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Some THÉMIS-MTR observations of the second solar spectrum(*)(**)

V. Bommier(1)(***) and G. Molodij(2)

(1) *Laboratoire "Atomes et Molécules en Astrophysique", CNRS UMR 8588 - DAMAp Observatoire de Paris, Section de Meudon, F-92195 Meudon, France*
(2) *THÉMIS S.L., c/o Instituto de Astrofísica de Canarias - E-38200 La Laguna Tenerife, Canary Islands, Spain*

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Summary. — The aim of the present paper is twofold: first, observations of the scattering polarization spectrum achieved near the solar limb in quiet regions (North Pole) are reported for a series of lines: Sr I 460.7 nm, Na I D_1 589.6 nm and D_2 589.0 nm, Ba II D_1 493.4 nm and D_2 455.4 nm, C I 493.2 nm. The THÉMIS observational and data reduction techniques are briefly described. Second, the depolarizing effect of the hyperfine structure on the scattering polarization of the Na I D_2 line is investigated, in view of future observations interpretation. Results of computation show that the depolarization due to the hyperfine splitting is important in Na I D_2. The lower-level polarization effect is investigated also.

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1. – Introduction

The so-called "second solar spectrum" [1] is the spectrum of the linear polarization observed near the solar limb, in quiet regions. The linear polarization is due to scattering of the anisotropic radiation. The radiation anisotropy results from the line formation in a layer, which is also responsible for the line limb-darkening. Such scattering linear polarization is weak: it is of the order of one percent or less, as can be seen for instance in a survey recently achieved between 462.5 and 699.5 nm [2]. One of the first purposes

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(***) E-mail: V.Bommier@obspm.fr

of the present work has been to measure this weak polarization with THÉMIS operating in the spectropolarimetric mode MTR, in order to test the instrumental capabilities, and to compare the results with other ones. Observational and data reduction procedures have been settled on, that are briefly described in sect. **2**. The spectrograph entrance slit has been positioned parallel to the solar limb in a quiet region (North Pole), and the data have been averaged along the slit and on time (*i.e.* on several images): the spatial and temporal resolutions have thus been reduced, in order to increase the polarimetric resolution. A series of lines has been observed.

The interpretation of the polarization measurements can bring information on the local magnetic field that is able to modify the polarization degree and direction through the Hanle effect, provided that the polarization in the absence of a magnetic field is known by solving the "non-LTE problem of the 2nd kind" [3, 4], which describes the formation of the line polarization. The emitted line polarization reflects the "atomic polarization", which is inequality and coherence factors between Zeeman sublevels populations, that are fully taken into account by the density matrix formalism (see a first application to the formation of the He I D_3 line polarization in prominences [5-7]). The solution of this problem remains an open question when the two-level approximation is not sufficient for the model atom, as is the case for the Na I D lines, when the hyperfine structure is taken into account. The second objective of the present paper is then to investigate the depolarizing effect of the hyperfine structure on the scattering polarization of the Na I D_2 line: sect. **3** is devoted to this aim. Besides our THÉMIS observations of the Na I D lines polarization, other observations have also been made [1, 8-11], and interpretation in the frame of the metalevel heuristic approach of coherent scattering [12] has led to a theoretical profile comparable with the observed one [13,14], that rules out eventual lower-level depolarization by a non-vertical magnetic field or by collisions. The depolarizing effect of the hyperfine structure is taken into account, and the aim of the present work is only to underline the importance of this effect.

2. – Description of the observations

2·1. *Observations and data reduction.* – The observations have been performed between 2000 August 27th and September 1st. A detailed description of the observations, of the data reduction procedure and of the results can be found in [15]. Some of the data reduction techniques are described in [16].

The series of observed lines is Sr I 460.7 nm, Na I D_1 589.6 nm and D_2 589.0 nm, Ba II D_1 493.4 nm and D_2 455.4 nm, C I 493.2 nm.

A high polarimetric accuracy (up to a few 10^{-5} in the 600 nm range) has been reached, thanks to the use of the beam exchange technique. In 2000, this technique was available in only one of the three polarization Stokes parameters Q, U and V. For the two other Stokes parameters where the beam exchange was unavailable, we have used a technique that we have called "generalized beam exchange", in which the polarization spectrum is obtained by combining six images: the two images obtained in the Stokes parameter under interest, the two images obtained in the other Stokes parameter where the beam exchange is available, and the two images obtained after application of the beam exchange in this Stokes parameter. This technique is the same as the so-called "spatio-temporal modulation method" discussed in [17].

Besides the advantage of a high polarimetric sensitivity, the beam exchange technique suffers the main limitation due to the fringes that are formed inside the polarization analyzer quarter wave plates, and that change together with the analyzer position. The fringes can be corrected in limb images by using flat-field images, provided that the fringes are not different between both limb and flat-field images. In fact, the instrumental drifts lead to fringes spectral displacement that prevents from performing the correction. However, we have succeeded in getting quite the same fringes on both images by interleaving flat-field and limb records, giving each a ~ 10 mn duration, and by manually correcting the drifts at every change.

The U Stokes parameter (in the analyzer reference frame) has been recorded by using the (0°, 45°) position of the analyzer quarter wave plates, which has much simpler and regular fringes than the (22.5°, 22.5°) position commonly used. Besides, our sequence of analyzer positions has been (Q, U, IQ, V), in the analyzer reference frame, and where IQ means "inversion of Q", as in [17].

Two different cameras have been simultaneously used, one camera per polarization state. Two different magnifying factors have been used in addition for the camera optics: 1/4 and 1/2. The 1/4 factor corresponds to one pixel per spectral resolution element, whereas the 1/2 factor corresponds to two pixels per spectral resolution element.

2˙2. *Results*. – We have obtained full-Stokes polarization profiles of the lines listed above, at a distance of about 4 arcsec from the solar limb. This limb distance may vary from spectrum to spectrum, but is determined as precisely as possible, by measuring the limb position on the slit-jaw image.

As for the polarization degree, our results are in full agreement with those of Arnaud *et al.* [18], who have observed the Sr I 460.7 nm and the Na I D lines with THÉMIS, at the same limb distance and during the same campaign, but with a different observation and reduction technique (their slit was oriented 45° from the solar limb). Full agreement is obtained also with the results of Trujillo Bueno *et al.* [17], who observed the Sr I 460.7 nm line closer to the limb. A detailed comparison of ours and their reduction technique has led to full agreement.

We obtain a linear polarization degree of 1.13×10^{-2} at 5.9 arcsec from the solar limb, in the center of Sr I 460.7 nm. We obtain, respectively, 3.2×10^{-3} and 2.0×10^{-3} at 4.1 arcsec from the solar limb in the line center and blue wing peaks of Na I D_2. The Na I D_1 polarization profile shows no global polarization, and has a perfectly antisymmetrical shape with respect to the line center, in full agreement with the theoretical profile of Landi Degl'Innocenti [13]. We obtain a linear polarization degree of 3×10^{-4} in excess with respect to the continuum polarization in the C I 493.2 nm line, and 5.5×10^{-3} in the Ba II D_2 455.4 nm line center, at 3.6 and 4.8 arcsec from the solar limb, respectively. No global polarization is observed in the Ba II D_1 493.4 nm line. For all these lines, the linear polarization direction is found parallel to the solar limb, and no circular polarization is observed.

These results are in good agreement with those given in the second solar spectrum atlas of Gandorfer [2], based on 1999-2000 observations. Nevertheless, with regard to a quantification of the polarization signal, we found that the signal is systematically smaller than previous results obtained during the 1994-96 observational period [19, 8, 11] and also observed as decreasing during the 1998 observational period [10], as if a 11-year cyclic variation of the limb polarization has occurred. This signal variability obviously requires further observational and interpretative investigations.

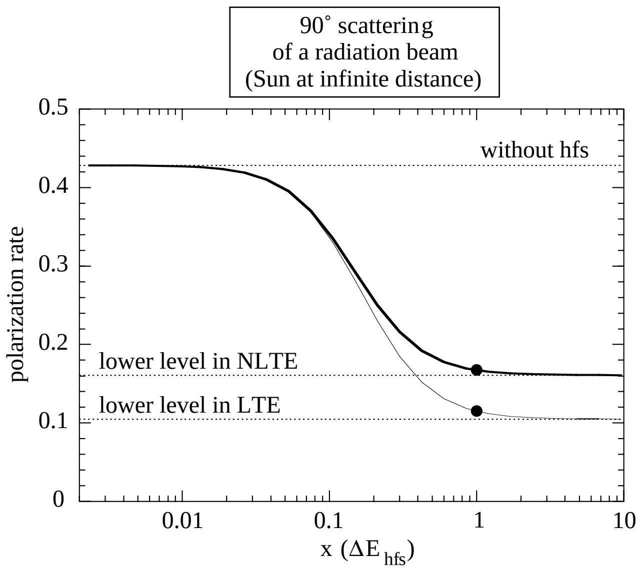

Fig. 1. – Abscissa: x factor by which the NA hyperfine splitting has been multiplied for computations. Dots indicate the true NA hyperfine splitting ($x = 1$). Zero or very small x corresponds to ignore the hyperfine structure (no hyperfine structure). "Lower level in NLTE" corresponds to the existence of lower-level polarization, whereas for "lower level in LTE", the lower level is assumed to be completely depolarized by collisions. This figure has been computed for right angle scattering of a radiation beam.

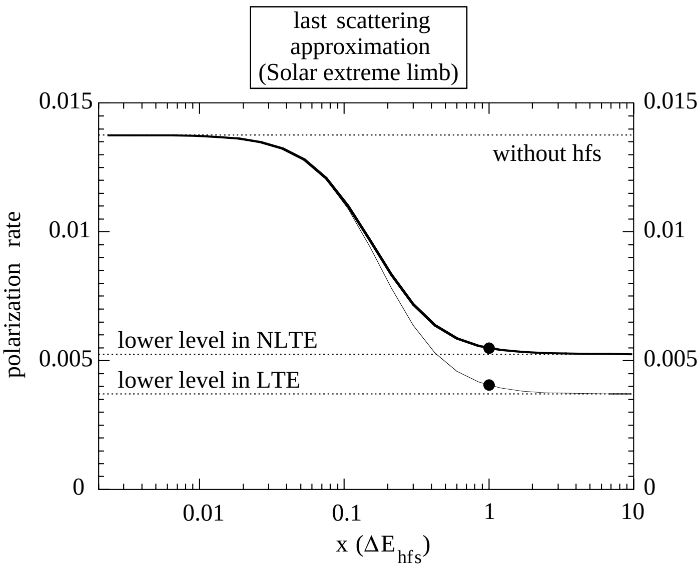

Fig. 2. – Same as fig. 1, but in the last scattering approximation: the anisotropy of the incident radiation is now the one resulting from the limb-darkening, as observed in the center of the NA I D_2 line [24].

3. – Effect of the hyperfine structure on the scattering linear polarization of the sodium D_2 line

As already stated in the introduction, the second aim of the present work is to investigate the depolarizing effect of the hyperfine structure on the linear polarization of the radiation scattered at right angle in the Na I D_2 line.

To this purpose, the statistical equilibrium equations for the atomic density matrix have been solved, and the polarization of the emitted radiation has been derived. In such a scheme, coherent scattering is ignored, so that the results qualitatively apply to the center of the solar line.

The statistical equilibrium equations for the atomic density matrix in the presence of anisotropic radiation are those of Bommier [5] and Bommier and Sahal-Bréchot [6], generalized to level-crossing coherences in [20] and to hyperfine structure in [21]. Thus, level-crossing hyperfine coherences ${}^{FF'}\rho_{MM'}$ are fully taken into account. Such coherences are the largest for a zero hyperfine splitting, and then decrease for increasing splitting, and contribute to the emitted polarization. For a very large hyperfine splitting, these coherences vanish. In the computation described below, the true hyperfine splitting of the Na levels, as measured by [22], has been multiplied by an x factor that has been made arbitrarily varying from 0 to 10, in order to investigate the depolarizing effect of the hyperfine structure.

The absorption of anisotropic radiation results in atomic polarization in the upper as well as in the lower level of the line. The lower level of the D_2 line, having $J_\ell = 1/2$, is unpolarizable when the hyperfine structure is ignored, but, when the hyperfine structure is introduced with the nuclear spin $I = 3/2$ resulting in two lower levels having $F_\ell = 1$ and $F_\ell = 2$, respectively, these two lower levels may be polarized. We have besides investigated the effect of this lower-level polarization, by assuming no lower-level depolarization on the one hand, and full lower-level depolarization on the other hand, as if a high collisional depolarizing rate was present, by forcing equal populations in all the Zeeman sublevels of the lower level. We call the first case (no lower-level *de*polarization) "lower level in NLTE", and the second case (full lower-level *de*polarization) "lower level in LTE".

The results of the computations can be seen in figs. 1 and 2, where the abscissa is the varying x factor, and where the dots represent the true Na hyperfine structure ($x = 1$). The two cases of no lower depolarization and full lower-level depolarization are plotted, putting in evidence the effect of the lower-level polarization. No lower-level polarization is visible when x goes to zero, because the lower level is unpolarizable in the absence of hyperfine structure.

First (fig. 1), a perfectly directive incident radiation is assumed. In this case, the polarization degree of the radiation scattered at right angle is found to be 42.9%, which is 3/7 for a $J_\ell = 1/2 \rightarrow J_u = 3/2$ line without hyperfine structure, as already stated by Percival and Seaton [23]. At the opposite, we obtain for a very large hyperfine structure (and negligible coherences ${}^{FF'}\rho_{MM'}$) a polarization degree of 16.1% for lower level in NLTE (no lower-level depolarization), and 10.5% for lower level in LTE (full lower-level depolarization—this value is also stated by Percival and Seaton [23]). These values become 16.7% and 11.5%, respectively, for the true Na hyperfine structure ($x = 1$).

Second (fig. 2), the last scattering approximation is assumed at the Sun's surface instead, and the anisotropy of the incident radiation is derived from limb-darkening observations [24]. In this case, the corresponding values are 1.38% for the polarization degree in the absence of hyperfine structure, 0.53% for lower level in NLTE (no lower-level depolarization), and 0.37% for lower level in LTE (full lower-level depolarization) for a very large hyperfine structure (and negligible coherences ${}^{FF'}\rho_{MM'}$), which become 0.55% and 0.40%, respectively, for the true NA hyperfine structure ($x = 1$).

These results show that, in the absence of a magnetic field, the hyperfine structure has an important effect on the scattered polarization, and has to be taken into account in NA I D_2 line polarization computations. This is due to the fact that the hyperfine splitting is larger than the natural width of the upper level(s). In the case of NA I D_2, the level-crossing coherences ${}^{FF'}\rho_{MM'}$ could eventually be ignored in the statistical equilibrium computation, in the absence of a magnetic field. However, if a magnetic field is present, these level-crossing coherences may increase and become non-negligible, if a level-crossing occurs between the two sublevels (F, M) and (F', M') under the effect of the magnetic field (see an example in [25], figs. 4 and 5).

A similar study had been made on the hydrogen Lyα line by Bommier and Sahal-Bréchot [21] (see their fig. 4), leading to a different result, where the level-crossing coherences ${}^{FF'}\rho_{MM'}$ were important, but the hyperfine structure can simply be ignored, because the hyperfine splitting is smaller than the natural width of the $2p_{3/2}$ upper level of hydrogen. This is not the case of the NA I D_2 line.

REFERENCES

[1] STENFLO J. O., *Solar Polarization*, edited by J. O. STENFLO and K. N. NAGENDRA, also *Solar Phys.,* **164** (1996) 1.

[2] GANDORFER A., *The Second Solar Spectrum, a High Spectral Resolution Polarimetric Survey of Scattering Polarization at the Solar Limb in Graphical Representation* (Hochschulverlag AG an der ETH Zürich) 2000.

[3] LANDI DEGL'INNOCENTI E., *Numerical Radiative Transfer,* edited by W. KALKOFEN (Cambridge University Press) 1987, p. 265.

[4] LANDI DEGL'INNOCENTI E., *Solar Polarization*, edited by J. O. STENFLO and K. N. NAGENDRA, also *Solar Phys.*, **164** (1996) 21.

[5] BOMMIER V., Thèse de 3ème cycle (Paris VI University) 1977.

[6] BOMMIER V. and SAHAL-BRÉCHOT S., *Astron. Astrophys.,* **69** (1978) 57.

[7] LANDI DEGL'INNOCENTI E., *Solar Phys.*, **79** (1982) 291.

[8] STENFLO J. O. and KELLER C. U., *Astron. Astrophys.,* **321** (1997) 927.

[9] KELLER C. U. and SHEELEY N. R., *Proceedings of the II Solar Polarization Workshop*, edited by K. N. NAGENDRA and J. O. STENFLO , *ASSL Series*, **243** (Kluwer, Dordrecht) 1999, pp. 17-30.

[10] STENFLO J. O., GANDORFER A. and KELLER C. U., *Astron. Astrophys.,* **355** (2000) 781.

[11] STENFLO J. O., KELLER C. U. and GANDORFER A., *Astron. Astrophys.,* **355** (2000) 789.

[12] LANDI DEGL'INNOCENTI E., LANDI DEGL'INNOCENTI M. and LANDOLFI M., *Density Matrix and Polarized Radiative Transfer: a Heuristic Approach to the Problem of Frequency Redistribution*, *Proceedings of Forum THÉMIS, Science with THÉMIS*, edited by N. MEIN and S. SAHAL-BRÉCHOT (Paris Observatory Publ.) 1997, p. 59.

[13] LANDI DEGL'INNOCENTI E., *Nature,* **392** (1998) 256.

[14] LANDI DEGL'INNOCENTI E., *Proceedings of the II Solar Polarization Workshop,* edited by K. N. NAGENDRA and J. O. STENFLO, *ASSL Series*, **243** (Kluwer, Dordrecht) 1999, pp. 61-71.

[15] BOMMIER V. and MOLODIJ J., *Astron. Astrophys.,* THÉMIS Special Issue, submitted (2001).

[16] BOMMIER V. and RAYROLE J., *Astron. Astrophys.,* THÉMIS Special Issue, in press (2001).

[17] Trujillo Bueno J., Collados M., Paletou F. and Molodij G., *Advanced Solar Polarimetry: Theory, Observations and Instrumentation*, *Proceedings of the XX International Sacramento Peak Summer Workshop*, edited by M. Sigwarth, *ASP Conf. Ser.*, **236** (2001).
[18] Arnaud J., Faurobert M., Vigneau J. and Paletou F., *Advanced Solar Polarimetry: Theory, Observations and Instrumentation*, *Proceedings of the XX International Sacramento Peak Summer Workshop*, edited by Sigwarth M., *ASP Conf. Ser.*, **236** (2001).
[19] Stenflo J. O., Bianda M., Keller C. U. and Solanki S. K., *Astron. Astrophys.,* **322** (1997) 985.
[20] Bommier V., *Astron. Astrophys.,* **87** (1980) 109.
[21] Bommier V. and Sahal-Bréchot S., *Solar Phys.,* **78** (1982) 157.
[22] Sagalyn P. L., *Phys. Rev.*, **94** (1954) 885.
[23] Percival I. C. and Seaton M.J., *Philos. Trans. R. Soc. London, Ser. A* **251** (1958) 113.
[24] Waddel J., *Astrophys. J.,* **136** (1962) 223.
[25] Landolfi M. and Landi Degl'Innocenti E., *Solar Phys.*, **98** (1985) 53.