A&A 398, 739–742 (2003)
DOI: 10.1051/0004-6361:20021515

Astronomy & Astrophysics

High spatial resolution solar polarimetry with interference filters

E. Wiehr[1] and M. Bianda[2]

[1] Universitäts-Sternwarte, Geismarlandstraße 11, 37083 Göttingen, Germany
[2] Istituto Ricerche Solari, via Patocchi, 6644 Locarno-Orselina, Switzerland

Received 31 July 2002 / Accepted 14 October 2002

Abstract. A new type of two-dimensional polarimeter is used to measure the center-to-limb variation of the scattering induced polarization in a narrow continuum window up to the extreme limb. The polarimeter is set on the Tenerife Gregory Coudé telescope's hour axis, where the two folding flat mirrors cancel their polarizing effects for zero solar declination at the equinox. The short CCD exposure of only 5 ms allows high spatial resolution images in polarized light. A beam switching technique together with an integration parallel to the solar limb over 20″, yields a high polarimetric accuracy with an rms noise of 2×10^{-4}. Our results for a continuum window at 4506–4508 Å agree with model calculations down to limb distances of 0.″32 (i.e. $\cos\vartheta < 0.025$).

Key words. Sun: atmosphere – techniques: polarimetric

1. Introduction

Scattering processes in the solar atmosphere produce deviations from a Planckian source function. Since the incident radiation shows limb darkening, the scattered part of the light exhibits a preferential direction, affecting a linear polarization which increases strongly toward the solar limb. If the lifetime of the respective transition is not short enough, the scattering process is disturbed by collisions. Hence, only favorable absorption lines show a limb polarization (e.g. Stenflo 1973). The continuum radiation also exhibits a limb polarization mostly arising from Rayleigh scattering of neutral hydrogen (cf., Unsöld 1956).

The limb polarization in the continuum has been observed by Leroy (1972), Mickey & Orall (1974), and Wiehr (1975, 1978). The results agree for limb distances down to a few arcsec. In particular for wavelengths near 5850 Å, these authors consistently find Q/I values of 0.9×10^{-4} and 6×10^{-4} at 25″ and 5″ limb distance, respectively. Closer to the limb, only Mickey & Orall (1974) give values which, however, hardly yield a smooth curve (cf., their Fig. 3). Model calculations by Fluri & Stenflo (1999) nicely fit these observations. However, a much stronger test would be the comparison of data with theory at the very limb where the rise of the polarization is very steep particularly at blue wavelengths. Such observations are rather difficult since the continuum limb polarization (i) is of very small amount, (ii) is superposed with the strong intensity gradient at the very limb, and (iii) interferes with the usually much larger instrumental polarization. The use of a

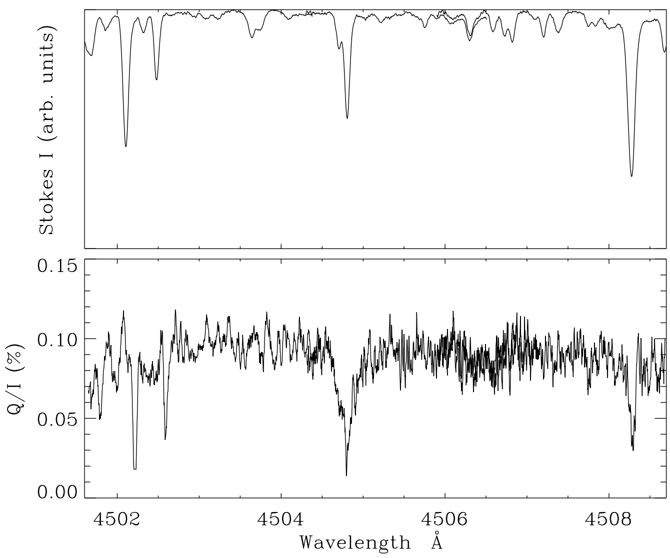

Fig. 1. Linear polarization at 5″ limb distance through the blue region, selected for measurements of the continuum polarization; two sub-spectra joined at at 4506.5 Å display the full wavelength window were taken with the spectrograph instead of the 2-D optics (cf., text); ordinate scale = polarization in %; intensity in arbitrary units.

spectrograph for high spectral resolution, involves multiple telescopic reflections which introduce polarization. For a "German type" coudé mounting with two nearly orthogonal folding flat mirrors (as, e.g., the telescopes at Locarno and at Tenerife; Wiehr 1987), the instrumental polarization varies only with the solar declination thus being largely constant over a day (cf., Wiehr 1971) and very small near the equinoxia, (where the two deflections are precisely orthogonal). The high

Send offprint requests to: E. Wiehr,
e-mail: ewiehr@uni-sw.gwdg.de

suitability of such a coudé type telescope allowed the detection of limb polarization in spectrally well resolved line profiles as Ca I 4227 (Brückner 1963), Sr II 4078, Ba II 4554, Na I 5890 (Wiehr 1975), Sr I 4607, Ba I 5535 (Wiehr 1978). Recent polarimetry with the "Zürich polarimeter" (ZIMPOL; Povel 1995) extended these measurements.

The Gregory Coudé Telescope at Locarno also enabled first measurements of the continuum polarization in spectrally well defined narrow windows free from absorption lines: at 5″ limb distance (cos $\vartheta = 0.23$) the continuum polarization decreases from 10^{-3} at 4234.8 Å to 5×10^{-5} at 6578.0 Å (Wiehr 1975). Such observations have also been made by Leroy (1972) who, however, used broader filters covering more lines, and did not reach the very limb. For the present continuum observations, the wavelength selection is done via filters instead of a spectrograph, a method which has already been used by Clarke & Ameijenda (2000) for the determination of the center-to-limb variation of the Hα resonance polarization. It yields very short exposure times of a few milliseconds which largely "freeze" seeing. The much longer exposures with "ZIMPOL" do not allow a determination of the strong increase of the linear polarization at the very limb, presented in this paper.

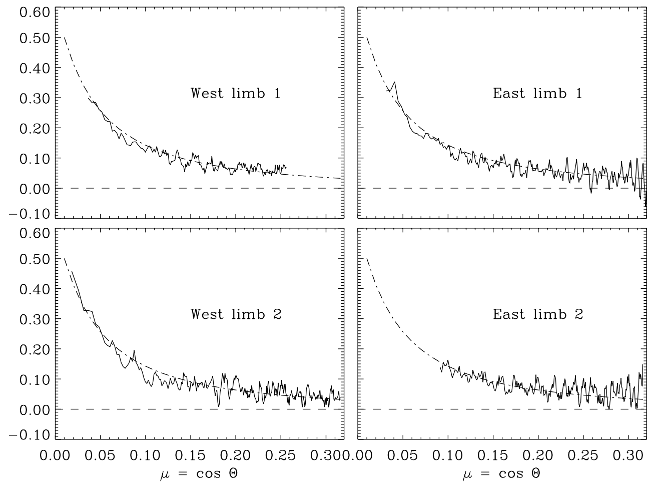

Fig. 3. Linear polarization in the 4506 Å window as function of the heliocentric angle cosΘ in comparison with calculations by Fluri & Stenflo (1999; dash points); the four curves represent data from different limb positions obtained when following the coudé rotation: 9 pairs for "west-limb-1", 2 pairs for "west-limb-2", 6 pairs for "east-limb-1", and 3 pairs for "east-limb-2".

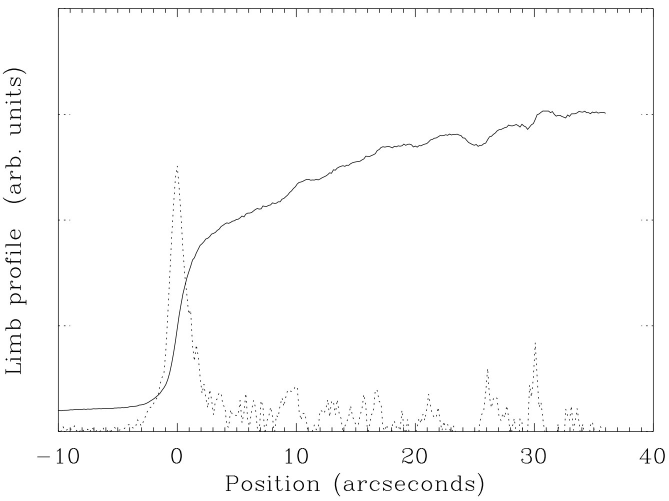

Fig. 2. Intensity profile of the solar limb (full line) and first derivative (dash points) of 2″ half-width showing the high spatial resolution achieved with the polarimeter described.

2. Observing method

We observed close to the spring equinox 2002, where the two folding flat mirrors of the Gregory Coudé Telescope (GCT) are orthogonally oriented, thus yielding very small instrumental linear polarization. The measurement of the polarized light was done with a beam switching technique where a $\lambda/2$ plate in front of a calcite (Savart plate) is operated alternately in two orthogonal orientations (Semel et al. 1993). We placed these optical components directly on the telescope's hour axis thus avoiding any further reflections. The finite field-of-view required for the Savart plate, is defined by a $32'' \times 125''$ aperture in front of the polarization optics and is imaged by telecentric optics on a CCD. Between the two lenses, an image of the telescope's entrance pupil occurs, which is precisely baffled in order to reduce scattered light from the optics. The total set-up can easily be removed, allowing a quick check of the filter transmission with the spectrograph. The possibility of an alternate use of the spectrograph keeping the polarization analyzer unchanged, also allowed us to check the adjustment and the accuracy of the polarimeter. We measured the resonance polarization of the Ca 4227 line and obtained a good agreement with previous data. In particular, the ratio of blue-to-red wing polarization of 5:4, consistently observed with the Locarno telescope (cf., Stenflo 1974; Wiehr 1981; Bianda et al. 1998), proves the reliability of our results. This shows that, at the equinoxia, the GCT does not introduce artificial Q-signals via cross-talk originating from the telescope mirrors and their actual surface state (cf., Wiehr 1971; Wiehr & Rossbach 1974). Accordingly, we do not obtain measurable U-signals (see below).

We selected a spectral window near 4505 Å with the filter used by Sütterlin & Wiehr (1998) for two-dimensional continuum photometry. Its transmission maximum of 3 Å half-intensity width was electrically heated to fit the 4505–4508 Å region which is free of polarization from lines. Since our blue region is not covered by the polarization atlas (Gandorfer 2000), this was proven switching to the spectrograph and orienting the slit at 5″ distance parallel to the solar limb. The linear polarization was measured successively in two wavelength intervals, overlapping each other near 4506 Å (cf., Fig. 1). Averaging ten Q/I profiles in the two wavelength intervals yields a high inner accuracy, as seen from the good agreement of the two Q/I profiles in the overlapping interval in Fig. 1. Since no significant line polarization occurs at $4505 < \lambda < 4508$ Å, that wavelength range can be considered as a sufficiently clean "continuum window" for limb polarization. Alternate control by means of the spectrograph also ensured

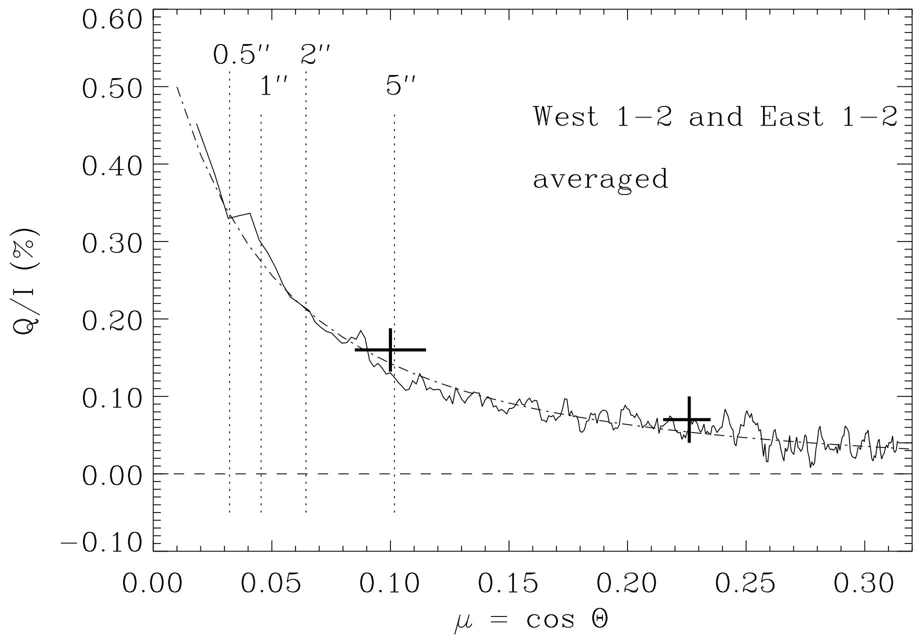

Fig. 4. Average of the four profiles in Fig. 3 together with calculations by Fluri and Stenflo for model FALC-5 from Fontenla et al.; vertical bars indicate the limb distance in arcsec; crosses give the data by Wiehr (1978).

the high wavelength stability of the filter heating. The transmission of the 3 Å filter allows exposures as short as 5 ms with more than 10 000 CCD counts, – as compared to about 600 CCD counts for our 500 ms spectrographic measurements. We selected images with "frozen seeing", i.e. without marked influences from the earth's atmosphere. The spatial resolution is then given by the two-pixel limit of 0.″32.

For a correction of instrumental polarization, we took data at disk center where a polarization of solar origin is assumed to be zero for symmetry reasons. The measured disk center signal yields an instrumental linear polarization of 0.0017 (0.17%) showing that near the equinox the GCT is, indeed, largely free from linear polarization. We subtract this value from the limb observations, assuming that the instrumental polarization does not differ between disc center and limb (the maximum declination difference over the solar disk being only 0.25 deg). The amount of linear polarization was checked by a tilted glass plate.

We also measured the U-signal operating the $\lambda/2$ plate at 22.5° and 67.5° (instead of the 0° and 45° for the Q-signal). The disk center polarization shows the expected variation between Q and U due to the coudé rotation. This shows that the instrument does not introduce cross-talk, as is expected from the perpendicular reflection planes of the two telescopic folding-flat mirrors.

3. Continuum polarization near the limb

We measured the continuum polarization at locations where the solar limb is oriented perpendicularly to the CCD rows. The corresponding limb position slightly varies with the coudé rotation, which was not compensated in order to avoid additional polarization from a de-rotator. The linear polarization was measured with the method introduced by Semel et al. (1993): two exposures taken with perpendicular orientations of the half wave plate give a total of four images. Since these are not subtracted but crosswise divided, variations of pixel response over the CCD chip and differences in the transmittances of the orthogonal beams are canceled out without the need of any flatfielding exercise. For the final determination of the degree of polarization, we use the algorithm described by Bianda et al. (1998).

The method of two successive exposures, taken with orthogonal orientations of the half-wave plate, requires constancy of both, the location and the steepness of the solar limb on the CCD. The first is assured by the primary image guider of the GCT (Küveler et al. 1998) which compensates drifts in the telescope pointing. The constant limb sharpness requires highly constant seeing and is assured by the short CCD exposures and by frame selection among several exposures at each limb position. The most suitable pairs of sub-images were selected via amount and location of the first derivative of the limb intensity profiles (Fig. 2). Only those pairs of sub-images were used which have largely equal sharpness and locations of the solar limb.

The noise was significantly reduced by averaging the two-dimensional polarization images in the direction parallel to the solar limb. For this 32″ tangent, the curvature of the limb yields a 0.″13 deviation which is below the 0.″32 spatial resolution achieved. This integration also smears spatial structures of the sun. The high inner accuracy of our method is demonstrated in Fig. 3 which gives the results from different limb positions following the coudé rotation. Figure 4 shows the average of the profiles in Fig. 3 together with the data by Wiehr (1978; Fig. 1) at 5″ and at 25″ limb distance, interpolated for 4506 Å. The calculations by Fluri & Stenflo (1999) yield a good coincidence for their model FALC-5 (from Fontenla et al.) up to a limb distance of 0.″32 (cos ϑ = 0.025). Although we regard values closer than 1″ from the limb with caution, the agreement with the calculations is amazing. Since the model assumes a homogeneous atmosphere, our results would indicate no significant influence of inhomogeneities.

4. Conclusion

The present study shows that polarimetry from two-dimensional images can be applied to research areas which require only limited spectral resolution such as for continua (or e.g. prominence emission lines). The short exposure time required for such 2-D observations with filters yields very high spatial resolution. The limitation of the polarimetric accuracy by the CCD's gain table is largely avoided using a differential method from pairs of images (e.g. Semel et al. 1993) which, however, requires the consideration of different image degradation by seeing. The scattering induced linear polarization of the continuum agrees with model calculations up to 0.32 arcsec limb distance (i.e. cos ϑ = 0.0228).

Acknowledgements. The evacuated Gregory Coudé telescope on Tenerife is operated by the Universitäts-Sternwarte, Göttingen (USG), at the Spanish "Observatorio del Teide" of the Instituto de Astrofísica de Canarias.

References

Bianda, M., Solanki, S., & Stenflo, J. O. 1998, A&A, 331, 760
Brückner, G. 1963, Z. f. Astrophys., 58, 73
Clarke, D., & Ameijenda, V. 2000, A&A, 355, 1138
Fluri, D. M., & Stenflo, J. O. 1999, A&A, 341, 902
Gandorfer, A. 2000, The Second Solar Spectrum, vol. I: 4625 Å to 6995 Å, ISBN No. 3 7281 2764 7 (Zurich: VdF)
Küveler, G., Wiehr, E., Thomas, M., et al. 1998, Sol. Phys., 182, 247
Leroy, J. L. 1972, A&A, 19, 287
Fluri, D. M., & Stenflo, J. O. 1974, A&A, 31, 179
Povel, H. P. 1995, Opt. Eng., 34, 1870
Semel, M., Donati, J.-F., & Rees, D. E. 1993, A&A, 278, 231
Stenflo, J. O. 1973, Sol. Phys., 32, 41
Stenflo, J. O. 1974, Sol. Phys., 37, 31
Stenflo, J. O., Baur, T. G., & Elmore, D. F. 1980, A&A, 84, 60
Sütterlin, P., & Wiehr, E. 1998, A&A, 336, 367
Unsöld, A. 1956, Physik der Sternatmosphären (Springer)
Wiehr, E. 1971, Sol. Phys., 18, 226
Wiehr, E. 1975, A&A, 38, 303
Wiehr, E. 1978, A&A, 67, 257
Wiehr, E. 1987, in The Role of Fine-Scale Magnetic Fields on the Structure of the Solar Atmosphere, ed. E. H. Schröter, M. Vázquez, & A. A. Wyller (Cambridge Univ. Press), 354
Wiehr, E., & Rossbach, M. 1974, Sol. Phys., 35, 343