Chromospheric Lyman-Alpha Spectro-Polarimeter

CLASP

Ryouhei Kano
(National Astronomical Observatory of Japan)

We would like to have magnetic-field measurements in low-$\beta$ plasma.
Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP)

A sounding rocket experiment aiming the followings:
- high-precision (0.1%) measurements of linear polarizations in vacuum-UV (VUV) lights,
- the first measurement of the linear polarization induced by atomic polarization and Hanle effect in the Lyman-alpha line (121.567nm), and
- the first exploration of magnetic fields in the upper chromosphere and transition region of the Sun.

The CLASP project was accepted by NASA in 2012, and CLASP will fly with NASA’s sounding rocket in 2015!
International Collaboration in **CLASP**

**12 institutes in 5 countries**

- **Japan**: R. Kano (PI, NAOJ)
  - All of **CLASP** science instrument (except CCD camera system and concave grating)
  - Development of empirical tool to diagnose ch.-magnetic fields

- **USA**: K. Kobayashi (PI, NASA/MSFC)
  - CCD camera system
  - Sounding rocket & operation

- **France**: F. Auchère (PI, IAS)
  - Concave grating

- **Spain**: J. Trujillo Bueno (PI, IAC)
  - Modeling of spectro-polarimetric profile in Lyman-alpha with Hanle effect

- **Norway**: M. Carlsson (Oslo U.)
  - 3D modeling of solar atmosphere
Why Lyα line?

- **Brightest line** in VUV chromospheric emission lines.
- **Bright even in quiet Sun** as well as active regions.
- **Line core** is emitted by the plasma located between **higher chromosphere** and **transition region**.
- **Good sensitivity** to magnetic field of **10 – 250 G** via Hanle effect.

⇒ **Lyα line** is a best candidate to infer magnetic fields in **low-β plasma (β<1)** over the entire solar disk.
Origin of linear polarization in scattered lights

Step 1: Population imbalance between atomic sublevels induced by anisotropic radiation illuminating atom.

isotropic radiation

\[
\begin{align*}
&m_z=-1 & m_z=0 & m_z=+1 \\
&\Rightarrow m_z=0
\end{align*}
\]

If Doppler width is wider than Zeeman splitting,
Polarizations are cancelled out.

anisotropic radiation

\[
\begin{align*}
&m_z=-1 & m_z=0 & m_z=+1 \\
&\text{Photon spin } -1 & m_z=0 & \text{Photon spin } +1 \\
&\Rightarrow m_z=0
\end{align*}
\]

Polarizations remain even after cancellation.
Origin of linear polarization in scattered lights

Step 2: Quantum coherency by rotation of quantization axes.

Step 3: Magnetic fields dephase and decrease the coherence (Hanle effect). It is a competition between Larmor motion and de-escitation.

\[ \frac{1}{\omega_0} \quad \text{VS.} \quad \frac{1}{A} \]

- time scale to change coherency
- time scale for de-excitation

\[ \omega_0 = \frac{e}{2m} gB : \text{Larmor frequency} \]

\[ \frac{1}{\omega_0} \sim \frac{1}{A} \]

**marginal field:** depolarization & rotation of linear polarization

**strong field (saturation regime):**

\[ \frac{1}{\omega_0} \ll \frac{1}{A} \]

depolarization

\[ B \sim 54G @ \text{Ly-alpha} \]

\[ A: \text{Einstein coefficient for spontaneous decay} \]
# CLASP Instrument: Optics


<table>
<thead>
<tr>
<th><strong>Cassegrain Telescope</strong></th>
<th><strong>Spectro-Polarimeter</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td><strong>Dual beam</strong> of Inverse Wadsworth mounting</td>
</tr>
<tr>
<td>Effective Focal Length</td>
<td>Wavelength</td>
</tr>
<tr>
<td>2614 mm (F/9.68)</td>
<td>121.567 ± 0.61 nm</td>
</tr>
<tr>
<td>Visible light rejection</td>
<td>Slit</td>
</tr>
<tr>
<td>“Cold Mirror” coating on primary mirror</td>
<td>1.45” (width), 400” (length)</td>
</tr>
<tr>
<td></td>
<td>Grating</td>
</tr>
<tr>
<td></td>
<td>Spherical constant-line-spacing, 3000 lines/mm</td>
</tr>
<tr>
<td></td>
<td>CCD camera</td>
</tr>
<tr>
<td></td>
<td>512 × 512 pixel</td>
</tr>
<tr>
<td></td>
<td>Plate scale</td>
</tr>
<tr>
<td></td>
<td>0.0048 nm/pixel</td>
</tr>
<tr>
<td></td>
<td>Resolution</td>
</tr>
<tr>
<td></td>
<td>0.01 nm</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
</tr>
</tbody>
</table>

| **Slitjaw Optics**                |                                                              |
|-----------------------------------|                                                              |
| Wavelength                        | 121.567 nm (narrowband filter)                               |
| Plate scale                       | 1.03”/pixel                                                  |
| FoV                               | 527” × 527”                                                  |
Polarization Measurement

- CLASP is optimized for linear polarization, because V/I is expected to be too small (~0.005% @10G in the Ly-alpha by Zeeman effect).

**CLASP Polarimeter**

- Reflective Polarization Analyzer
- Rotating Half-Waveplate (4.8 s/rot)
- Un-pol. Comp.
- Pol. Comp.
- principal axes

**Modulation**

- by rotating WP
- detected by CCD

**Demodulation from CCD exposures**

\[
Q = aK\{(D_1 - D_2 - D_3 + D_4) + \ldots\}
\]

\[
U = aK\{(D_2 - D_3 - D_4 + D_5) + \ldots\}
\]

\[
I = K\{(D_1 + D_2 + D_3 + D_4) + \ldots\}
\]

a: modulation coefficient
K: throughput value
Dual-beam demodulation

- It will reduce spurious polarizations from time variations.

<table>
<thead>
<tr>
<th></th>
<th>t1</th>
<th>t2</th>
<th>t3</th>
<th>t4</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch1</td>
<td>(+aQ+aU)</td>
<td>(+aQ+aU)</td>
<td>(-aQ-aU)</td>
<td>(+aQ-aU)</td>
<td>...</td>
</tr>
<tr>
<td>Ch2</td>
<td>(-aQ-aU)</td>
<td>(+aQ-aU)</td>
<td>(+aQ+aU)</td>
<td>(-aQ+aU)</td>
<td>...</td>
</tr>
</tbody>
</table>

\[
\frac{Q}{I} = \left[ \frac{Q}{I} \right]_0 + \frac{\Delta^2}{2a} \cdot \frac{1}{I_0} \frac{d^2 I}{dt^2} \frac{K_2 - K_1}{K_2 + K_1}
\]

Difference of throughput $K$ between 2 Ch
- We expect that the symmetric optics reduces the difference.

Time variation of intensity of targets
- The modulation/demodulation scheme removes a sensitivity to the linear change.
- The 1.2s period to take one set for the demodulation (i.e. 4 exposures) may be short enough.

$\Delta$: exposure interval (~0.3s)
## Error budget for spurious polarization


<table>
<thead>
<tr>
<th>Cause of error</th>
<th>error (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Random noise</strong></td>
<td></td>
</tr>
<tr>
<td>Photon noise at Ly-α center</td>
<td>0.026%</td>
</tr>
<tr>
<td>(10″ along slit and 200s obs. period)</td>
<td></td>
</tr>
<tr>
<td>Readout noise of CCD cameras</td>
<td>0.011%</td>
</tr>
<tr>
<td>Fluctuation of exposure durations</td>
<td>5x10⁻⁵%</td>
</tr>
<tr>
<td><strong>dI/dt</strong></td>
<td></td>
</tr>
<tr>
<td>Time variation of source intensity</td>
<td>&lt;0.018%† (~0%)</td>
</tr>
<tr>
<td>Intensity variation from pointing jitter</td>
<td>&lt;0.018%† (~0%)</td>
</tr>
<tr>
<td>Image shift from waveplate rotation</td>
<td>~0%</td>
</tr>
<tr>
<td><strong>Tel.</strong></td>
<td></td>
</tr>
<tr>
<td>Off-axis incidence with 200″</td>
<td>~10⁻⁴%</td>
</tr>
<tr>
<td>Non-uniformity of coating on primary</td>
<td>10⁻³%</td>
</tr>
<tr>
<td><strong>SP</strong> Error in polarization calibration</td>
<td>0.017%</td>
</tr>
<tr>
<td><strong>RSS</strong></td>
<td>&lt;0.042% (~0.033%)</td>
</tr>
</tbody>
</table>

†: These values are the case for the single channel demodulation, and can be reduced by dual channel modulations.
Flight instrument is in fabrication.
Measurements of flight components are also in progress.

**Half waveplate**
MgF$_2$ WP optimized by Ishikawa, R. et al. (2013, Applied Optics)

Half @ Ly$_{\alpha}$, actually!

**Reflective pol. analyzer**
Multi-layer designed by Bridou et al. (2011, Applied Physics A)

High and uniform pol.-power = 98.9%

Rs~54.7%

Rp~0.3%

“Cold mirror” coating for primary mirror

High and uniform reflectivity @ Ly$_{\alpha}$ over the 30cm diameter

2014/08/03 COSPAR in Moscow
How ambiguous is $B$-inversion?

How to solve the ambiguity?


Close-to-limb ($\mu = 0.3$) obs. of $B=50$G, $\theta_B=90^\circ$, $\chi_B=120^\circ$

Simulated observation

- $\lambda$-res.: $\sigma = 0.013$nm
- noise: $\sigma = 0.033$

Take $\chi^2$ with all synthetic profiles.

Black dots:

$\Delta \chi^2 = \chi^2 - \chi_{\text{min}}^2 \leq 3.53$, which corresponds to the confidence level of 63.8% (1$\sigma$) for 3-degree of freedom.

Two regimes:

- strong, less inclined
- weak, largely inclined

COSPAR in Moscow
Procedure to infer magnetic fields

Estimate azimuth $\chi_B$ using fibril and thread structures from IRIS, CLASP SJ, ground-based obs

Determine $B$ and $\vartheta_B$ from the inversion by fixing azimuth $\chi_B$

Estimate $B$, $\vartheta_B$, and $\chi_B$ from extrapolations using photospheric magnetic field measurement from Hinode/SP and HMI etc


Wiegelmann et al. (2010)

10"
What will CLASP observe?

Observables

C-to-L Variation of Polarization

Polarization in Line Core

Polarization in Line Wing

Solar Atmosphere

Global Structure $T(h), \rho(h)$

Magnetic fields in Chrom. & TR $B, \vartheta_B, \chi_B$

Local Structure $T(\mathbf{x}), \rho(\mathbf{x})$

2014/08/03

COSPAR in Moscow

Draft for Coordinated Observation

IRIS
• during the CLASP flight
  – Raster scan of 30”(scan)x175”(slit)
  – Near the limb: μ~0.4 and 0.6
    (Scat-pol is maximum at μ~0.4.)
  – Mg II h&k observation.

Hinode/SOT
• before/after the CLASP flight
  – Near the limb: μ~0.4.
  – Hα imaging & Photospheric Vector magnetic fields by SP.
Summary

• The CLASP project is on-going to infer magnetic fields in upper-chromosphere and transition region.
• The CLASP, a sounding rocket experiment, will be performed in 2015 summer at White Sands in USA.
• Coordinated imaging observations of chromosphere and photospheric magnetic fields are necessary.
• A quick inversion based on plane-parallel atmospheres will be tried at first, but will be followed by precise analysis collaborated with 3D simulations.