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R. Casini and B. W. Lites

The Ba II 4554 / Hβ Imaging Polarimeter for the Dutch Open Telescope

F. Snik, F. C. M. Bettonvil, A. P. L. Jägers, R. H. Hammerschlag, R. J. Rutten, and C. U. Keller

Sterrekundig Instituut, P.O. Box 80000, NL-3508 TA Utrecht, The Netherlands

Abstract. In order to expand the high-resolution, multi-wavelength imaging capabilities of the Dutch Open Telescope (DOT), an additional polarimetric channel based on a 80 mÅ tunable Lyot filter for Ba II 4554 and Hβ has been designed and constructed. The large atomic mass and the resulting steep line wings, make Ba II 4554 particularly suitable for the creation of photospheric Dopplergrams and Stokes-V magnetograms. The line also yields a significant degree of linear (scattering) polarization for observations near the limb of the Sun, which is modified by both horizontal and vertical weak-field topologies through the Hanle effect and hyperfine-structure level crossing. The polarimeter is based on liquid crystal variable retarders (LCVRs) as polarization modulators in combination with the Lyot filter's entrance polarizer. The tunability of the LCVRs is exploited to enable specific wavelength calibration, selection of the reference frame of linear polarization, and optimization of instrumental polarization cross-talk, which for the DOT is constant in time. With the future Ba II 4554 photospheric magnetograms, we expect to be able to discern magnetic structures of about 150 km with field strengths down to 100 G, and that Hanle-type observations can be performed at a resolution of about $1''$. The range of applicability of Hβ imaging polarimetry has to be explored after installation.

1. The Dutch Open Telescope

The Dutch Open Telescope (DOT) on La Palma (Rutten et al. 2004) excels at high-resolution tomographic imaging of the solar atmosphere. Its open design relies on the wind to "flush out" atmospheric turbulence to improve the local seeing conditions. Utilizing speckle reconstruction to remove the remaining atmospheric contributions, the 45 cm DOT is able to reach the diffraction limit for its observations during several hours. By obtaining co-spatial and co-temporal images in different wavelength bands (G-band, blue and red continuum, Ca II H, Hα), dynamic processes in the solar atmosphere are observed in different layers at a length scale of $\sim$ 150 km (see the examples at `http://dot.astro.uu.nl`). It is valuable to also be able to simultaneously obtain direct information about the magnetic field topology. Therefore the next and last wavelengths of the DOT multi-wavelength speckle imaging system are Ba II 4554 and Hβ, which will be utilized for full Stokes polarimetric imaging. The polarimeter employs a tunable Lyot filter with a 80 mÅ band-pass (Kushtal & Skomorovsky 2002). Sütterlin et al. (2001) have used the filter at the SVST and obtained a richly detailed Dopplergram by tuning through the strong barium line. The filter also has a principal transmission maximum at Hβ (4861 Å).

2. Ba II 4554 Polarimetry

Zeeman Effect. With an effective Landé factor of 1.167 and a relatively short wavelength, Ba II 4554 is not expected to be particularly sensitive to the Zeeman effect. However, the large steepness of the line wings due to the large atomic weight of barium causes high degrees of circular polarization V/I according to the standard magnetograph formula. The Zeeman splitting becomes significant with respect to the thermal Doppler broadening already for low magnetic field strengths. The spectro-polarimetric observations presented in Fig. 1 show that the response to small field strengths even exceeds the expectations from the magnetograph formula. This may be caused by the group of hyperfine structure (HFS) components in both line wings due to the 18% of barium isotopes with non-zero nuclear magnetic moment. Careful modeling is required to investigate the magnetograph signal of Ba II 4554 in order to obtain valid inversion curves for the future DOT magnetograms. In comparison with the standard magnetograph line Fe I 6302, Ba II 4554 yields higher degrees of circular polarization for longitudinal field topologies and allows for diffraction limited observations at higher spatial resolution due to the shorter wavelength.

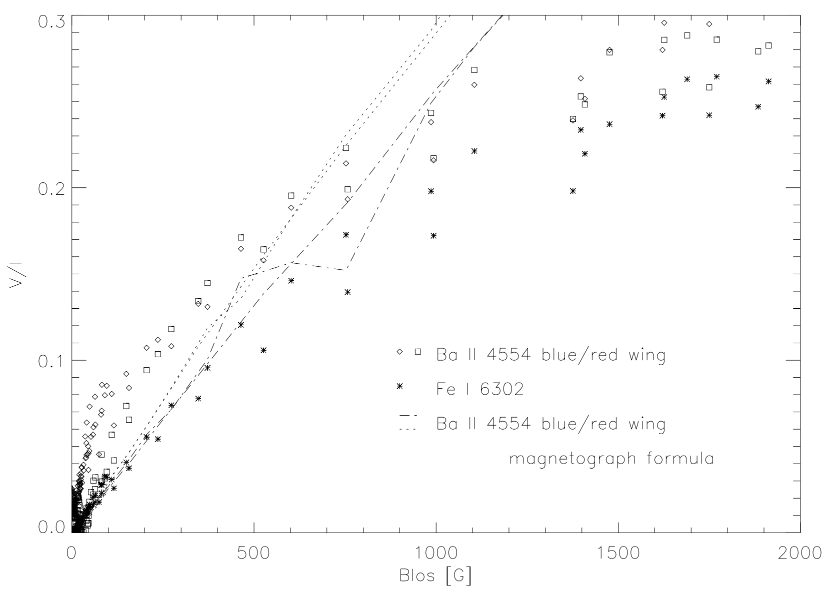

Figure 1. Results of spectro-polarimetric observations of AR 10713 at $\theta=19^{\circ}.9$, on Dec. 24, 2004 at IRSOL with ZIMPOL II. The longitudinal magnetic field strength as a function of slit position across the unipolar sunspot was derived from the Stokes-V spectrum in Fe I 6302 using both the weak and strong field approximations. The plot shows the maximum absolute signal V/I in the blue and the red wing ± 66 mÅ from line center of Ba II 4554 at the same slit position. It is clear that the polarization degree of V in Ba II 4554 has a steeper response to longitudinal magnetic fields than the standard magnetogram signal of Fe I 6302. Application of the magnetograph formula shows that possibly also the presence of the asymmetric HFS components in the line wings contribute to the steep response. For $|\boldsymbol{B}| > 1$ kG the Zeeman splitting becomes larger than the Doppler broadening and the signal saturates.

Hanle Effect. Ba II 4554 also has one of the strongest signals in the "second solar spectrum" (the linear polarization parallel to the solar limb caused by 90° scattering; Stenflo & Keller 1997). Contrary to the regular spectrum, the HFS components in the wings are clearly discernable in the second solar spectrum. According to the Hanle effect, weak horizontal magnetic fields depolarize the line core and rotate the direction of linear polarization when the field is parallel to the line-of-sight. The Hanle effect is not sensitive to vertical fields, but the presence of HFS can lead to an enhancement of the scattering polarization for increasing vertical field strengths as shown by Belluzzi et al. (2006). Using Stokes-Q imaging polarimetry (with $\pm Q$ chosen parallel to the limb) "Hanlegrams" can be acquired to study the topology of weak, turbulent magnetic fields.

3. Polarimeter Design

Imaging Optics. The DOT multi-wavelength system is fed with an achromatic, telecentric $f/45$ beam. This beam is split by means of dichroic and regular beam-splitters to allow for synchronous imaging in 7 different wavelength bands. Due to mechanical constraints concerning the size of the Lyot filter in the Ba II 4554 / Hβ channel, its image plane is re-imaged three times and the beam is transported using several right-angle prisms.

The neighboring broadband continuum beam contains 6 Å band-pass interference filters at 4505 and 4817 Å, and will be used to obtain atmospheric and alignment information for speckle reconstructing the polarimetric bursts according to the method described by Keller & von der Lühe (1992). The position of the final lens set and camera of both these channels can be adjusted to de-magnify the image on the CCD to increase the photon flux per pixel.

Polarization Optics. To avoid unnecessary light losses, the Lyot filter's entrance polarizer also serves as selection polarizer of the polarization modulation package. This means that the many optical components before the polarization modulators will introduce a significant amount of instrumental polarization. The influence of the beam-splitters and the right-angle prisms is minimized by placing them in sets of two identical ones with their polarizing axes at 90° in order to compensate their mutual effects.

Liquid crystal variable retarders (LCVRs) were chosen as polarization modulators for the following reasons:

1 They have no macroscopic moving parts and therefore do not cause beam shake.
2 Their modulation is faster than the camera's read-out speed.
3 They enable specific wavelength calibration and can therefore be used at both Ba II 4554 and Hβ.
4 Their tunable retardance can be utilized for different modulation schemes, including $I \pm \{Q, U, V\}$.
5 By attaching an additional quarter-wave plate the angle θ of $+Q$ on the disk can be chosen by applying an offset of 2θ to the retardance of LCVR2.
6 By choosing appropriate offsets to the retardances of both LCVRs, the instrumental cross-talk components (especially $V \rightarrow Q, U$) can be minimized.

In order to measure the instrumental polarization at both operating wavelengths, a calibration unit can be installed after prime focus and the magnification lens set. There, a rotating linear polarizer and an independently rotating QWP will produce known input polarization states. The measured output states are then used to compute the instrumental Mueller matrix. Because of the DOT's equatorial mount, this matrix is in principle not subject to diurnal or annual variations. The instrumental polarization due to the non-circular aperture can safely be neglected. The influence of the first lens set and the temperature dependence of the rest of the instrumental polarization will be investigated. More details are given in Bettonvil et al. (2003) and Snik (2005, see also `http://dot.astro.uu.nl/dot-documents/snik-report-2005.pdf`).

4. Outlook

Due to the high degrees of line polarization that Ba II 4554 yields, both the Zeeman effect and the Hanle effect will constitute excellent diagnostics of solar magnetism at high resolution. Stokes-V magnetograms are likely to provide sufficient S/N to form a standard DOT observational capability to probe the LOS magnetic polarities and field strengths at the diffraction limit of $0\farcs2$. In order to measure the linear polarization due to both the transverse Zeeman effect and from scattering polarization including Hanle depolarization, longer exposures and de-magnification are necessary. With excellent La Palma seeing such observations may be possible at a resolution of $\sim 1''$.

Polarimetry in the Hydrogen Balmer lines has been used to measure chromospheric magnetic fields. However, the complicated line formation substantially hampers the interpretation of Hβ Stokes data.

Performing polarimetry at the diffraction limit of the 45 cm mirror with an extremely narrow-banded Lyot filter in the blue, the major problem for this instrument will be the low photon flux. Installation of the Ba II 4554 / Hβ channel at the DOT has begun in the summer of 2005. The first polarimetric observations are expected in 2006.

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