The Interstellar Medium
A brief introduction

Planets and Astrobiology (2018-2019)
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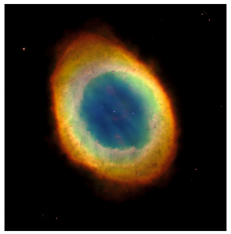
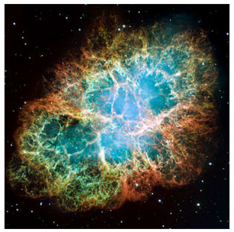
Constituents of the ISM: circumstellar regions

Reflection nebulae
HII regions
Planetary nebulae
Supernova remnants





The diffuse interstellar medium

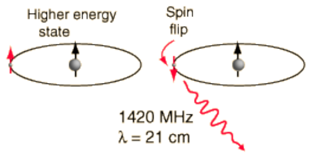
Gas (≈ 99% by mass)
Atomic, ionized, molecular
Covering a broad interval of temperature and pressure
Dust (≈ 1% by mass)
Cosmic rays
Magnetic fields

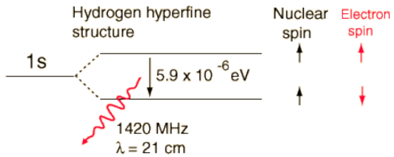
Occupies most of the volume of the Galaxy
Can be studied with a variety of techniques:

Absorption spectroscopy
21 cm emission
Galactic surveys in different spectral bands

Neutral interstellar gas: HI 21-cm emission

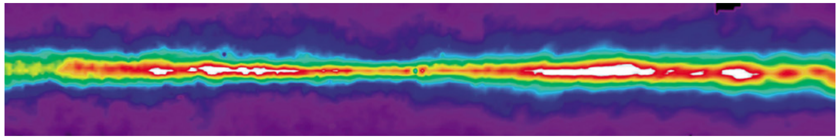
- Van de Hulst, 1945
  - Prediction of the existence of the 21 cm line
    - Transition between two possible states of the proton-electron spin coupling
      - parallel spins (higher energy)
      - antiparallel spins (lower energy)
  - “Forbidden” transition
    - Einstein coefficient of spontaneous emission
      - $A_{ul} = 2.87\text{x}10^{-15}\ \text{s}^{-1}$
    - Life time of the higher level
      - $t = 1/A_{ul} = 1.1\text{x}10^{7}$ yr
- Ewen & Purcell, Oort & Muller, 1951
  - Discovery of the 21 cm emission





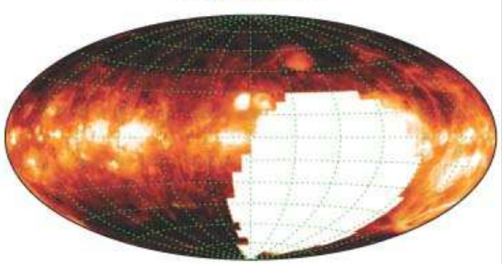
HI 21-cm emission

- Early maps of the Galaxy: 1950's and 1960's
- Main characteristics
  - Neutral hydrogen concentrated in the midplane of the Galaxy
    Scale height of the neutral gas: ~210 pc (Malhotra, 1995)
  - The HI disk has a mass of ~5×10^9 M_{sun}
    ~10% of the total mass of the disk (stars+ISM)
  - The mean density is $<n> \sim 1$ atom cm^{-3}



Diffuse HII gas

- A fraction of hydrogen is ionized in the diffuse ISM
- High resolution maps of Hα emission (Reynolds, 1980)
  - Proves the existence of diffuse component of (partially) ionized hydrogen
    Not to be confused with classic (circumstellar) HII regions
    The Hα emission is very weak
    The emission is more intense in the Galactic plane, but extends well outside the plane, with a scale height of ~ 1 kpc



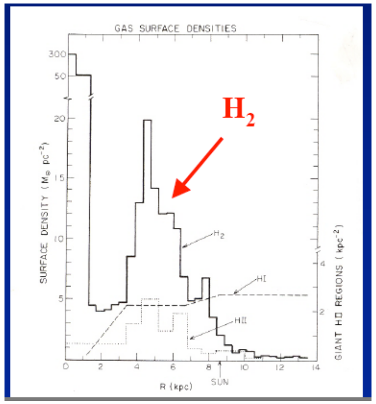
Diffuse emission in the soft X band

- ROSAT Satellite
  - Three soft X-ray bands at 0.25 , 0.75, and 1.5 keV
- Diffuse emission
  - Evidence for gas with coronal temperatures heated collisionally
- Absorption regions
  - At the lowest X-ray energies the ISM is strongly absorbing
  - Foreground cold clouds are seen in absorption againts the soft-X interstellar background

ROSAT soft X-ray bands centered at 0.25 , 0.75, and 1.5 keV are encoded in red, green, and blue colors, respectively
Color variations indicate variations of absorption or of the temperatures of the emitting regions; black regions indicate gaps in the survey

Molecular gas in the ISM

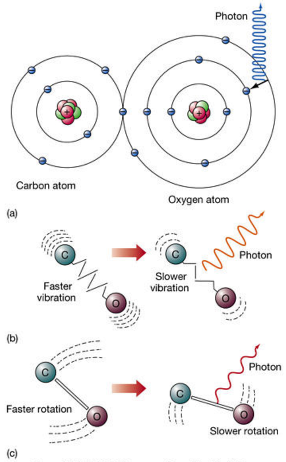
- In some regions of the ISM hydrogen is found in molecular, rather than atomic form
- The bulk of molecular gas is found in the direction of the Galactic center
  - Molecular ring between 4 and 8 kpc
- Vertical thickness (FWHM)
  - 80 pc at R=3 kpc
  - 150-300 pc at R=10-12 kpc



Molecular spectra

- Molecular spectra are much more complex than atomic spectra
- Molecular lines result from the combination of different types of transitions
  - Electronic
  - Vibrational
  - Rotational

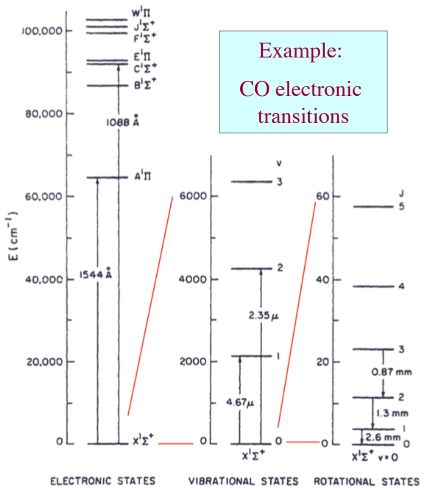
Example in figure:
CO molecule



Electronic transitions in molecules

- Electronic transitions in molecules are equivalent to atomic transitions
  - Typical energies are in the order of some eV

    They generally lie in the optical/UV spectral range
  - When observed at high spectral resolution, they can be solved in vibrational sub-levels which, in turn, can be solved in rotational sub-levels



Example:

CO electronic transitions

Quantization of vibrational and rotational motions

- Motions of atomic nuclei with respect the molecule's center of mass
- Main physical quantities that describe vibrational and rotational motions:
  - Total angular momentum

    The symbol *J* is used for diatomic molecules

    For polyatomic molecules the treatment is more complex
  - Reduced mass

    For diatomic molecules $\mu = m_1 m_2 / (m_1 + m_2)$

Vibrational transitions

- Between energy levels that result from the quantization of vibrational modes
  - They are mostly "stretching" modes

    (variations of interatomic distances)

    Stretching is the only possible mode for diatomic molecules

    Complex molecules also have "bending" and "deformation" modes
- The quantum number v indicates the vibrational state of the system

  (for v=0 the vibrational energy is not null)

$$E^{vib} = \hbar\omega_e(\mathrm{v} + \frac{1}{2})$$

$$\mathrm{v} = 0, 1, 2, \ldots$$

As v varies ina given molecule, the vibrational energy levels are equidistant

For different molecules the separation of the vibrational levels is a function of the reduced mass μ

For instance, H_2, HD e D_2 produce different vibrational spectra

Vibrational transitions

- The typical energies of vibrational modes lie in the range 0.1 e 0.3 eV
  - The corresponding wavelength λ lies in the near IR

$$\begin{array}{llll} \text{CO:} & v = 1-0 \text{ band} & \lambda = 4.67\ \mu\text{m} \Leftrightarrow & 2140\ \text{cm}^{-1} \\ & v = 2-0 \text{ band} & \lambda = 2.35\ \mu\text{m} \Leftrightarrow & 4250\ \text{cm}^{-1} \\ H_2\text{:} & v = 1-0 \text{ band} & \lambda = 2.40\ \mu\text{m} \Leftrightarrow & 4150\ \text{cm}^{-1} \end{array}$$

The energy of the transitions scales as λ^{-1} and can be expressed in cm^{-1}

Conversion factor: 1 cm^{-1} = 1.24 x 10^{-4} eV

- Every chemical group has a characteristic vibrational energy
  - Examples: C−H stretch, C≡H stretch, CH_2 angle bending
    Different complex molecules that have in common a chemical group will show the same vibrational transitions characteristic of that group
    Problem of identification of complex molecules

Rotational transitions

- Result from the quantization of the molecular rotational energies
  - The rotation can take place around the main axis of inertia
  - For complex molecules it could be a form of internal rotation
- Rotational transitions have energies in the order of ~ 10^{-3} eV
  - The wavelength λ generally lies in the millimetric or sub-millimetric spectral bands
- Rotational states are identified with the quantum number *J*

Example: CO

$$\begin{array}{llll} \text{CO} & J = 1-0 & \nu = 115\ \text{GHz} & \Leftrightarrow \lambda = 2.6\ \text{mm} \\ & J = 2-1 & \nu = 230\ \text{GHz} & \Leftrightarrow \lambda = 1.3\ \text{mm} \\ & J = 3-2 & \nu = 345\ \text{GHz} & \Leftrightarrow \lambda = 0.87\ \text{mm} \end{array}$$

Roto-vibrational transitions

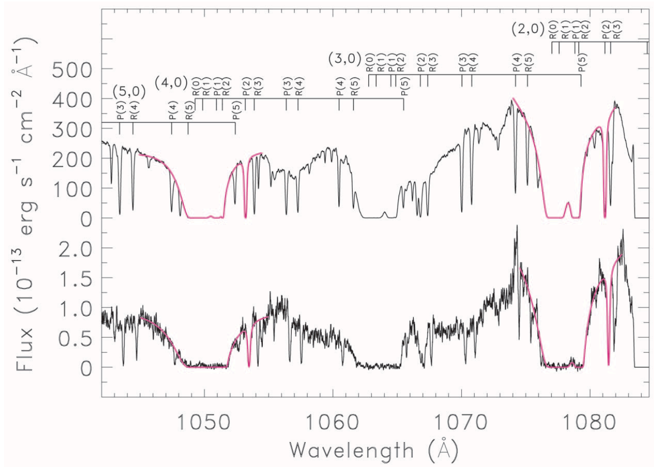
- Vibrational transitions can be decomposed in rotational levels, the combination of the two giving rise to a roto-vibrational band
- Selection rules:
  - There are no restrictions on the variation of the vibrational state, Δv
  - Variations of angular momentum are constrained by the selection rules $\Delta J = 0, \pm 1$

Depending on the value ΔJ the bands are called as follows:

$\Delta J = -1$ "P branch"
$\Delta J = 0$ "Q branch" (but J=0 → J=0 is forbidden)
$\Delta J = +1$ "R branch"

H_2 absorption lines

- Observations with high resolution spectroscopy show the extreme complexity of the molecular spectrum



H_2 emission

- Molecular hydrogen is a symmetric molecule
  - The electric dipole moment is zero

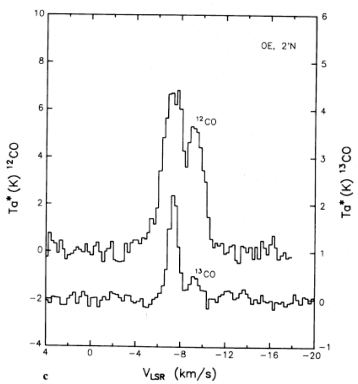
    Rotational transitions are forbidden, even though electronic transitions are allowed
- Quadrupole transitions are possible, but very weak
  - Their energies are much higher than the typical rotational energies
  - Can only be observed in relatively warm regions

    Thanks to the abundance of H_2 some of these transitions have been observed in the mid IR
- Due to the lack of H_2 emissions it is hard to map the distribution of molecular hydrogen in galaxies
  - UV absorptions require (rare) bright background sources and are not suited to map the molecular gas, especially in dust-rich regions, where the background sources are obscured

Molecular emission spectra in the millimetric band

- CO emission lines

  $J = 1{-}0$ at 2.6 mm
- Advantages
  - CO is relatively abundant and has rotational transitions (not a symmetric molecule)
  - the dipole moment is relatively small and the molecule can be easily excited also in gas with relatively low density
- Used as a tracer of H_2
- If the emission is too strong one can use less abundant istotopes, such as ^{13}CO, to obtain optically thin emissions

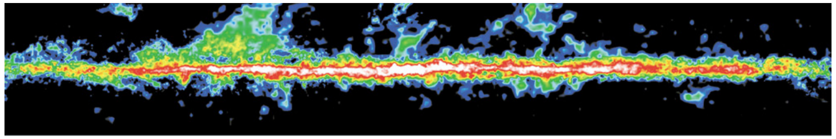


Molecular emission in the millimetric band

- OH, NH_3, H_2O (1965)

  In the radio band
- First measurement of CO emission (1970)
- Maps of the Galactic distribution of CO (1970's and 1980's)

  Tracer of molecular gas in the Galaxy



Chemical bonds of interstellar molecules

- Atoms in interstellar molecules are held together by covalent bonds
  - Superposition of the atomic orbitals
  - Sharing of the eletrons in external shells
- Typical energies of covalent bonds
  - ~100 kcal/mol ⇛ ~ 4 eV
- In the harsh conditions of the ISM the molecules can be easily dissociated
  - Kinetic temperatures in excess of ~10^4 K would dissociate molecules by collisions
  - Photons with energies up to13.6 eV can penetrate HI regions and photodissociate molecules
  - Interstellar molecules can survive in cold regions protected by the interstellar radiation field

Interstellar chemical reactions

Formation of bonds

- Radiative association
  - Between neutrals and ions
- Reactions on the surface of dust grains
  - Also between neutrals
  - example: H_2 formation

Destruction of bonds

- Photo-dissociation
- Dissociative recombination

$$X^+ + Y \rightarrow XY^+ + h\nu$$

$$X + Y{:}g \rightarrow XY + g$$

$$XY + h\nu \rightarrow X + Y$$

$$XY^+ + e \rightarrow X + Y$$

H_2 formation on dust grains

Credits: van Dishoeck