Space-based UV Spectropolarimetry for Chromospheric Magnetic Field Measurements

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Introduction: High-resolution observations with space- and ground-based telescopes, along with advanced numerical modeling, have highlighted the intricate coupling between the chromosphere, transition region, and corona, and *the critical role the chromosphere plays in the mass and energy balance of the outer solar atmosphere*. Despite these recent advances, a major impediment to better understanding the solar atmosphere is our lack of empirical knowledge regarding the direction and strength of the magnetic field in the upper chromosphere (Decadal Survey, 2012). Such measurements are crucial to address several major unresolved issues in solar physics: for example, to constrain the energy flux carried by the Alfvén waves propagating through the chromosphere, and to determine the height at which the plasma $\beta = 1$ transition occurs, which has important consequences for the braiding of magnetic fields, for propagation and mode conversion of waves and for non-linear force-free extrapolation methods that are key to determining what drives instabilities such as flares or coronal mass ejections.

Probing the magnetic nature of the Sun's atmosphere requires measurement of the Stokes I, Q, U and V profiles of relevant spectral lines (of which Q, U and V encode the magnetic field information). Many of the magnetically sensitive lines formed in the chromosphere and transition region are in the ultraviolet spectrum, necessitating observations above the absorbing terrestrial atmosphere. The Chromospheric Layer Spectro-Polarimeter ("CLASP2") sounding rocket was flown successfully in April 2019, as a follow-on to the successful flight in September 2015 of the Chromospheric Lyman-Alpha Spectro-Polarimeter ("CLASP1"). In October of 2021, we re-flew the CLASP2 experiment with a modified observing program to further demonstrate the maturity of the UV spectropolarimetry techniques, and readiness for development into a satellite observatory. During the reflight, called "CLASP2.1", the spectrograph slit was scanned across an active region plage to acquire a two-dimensional map of Stokes V/I, to demonstrate the ability of UV spectropolarimetry to yield chromospheric magnetic fields over a large area.

Proven UV spectropolarimetry: The CLASP1 and CLASP2 missions demonstrated the necessary technology to spectroscopically resolve the linear and circular polarization in UV lines formed in the chromosphere (Figures 1-3). CLASP1 and CLASP2 showed, through the use of the Hanle and Zeeman effects, that magnetic measurements could be achieved in the chromosphere, and that those magnetic fields have spatial variations similar – but not identical – to the variations in the photosphere. As clearly shown in Fig. 3, the CLASP2 observations allowed us to directly determine the longitudinal component of the magnetic field from the low to the very top layers in the chromosphere of active region plages and enhanced network features, at each position along the spatial direction of the spectrograph slit. Figure 3 is essentially a 1-dimensional, multi-height magnetogram of the plage target on 11 April 2019. *Routine satellite mapping of the spatially varying chromospheric magnetic field will therefore dramatically improve our understanding of the chromosphere and its connection to the rest of the solar atmosphere.*

To further demonstrate the power of UV spectropolarimetry, and as a test of the maturity and readiness for development into a satellite observatory, we flew CLASP2.1 with the objective *to produce a two-dimensional multi-height magnetogram, similar to those commonly displayed for the solar photosphere.* With no changes to the instrument since the 2019 flight, CLASP2.1 was launched 08 October 2021 to observe AR 12882. Maintaining the instrument configuration ensured the same wavelength range, spectral resolution, and spatial resolution as the previous investigation of the Mg II lines. Using the SPARCS attitude control system of NASA's Sounding Rocket Program, the spectrograph slit was placed initially at the southern edge of AR 12882, and then subsequently re-targeted 15 times, with separations of slightly less than 2". The result is a sampling of AR 12882 over an area of approximately 200" x 30", significantly expanding the magnetic measurements made by CLASP2. As with the previous flights, co-observations were made in the same target with the *Hinode* and IRIS satellites. These co-observations are extremely valuable for interpretation of the CLASP1/2/2.1 data.

Future: While the CLASP series of observations demonstrate the enormous diagnostic potential of spectropolarimetry in the spectral regions of Hydrogen Lyman-α and the Mg ii h & k lines, a suborbital space experiment can only provide a few minutes of observing time. For such measurements to be useful for diagnosing the magnetic strength and structure in the Sun's atmosphere, and the flow of energy between the photosphere and the corona, *these measurements must be made routinely, and across wide fields of view of the solar disk.* Extension of the capability to allow observation of the same solar structures with identical instrumentation from two vantage points will greatly improve the diagnosis of the magnetic topology of the chromosphere and transition region, and will provide critical modeling constraints on the 3-D structure of the underlying atmosphere.

CLASP1

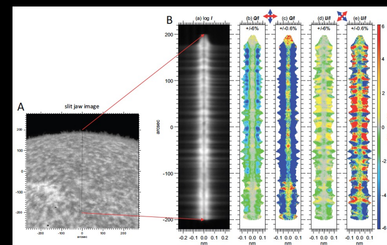

Figure 1: A: Lyman-α image taken by the CLASP1 slitjaw camera. B: The Stokes *I*, *Q/I*, and *U/I* profiles of Lyman- α observed by CLASP1 along the slit direction: (a) Stokes *I* in logarithmic scale; (b) & (c) Stokes-*Q/I* in two different scales +/- 6% & +/- 0.6%, and (d) & (e) the same for Stokes-*U/I*. The *Q/I* wings show a clear center-to-limb variation, from ~5% close to the limb to ~1% near the disk center. The positive reference direction for Stokes *Q* is parallel to the limb.

CLASP2

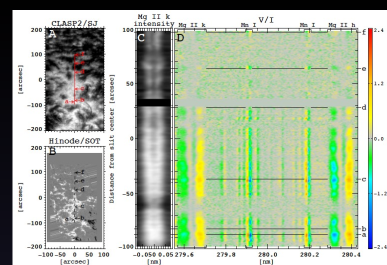

Figure 2: A: CLASP2 slitjaw image of plage on 11 April 2019. B: Orientation of the CLASP2 measurements with respect to *Hinode*/SOT photospheric magnetogram. The spectrograph slit is the faint dark line in the center. C: Mg II *k* intensity measured by CLASP2. D: Stokes *V/I* derived from CLASP2 observations of chromospheric plage; key spectral lines are labeled.

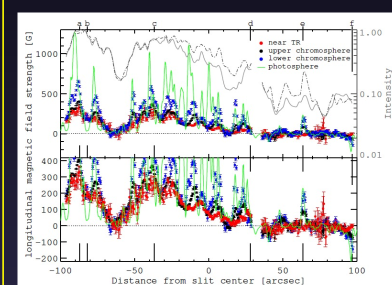

Figure 3: A: The longitudinal component of the magnetic field (B_{los}) inferred from the Stokes V/I signals shown in Fig. 2. The black and red points show B_{los} in the middle and upper chromosphere, respectively; they have been determined from the external lobes of Mg II *h* (black points) and from the inner lobes of Mg II *h* & *k* (red points). The blue points give B_{los} in the lower chromosphere, inferred from the Mn I lines. CLASP2 thus measured B_{los} at three heights in the plage atmosphere. Error bars are 1sigma. The green line is the photospheric B_{los} measured by *Hinode*. This thin black curves show the Mg II *k* line intensity along the spectrograph slit, at the k_3 line center (solid) and at the k_{2v} emission peak (dash-dotted).

CLASP2.1

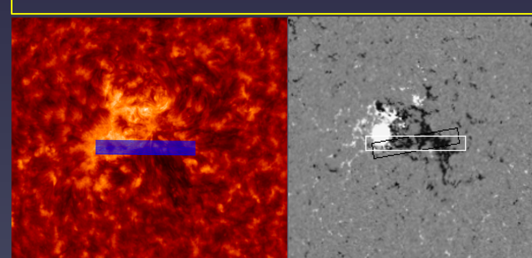

Figure 4: Area of AR 12882 scanned by CLASP2.1. Left-hand panel: slitjaw image with *actual* locations of the CLASP2.1 slit. A total of 16 slit pointings were achieved. Right-hand panel: The white box shows the planned location of the CLASP2.1 scan, and the black box shows the planned location of IRIS scans, overlaid on an HMI magnetogram of AR 12882.

Important references:

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