Lyman-Alpha Imaging Polarimetry with the CLASP2 Sounding Rocket Mission

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CLASP2: Exploring the magnetic chromosphere

CLASP Chromospheric Layer Spectro Polarimeter April 2019

Abstract

Ultraviolet polarimetry offers a unique opportunity to explore the upper solar chromosphere and the transition region (TR) to the million-degree corona. These outer atmospheric regions play a key role in the transfer of mass and energy from the solar photosphere to the corona. With a sounding rocket experiment called the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP), in September 2015 we succeeded in obtaining the first measurement of the linear polarization produced by scattering processes in the hydrogen Lyman-α line of the solar disk radiation. The analysis and interpretation of such spectro-polarimetric observation allowed us to obtain information on the geometrical complexity of the corrugated surface that delineates the TR, as well as on the magnetic field strength via the Hanle effect. At the same time, the CLASP slit-jaw (SJ) optics system, which is a Lyman-α filter imager characterized by a FWHM = 7 nm, allowed us to obtain broad-band Stokes-I and Q/I images over a large field of view. The obtained broad-band Q/I images are dominated by the scattering polarization signals of the Lyman-α wings, and not by the much weaker line-center signals where the Hanle effect operates

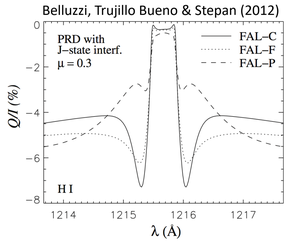
On April 11, 2019, we performed another sounding rocket experiment, called the Chromospheric LAyer Spectro-Polarimeter (CLASP2). We used the same instrument after significant modifications in order to obtain spectro-polarimetric observations of a plage and a quiet region in the Mg II h & k lines. At the same time, the CLASP2 SJ optics system allowed us to obtain broad-band Q/I and U/I images around the Lyman-α wavelength, in addition to the well-known SJ intensity images.

Motivation

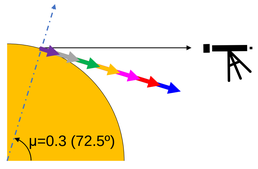
- The scattering polarization signals of the Lyman-α wings are sensitive to:

1. **The thermal structure of the chromosphere:** Belluzzi, Trujillo Bueno & Stepan (2012, ApJ) presented theoretical results from radiative transfer calculations in semi-empirical models representative of quiet (FAL-C), network (FAL-F), and plage (FAL-P) regions. They also pointed out that the wavelength-integrated scattering polarization in dominated by the wing signals.

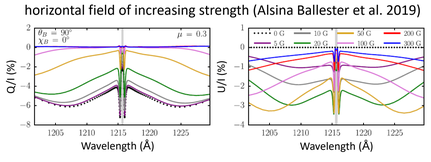
Belluzzi, Trujillo Bueno & Stepan (2012)



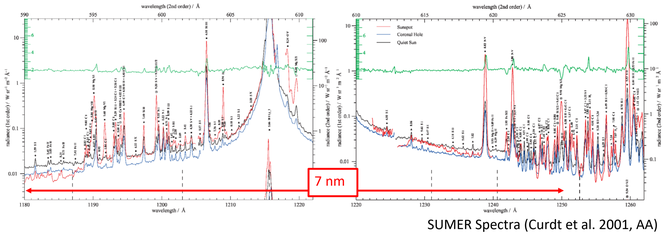
2. **The magnetic structure of the chromosphere:** Alsina Ballester, Belluzzi & Trujillo Bueno (2019, ApJ, in press) theoretically demonstrated that the magneto-optical terms, which couple the transfer equations for Stokes-Q and U, introduce an interesting magnetic sensitivity in the wings of Q/I and U/I. Therefore, Lyman-α imaging polarimetry is of scientific interest also for magnetic-field investigations.



Example of magnetic sensitivity in the Lyman-α wings for a horizontal field of increasing strength (Alsina Ballester et al. 2019)



- The hydrogen Lyman-α line is a strong UV emission line on a negligible continuum. With a 7nm bandwidth filter, the measured broad-band linear polarization is dominated by the Lyman-α wing signals.



SUMER Spectra (Curdt et al. 2001, AA)

Summary

- CLASP2 successfully obtained board-band Q/I and U/I images.
- Our preliminary analysis suggests linear polarization amplitudes of a few % in the quiet Sun near the limb, and very low polarization in the active region.
- A more detailed analysis is in progress, based on the pre-flight polarization calibration of CLASP2/SJ.

NASA Sounding Rocket Experiments: CLASP & CLASP2

The main objectives are:

- to explore the solar **chromosphere** and **transition region** via **high-precision** (<0.1%) **spectro-polarimetry** in UV spectral lines, and then
- to infer the **magnetic fields** and the **geometrical complexity of the plasma** in the upper solar atmosphere.

CLASP

Chromospheric **L**yman-**A**lpha **S**pectro-**P**olarimeter

- performed on September 3, 2015.

CLASP2

Chromospheric **LA**yer **S**pectro-**P**olarimeter

- **performed on April 11, 2019.**

Slit-Jaw Imager SJ as an Imaging Polarimeter

- The SJ optics system in the CLASP/CLASP2 instrument is an imager to confirm the pointing of the spectro-polarimeter (SP).
- Interestingly, the SJ also has the capability to measure the broad-band linear polarization of the Lyα line.
  - Because of the inclined angle-of-incidence (AOI) on each mirror, the SJ is has the polarization power.
    - Total Reflectivity: $R_s = 34\%$, and $R_p = 20\%$
    - Polarization Power: $P = \frac{R_s - R_p}{R_s + R_p} = 26\%$
  - The PMU *(polarization modulation unit)*, which is a rotating half-waveplate for Lyα located in front of the SJ, modulates not only SP's intensity but also SJ's intensity.

Fig.1: CLASP2 optics

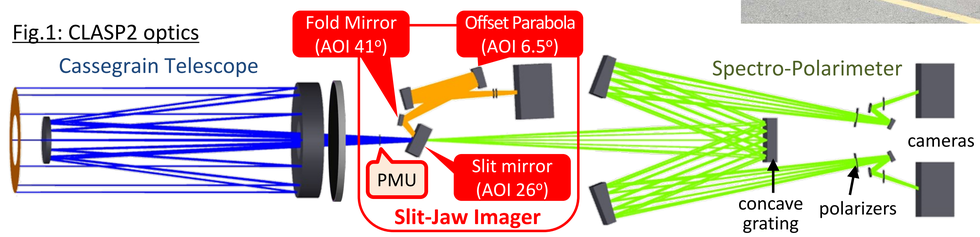
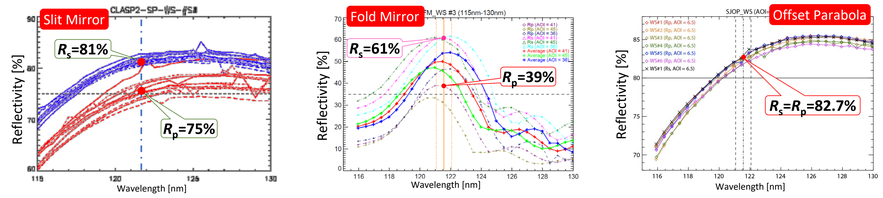


Fig.2: Reflectivity for s- and p-polarizations of mirrors in CLASP2/SJ



CLASP/SJ

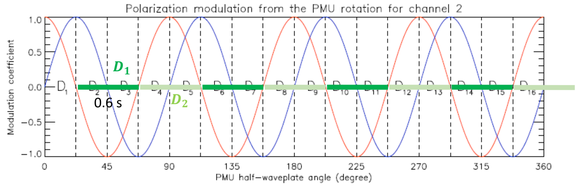
Modulation Pattern

- The PMU rotation was 4.8s/rot for SP.
- The SJ exposure (green lines) was 0.6s, and almost synchronized to Q modulation (red line).
  [difference: 40ms (=3º, initially) - 26ms (=2º, last)]

Stokes-Q can be observed.

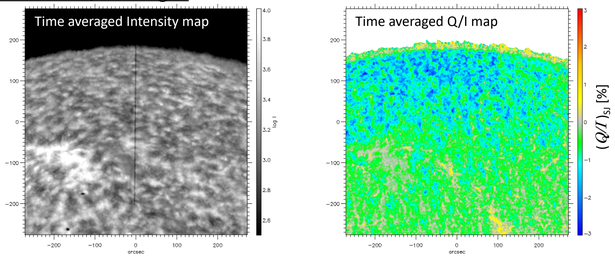
$$\frac{Q}{I} = 0.64\frac{-D_1 + D_2}{+D_1 + D_2}$$
$$\frac{U}{I} = 0$$

Fig.3a: Modulation pattern in CLASP



Results (Kano et al. 2017, ApJL)

Fig.4a: CLASP/SJ images



- Clear Center-to-Limb Variation in Stokes-Q/I.
- Stokes-Q/I of –2% ~ –3% near the limb.
- Anti-correlation between the intensity and Stokes-Q/I.
  - Especially, the active region showed very low polarization.

🡐 These are consistent with the behavior of the scattering polarization in the Lyα wings observed by the spectro-polarimeter in the CLASP instrument.

CLASP2/SJ

Modulation Pattern

- The PMU rotation changed to 3.2s/rot.
- The SJ keeps the exposure time (~ 0.6s).

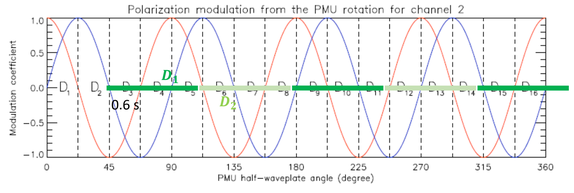
Both Q & U can be observed.

Matched timing case:

$$\frac{Q}{I} = 0.21\frac{+D_1 - D_2 - D_3 + D_4}{+D_1 + D_2 + D_3 + D_4}$$
$$\frac{U}{I} = 0.21\frac{-D_2 + D_3 + D_4 - D_5}{+D_2 + D_3 + D_4 + D_5}$$

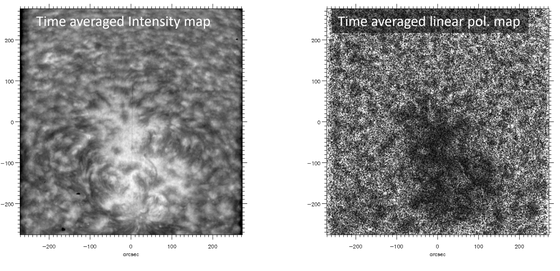
Even though unmatched case , Q & U can be derived by the coordinate rotation.

Fig.3b: Modulation pattern in CLASP2



Preliminary Results

Fig.4b: CLASP2/SJ images



We succeeded to obtain both Stokes-Q/I and U/I broad-band images.
A preliminary analysis suggests the followings:

- In quiet regions, the total linear polarization can be up to a few %.
- Anti-correlation between the intensity and the total linear polarization.
- Almost no polarization in the active region.

🡐 These CLASP2/SJ results are consistent with those obtained with CLASP/SJ.