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Design of an adaptable Stokes polarimeter for exploring chromospheric magnetism

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Abstract

The chromosphere is a highly complex and dynamic layer of the Sun, that serves as a conduit for mass and energy supply between two, very distinct regions of the solar atmosphere, namely, the photosphere and corona. Inferring magnetic fields in the chromosphere, has thus become an important topic, that can be addressed with large-aperture solar telescopes to carry out highly sensitive polarimetric measurements. In this article, we present a design of a polarimeter for investigating the chromospheric magnetic field. The instrument consists of a number of lenses, two ferro-electric liquid crystals, a Wollaston prism, and a CCD camera. The optical design is similar to that of a commercial zoom lens which allows a variable f# while maintaining focus and aberrations well within the Airy disc. The optical design of the Adaptable ChRomOspheric POLarimeter (ACROPOL) makes use of off-the-shelf components and is described for the 70 cm Vacuum Tower Telescope and the 1.5 m GREGOR telescope at Observatorio del Teide, Tenerife, Spain. Our design shows that the optical train can be separated into two units where the first unit, consisting of a single lens, has to be changed while going from the VTT to the GREGOR configuration. We also discuss the tolerances within which, diffraction limited performance can be achieved with our design.

Keywords: Solar magnetic field; Solar chromosphere; Solar photosphere; High resolution; Polarimeters

1. Introduction

The chromosphere couples the photosphere to the corona. It represents an important region in the solar atmosphere where nearly all of the mechanical energy that drives solar activity is converted into heat and radiation, with only a small fraction leaking through to heat the overlying corona and power the solar wind (Withbroe and Noyes, 1977). Several processes, such as wave propagation and dissipation (McIntosh and Judge, 2001), electrical currents (Judge and Centeno, 2008), and magnetic reconnection occur in the chromosphere, which regulate the mass and energy supply to the corona. However, the relative contribution of the individual processes, their dependence on local conditions, and the nature of non-thermal to thermal energy conversion, remains an open question. Thus, understanding the chromosphere and its magnetism is a significant necessity for explaining the corona and heliosphere (Pontieu et al., 2014).

As the pressure scale height in the solar atmosphere is about 150 km (Durrant, 1988), the chromospheric density is about four orders of magnitude lower than that in the photosphere. Subsequently, the Alfvén and sound speeds

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in the chromosphere necessitate measurements at high temporal and spatial resolution so as to resolve gas, plasma, and wave motions (Kano et al., 2012). Diagnosis of the chromospheric magnetic field is mainly done through spectro-polarimetry in spectral lines formed under non-LTE conditions (Socas-Navarro et al., 2000). More importantly, the chromospheric signature in these spectral lines is only evident in a narrow range around the line core, where the photon flux is only 10–20% of the continuum intensity. A polarimetric sensitivity of the order of 10^{-4} is required to detect weak chromospheric fields (Socas-Navarro, 2010). The extraction of the chromospheric magnetic field at high spatial and temporal resolution is quintessential to shed light into this complex region of the Sun and requires large-aperture solar telescopes with photon-efficient instruments. While the 4-m Daniel K. Inouye Solar Telescope (DKIST, previously ATST; Rimmele, 2008), and the 4-m European Solar Telescope (EST; Collados et al., 2013) are important steps in this direction, the former is presently under construction and it will be several years until the latter is realised. As Europe's largest operational solar telescope, the 1.5-m GREGOR (Schmidt et al., 2012), at Observatorio del Teide, is pivotal for exploring chromospheric magnetism and on the verge of creating several important scientific milestones which will serve as a foundation for future large-aperture solar telescopes.

A design for a dual-beam polarimeter is presented in this article which will probe the chromospheric magnetic field using the Ca II infrared line at 854.2 nm. The aim of this work is to determine the feasibility of designing a single optical configuration that can modify the f# at the detector plane, analogous to commercial zoom lenses. In this article we discuss the design specifically for different input f-numbers corresponding to the 70 cm Vacuum Tower Telescope (VTT) and the 1.5 m GREGOR.

The organisation of this article is as follows: diagnostics for chromospheric spectro-polarimetry and some key scientific questions which could be addressed, are presented in Sections 2 and 3, respectively. The instrument and its performance are described in Section 4, and the concluding remarks are highlighted in Section 5.

2. Diagnostics for chromospheric spectro-polarimetry

There are a number of spectral lines that can be used for chromospheric observations. The Hydrogen Hα Balmer line at 656 nm is historically significant and has been traditionally used for flare, spicule, and prominence/filament studies. Despite this, its interpretation is enormously challenging as the population of the excited $n = 3$ level is strongly dependent on the temperature and radiative conditions in the solar atmosphere, with quantitative estimates confined to simplistic assumptions such as the cloud model (Beckers, 1964). Other prominent spectral lines are the Ca II H&K lines at 390 nm, the NaD line pair at 589 nm, the Mg I B2 at 517 nm, the He I D3 at 588 nm, the Ca II infrared triplet at 850 nm, and the He I infrared triplet at 1083 nm. The Ca II and He I infrared lines have gained considerable importance over the last decade due to sensitive polarimeters (references provided below) and the availability of standard inversion codes (Asensio Ramos et al., 2008; Lagg et al., 2009; Socas-Navarro et al., 2015) that provide physical parameters in the relevant part of the solar atmosphere.

The He I 1083 nm line forms through ionisation by coronal ultra-violet (UV) radiation, thus forming in a narrow region in the upper layers of the chromosphere (Mohler and Goldberg, 1956; Harvey and Sheeley, 1977; Venkatakrishnan et al., 1992; Fontenla et al., 1993). While the line is free from photospheric contamination, it is extremely weak in the quiet Sun. The Ca II infrared triplet on the other hand, has a low excitation potential of 1.69 eV and extends from the upper photosphere well into the chromosphere. For instance, at ±60 pm from the line core, one can probe the photosphere at a height of about 200 km which exhibits reversed granulation. The "knees" of the intensity profile at around ±30 pm sample the temperature minimum region, some 500 km above the continuum forming layer. The line core, representing heights of approximately 1300 km, is purely chromospheric (Leenaarts et al., 2009). Thus, the Ca II infrared line has the advantage, that it can be combined with photospheric observations to extract the stratification of physical parameters over a large height range in the atmosphere. The sensitivity of the Ca II infrared line to longitudinal and transverse magnetic fields has been recently studied by Noda et al., 2016 and the authors conclude that the line is mostly sensitive to the layers between $\log \tau = 0$ and $\log \tau = -5.5$, under the prescribed conditions in their model atmospheres.

Several instruments at various ground-based telescopes observe the He I infrared triplet. They are the Spectro-Polarimeter for Infrared and Optical Regions (SPINOR; Socas-Navarro et al., 2006), the Facility Infrared Spectropolarimeter (FIRS; Jaeggli et al., 2010), and the SOLIS Vector SpectroMagnetograph (VSM; Henney et al., 2006) at the National Solar Observatory (NSO), and the The Near-InfraRed Imaging Spectropolarimeter (NIRIS; Cao et al., 2012) at the Big Bear Solar Observatory. Observations in the Ca II infrared line are done with the Interferometric BIdimensional Spectrometer (IBIS Cavallini, 2006) and SPINOR at NSO, as well as with the CRisp Imaging SpectroPolarimeter (CRISP; Scharmer et al., 2008) at the Swedish Solar Telescope.

The 1.5-m GREGOR Infrared Spectrograph (GRIS; Collados et al., 2012) is routinely providing observations of the He I infrared triplet, in continuation to the Tenerife Infrared Polarimeter (TIP-I/II; Collados et al., 2007), which was operational at the adjacent 70 cm VTT for more than a decade. Our optical design for the polarimeter, allows it to be mounted at the VTT or GREGOR, which will provide a comprehensive coverage of the solar chromosphere and significantly reinforce the instrumentation capability of the two telescopes.

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