Polarized Spectra of the Sun & Stars

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*erc HotMol.eu* Hot Molecules in Exoplanets and Inner Disks
1. Non-magnetic scattering
   – Continuum
   – Lines

2. Scattering in magnetic fields: Hanle effect
   – Spatially unresolved solar magnetic fields

3. Polarized RT in magnetic fields

4. Sun and stars:
   – Small-scale solar magnetic fields
   – Sunspots
   – Starspots
Diatomic molecules on the Sun and stars

- Visible and NIR
- Useful “Noise”
  (Berdyugina 2011, SPW6)

<table>
<thead>
<tr>
<th>System</th>
<th>$\lambda$ [Å]</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO $\gamma: A^3\Phi - X^3\Delta$</td>
<td>7054 (0,0)</td>
<td>4, 1, 5, 8, 0</td>
</tr>
<tr>
<td>TiO $\gamma': B^3\Pi - X^3\Delta$</td>
<td>6224 (0,0)</td>
<td>4, 5</td>
</tr>
<tr>
<td>TiO $\alpha: C^3\Delta - X^3\Delta$</td>
<td>4950 (0,0)</td>
<td>4, 5</td>
</tr>
<tr>
<td>TiO $\delta: b^1\Pi - a^1\Delta$</td>
<td>8860 (0,0)</td>
<td>4, 5</td>
</tr>
<tr>
<td>TiO $\beta: c^1\Phi - a^1\Delta$</td>
<td>5597 (0,0)</td>
<td>4, 5</td>
</tr>
<tr>
<td>OH $X^2\Pi$</td>
<td>15328 (3,1)</td>
<td>4, 19, 5</td>
</tr>
<tr>
<td>FeH $F^4\Delta - X^4\Delta$</td>
<td>10062 (0,0)</td>
<td>4, 14, 5, 13, 14</td>
</tr>
<tr>
<td>C$_2$ $d^3\Pi - a^3\Pi$</td>
<td>5165 (0,0)</td>
<td>4, 19, 9, 10, 15, +</td>
</tr>
<tr>
<td>OH $A^2\Sigma - X^2\Pi$</td>
<td>2800–3400</td>
<td>4, 6, 11, 3</td>
</tr>
<tr>
<td>CN $A^2\Pi - X^2\Sigma$</td>
<td>7350–11580</td>
<td>4, 6, 11, 19, 2, 18</td>
</tr>
<tr>
<td>MgH $A^2\Pi - X^2\Sigma^+$</td>
<td>4780–5620</td>
<td>4, 6, 11, 19, 1, 6, 9, +</td>
</tr>
<tr>
<td>CaH $A^2\Pi - X^2\Sigma^+$</td>
<td>5370–7590</td>
<td>4, 6, 11</td>
</tr>
<tr>
<td>MgH $B^2\Sigma^+ - X^2\Sigma^+$</td>
<td>6680–7590</td>
<td>4, 6, 11</td>
</tr>
<tr>
<td>CaH $B^2\Sigma^+ - X^2\Sigma^+$</td>
<td>6170–6870</td>
<td>4, 6, 11</td>
</tr>
<tr>
<td>CH $A^2\Delta - X^2\Pi$</td>
<td>3870–4120</td>
<td>4, 6, 11, 16</td>
</tr>
<tr>
<td>SH $A^2\Sigma - X^2\Pi$</td>
<td>3250–3300</td>
<td>6, 11</td>
</tr>
</tbody>
</table>


CrH $A^6\Sigma - X^6\Sigma$
Kuzmychov & Berdyugina (2013)
Scattering

- polarization depends on the scattering angle
- polarization is determined by the projection of dipoles towards observer
- polarization is perpendicular to the scattering plane
- polarization arises because of the spatial symmetry braking
  - anisotropic radiation
  - non-spherical geometry
  - magnetic/electric field
Continuum polarization

- Radiative transport equation:
  \[ \mu \frac{dI_v}{d\tau_c} = I_v - S_v \]

- Scattering source function:
  \[ S_{v,c,s}(\mu) = \int P_R(\mu, \mu')I_v(\mu') \frac{d\Omega'}{4\pi} \]


HotMol tools: StarPol
• Source function should take into account de-excitation by inelastic collision, i.e. by pure absorption (thermalization of the photon), and elastic collisions modifying scattering through redistribution function $R$:

$$S_{\nu,l}(\mu) = \frac{(1-\varepsilon)}{2\varphi_\nu} \int_{-\infty}^{+\infty} \int_{-1}^{+1} R(\nu,\nu';\mu,\mu')I_{\nu'}(\mu')d\mu'd\nu' + \varepsilon B_{\nu}$$

• Prominent molecular line polarization:
Scattering in magnetic field: Hanle effect

- Hanle effect (Hanle 1924): modification scattering polarization due to the presence of a magnetic field

  - the dipole perpendicular to the field starts to rotate around the field direction, forming a so-called “rosette”
    - **Weak field**: slow rotation of the dipole & small depolarization
    - **Intermediate field**: faster rotation & more depolarization
    - **Strong field**: very fast rotation, average scattering polarization is zero, polarization plane is not defined

\[
10^6 B g \approx \gamma_{rad} = \frac{1}{\Delta t}
\]
Molecular polarizability

- Polarization amplitudes scale with
  - intrinsic polarizability, $W_2$
  - opacity

- Hanle effect: modification of polarization
  - magnetic field strength, $B$
  - upper level Landé factor, $g'$
  - upper level life time (1/damping), $\tau'$

- Rayleigh scattering: positive intrinsic polarizability with two asymptotic values
  - 0.4 in Q branch lines
  - 0.1 in R and P branch lines

- Raman scattering: positive and negative intrinsic polarizability with asymptotic values
  - 0.1 in R→P and P→R transitions
  - 0.2 in Q→P and R→Q transitions

Berdyugina et al. (2002)
Hanle effect in molecular lines: $C_2$

- Entangled (turbulent) magnetic field on the Sun

$g_{\text{eff}} = 0.12 - 0.12$

$g_{\text{eff}} = 0.05 - 0.05$

Quiet Sun: Entangled magnetic fields

- Mixed polarity, spatially unresolved fields

Stenflo (2004)
Polarized spectra in strong magnetic fields

- Transport equation in lines (LTE):
  \[
  \mu \frac{dI_\nu}{d\tau_c} = (\eta + E)I_\nu - S_\nu \quad \text{with} \quad S_\nu = B_\nu (\eta + E)1
  \]

- Absorption (Müller) matrix:
  \[
  \eta = \begin{pmatrix}
  \eta_I & \eta_Q & \eta_U & \eta_V \\
  \eta_Q & \eta_I & \rho_V - \rho_U \\
  \eta_U - \rho_V & \eta_I & \rho_Q \\
  \eta_V & \rho_U - \rho_Q & \eta_I
  \end{pmatrix}
  \]
  \[
  \begin{align*}
  \eta_I &= \frac{1}{2} \left[ \eta_0 - \frac{1}{2} (\eta_+ + \eta_-) \right] \sin^2 \gamma + \frac{1}{2} (\eta_+ + \eta_-) \\
  \eta_Q &= \frac{1}{2} \left[ \eta_0 - \frac{1}{2} (\eta_+ + \eta_-) \right] \sin^2 \gamma \cos 2\chi \\
  \eta_U &= \frac{1}{2} \left[ \eta_0 - \frac{1}{2} (\eta_+ + \eta_-) \right] \sin^2 \gamma \sin 2\chi \\
  \eta_V &= \frac{1}{2} (\eta_+ - \eta_-) \cos \gamma
  \end{align*}
  \]
  \[
  \eta_0 = \sum_{M,\Delta M=0} S_{MM}^{(0)} H(a, v - v_M^{(0)}) \quad \Delta M = 0 \quad (\pi)
  \]
  \[
  \eta_+ = \sum_{M,\Delta M=+1} S_{MM}^{(+)} H(a, v - v_M^{(+)}) \quad \Delta M = +1 \quad (\sigma_+)
  \]
  \[
  \eta_- = \sum_{M,\Delta M=-1} S_{MM}^{(-)} H(a, v - v_M^{(-)}) \quad \Delta M = -1 \quad (\sigma_-)
  \]

HotMol tools: Mol Stokes
Polarized spectra in strong magnetic fields

- Longitudinal field:
  \[ \eta_I = \frac{1}{2} (\eta_+ + \eta_-) \quad \eta_Q = 0 \quad \eta_U = 0 \quad \eta_V = \frac{1}{2} (\eta_+ - \eta_-) \]

  \[ \gamma = 0 \quad \Rightarrow \quad \begin{pmatrix} I \\ 0 \\ 0 \\ V \end{pmatrix} \]

- Transverse field:
  \[ \eta_I = \frac{1}{2} \eta_0 + \frac{1}{4} (\eta_+ + \eta_-) \quad \eta_Q = \frac{1}{2} \left[ \eta_0 - \frac{1}{2} (\eta_+ + \eta_-) \right] \cos 2\chi \quad \eta_U = \frac{1}{2} \left[ \eta_0 - \frac{1}{2} (\eta_+ + \eta_-) \right] \sin 2\chi \quad \eta_V = 0 \]

  \[ \gamma = \frac{\pi}{2} \quad \Rightarrow \quad \begin{pmatrix} I \\ Q \\ U \\ 0 \end{pmatrix} \]

  \[ 2\chi = 0 \quad \Rightarrow \quad \eta_Q = \frac{1}{2} \eta_0 - \frac{1}{4} (\eta_+ + \eta_-) \quad \eta_U = 0 \]

  \[ 2\chi = \frac{\pi}{2} \quad \Rightarrow \quad \eta_Q = 0 \quad \eta_U = \frac{1}{2} \eta_0 - \frac{1}{4} (\eta_+ + \eta_-) \]
Small-scale m.f. imaged in molecular bands

- Small-scale magnetic flux tubes in the lower photosphere – elemental "building blocks"

- **G-band**, the CH 4308 Å band head: high contrast images of the magnetic elements *(Berger et al. 1995; Muller 1985)*

- **CN 3880 Å** band head: high contrast imaging *(Sunrise: Riethmüller et al. 2010)*

- **TiO 7054 Å** band head: highest resolution solar images at SST/La Palma, NST/BBSO *(Berger & Berdyugina 2003; Goode et al. 2010)*

- **Molecular dissociation equilibrium** *(Sánchez Almeida et al. 2001; Steiner et al. 2001; Schüssler et al. 2003; Berdyugina et al. 2003)*
Molecular dissociation equilibrium

\[ A + B \leftrightarrow AB \]

\[
\frac{N(A)N(B)}{N(AB)} = \left( \frac{2\pi m_{AB}kT}{\hbar^2} \right)^\frac{2}{3} \frac{Q_AQ_B}{Q_{AB}} e^{-\frac{D_0}{kT}}
\]

\[
\frac{\Delta N_{AB}}{N_{AB}} \approx - \frac{\Delta T}{T} (1.5 + 2.3\theta D_0),
\]

\[ N_{AB} \propto N_AN_B \]

- Molecules are very sensitive tracers of temperature and density!

- Molecules in the solar photosphere:

<table>
<thead>
<tr>
<th>Molecule</th>
<th>(D_0, eV)</th>
<th>(\Delta N/N (250K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH (4305)</td>
<td>3.5</td>
<td>0.37</td>
</tr>
<tr>
<td>OH (3150)</td>
<td>4.4</td>
<td>0.45</td>
</tr>
<tr>
<td>CN (3883)</td>
<td>7.8</td>
<td>0.75</td>
</tr>
<tr>
<td>CO (2(\mu)m)</td>
<td>11.1</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Berdyugina et al. (2003)
Sunspot structure imaged in molecular bands:

- **TiO 7054 Å** band imaging is proven to reveal small-scale structures in sunspot umbrae and penumbrae.

- Molecules in sunspots:

<table>
<thead>
<tr>
<th>Molecule</th>
<th>(D_0, eV)</th>
<th>(\Delta N/N) (100K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO (2µm)</td>
<td>11.1</td>
<td>0.84</td>
</tr>
<tr>
<td>TiO (7054)</td>
<td>6.8</td>
<td>0.53</td>
</tr>
<tr>
<td>OH (UV,IR)</td>
<td>4.4</td>
<td>0.36</td>
</tr>
<tr>
<td>MgH (5100)</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>CaH (6700)</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>CH (4305)</td>
<td>4.4</td>
<td></td>
</tr>
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Berdyugina et al. (2003)
Magnetic diagnostics TiO $\gamma(0,0)R_3$ at 7054-7059 Å with $|g_{\text{eff}}| \leq 1.1$
Sunspot magnetic fields

- By combining atomic and molecular lines, e.g. Fe I + OH at 1.56 μm, we infer 3D models of sunspots

- Mol Stokes tool: Teff=4000K, inclined B=3kG
Sunspots: 3D structure

Mathew et al. (2003)

Wilson depression at $\tau_{1.6}=1$

Mathew et al. (2004)
Sunspots: 3D Umbra

\[ \log \tau = 0, -1, -2, -3 \]

Berdyugina (2011)
Starspots

- Direct Imaging

- Doppler Imaging
Molecular polarization from starspots

Red Dwarfs: Mol Stokes tool

Berdyugina et al. (2005, 2006)
Starspots: Molecular lines

Berdyugina (2011)
Starspots: 3D structure $T$

AU Mic

Berdyugina (2011)
Starspots: 3D structure B

Berdyugina (2011)
Molecules in very strong magnetic fields

- Cool white dwarfs: MG fields, Molecular Magnetic Dichroism (MMD)
- 4 electronic systems: CH A-X, B-X, C2 Swan & Philips, $3 \times 10^6$ lines

*B* = 7 MG

*Berdyugina et al. (2006), PRL*
MMD: PBE on fine and rotational structure

- CH A-X system, 4300 Å (~G-band)
- $3 \times 10^6$ lines -> Milne-Eddington, $T=6500$K
- Polarized radiative transfer:
  - analytical solution by Rachkovsky (1962)
  - including magneto-optical effects

*Berdyugina et al. (2006), PRL*
MMD: PBE on fine and rotational structure

- CH B-X system, 3900 Å

\[ \text{B}^2\Sigma \quad \text{X}^2\Pi \]

Berdyugina et al. (2006), PRL
MMD: PBE on fine and rotational structure

- $C_2$ d-a Swan system

Berdyugina et al. (2006), PRL
MMD: PBE on rotational structure

- $C_2$ C-A, Deslandres-d’Azambuja system

Berdyugina et al. (2006), PRL
The second WD with CH bands

- Magnetic field is discovered thanks to polarization in CH $\Rightarrow$ 2MG

Vornanen et al. (2010), ApJL
Conclusions

- Molecular lines show remarkable scattering polarization:
  - Polarization amplitude ratio of molecular lines (C2) unambiguously reveals weak entangled magnetic fields.

- Molecular lines are excellent diagnostics of sunspots and photosphere:
  - Simultaneous inversion of atomic and molecular lines reveal 3D structure of sunspots: temperature, magnetic field, velocity, etc.
  - Imaging in molecular bands is useful for studying small-scale structures in sunspot umbrae, penumbrae and the photosphere

- Molecular lines are unique diagnostics of starspot interiors
  - They provide the evidence for cool spots on stellar surfaces
  - They help to disentangle starspot filling factors and magnetic field strength
  - Inversions of Stokes profiles of molecular lines provide 3D temperature structure, magnetic and velocity fields inside spatially unresolved starspots.

- Molecular band net polarization is an indicator of very strong magnetic fields on WD, red dwarfs and brown dwarfs
  - Brown dwarfs: Kuzmychov et al. (2017)