Solar and Stellar Magnetic Fields: Origins and Manifestations
Proceedings IAU Symposium No. 354, 2019
A. Kosovichev, K. Strassmeier & M. Jardine, ed.
doi:10.1017/S1743921320000125

Ca II 854.2 nm spectropolarimetry compared with ALMA and with scattering polarization theory

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Abstract. Ca II 854.2 nm spectropolarimetric observations of the Sun are compared with nearly simultaneous ALMA observations. These two types of chromospheric observations show rough agreement but also several notable differences. High-sensitivity ($\simeq 0.01\%$) observations reveal ubiquitous linear polarization structures across the solar disk in the core of the 854.2 nm line that are consistent with previous theoretical studies.

Keywords. Sun: chromosphere, Sun: magnetic fields, Sun: radio radiation, polarization, radiative transfer, scattering.

1. Introduction

Since 2003, regular spectropolarimetric observations of the full solar disk have been made at the National Science Foundation's National Solar Observatory using the Synoptic Optical Long-term Investigations of the Sun (SOLIS) Vector Spectromagnetograph (VSM) (Keller *et al.* (2003)). Starting in 2016 VSM observations include full Stokes spectra using the 854.2 nm Ca II line (Gosain (2017)). Such observations are valuable for studying the physical conditions in the chromosphere that produce spectrum line polarization; in particular, magnetic and velocity fields, and light scattering in the anisotropic atmosphere. This poster presents some examples of VSM observations compared with ALMA images and also first 854.2 nm Ca II observations of ubiquitous linear polarization structures across the solar disk. Some of these latter results were previously shown in preliminary form (Harvey *et al.* (2016)).

2. 854.2 nm Ca II Compared with ALMA

Fig. 1 compares ALMA 100 and 239 GHz full-disk solar images from 2015 December with nearly simultaneous VSM Ca II images. Intensity images from near the core of the Ca II line are roughly similar to ALMA brightness images when the former are raised to the 0.2 power. However, ALMA prominently shows network features while they are much less evident relative to plages in the Ca II line core. While ALMA shows limb brightening, Ca II shows limb darkening. Both types of observations show dark circumfacule structures around active regions and dark filament channels where horizontal magnetic fields are dominant. The poster includes Ca II images blurred to match the quoted ALMA resolutions. This does not significantly improve the comparisons. The differences between ALMA and Ca II may be due to different height ranges of the two observations or Ca emission arising from radiative transfer processes in addition to just temperature.

Fig. 2 compares Ca II with ALMA array observations of a small area near a sunspot with improved resolution. Filamentary structures emerge from the sunspot in the ALMA

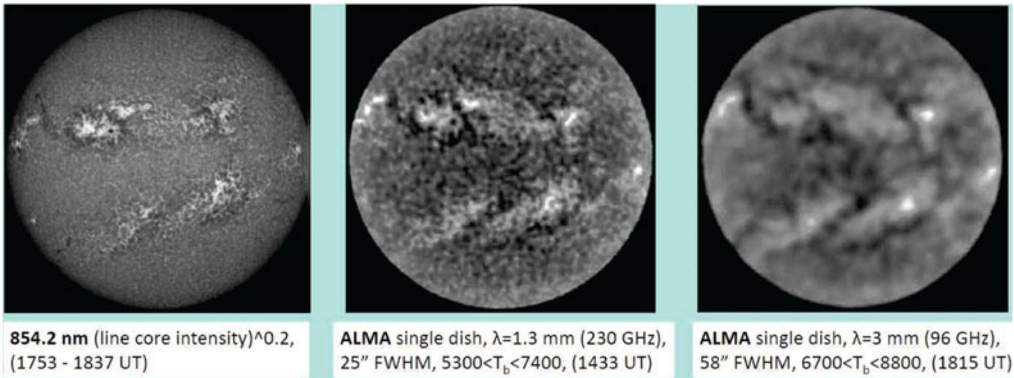

Figure 1. Full-disk SOLIS/VSM 854.2 nm and single-dish ALMA observations on 2015.12.17

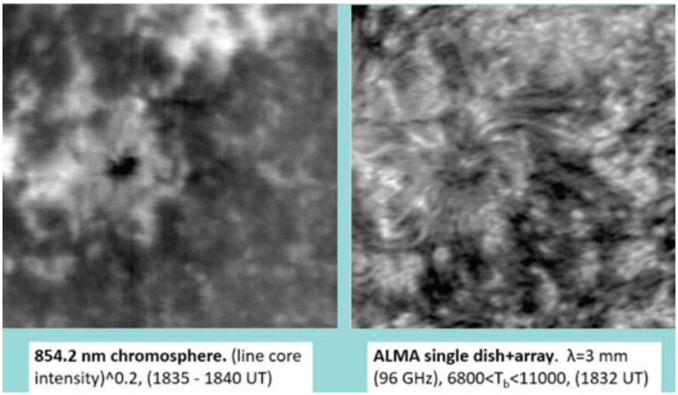

Figure 2. AR 12470 SOLIS/VSM 854.2 nm and ALMA array observations on 2015.12.16

image but are less obvious in the lower resolution Ca image. Again, network features are prominent in the ALMA image but less so in the Ca image. Curiously, the plage near the top of the Ca image is scarcely visible in ALMA observations. We note recent publication of higher resolution comparisons of small-area ALMA images with several chromospheric lines including Ca II 854.2 nm (Molnar *et al.* (2019)).

3. Scattering Linear Polarization in 854.2 nm Ca II

Ubiquitous linear polarization structures across the solar disk in the core of the Ca II line are revealed in VSM results from 2016.03.23 with spectropolarimetric sensitivity close to 0.01% (Fig. 3). The poster includes context images that show where these high-sensitivity observations were made. These observations confirm theoretical studies that predicted this scattering linear polarization and also earlier observations of linear polarization in small areas near the solar limb. Sequential measurements show that the linear polarization features change rapidly in time. Spatially, the polarized structures are closely associated with bright Ca II mottles and dark elongated fibril structures. Bright (dark) features tend to be polarized parallel (perpendicular) to the closest limb as illustrated in the poster. The transverse Zeeman effect is generally overwhelmed by the scattering polarization, except in sunspots and strong plages (see panel A in Fig. 3). This dominance of linear polarization by scattering presents a severe challenge to measuring the chromospheric vector magnetic field using the 854.2 nm line.

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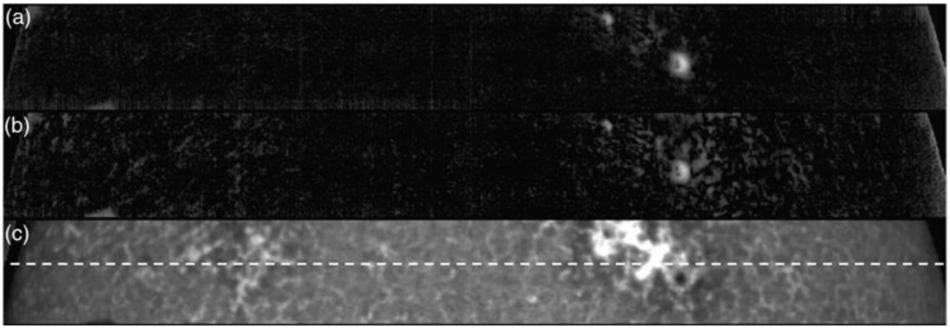

Figure 3. Linear polarization fraction in line wing and line core. (A) Zeeman effect dominates the 0.1 to 0.3 Å average from both sides of the line core. (B) Scattering polarization averaged ±0.1 Å across the line core. (C) Line core intensity with dashed line indicating the slit position of the Stokes spectra in Fig. 4. Linear polarization strength is displayed on a log intensity scale ranging from 0.001% to 5% for (A) and 0.01% to 5% for (B).

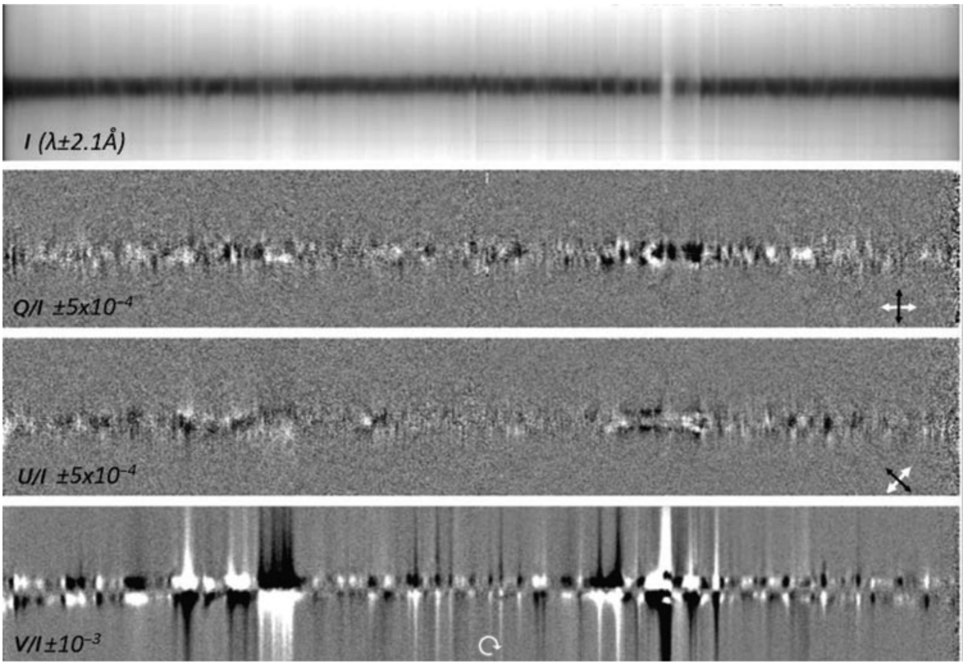

Figure 4. Typical full Stokes spectra showing that linear polarization structures are ubiquitous across the disk in the line core of 854.2 nm Ca II. The location of these spectra is the dashed line in Fig. 3. Top panel is intensity. Middle panels are Q/I and U/I linear polarization. Bottom panel is V/I circular polarization. The linear polarization noise levels are ±0.012%.

In Fig. 4 we see that transverse Zeeman splitting patterns are present only in strong magnetic regions. Elsewhere, scattering linear polarization dominates spectra near the core of the Ca line. Compared with circularly polarized spectral features arising from the line-of-sight magnetic field, the scattering linear polarization shows much more erratic wavelength variations. There is a gradual increase of linear polarization strengths moving toward the limb. Not shown here is a strong increase of a correlation between linear polarization strength and intensity toward the limb. Also noted in the spectra, and visible near the bottom left of panels A and B of Fig. 3, is a strong linear polarization signal

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in a disk filament. The azimuth of this linear polarization appears to be modified by the magnetic field of the filament.

Jurčák *et al.* (2018) observed with a slit near the solar disk center and found linear polarization features similar to the ubiquitous ones reported in this poster. Both sets of observations are remarkably similar to the models of Štěpán & Trujillo Bueno (2016) confirming that the models include the relevant physics. An essential finding is that the chromosphere is extremely inhomogeneous and dynamic, which is no surprise.

Acknowledgements

This work utilizes SOLIS data obtained by the NSO Integrated Synoptic Program (NISP), managed by the National Science Foundation's National Solar Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the National Science Foundation.

This paper makes use of the following ALMA data: ADS/JAO.ALMA#2011.0.00020.SV.. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The National Radio Astronomy Observatory is a facility of the National Science Foundation (NSF) operated under cooperative agreement by Associated Universities, Inc.

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