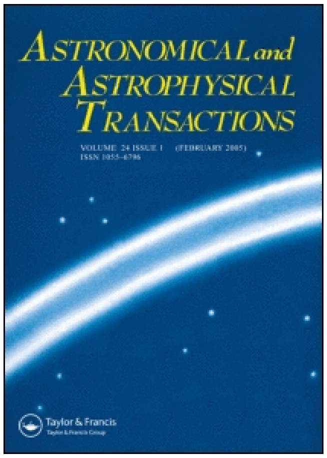


Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Line profile steepness as an additional tool for studies of magnetic field total energy

V. M. Grigoryev [a]; N. I. Kobanov [a]
[a] Institute of Solar-Terrestrial Physics, Irkutsk, Russia

Online Publication Date: 01 November 1996
To cite this Article: Grigoryev, V. M. and Kobanov, N. I. (1996) 'Line profile steepness as an additional tool for studies of magnetic field total energy', Astronomical & Astrophysical Transactions, 11:2, 175 - 183
To link to this article: DOI: 10.1080/10556799608205463
URL: http://dx.doi.org/10.1080/10556799608205463

Astronomical and Astrophysical Transactions, 1996, Vol. 11, pp. 175-183
Reprints available directly from the publisher
Photocopying permitted by license only

LINE PROFILE STEEPNESS AS AN ADDITIONAL TOOL FOR STUDIES OF MAGNETIC FIELD TOTAL ENERGY

V. M. GRIGORYEV and N. I. KOBANOV

Institute of Solar-Terrestrial Physics, P. O. Box 4026, Irkutsk, 664033, Russia

(Received August 23, 1995)

We believe, that conventional magnetograms of active regions give no means of extracting adequate information about the magnetic field energy in the vicinity of a neutral line, especially in areas where fine-structure opposite-polarity strong fields are most close together and mixed. Magnetic broadening measurements of the magnetosensitive line profile would make up tangibly for this deficiency. To accomplish this, we suggest that the spectral line profile steepness $\partial I/\partial\lambda$ should be measured, considering just this parameter to be most suitable for measurement and to ensure sufficiently high sensitivity of measurements. In this paper it is shown that in the line wing it is possible to determine two parts, for which the magnetic field influence upon the line steepness is the largest and opposite in sign. This can be used to separate "nonmagnetic" sources of line broadening. The line FeII 6149.2Å is of interest for measuring the profile steepness when using the spectrograph. With a measurement sensitivity comparable with the magnetograph's sensitivity to $H_{||}$, the measured signal is nearly independent of the profile asymmetry and is sensitive only to coincident changes in steepness of both wings. Examples of test measurements in the plage regions and near sunspots are given.

KEY WORDS Magnetic fields, spectral line profiles

1 INTRODUCTION

It is well known that, in the magnetographic measurements using a spectrograph, an algebraic addition of different-polarity magnetic fluxes occures that fill the spectrograph entrance aperture. For filter magnetographs, the role of such an aperture is played by a limiting resolution determined in ground conditions by the "atmosphere-telescope" system. In a variety of observing programs involving the magnetic field topology, the position and shape of the neutral line separating regions of different magnetic polarity is important. The above-mentioned factor leads to a serious uncertainty of these parameters deducible from magnetograms. For instance, parts of a neutral line with true zero of the magnetic field are indistinguishable from parts where strong fields of opposite polarity are extremely close together and intermingled. But energetically, these are totally different objects with a dissimilar probability that an active dynamic process would occur, which is accompanied by considerable energy release. In addition, there is evidence that the appearance and development of new active regions near a neutral line (NL) are accompanied by a strong transverse component of the field. It is well known that the magnetograph sensitivity to $H_\perp$ is worse than that to $H_\parallel$ by more than an order of magnitude. This adds further complexity to the problem at hand. In such a situation, additional information about the total energy of the magnetic field in the neighborhood of the NL is important. Such a capability is inherent in the method used to measure magnetic fields of stars (Robinson, 1980). This method is based upon measuring magnetic broadening of magnetosensitive line profiles. Variations of magnetosensitive line parameters are in wide use in investigations of line-structure magnetic fields on the Sun (Stenflo and Lendegrem, 1977; Stenflo, 1987; Solanki and Stenflo, 1985; Brandt and Steinegger, 1990). In this case, useful information is most commonly extracted from measurements of the profile width, the intensity in the line core and its asymmetry. The steepness of the magnetosensitive line profile $\partial I/\partial\lambda$ is, in our view, an equally informative (and, on some occasions, more useful) parameter. What is more, it is this parameter which is directly involved in the signal processing of most solar magnetographs.

2 ANALYTIC ESTIMATES

In what follows, in a most simplified form, an analytic justification for our proposal is given. The magnetosensitive line profile for the case of $H_\parallel$ can be represented in terms of residual intensity as the sum of profiles of two sigma components:

$$r^*(v) = 0.5r(v + v_H) + 0.5r(v - v_H), \tag{1}$$

where $v = \Delta\lambda_0/\Delta\lambda_d$ is the distance from the line core, $v_H = \Delta\lambda_H/\Delta\lambda_d$ is the value of Zeeman splitting in terms of the Doppler line width. By expanding each of the two terms of Equation (1) into a power series, and limiting ourselves to the second order of terms, we obtain

$$r(v + v_H) = r(v) + \frac{\partial r(v)}{\partial v}v_H + 0.5\frac{\partial^2 r(v)}{\partial v^2}v_H^2 + \dots \tag{2}$$

$$r(v - v_H) = r(v) - \frac{\partial r(v)}{\partial v}v_H + 0.5\frac{\partial^2 r(v)}{\partial v^2}v_H^2 - \dots .$$

Now, upon substituting Equation (2) into Equation (1) we obtain:

$$r^*(v) = r(v) + 0.5\frac{\partial^2 r(v)}{\partial v^2}v_H^2 + \dots . \tag{3}$$

The steepness of the magnetosensitive line profile can be defined in terms of v as the first derivative:

$$\frac{\partial r^*(v)}{\partial v} = \frac{\partial r(v)}{\partial v} + 0.5\frac{\partial^3 r(v)}{\partial v^3}v_H^2. \tag{4}$$

Equation (4) shows that the steepness of the magnetosensitive line profile depends on the third derivative of the undisturbed profile and on v_H^2.

To obtain an approximate numerical estimate of the variation of the profile steepness due to magnetic broadening, we represent the initial profile as a Gaussian one:

$$r(v) = [1 - (1 - r_0) \exp -v^2]. \tag{5}$$

Equation (4) for such a profile assumes the form:

$$\frac{\partial r^*(v)}{\partial v} = \frac{\partial r(v)}{\partial v}[1 - (3 - 2v^2)v_H^2]. \tag{6}$$

Let us further consider the difference between the steepness of a magnetosplit profile and that of the nonsplit profile:

$$\frac{\partial r(v)}{\partial v} - \frac{\partial r^*(v)}{\partial v} = \frac{\partial r(v)}{\partial v}(3 - 2v)v_H^2. \tag{7}$$

Upon differentiating Eq. (7) and assuming $v_H = 1$, which corresponds to $H = 1$ kilogauss, we determine extremum points. One maximum at $v = 0.524$ and one minimum at $v = 1.65$ are present between the line core and the far wing. Thus, the line wing includes two parts, on which variations in line steepness are the largest in value and opposite in sign. This fact is useful for separating magnetic field effects from variations caused by other factors (temperature, pressure). In the latter case, it is logical to expect that changes in steepness would be of the same sign in both parts of the profile.

3 METHOD OF MEASUREMENT

We suggest that the profile steepness should be measured using the method developed to measure the Zeeman splitting. For the magnetograph signal, when measuring the longitudinal component of the magnetic field, as a simplification one may put:

$$S = \frac{\partial I}{\partial \lambda}\Delta\lambda_H. \tag{8}$$

The calibration procedure of magnetographic measurements involves, in effect, determining the value of $\partial I/\partial\lambda$ at a given $\Delta\lambda_H = \Delta\lambda_c = \text{const}$. If we deal in this case with the total spectral line profile rather than with its separate Zeeman components, then $S = F(\partial I/\partial\lambda)$ holds true; $\partial I/\partial\lambda$ in this case is a function of H, and this was indeed demonstrated in Eq. (6).

The value of $\Delta\lambda_c$ is specified based on spectral line parameters and spectral resolution of the instrument used. In the case of a spectrograph, the spectral line being investigated is split into two by means of a thin calcite plate supplemented by a quarter-wave phase plate (Kobanov, 1993). This combination is placed immediately behind the spectrograph entrance split. Subsequent operations are not different from those applied when measuring $H_{\|}$ and allow the use of any type of magnetograph, both one-channel and multichannel ones using CCD chips. This makes it possible to achieve the principal advantage of the magnetograph, namely the modulational method of measurement. The signal $\partial I/\partial\lambda$, corresponding to an individual element of the solar surface and to an individual element of the line profile, is measured by a single photoreceiver element in the alternate current mode. A gain in sensitivity is no less than 10 compared to the situation where such a steepness $\partial I/\partial\lambda$ would be measured in the mode of subtraction of direct currents of neighboring elements of CCD chips. According to Kotov, Severny and Tsap (1982) this gain in analogous measurements is as high as a factor of 100. Currently there exists a familiar method of using CCD chips in the mode of a synchronous detector for receiving a modulated light flux (Povel, Aebersold, Stenflo, 1990; Povel, Keller and Yadigaroglu, 1994). Furthermore, we are applying the modulation method which permits us to make measurements simultaneously in two spectral bands using a single photoreceiver. This leads to improved signal/noise ratio, and minimizes the influence of Doppler shifts of the spectral line and its asymmetry. This occurs because, in the case of the profile asymmetry, an increase in profile steepness in one wing is accompanied by its decrease in the other wing – hence a peculiar kind of compensation occurs.

4 SELECTING SPECTRAL LINES

When selecting spectral lines, one should be guided by the following considerations. First, it is desirable to employ spectral lines with such a structure of the Zeeman splitting that the σ and π-components are coincident. In this case, the magnetic field effect on the wing steepness would be the largest for a given Lande factor and would depend weakly on the field inclination. Accordingly, the signal $\partial I/\partial\lambda$ would contain more reliable information about the total energy of the magnetic field. Second, the line depth and an effective value of the Lande factor must be sufficient for the confident recording of the signal. Third, it is desirable to make use of blend-free spectral lines with low temperature sensitivity.

Determining the lines that would satisfy all the above requirements is a challenging task. As a preliminary exercise, we examined about 20 spectral lines in the range 5000–7000Å that are rarely used in magnetic measurements. The following lines attracted our attention: FeII 6149.2Å, FeI 5197.9Å, 5705.4Å, and 6213.4Å; while the 5705Å and 5197Å lines have a central component and for the 6213.4Å and 6336.8Å lines the circularly and linearly polarized components form two more or less compact groups, for the FeII 6149.2Å line the positions of the σ and π-components almost exactly coincide in total absence of central components. To determine the parts of the profile which would be most advantageous for measurements, we carried out calculations of profiles for all the lines concerned in the undisturbed photosphere model (Holweger and Muller, 1974) and the sunspot model (Zwaan, 1974). The value of macroturbulent velocity was set to 0 or 1.8 km/s, and the value of microturbulent velocity was 1 km/s. The line steepness $\partial I/\partial\lambda$ was calculated at steps of 10^{-2}Å for discretely specified magnetic field strengths $H = 0$, 100, 300, 1000, 2000 and 3000 G. The three values of the angle γ: 0, 45 and 90° were employed. The filling factor was taken to be 1. Some of the results obtained are shown in Figure 1. As expected, the steepness of line FeI 6149.2Å depends weakly on the angle γ and shows almost the same sensitivity to both the longitudinal and the transverse magnetic field. All of the lines under consideration are characterized by the presence of two parts of the wing, for which variations in steepness as a function of the magnetic field are the largest and opposite in sign. Our calculations have confirmed the approximate estimates obtained above when investigating Eq. (7). Figures 2*a*, *b* show how the steepness of the 6149.2Å and 6302Å lines varies with increasing field strength at different γ.

5 TEST MEASUREMENTS

To assess the actual capabilities of the method, we conducted a series of experiments using the Sayan observatory solar magnetograph. The object chosen for the study, was scanned twice: in the mode of magnetic field measurement, and then in the mode of line steepness measurement. The measurements were made on the part of the line profile which corresponds to the first extremum point. Figures 3*a*, *b* present portions of the scans across various objects.

Correlation analysis shows that our proposed method of measurement reveals sufficient sensitivity to magnetic field strength fluctuations. The sensitivity of measurements is comparable to that used to measure the longitudinal component of H, although it is lower than it by a factor of 2–4. As far as the transverse field is concerned, the sensitivity of our method exceeds that of conventional magnetographic measurements.

6 DISCUSSION

It may appear that, because of the availability of two-dimensional CCD detectors, the problem of measuring all parameters of a magnetosensitive line is resolved, and that measurements on individual parts of the profile are no longer important. However, it is not the case due to the following reasons:

first, this paper is concerned with a modulation method to measure $\partial I/\partial\lambda$, whose sensitivity, as it has already been pointed out, is significantly higher than the constant current measurements and compares quite well with the magnetograph's sensitivity;

second, the magnetic field effect on this parameter is different in the profile and is most clearly manifested in two parts of the wing where it is maximal and opposite in sign. It is these parts that are of prime interest for our case;

and third, the extensive use of filter magnetographs does dictate measurements made only in given parts of the profile. We have particular suggestions concerning the way of carrying out such measurements of $\partial I/\partial\lambda$ using a filter magnetograph; this is subject of a separate paper.

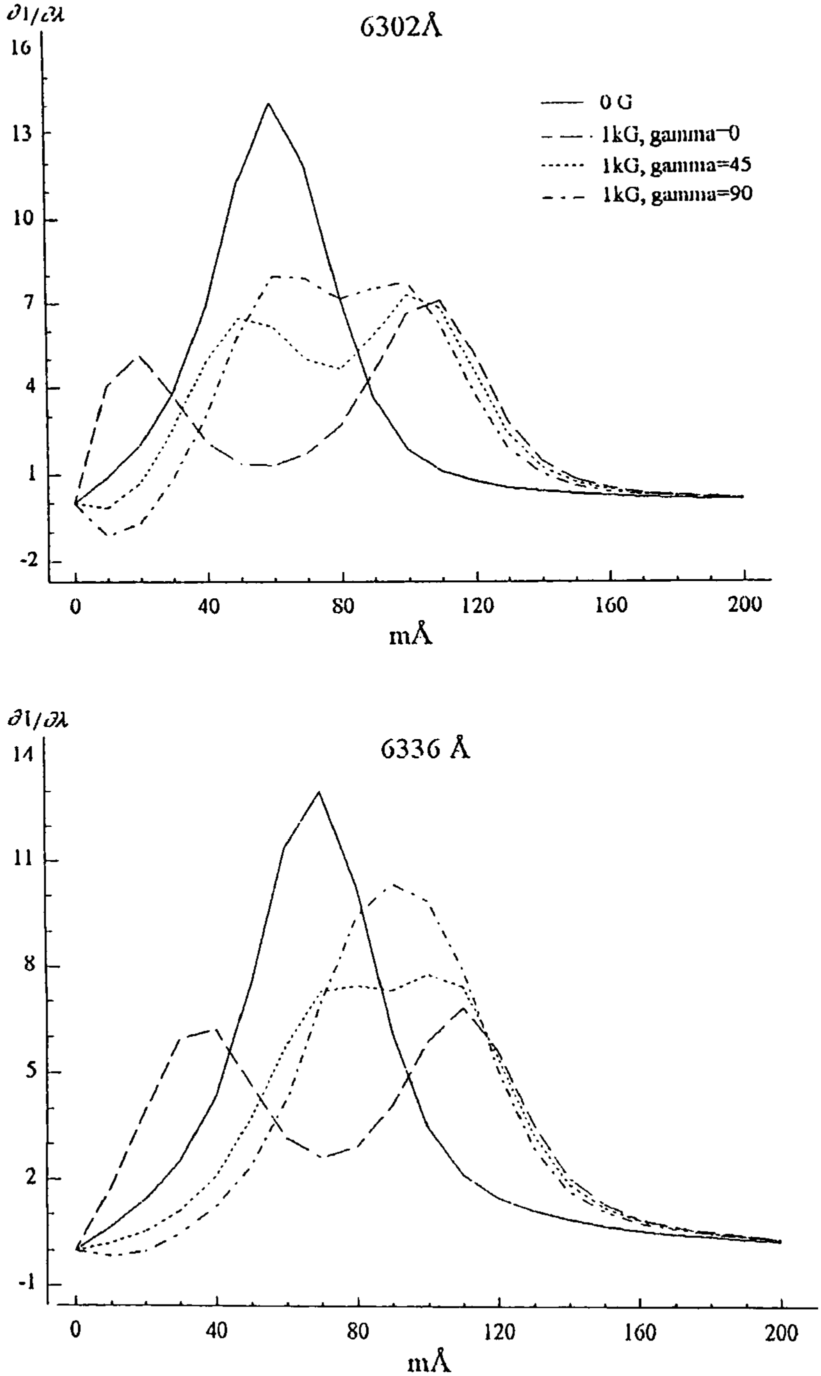
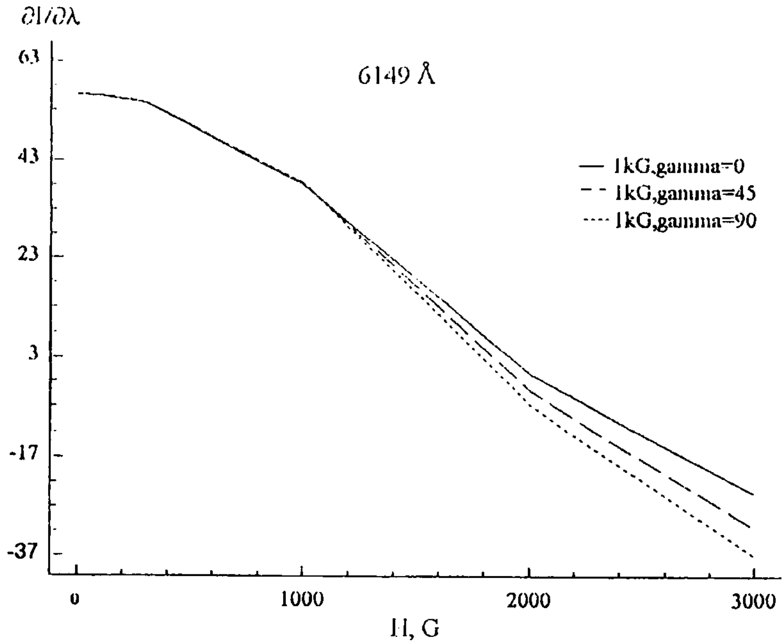


Figure 1 $\partial I/\partial\lambda$ (in arbitrary units) in the red wing of the profile as a function of λ.



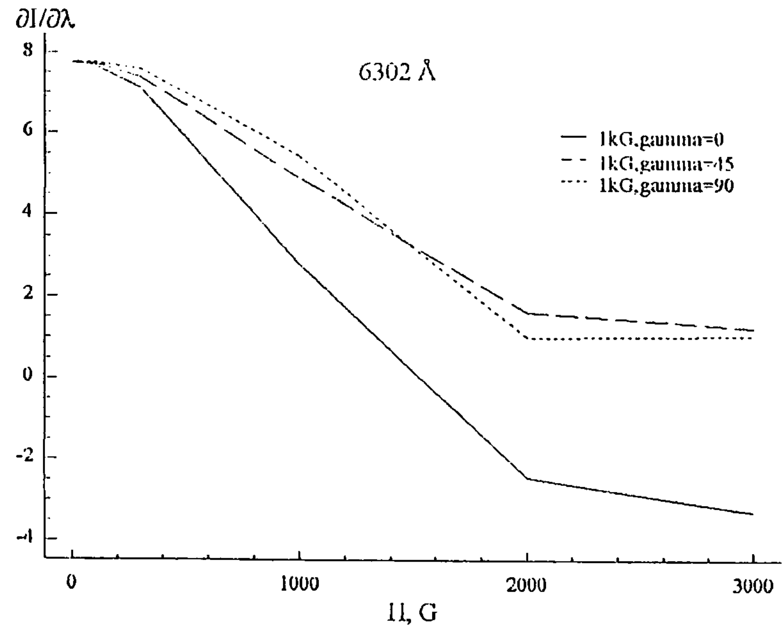


Figure 2 $\partial I/\partial\lambda$ (in arbitrary units) at the point of the first extremum as a function of H.

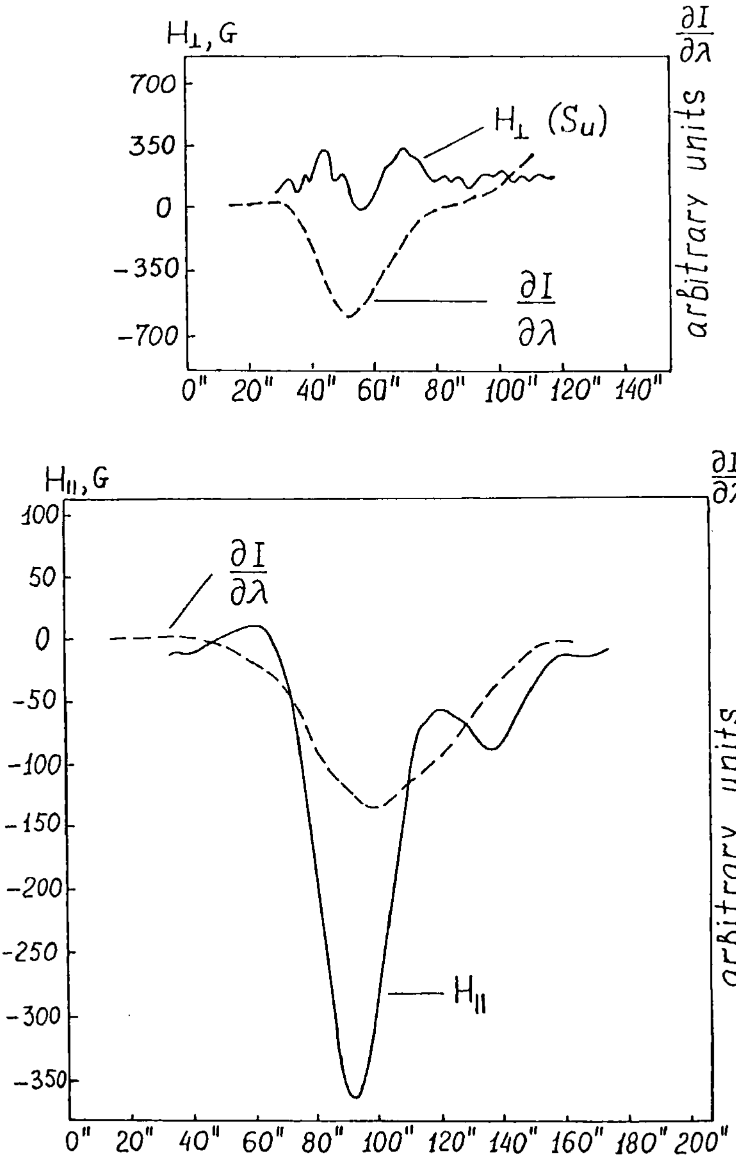


Figure 3 Fragments of scans in the line FeII 6149.2Å; entrance aperture 8″ × 1.5″. Top: scan through a plage area at the limb. Bottom: scan through an active region.

Acknowledgements

We are grateful to Drs. L. V. Ermakova and M. V. Nikonova for helpful discussion, and to Mr. V. G. Mikhalkovsky for his assistance in preparing the English version of the manuscript. This work was supported by Russian Foundation for Basic Research, Grant 93-02-3115.

References

Brandt, P. N., Steinegger, M. (1990) In *Solar Photosphere: Structure, Convection, and Magnetic Fields*, J. O. Stenflo (ed.), p. 41.
Holweger, H., Muller, E. A. (1974) *Solar Phys.* **39**, 19.
Kobanov, N. I. (1993) *Solar Phys.* **145**, 11.
Kotov, V. A., Severny, A. B., Tsap, T. T. (1982) *Izvestiya Krymsk. Astrofiz. Observ.* **65**, 3.
Povel, H., Aebersold, H., Stenflo, J. O. (1990) *Applied Optics* **29**, No. 8, 1186.
Povel, H. P., Keller, C. U., and Yadigaroglu, J. -A. (1994) *Applied Optics* **33**, No. 19, 4254.
Robinson, R. D. (1980) *Astrophys. J.* **239**, 961.
Stenflo, J. O., Lendegrem, L. (1977) *Astron. Astrophys.* **59**, 367.
Stenflo, J. O. (1987) *Mitteilungen der Astronomischen Gesellschaft* **Nr. 65**, 25.
Solanki, S. K., Stenflo, J. O. (1985) *Astron. Astrophys.* **148**, 123.
Zwaan, C. (1974) *Solar Phys.* **37**, 99.