Spectral Line Observing

- Measurement goals
- Spectral line formation processes
- Line Shapes / Doppler effect
- Spectrometers
- Observing techniques
- Calibration
- Data reduction / Data products
- Data visualization
Measurement Goals

- What can we learn from radio spectral lines?
- We can probe the physical, chemical and dynamical conditions of the interstellar matter (ISM) in the Milky Way and in external galaxies.
- Most ISM gas phases produce spectral lines:
  - Cold: $10 \, \text{K}$, dense molecular gas ($\text{H}_2$)
  - Cool: $10^2 \, \text{K}$, neutral gas (HI)
  - Warm: $10^4 \, \text{K}$, ionized gas (HII)
  - Hot: $10^6 \, \text{K}$, low-density ionized (SNR bubbles)
Measurement Goals (ctd.)

- Intensities can tell us about:
  - Gas temperature
    - Energy Sources
  - Gas density
    - Gravity / Cloud Criticality
  - Chemical composition
    - Abundances / Evolutionary State
  - Ionization / Magnetic Fields
    - Cloud Support
Frequencies and line widths can be used to derive:

- Dynamical models
  - Galaxy and Cloud Rotation
  - Cloud Collapse
  - Protostellar Outflows
- Redshifts
  - Age
  - Distance
Spectroscopy

- Spectroscopy:
  Any measurement of a quantity as a function of either wavelength ($\lambda$) or frequency ($\nu$), i.e. also of energy ($E = h\nu$).

- Spectral Line:
  Result of the interaction between a quantum system and a single photon.
How do spectral lines form?

- Quantum systems (atoms or molecules) can change their states only in discrete amounts of energy $\Delta E$.
- The transition between these states leads to emission or absorption of light at a single frequency $\nu = \Delta E/h$, the so-called rest frequency.
- Spectrally this transition is seen as a line.
Types of Spectra

Types of Spectra

- HOT GAS
- COLD GAS

**Emission Spectrum**

**Absorption Spectrum**

[Graph showing emission and absorption spectra with labeled frequencies and waves.]
Types of Spectra

- Sgr B2 (N)
- Sgr B2 (M)

Emission Spectrum

Absorption Spectrum

Cold Gas
Atomic Lines I

- Electronic transitions (e.g. recombination lines (H\(<n>\alpha\), etc.))
Atomic Lines II

- Hyperfine splitting / spin flips (e.g. HI 21 cm line → separate talk on Tuesday)
Molecular Lines I

- Electronic transitions (rather in VIS / UV)
- Rotational transitions (needs dipole, so no $H_2$ !)
- Vibrational transitions

Animations: http://www.shokabo.co.jp/sp_e/optical/lab/o1opt_line/opt_line.htm
Molecular Lines I

Animations: http://www.shokabo.co.jp/sp_e/optical/lab/opt_line/opt_line.htm
Inversion

Here: Nitrogen tunnels through double well potential

Hyperfine splitting
Molecular Lines II

- Inversion
- Hyperfine splitting

\[ \text{NH}_3 \]
Interstellar Fingerprints

- Set of all possible lines of an atom or molecule is its personal “fingerprint”

<table>
<thead>
<tr>
<th>2 atoms</th>
<th>3 atoms</th>
<th>4 atoms</th>
<th>5 atoms</th>
<th>6 atoms</th>
<th>7 atoms</th>
<th>8 atoms</th>
<th>9 atoms</th>
<th>10 atoms</th>
<th>11 atoms</th>
<th>12 atoms</th>
<th>13 atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>C₂⁺</td>
<td>c-C₂H</td>
<td>C₄⁺</td>
<td>C₆H</td>
<td>C₈H</td>
<td>C₁₀H</td>
<td>C₁₂H</td>
<td>C₁₄H</td>
<td>C₁₆H</td>
<td>C₁₈H</td>
<td>C₂₀H</td>
</tr>
<tr>
<td>AIF</td>
<td>C₃H</td>
<td>l-C₃H</td>
<td>C₄H</td>
<td>l-H₃C₃</td>
<td>CH₂CHCN</td>
<td>CH₂CHCN</td>
<td>CH₃C₂N</td>
<td>CH₃C₂H</td>
<td>CH₃C₂N</td>
<td>CH₃C₂H</td>
<td>CH₃C₂N</td>
</tr>
<tr>
<td>NCl</td>
<td>C₄N</td>
<td>C₅N</td>
<td>C₆N</td>
<td>C₇N</td>
<td>C₈N</td>
<td>C₉N</td>
<td>C₁₀N</td>
<td>C₁₁N</td>
<td>C₁₂N</td>
<td>C₁₃N</td>
<td>C₁₄N</td>
</tr>
<tr>
<td>AlCl</td>
<td>C₂H</td>
<td>C₃H</td>
<td>C₄H</td>
<td>C₅H</td>
<td>C₆H</td>
<td>C₇H</td>
<td>C₈H</td>
<td>C₉H</td>
<td>C₁₀H</td>
<td>C₁₁H</td>
<td>C₁₂H</td>
</tr>
<tr>
<td>CH₂</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
<td>CH₂⁺</td>
</tr>
<tr>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
</tr>
<tr>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
<td>CN</td>
</tr>
<tr>
<td>CO</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
</tr>
<tr>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
<td>CO⁺</td>
</tr>
<tr>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
<td>CP</td>
</tr>
<tr>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
<td>H₂CO</td>
</tr>
<tr>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
<td>SiC</td>
</tr>
<tr>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
<td>HCl</td>
</tr>
<tr>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
<td>KCl</td>
</tr>
<tr>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
</tr>
<tr>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
<td>MgCN</td>
</tr>
<tr>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
<td>MgNC</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
<td>NH₄⁺</td>
</tr>
<tr>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
</tr>
<tr>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
<td>CO₂⁺</td>
</tr>
<tr>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
<td>SiO</td>
</tr>
<tr>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
<td>SiS</td>
</tr>
<tr>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
<td>CS</td>
</tr>
<tr>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
<td>CS₂</td>
</tr>
<tr>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
<td>H₂S</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
<td>H₂O⁺</td>
</tr>
<tr>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
<td>CN⁻</td>
</tr>
<tr>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
<td>OH⁻</td>
</tr>
<tr>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
<td>CH₂⁻</td>
</tr>
<tr>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
<td>CH₃⁻</td>
</tr>
</tbody>
</table>

www.cdms.de 08/2010
## Interstellar Molecular Zoo

<table>
<thead>
<tr>
<th>2 atoms</th>
<th>3 atoms</th>
<th>4 atoms</th>
<th>5 atoms</th>
<th>6 atoms</th>
<th>7 atoms</th>
<th>8 atoms</th>
<th>9 atoms</th>
<th>10 atoms</th>
<th>11 atoms</th>
<th>12 atoms</th>
<th>13 atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>C₂⁺</td>
<td>c-C₂H</td>
<td>C₆H</td>
<td>C₆H</td>
<td>C₆H</td>
<td>CH₂CN</td>
<td>CH₃CN</td>
<td>CH₃CN</td>
<td>CH₃CN</td>
<td>H₃CN</td>
<td>H₃CN</td>
</tr>
<tr>
<td>AI⁺</td>
<td>C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
<td>H₂C₂H</td>
</tr>
<tr>
<td>NHCl</td>
<td>CN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
</tr>
<tr>
<td>C₂⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
<td>C₂H⁺</td>
</tr>
<tr>
<td>CH⁺</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
<td>HCN</td>
</tr>
<tr>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
<td>CH⁺</td>
</tr>
<tr>
<td>CN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
<td>HCN⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
<tr>
<td>CO⁺</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
<td>HCNO⁻</td>
</tr>
</tbody>
</table>

**Total of 164 and counting!**

**Ethyl formate**


[Image of ethyl formate molecule]

www.cdms.de 08/2010
Spectral Line Excitation

- Near HII regions radiatively via UV fields
- In cold molecular clouds via CMB but predominantly via collisions with H$_2$
- In case of a level inversion one gets a maser (→ see also special maser talk tomorrow)
Collisional Excitation

Rotational energy comes in discrete quantities ("quanta")

Collisions with hydrogen molecules and helium atoms change the rotational energy

\[ \Delta E = \frac{1}{2} m \left( V_{in}^2 - V_{out}^2 \right) \]

Only \( \Delta n = -1 \) transitions are allowed for radiation

\[ f = \frac{\Delta E}{\hbar} \]

http://dsnra.jpl.nasa.gov/IMS/
## Maser Molecules

<table>
<thead>
<tr>
<th>molecule</th>
<th>name</th>
<th>frequency (GHz)</th>
<th>characteristics*</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH</td>
<td>hydroxyl</td>
<td>1.612</td>
<td>O, M</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.667</td>
<td></td>
<td>O, M</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.720</td>
<td></td>
<td>O</td>
</tr>
<tr>
<td>H$_2$CO</td>
<td></td>
<td>4.829</td>
<td>O</td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>methanol</td>
<td>12.178</td>
<td>O</td>
</tr>
<tr>
<td>SiS</td>
<td>silicon sulfide</td>
<td>18.155</td>
<td>C</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>water</td>
<td>22.235</td>
<td>O, M</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>ammonia</td>
<td>23.870</td>
<td>O</td>
</tr>
<tr>
<td>SiO</td>
<td>silicon oxide</td>
<td>43.122</td>
<td>M, S, O</td>
</tr>
<tr>
<td>&quot;</td>
<td>86.243</td>
<td></td>
<td>M, S</td>
</tr>
<tr>
<td>HCN</td>
<td>hydrogen cyanide</td>
<td>89.087</td>
<td>C</td>
</tr>
</tbody>
</table>

*O means that the maser emission is frequently found in star-forming regions; M, in M stars; S, in S stars; C, in carbon stars

http://www.daviddarling.info/encyclopedia/I/interstellar_maser.html
Zeeman Effect

- Degenerate energy levels split up if an external magnetic field is applied
- This leads to additional transitions and allows to measure the magnetic field

Kingshuk Majumdar (2000)
Optical Depth Effects

- Depending on the density and temperature, spectral line emission can be optically thin or thick.
- In the case of optical depth $\tau \ll 1$, one can look through a cloud and determine column densities and internal dynamics.
- For $\tau \gg 1$, one can see only the surface of an object. Using radiative transfer, one can calculate the cloud temperature.
Line Profile Shape

- Ideal line should be infinitely sharp because there is a fixed energy difference $\Delta E = h\nu_0$

- Energy uncertainty causes a small broadening, the “natural line width”

- Thermal motion of emitters leads to Doppler shifted line frequencies
Thermal Broadening

- Considering statistical ensembles one can derive a Gaussian shape for the broadened line.
- Only the line-of-sight, i.e. the radial component adds to this effect.
Larger Doppler shifts can occur due to several effects:

- Galactic rotation
- Dynamical processes in molecular clouds and stars
- Expansion of the universe (redshift can be so large that submm lines are shifted to cm wavelengths!)

Each type of shift creates typical line profile shapes

We often use radial Doppler velocity as x-axis
Dynamics: Rotation
Dynamics: Cloud Collapse

http://www.oglethorpe.edu/faculty/~m_rulison

Neal J. Evans II, ARAA, 37, 311, 1999
Dynamics: Outflows


Schmid-Burgk et al. LIACo, 29, 193, 1990
What does one need to observe radio astronomical spectral lines?

- Heterodyne frontend (→ special talk)
- Usually a down-converter from observing frequencies to a “low” (0-4 GHz) intermediate frequency (IF) band
- Spectrometers to analyze the signal

Will concentrate on spectrometers here
Spectrometers

- Spectrometers measure the frontend signal in many frequency bins across the available bandwidth

- There are several techniques:
  - Filter banks: Series of analog filters; complex electronics
  - Auto-correlators: Special purpose computers; correlation function of time series signals; low number of bits
More spectrometer types

- Acousto-optical spectrometers (AOS): Diffraction of laser light at ultrasonic waves in a Bragg crystal; delicate optical setup

- Fast Fourier Transform Spectrometers: High speed ADCs and FPGAs → Development at the MPIfR
**Fast Fourier Transform Spectrometer**

**XFFTS:** 2.5 GHz bandwidth / 32768 channels (ENBW 88.5 kHz)

E2V 5 GS/s 10-bit ADC, XILINX Virtex-6 LX240T

[40 nm, 1.0 volt core voltage, >240‘000 logic cells, 768 DSP48 slices]
Observations

- Source signal is partially absorbed by the earth atmosphere
- The atmosphere also radiates itself and thus contributes to the signal
Observations

- Source signal is partially absorbed by the earth atmosphere
- The atmosphere also radiates itself and thus contributes to the signal
- The telescope beam picks up ground spillover
- Receiver etc. add a signal too
- Direct measurement therefore yields

\[ C_{\text{on}} = C_{\text{source}} e^{-\tau_A} + C_{\text{atm}} (1-e^{-\tau_A}) + C_{\text{spillover}} + C_{\text{rec}} \]
On-Off Technique

- To remove the atmospheric and instrumental emissions one observes the target and then a position on sky without astronomical emission:

\[ C_{\text{off}} = C_{\text{atm}} (1-e^{-\tau A}) + C_{\text{spillover}} + C_{\text{rec}} \]

- The difference of the two measurements contains only the source signal (still weakened by atmospheric absorption):

\[ C_{\text{on}} - C_{\text{off}} = C_{\text{source}} e^{-\tau A} \]
On-Off Technique

Source signal plus atmosphere and receiver / amplifiers
On-Off Technique

Reference signal plus atmosphere and receiver / amplifiers
On-Off Technique

Source minus Reference
On-Off Technique

Source minus Reference

Reference
On-Off Alternatives

- On-Off measurements can be taken by moving the telescope between two positions.
- If the source is small, then one can use horn or wobbler switching which is faster. This helps if the atmospheric emission varies quickly.
- One can also measure the “off” at a slightly shifted frequency but pointing to the source. This doubles the actual “on” time and reduces telescope movements.
Frequency Switching

- Reference at a slightly different frequency but same position on the target
Frequency Switching

- Reference at a slightly different frequency but same position on the target
Frequency Switching

- Reference at a slightly different frequency but same position on the target
Observing Patterns

- Most radio receivers are still single pixel or small multi-beam systems
- To cover an extended source area one must observe several spatial offset positions
- Typical patterns are
  - (Rectangular) rasters with half beam spacing
  - (Rectangular) “On-The-Fly” rasters
  - Advanced figures like spirals, Lissajous figures, Rotating bow ties, etc.
- Most radio receivers are still single pixel or small multi-beam systems.
- To cover an extended source area, one must observe several spatial offset positions.
- Typical patterns include:
  - (Rectangular) rasters with half beam spacing
  - (Rectangular) "On-The-Fly" rasters
  - Advanced figures like spirals, Lissajous figures, Rotating bow ties, etc.
Calibration

- The measurements in arbitrary counts need to be calibrated to physical units.
- For spectral lines one usually uses the “Antenna Temperature” scale.
- The receiver system is calibrated against “hot” (usually ambient temperature) and “cold” (usually LN$_2$ @ 77 K) black bodies.
- In cm wave receivers one uses a noise diode that was hot/cold calibrated in the lab.
The absorption of astronomical signals needs to be corrected too:

- Scaling according to measurements of secondary calibrator sources
- Sky measurements and atmospheric models can be used to derive $\tau$
- More details in the calibration talk on Thursday
Data reduction

- Atmospheric and instrumental instabilities lead to spectral baseline artifacts
Data reduction

- Atmospheric and instrumental instabilities lead to spectral baseline artifacts
- Techniques to process spectral line data include:
  - Spectral baseline fits using polynomials
  - FFT analysis to remove sinusoidal components due to standing waves
  - Flagging of very bad data
- Caveat: Must be very careful not to alter the line emission, esp. for broad lines
Data Products

- Primary data products are calibrated spectra.
- For mapping projects the spatially distributed spectra are interpolated onto a regular grid to make 3D data cubes with two spatial and one spectral axis.
- ALMA Pipeline Heuristics development (led by MPIfR) attempts to provide automatic data reduction (also applicable to Effelsberg data).
Spectral Data Visualization

- Usually display maps as false color images and contour plots
- Frequency axis allows for additional analysis, e.g. via so called channel maps or via position-velocity plots
- Since we have a data cube, one can apply 3D rendering techniques but one must be careful interpreting the graphs because of the frequency axis
Channel Maps

L1512, SO 1-0
30 GHz
Effelsberg 100m
Position Velocity Plots

- Plot spatial axis against velocity to study cloud dynamics, e.g. Keplerian rotation

A. Gomez, CTIO, NOAO, HST, NASA

Gomez's Hamburger (IRAS 18059-3211)
COMPLETE=COordinated Molecular Probe Line Extinction Thermal Emission

http://am.iic.harvard.edu

ESSEA, Spectral Line Observing, D. Muders
Deriving Physical Parameters

Spectra and data cubes of several transitions are used in conjunction with models to derive physical parameters of the ISM:

- Optically thin lines (involving isotopologues) to calculate column and volume densities
- Line Ratios are modeled with chemical networks and radiative transfer programs
- Spectral signatures of dynamical processes are fitted against the data
- And many more ...
Summary

- Spectral lines provide a wealth of information about the interstellar medium.
- Different atomic and molecular processes generate numerous spectral lines in the cm to submm wavelength range.
- More than 160 molecules detected in space.
- Physical, chemical, and dynamical state of interstellar medium can be studied using spectral lines.
Happy Observing!
Since the thermal velocities are non-relativistic, the Doppler shift in the angular frequency is given by the simple form

\[ \omega = \omega_0 \left(1 \pm \frac{v}{c}\right) \]

\( \omega_0 \) = frequency for an atom at rest

From the Boltzmann distribution, the number of atoms with velocity \( v \) in the direction of the observed light is given by

\[ n(v)dv = N \sqrt{\frac{m_0}{2\pi kT}} e^{-\frac{m_0 v^2}{2kT}} dv \]

\( N \) = total number of atoms
\( m_0 \) = atomic mass

The distribution of radiation around the center frequency is then given by

\[ I(\omega) = I_0 \exp\left[\frac{-m_0 c^2 (\omega_0 - \omega)^2}{2kT \omega_0^2}\right] \]

http://hyperphysics.phy-astr.gsu.edu/hbase/atomic/broaden.html
Antenna temperature is a measure of signal strength in radio astronomy. It is defined as the temperature of a black-body enclosure which, if completely surrounding a radio telescope, would produce the same signal power as the source under observation. Antenna temperature is a property of the source, not of the antenna itself.

\[ T_A = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} R(\theta, \phi) I(\theta, \phi) \sin \theta d\theta d\phi \]

\( R(\Theta, \Phi) \) is the antenna pattern.