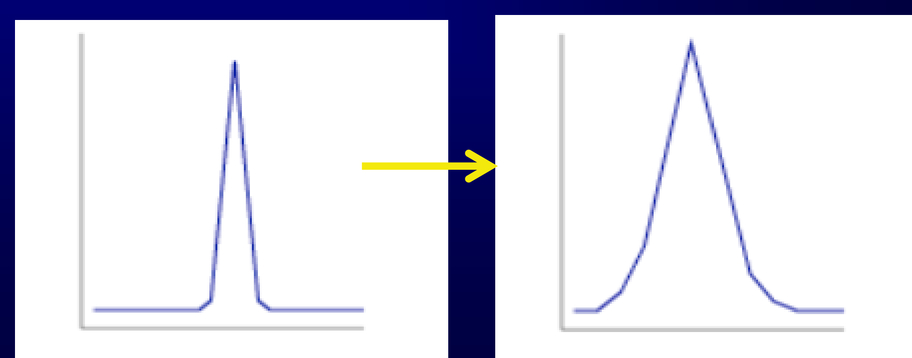
=> increase in spread of energies of emitted photons

more collisions when atoms/molecules closer, i.e. when pressure higher, collision reduce effective lifetime of an energy state

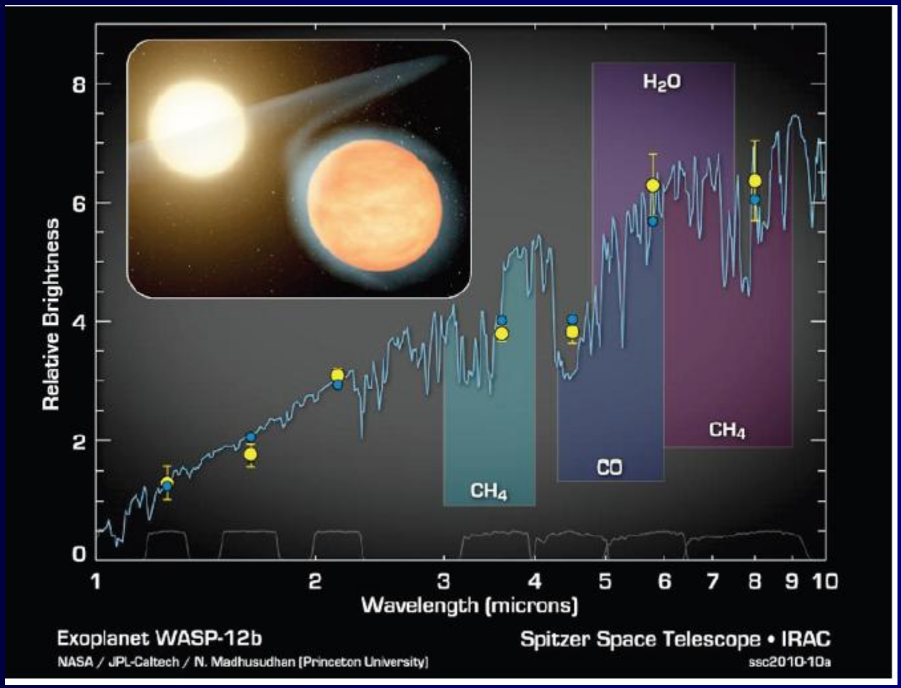
=> "pressure broadening"

still Lorentz, but wider

dominate in high density (dwarfs)

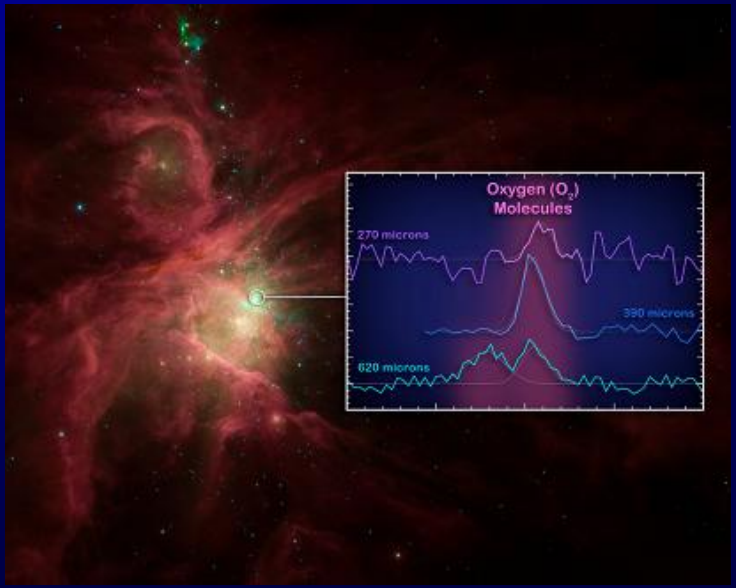


Molecular astrophysics - fields of study



NASA Spitzer Space Telescope, molecules in the planet WASP-12b - a super-hot gas giant that orbits tightly around its star. CO, CH4

In Eagle Nebula, cool molecular hydrogen gas, HST



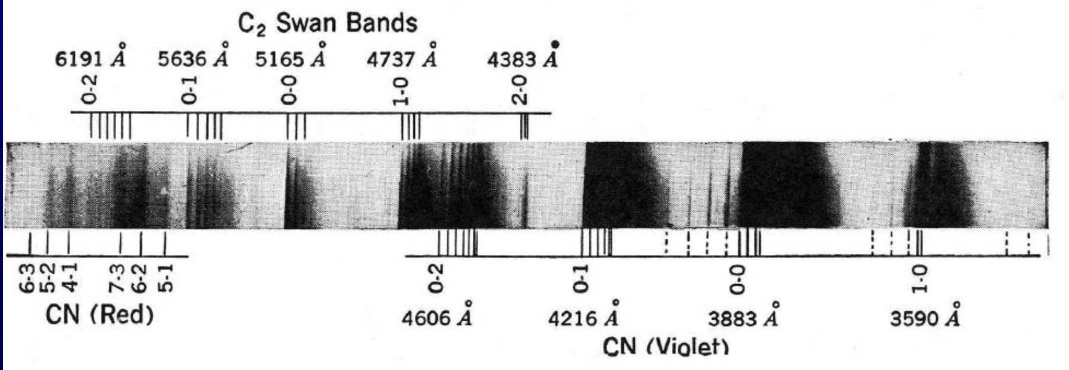
Orion nebula, O_2, ESA Herschel

Why molecules?

- Why study molecules in Astrophysics?
  - molecules are ubiquitous
  - universe as laboratory for molecular physics
- Why study molecules in cool stars?
  - dominating species
  - large number of transitions
  - high temperature and pressure sensitivity
  - molecular spectra as diagnostics:
    - thermodynamic structure of cool stars
    - chemical composition
    - isotopic composition
    - stellar magnetic fields

Molecular Spectroscopy

- In addition to the continuous and line spectra, spectra with entirely different structure: without single sharp lines but broad wavelength feature (bands): band spectra: sources are molecules
- Bands result from large number of blended individual molecular lines
- Molecular spectroscopy: study of the absorption, emission, and scattering of electromagnetic radiation by molecules



C_2 and CN
(from Herzberg 1950)

Molecular Spectroscopy

Bohr postulates:

- a molecule can exist only in states of definite energies, in the stationary states; as long as the molecule is in one of these states, it does not emit or absorb light;
- light absorption or light emission is possible only as a result of a transition between two stationary states.

<u>For the interpretation of a spectrum: establish the terms/energy levels of the stationary states</u>

Molecular Spectroscopy (vs. Atomic spectroscopy)

- Much more complex because of greater complexity of internal motion in molecules
- In addition to motion of electrons, vibrational motion of the nuclei about equilibrium positions and rotational motion of the molecule as a whole
- Three types of energy levels and three types of spectra - electronic, vibrational, and rotational - correspond to these three types of motion
- $m_{electron}/M_{nucleus} \simeq 10^{-3}$–$10^{-5}$: rates of motion of nuclei small compared to the velocities of the electrons => dynamics of nuclei and electrons largely independent

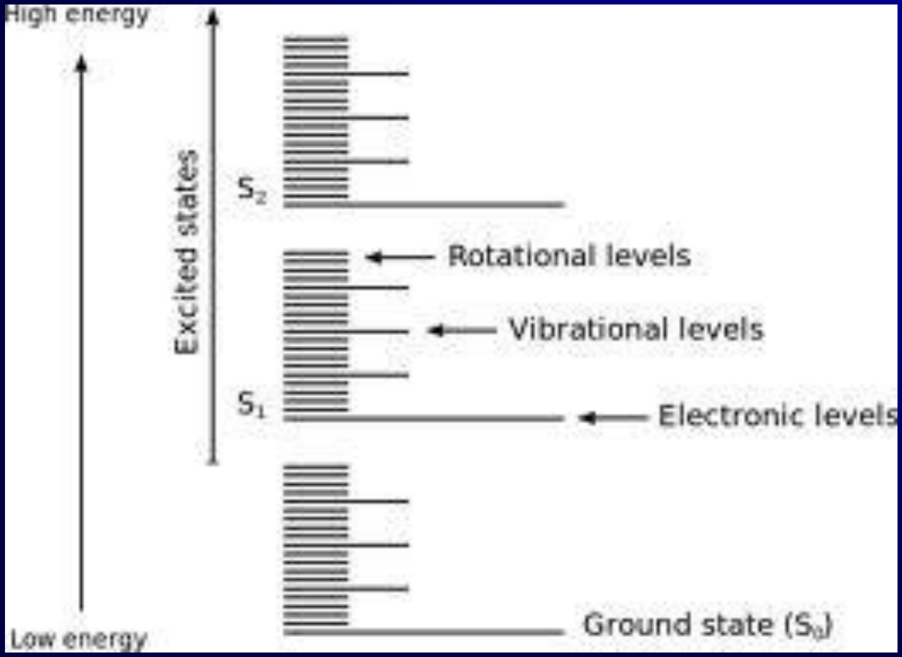
Molecular Spectroscopy

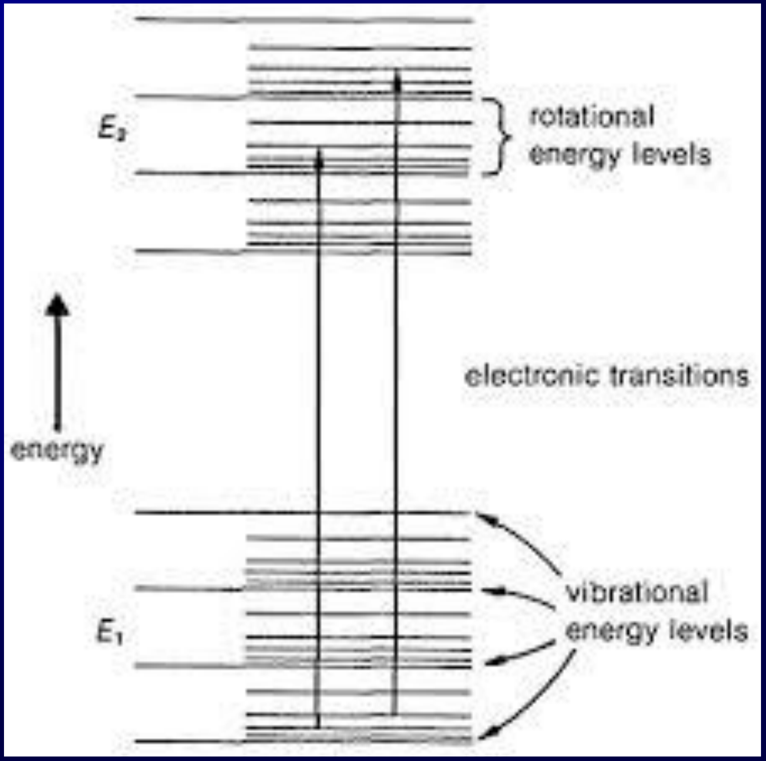
- Atoms/Molecules interact with electromagnetic-radiation to transition between energy levels
- Study transitions between energy levels
- Different transitions
  - Electronic: UV-visible
  - Vibrational: IR
  - Rotational: microwave

↑ energy ↓ λ

Molecular Spectroscopy

- Depending on which radiation, the molecule will induce a transition corresponding to the wavelength of the radiation





Molecular Spectroscopy (diatomic molecules)

- Total energy of molecule (without spin and magnetic interactions): $E = E_e + E_v + E_r + \Delta E_{ev} + \Delta E_{er} + \Delta E_{vr}$

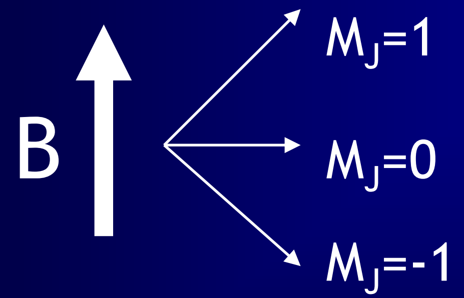
  E_e: electronic energy,
  E_v: vibrational energy,
  E_r: rotational energy,
  ΔE_{ev}: electronic-vibrational interaction,
  ΔE_{er}: electronic-rotational interaction,
  ΔE_{vr}: vibrational-rotational interaction.

  $E_e \gg E_v \gg E_r.$

  => changes in electronic configuration around nuclei give rise to the band systems
- the bands within the band systems come from transitions between different vibrational states of the nuclei
- the transitions between the different rotational states give rise to the lines within the bands.

Magnetic Fields and Molecular Spectra

- Spinning electrons induce magnetic fields
- Magnetic dipoles
- Magnetic dipoles interact with external magnetic field to split electronic energy levels that are normally degenerate

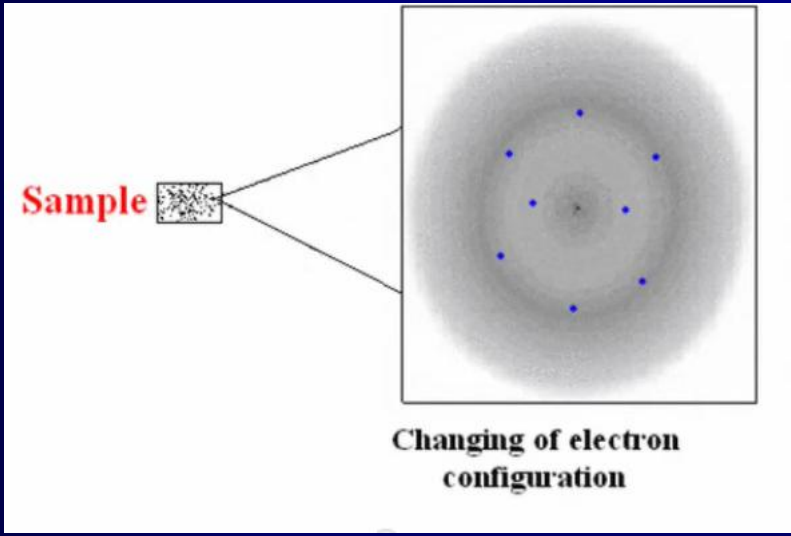


energy of each magn.dipole will change with external magnetic field

<u>Zeeman effect: splitting of energy levels in presence of magnetic field</u>

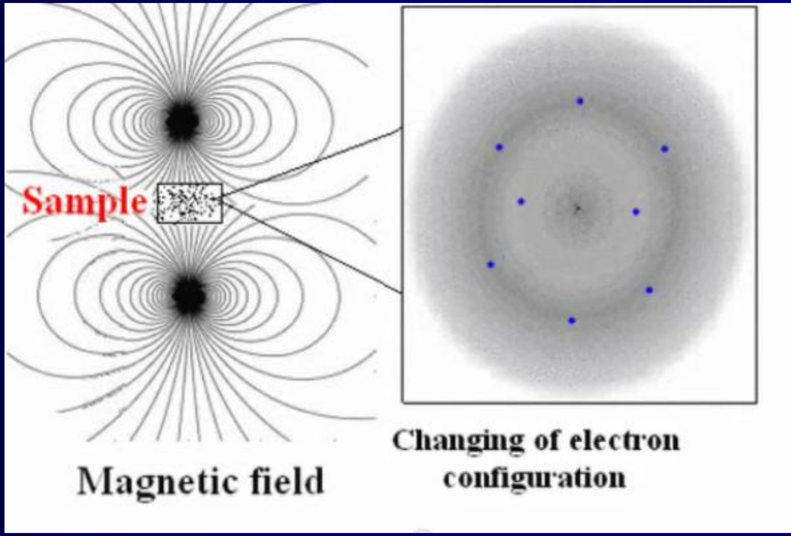
Zeeman Effect in Molecular Spectra

- Change of electron configuration in presence of magnetic field:



Zeeman Effect in Molecular Spectra

- Change of electron configuration in presence of magnetic field:



Zeeman Diagnostics

Direct magnetic field measurement with Zeeman effect:

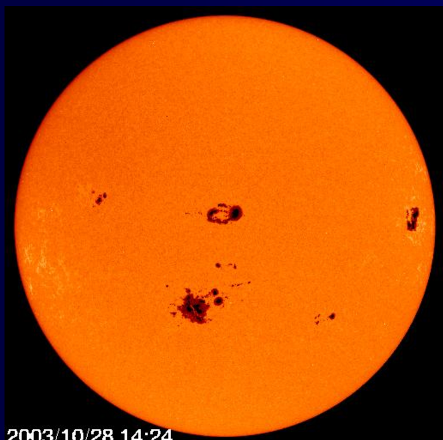
- Observation of magnetically induced splitting (change of shape of spectral line)
- Measurement of polarization important for measuring solar magnetic fields

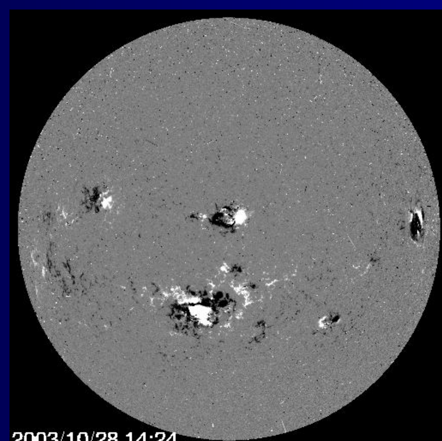
Magnetic Fields

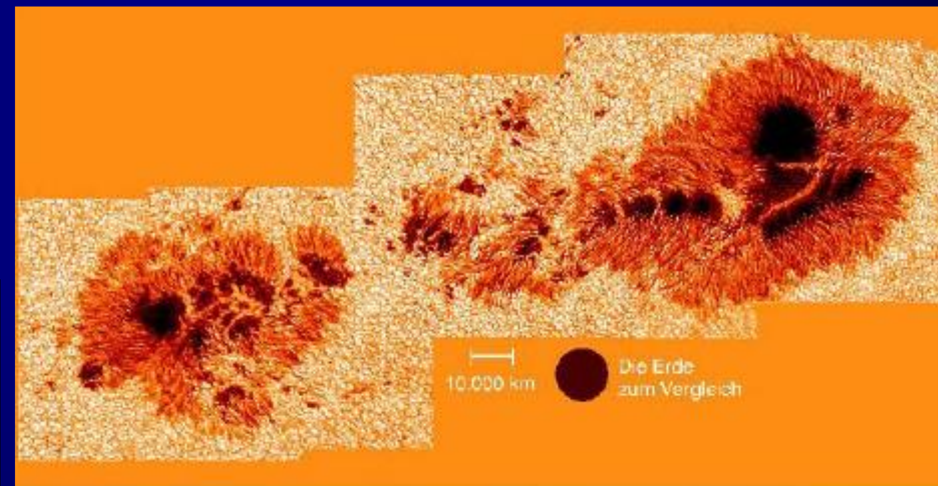
- Importance of magnetic fields
  - Solar magnetic field: variety of magnetic phenomena, laboratory, dynamo theories, Sun as star, source of activity, evolution
  - M-dwarfs: transition from stars with an outer convection zone to fully convective stars, where solar type dynamo is replaced by alternative mechanism to amplify magnetic fields
  - Exoplanets: magnetospheres as protective shields -> habitability

Applications in Solar Astrophysics

Sunspots



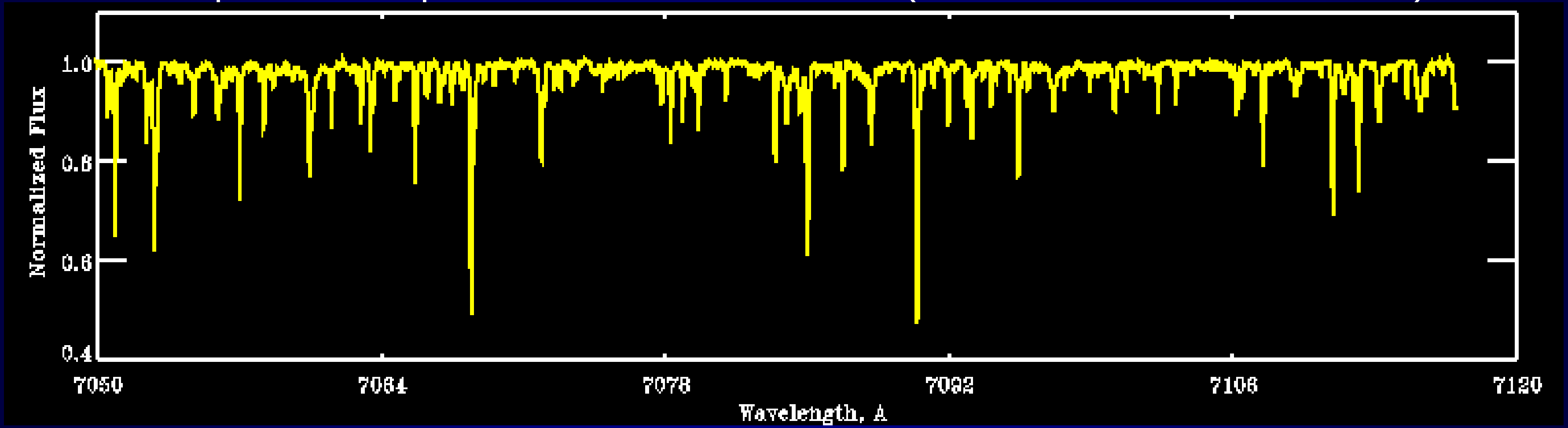




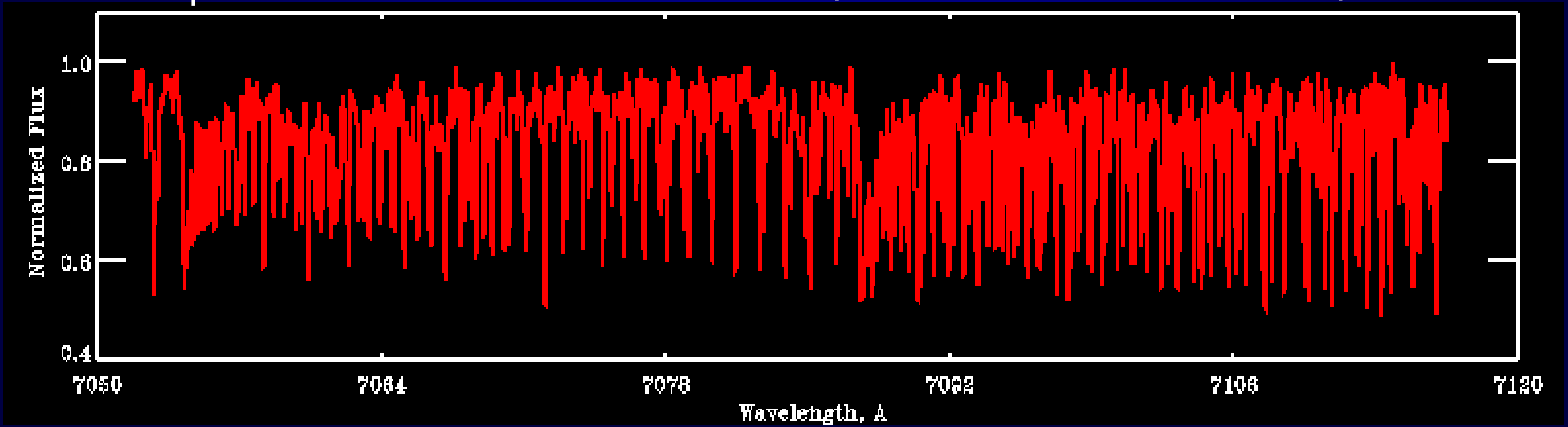
Chronicles, John of Worcester, 1128

Molecules in Sunspots

- Solar photosphere = G stars (5000K<T<6000K)

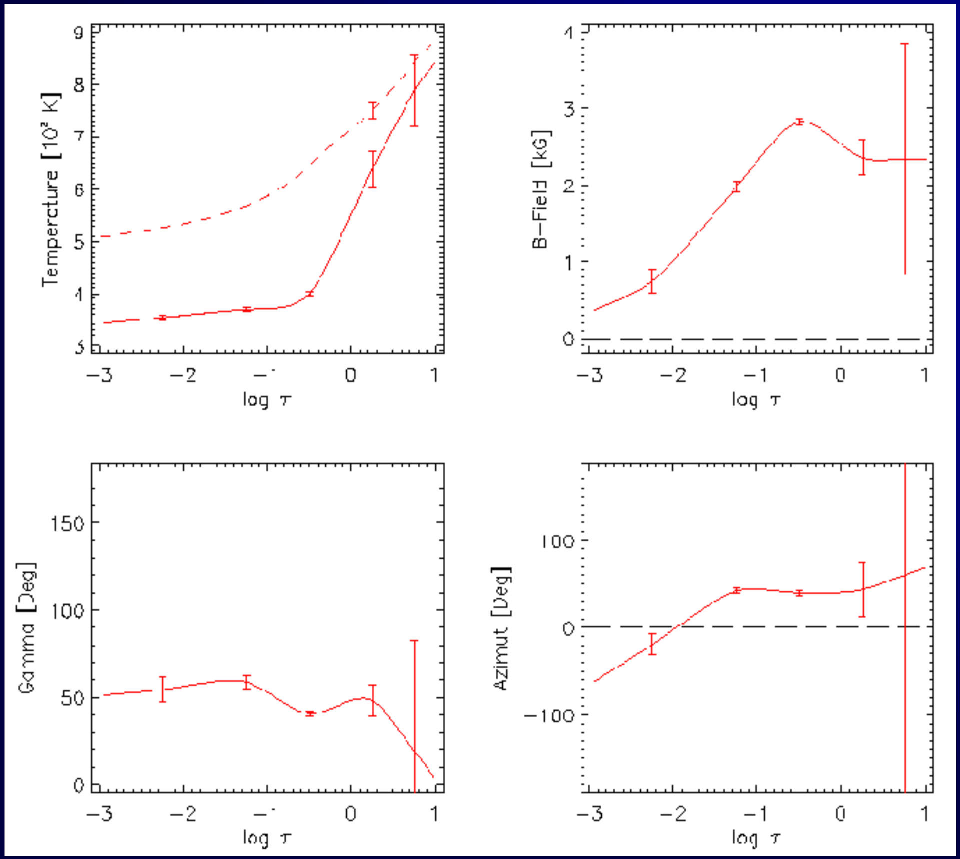


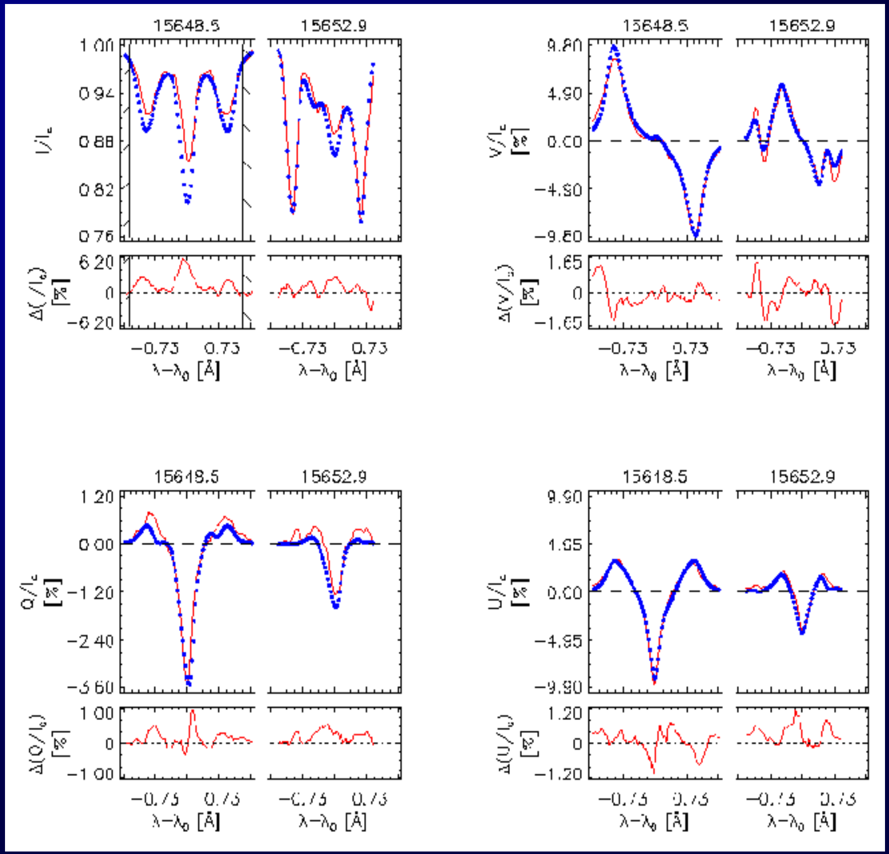
- Sunspot umbra = M stars (2000K<T<4000K)



Interiors of Sunspots - Inversions

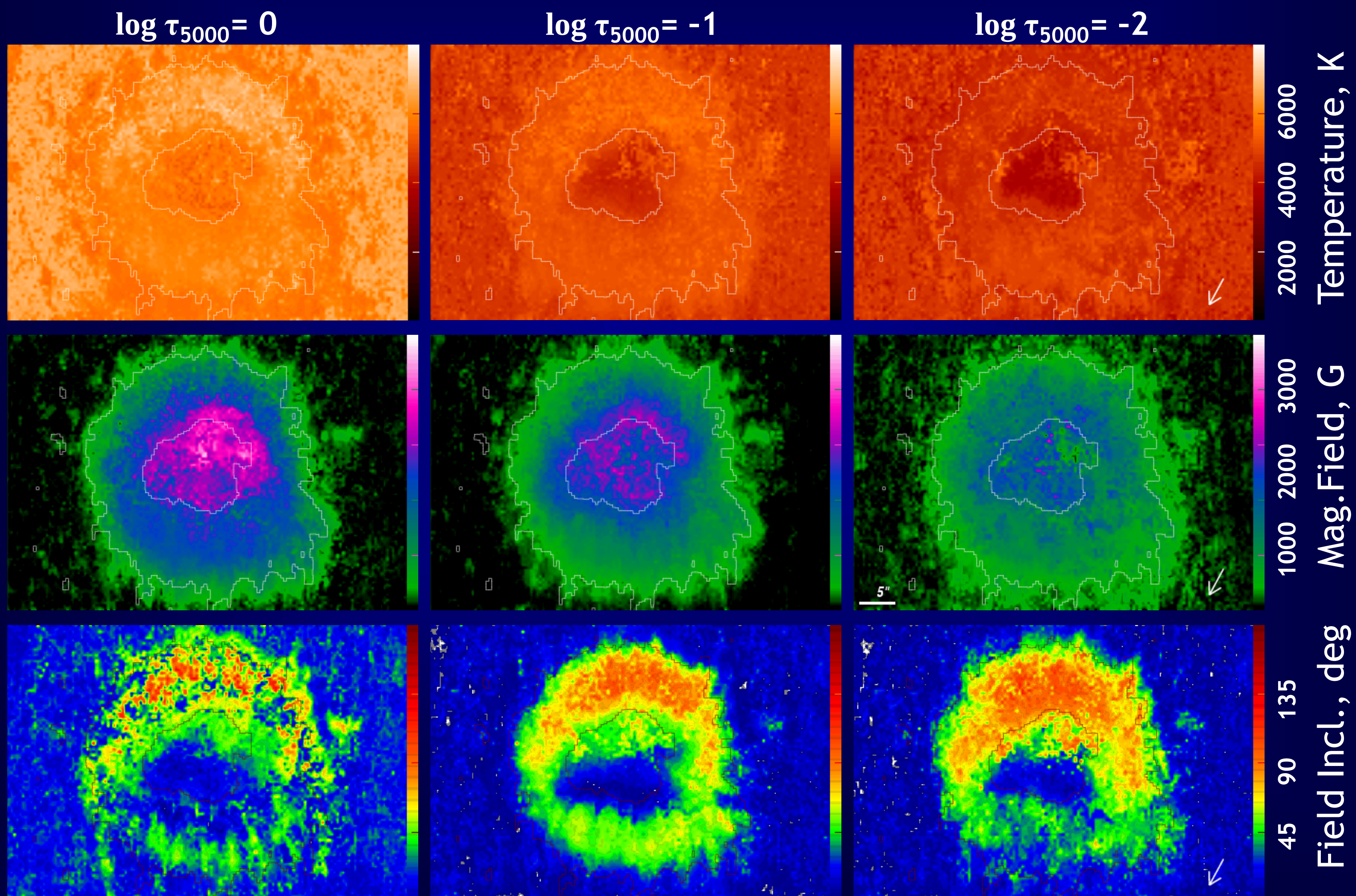
- The nonmagnetic component becomes as hot as the photosphere
- The field strength of the magnetic component drops towards higher layers
- The field direction corresponds well to the observed position of the sunspot on the solar disk





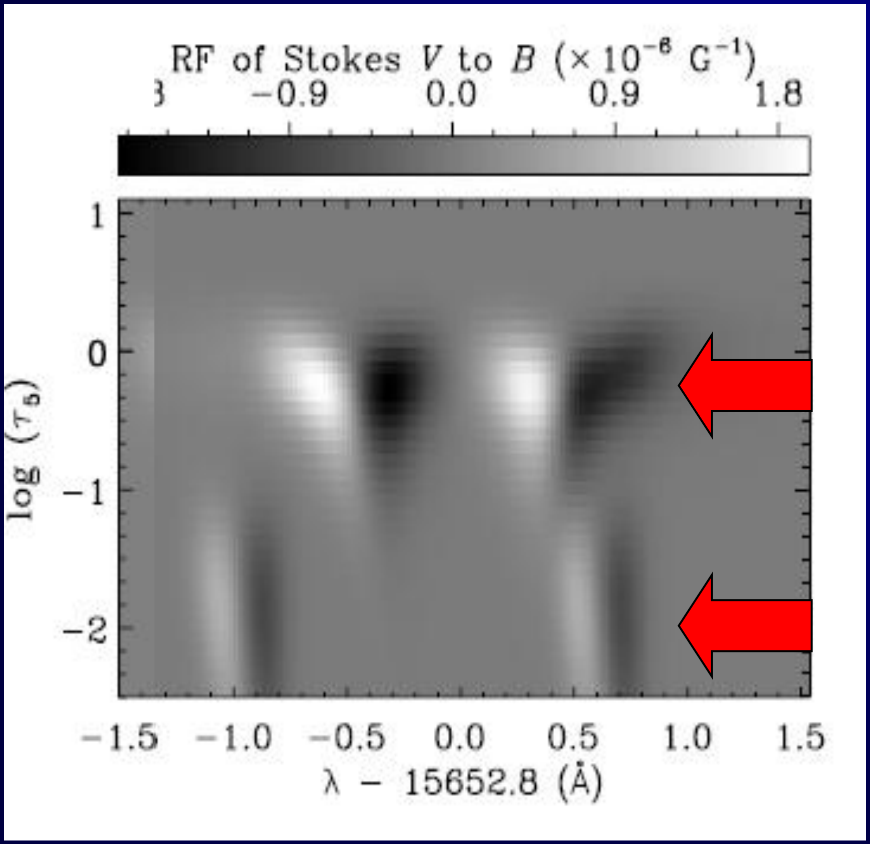
Interiors of Sunspots

(Mathew et al. 2002)



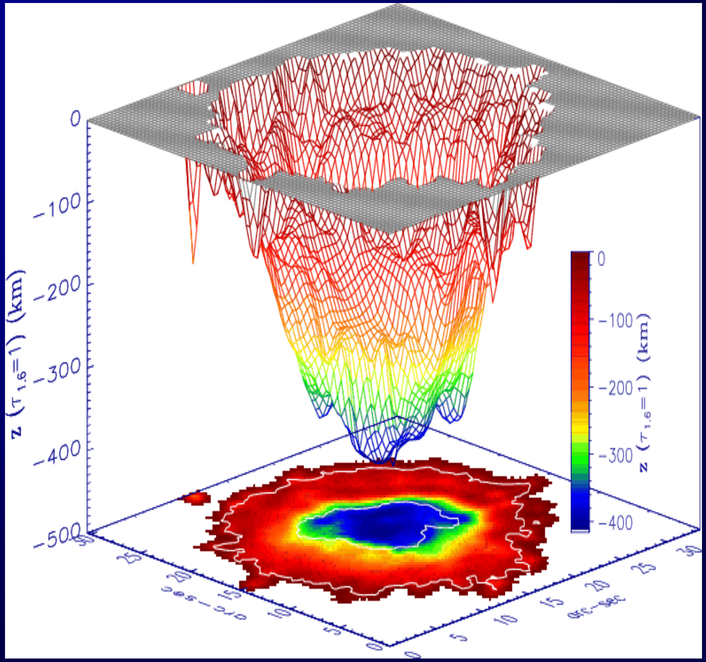
Sunspots – 3D structure

- Simultaneous inversion of atomic and molecular lines



Fe I

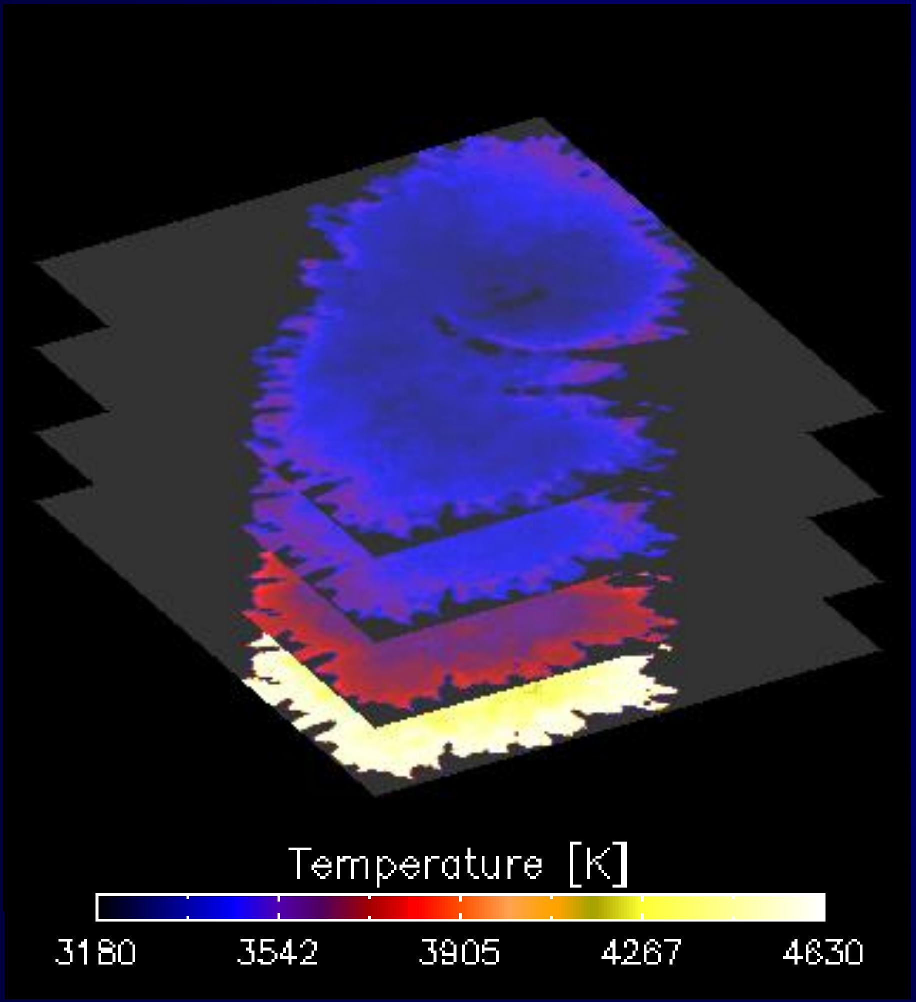
OH

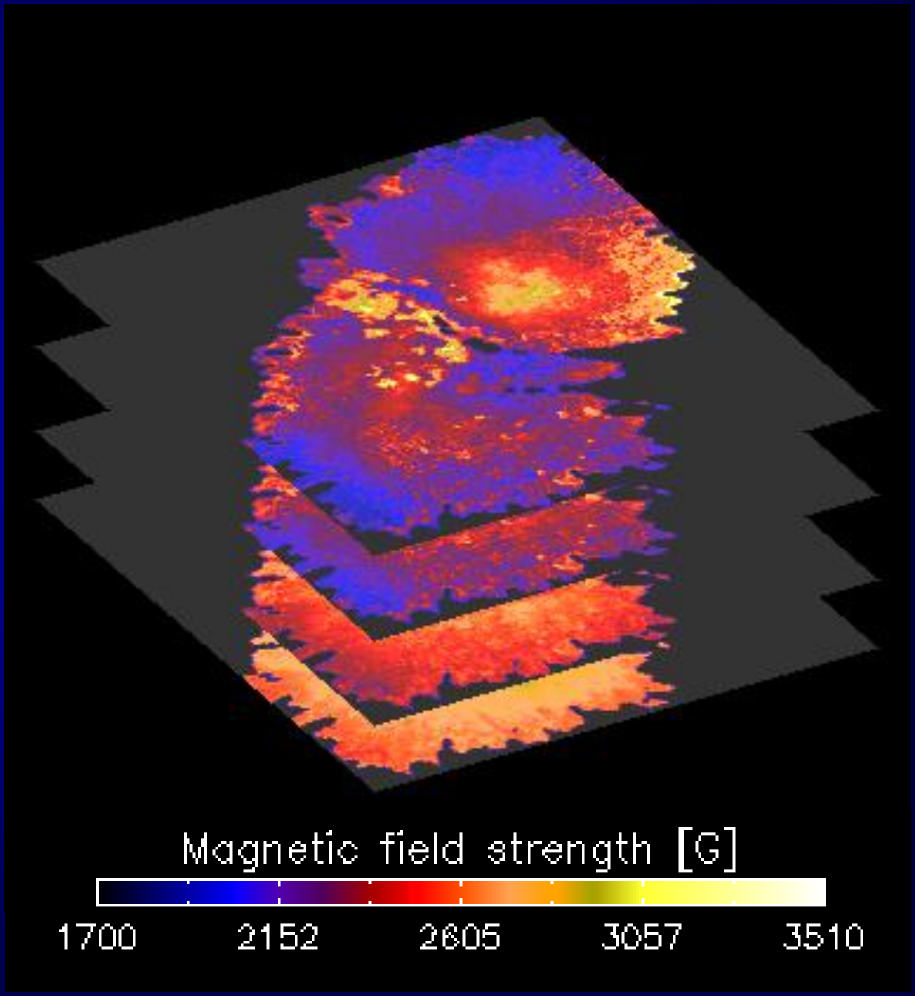


Mathew et al. (2003)

Mathew et al. (2004)

Sunspots - 3D structure



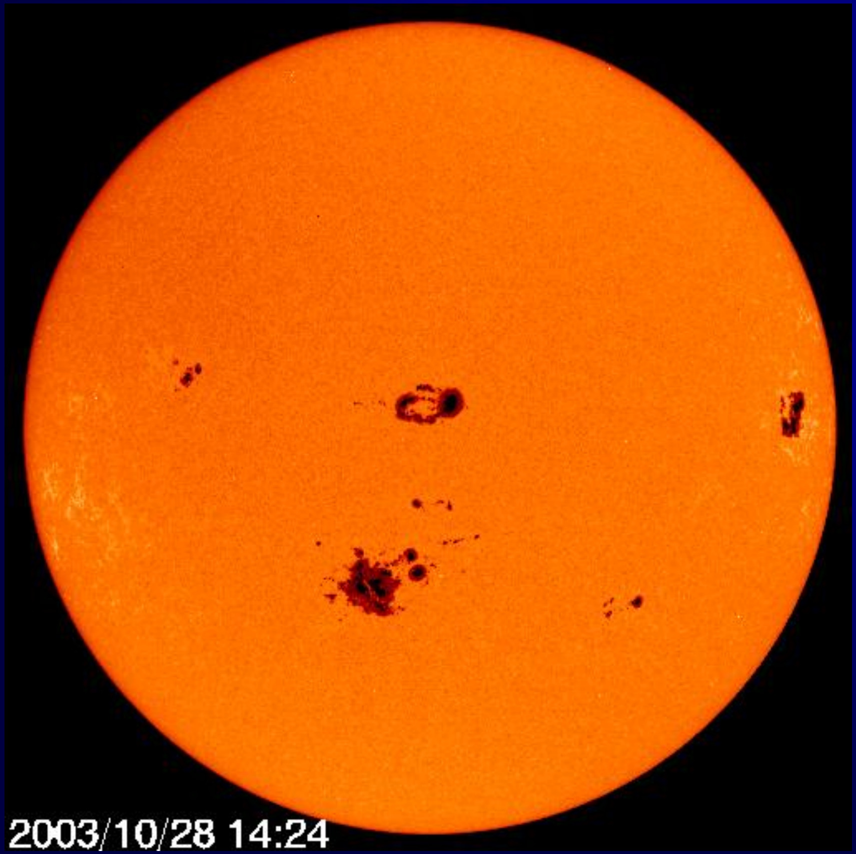


log τ = 0, −1, −2, −3

Berdyugina et al. (in prep)

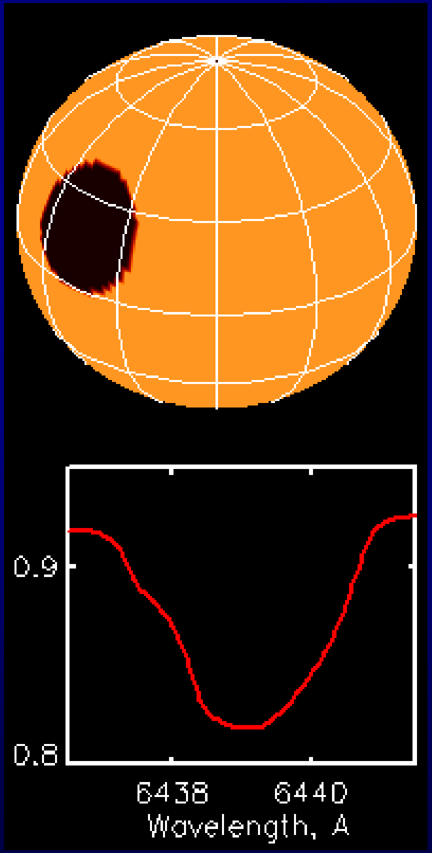
Starspots

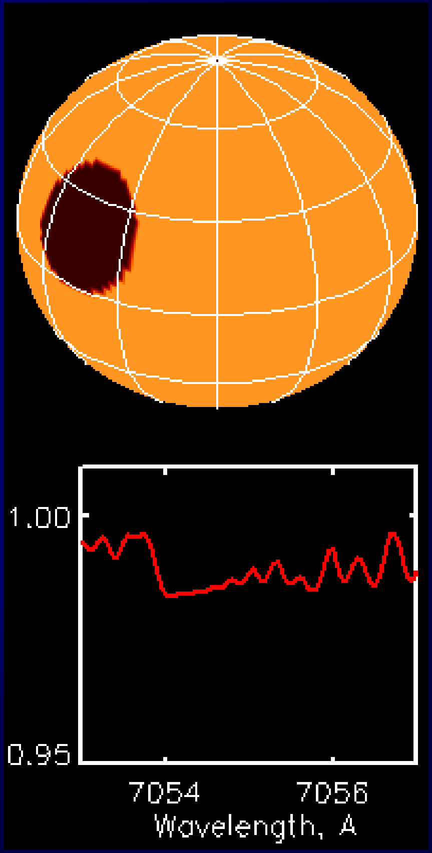
- Direct Imaging



SOHO/MDI

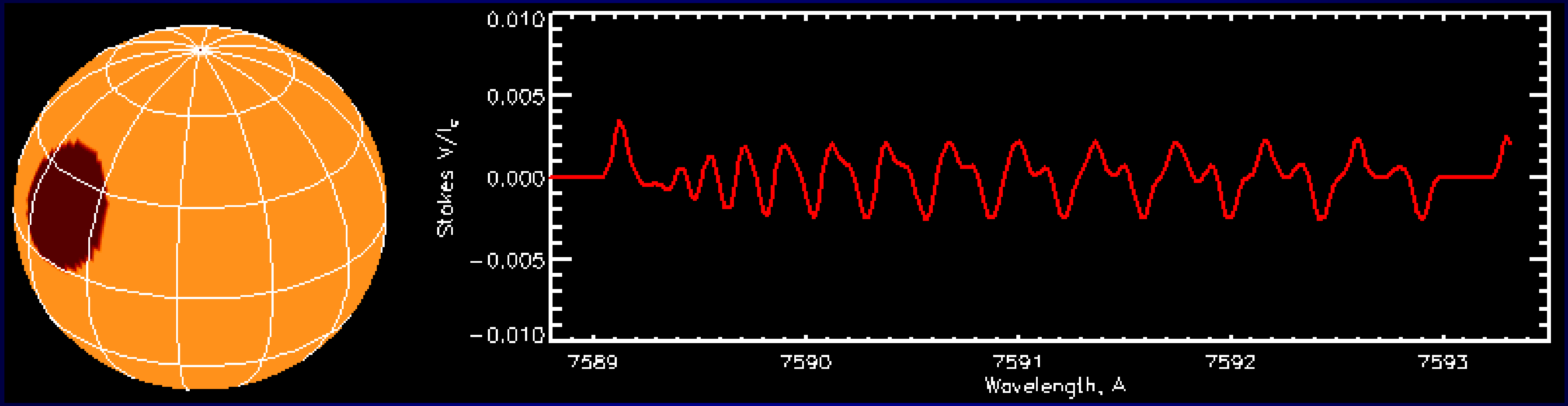
- Doppler Imaging





Molecular Polarization in Starspots

TiO

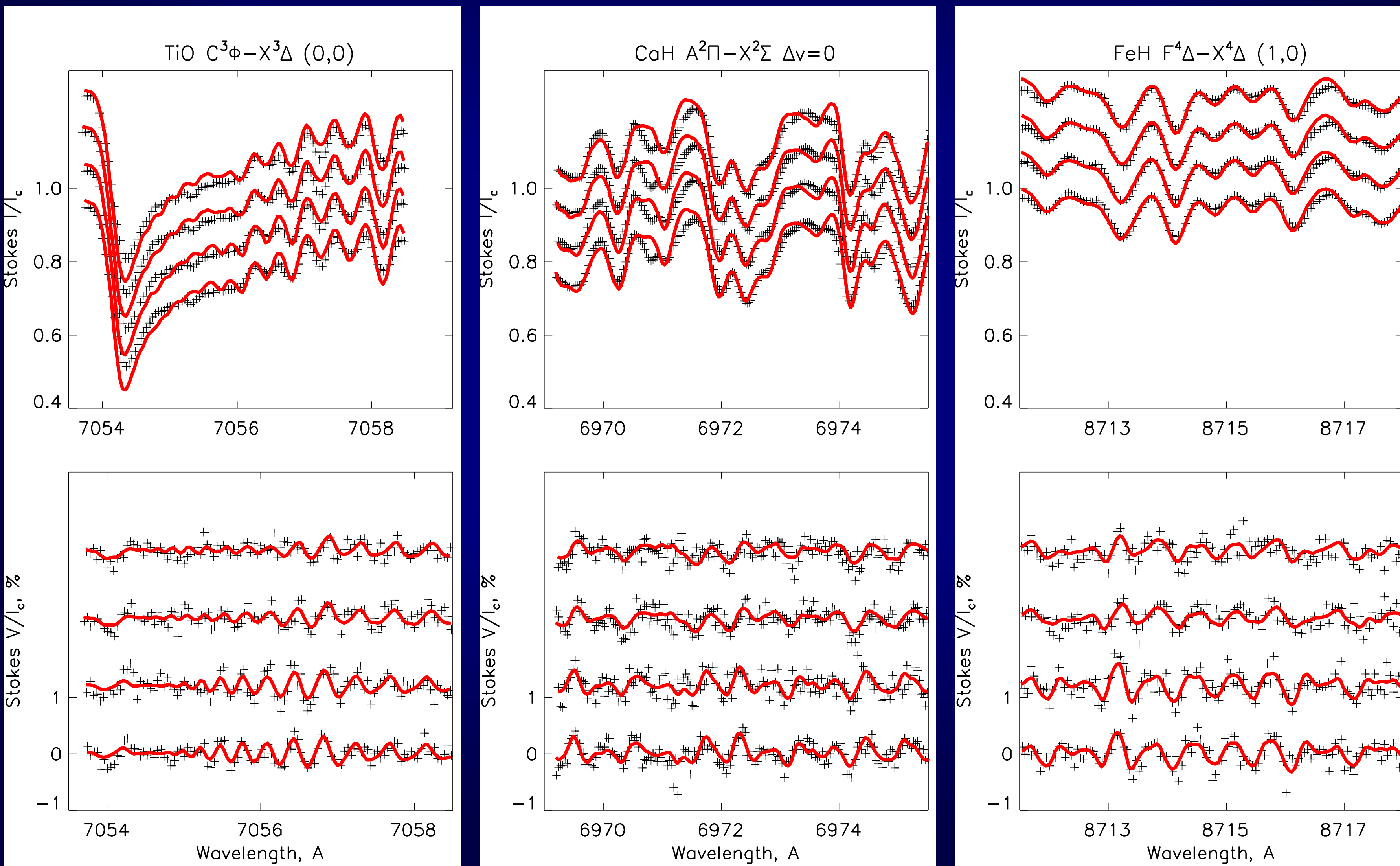


Observations:

- 2005-2007, CFHT, ESPaDOnS
- Noise in V/I_c ~ 10^{-3}, R~67' 000
- Max(V/I_c) ~ 1%
- First detections: TiO, CaH, FeH, MgH

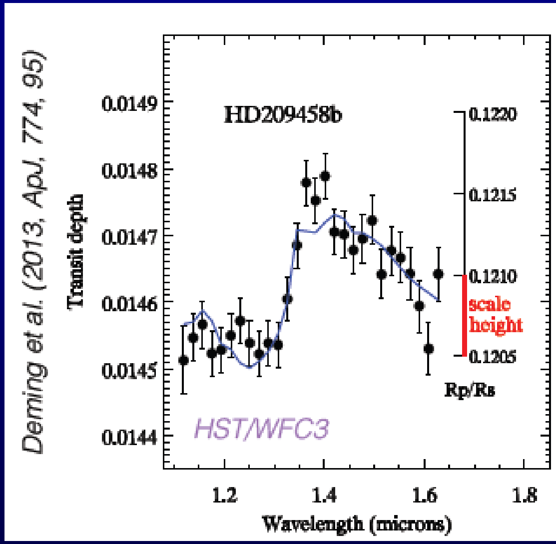
Berdyugina et al. (2006,2008)

Starspots - Molecular Lines



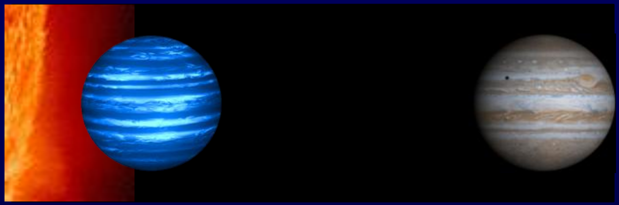
Exoplanet spectra

- Search for bio-signatures in exoplanetary spectra
- Water features (HD209458b)
- Cloudy atmospheres



Molecules as probes of exoplanet atmospheres

- Clouds important in exoplanetary atmosphere (main opacity source)
- Formation and evolution of clouds not understood
- => Modeling of cloudy atmosphere in Hot Jupiters and Brown Dwarfs
- Hot Jupiters: exoplanet similar to Jupiter, higher surface temperatures (closer orbit)



- Brown dwarf: form similar to star, but not massive enough for Hydrogen fusion

Method

- model molecular (reflectance) spectra (H_2O, TiO, FeH) with/out clouds
- vary cloud parameters (dust density, dust size, cloud position, cloud extension)
- study changes in molecular signal due to cloud parameter change, as molecules are formed at different depths => info about cloud

Literature

- **Tennyson** ‚Astronomical Spectroscopy'
- **Herzberg** ‚Molecular Spectra and Molecular Structure: Spectra of Diatomic Molecules'
- **Haken/Wolf** ‚Molecular Physics and Elements of Quantum Chemistry: Introduction to Experiments and Theory'
- **Khristenko** ‚Molecules and their Spectroscopic Properties'