IL NUOVO CIMENTO Vol. 25 C, N. 5-6 Settembre-Dicembre 2002

Properties of the quiet-Sun magnetic fields as revealed by the spectrovideomagnetograph(*)

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(ricevuto il 10 Giugno 2002; approvato il 7 Agosto 2002)

Summary. — We present new observations of weak solar magnetic fields with an instrument which we term the spectrovideomagnetograph (SPVMG). Using the criteria introduced by Stenflo, we measure the Stokes V components for the lines FeI 5250 and 5247 in thousands of spectra. We find the ratios of the V amplitudes of the two lines track the g-factors closely and there is no evidence for fractional kilogauss fields in the quiet Sun. The strength of the flux threading the solar surface is just what we measure, with a filling factor near unity. Network elements range from 200 to 1200 gauss, as measured in the IR, again without a filling factor. We calibrate by direct measures of the Zeeman splitting at 1000 gauss. The g-factor ratio holds down to 20 gauss. The integral area (outside of sunspots) above a given field strength follows a power law with index -2, down to a turnover level of 200–300 G. At least 90% of the solar surface is covered by weak fields above 5 gauss, unipolar and mixed.

PACS `95.55.Ev` – Solar instruments.
PACS `95.75.Hi` – Polarimetry.
PACS `96.60.Hv` – Electric and magnetic fields.
PACS `96.60.Mz` – Photosphere, granulation.
PACS `01.30.Cc` – Conference proceedings.

1. – Introduction

Stenflo [1] proposed that the low resolution of the magnetograph might hide kilogauss fields, and comparison of 5250 ($g = 3$) and 5247 ($g = 2$) lines would show saturation of the 5250 signal by divergence of the V signal ratio of these lines from 3/2. Various papers with low-resolution instruments [2] agreed. This data was obtained with the Fourier Transform Spectrometer with a $4 \times 4''$ resolution. For fields measuring 25 gauss,

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(*) Paper presented at the International Meeting on THEMIS and the New Frontiers of Solar Atmosphere Dynamics, Rome, Italy, March 19-21, 2001.

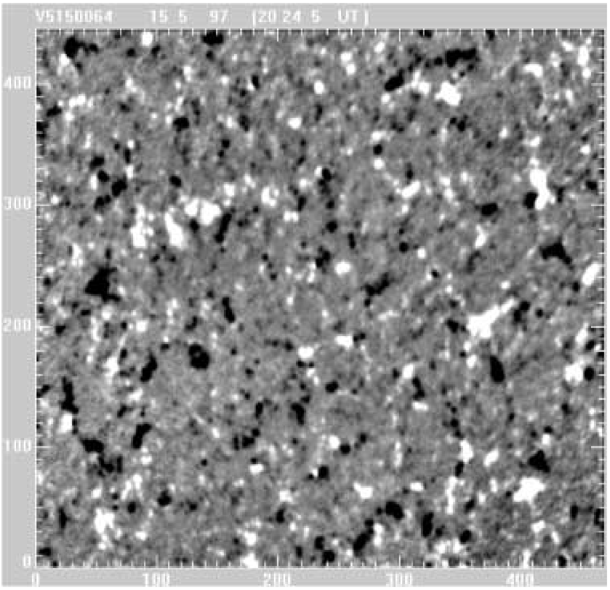

Fig. 1. – A high-resolution videomagnetogram. The elements are fully resolved.

the filling factor for 1000 gauss elements would be 2.5 %, and an unheard of accuracy of one part in 2000 would be required to match the 5250/5247 ratio to a few per cent. Direct spectroscopy in the IR at 1.5 and 12 microns [3-6], where splittings are 9 times greater, showed fields from 200 to 1000 gauss, with no evidence of filling factor effects. These authors measured only the strongest elements in the field. The fact that no filling factor was required for that data indicates that the elements are fully resolved. The "invisible sunspots" required to stabilize invisible kilogauss fields were observed [7], showing that "invisible sunspots" did in fact exist in that case. However, no more such spots have been detected in any of thousands of images. The region observed was an EFR, and the tiny spots may only occur there. So, while the plage fields were undoubtedly 1000 gauss, there was no evidence on the strength of the weakest fields. Many doubts remained which are outlined in the debate between Stenflo and Zirin [8] at IAU colloquium No. 141.

Figure 1 shows a videomagnetograph (VMG) image obtained by adding 512 σ_1-σ_2 pairs of center disk in a very quiet Sun. The polarity is mixed and the magnetic network is not well defined. No one, to our knowledge, has ever tried to explain how the Stenflo model applies to these varied elements. Do the larger elements represent larger invisible spots? In that case the spots should be visible. Are there multiple invisible spots? The larger elements are easily resolved, so we should see separate elements. Yet we find a solid 3:2 ratio for the V components. We tested this idea with the new instrument.

The kilogauss field picture has never been very clear about the weaker fields; network elements are restricted to fields above 1000 gauss (although they are permitted intermediate values for a brief growth or decay period), but the IN fields are permitted lesser values, and even Stenflo [9] has agreed that most of the surface fields are intrinsically weak. Lin's 500 gauss measurement was initially disregarded.

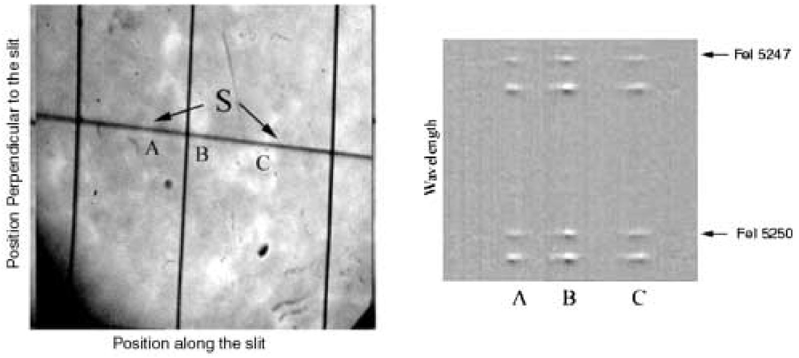

Fig. 2. – A slit jaw image (slit marked S) with resulting spectra on the right. Network elements are marked A, B, C.

2. – Observations

By attaching the sensor of the Leighton-Smithson magnetograph to the Coudé spectrograph of the 65 cm vacuum telescope at Big Bear we have been able to produce very sensitive V profiles and measure line splittings down to 1000 gauss. We have measured the V profile, the integrated V profile over the line, M, and the direct splitting. To check the accuracy of our data, we compared Stokes V for the Fe I lines 5250 ($g = 3$) and 5247 ($g = 2$). In general the direct spectroscopic IR measurements are limited by noise and the low pixel number of IR cameras. They measure only network elements and find typically 500 gauss. Our instrument obtains similar values for such elements, but extends the measurements to the remaining 90% of the Sun's surface. We find our measures meet the 3/2 test down to about 20 gauss.

The SPVMG itself consists of a quarter wave plate, a liquid-crystal modulator and a linear polarizer inserted in the beam path in front of the Coudé spectrograph of the 65 cm vacuum reflector at BBSO. The image is modulated and alternating frames of left and right circular polarization are captured by the video camera and digitized. The difference between the two polarizations is measured, and an average is taken over 32 (for strong field) to 1024 such pairs. The 480 pixel high image thus displays (fig. 2) 480 individual Stokes I and V spectra per image. Many images can be quickly acquired (with a cadence of several minutes), with each pair (left and right circular polarizations) being taken within 60 ms, and the entire set of pairs being taken within about 10 seconds (60 s for quiet Sun). This produces highly sensitive Stokes V and I spectra with few seeing induced artifacts. In each case the slit is placed in a quiet-sun region; if possible, a network element is included to illustrate the range of measurement. The spectrum is scanned along the slit and the measured fields are plotted for both lines.

We adopt the essential idea of Stenflo's [1] paper: we compare the Fe I 5247 and 5250 lines. We find, in contrast to Stenflo and coworkers, that the ratio of the splittings is exactly 3:2; there is no saturation. Surprisingly, weak measurable field is found almost everywhere. While some have criticized the use of these two lines, it is essential to compare directly with the quantities measured by Stenflo and colleagues. We calibrate by the splittings of stronger elements.

3. – The observational data set

The data presented here are the results of observations made in good seeing near disk center on 12 July 1994 and on 23 June 2000. We have many other sets; these are the best quiet-Sun data. On the first set we measured 49 images comprising 20000 scans, on the second occasion we obtained an additional 120 images (50000 individual spectral scans). In each case we make the same comparison as Stenflo of the V signal from each line, except that we calculate the integral, as seen in the next section. An example of the corresponding Stokes V and slit images is shown in fig. 2. On the left we have a slit jaw image of a 80 arc sec field using a broad K-line filter. The spectrograph slit, which is horizontal, passes through three network elements, and the spectrogram on the right shows the V images of the four lines near 5250. 5250 is second from the bottom and 5247 is the top line. We estimate the effective resolution as about $2'' \times 2''$. By contrast Stenflo's data used an aperture of 4×4 arc sec square and had longer integration times [10]. Subtraction blanks out the spectrum lines, and only the V signal appears. This frame uses 64 pairs, requiring a few seconds exposure. With longer integrations, weaker fields appear all over the Sun. In each case the program calculates the data for each point and derives the field from the integrated V signal as described below.

To directly measure the true field strength, we must measure the splitting, which the SPVMG detects down to 1000 gauss. For weaker fields we must use Stenflo's method, comparing the V signal from the two lines. This method also decouples the magnetic and non-magnetic effects to as great an extent as is possible. This is because the non-magnetic effects have a first-order impact on the line shape, but only a second-order effect on the integral over the whole line. We therefore introduce the measure $M_{\lambda 1}$ of the magnetic effect at each point in the line λ_1. We define M as the total V signal, adding the two bands:

$$M_{\lambda 1} = \int_{\lambda_1}^{\lambda_0} (V/g_{\lambda 1})\mathrm{d}\lambda - \int_{\lambda_0}^{\lambda_2} (V/g_{\lambda 1})\mathrm{d}\lambda \,, \tag{1}$$

where $M_{\lambda 1}$ and $M_{\lambda 2}$ are ± 150 mÅ from the line center $M_{\lambda 0}$. In the absence of saturation

$$V = -\alpha_m \Delta\lambda_H \frac{\partial I_m}{\partial \lambda} \,, \tag{2}$$

where α_m is the filling factor of the magnetized region m.

$$\Delta\lambda_H = 4.67 \times 10^{-13} \lambda_0^2 g B \,, \tag{3}$$

and I_m is the line profile. Integrating over λ, we get

$$M = 9.33 \times 10^{-13} \alpha_m \lambda_0^2 B (I_m(\infty) - I_m(0)) = 9.34 \times 10^{-13} \alpha_m \lambda_0^2 B D_m \,. \tag{4}$$

4. – Results

In fig. 3 we plot the observed average value of M_{5250} for all pixels corresponding to a given value of M_{5247} against that value. This was Stenflo's basic test. If the field in the element sampled is weak (so that we are in the linear regime), then the ratio should be one and this line should have a 45° slope. However, as the measured fields grow stronger,

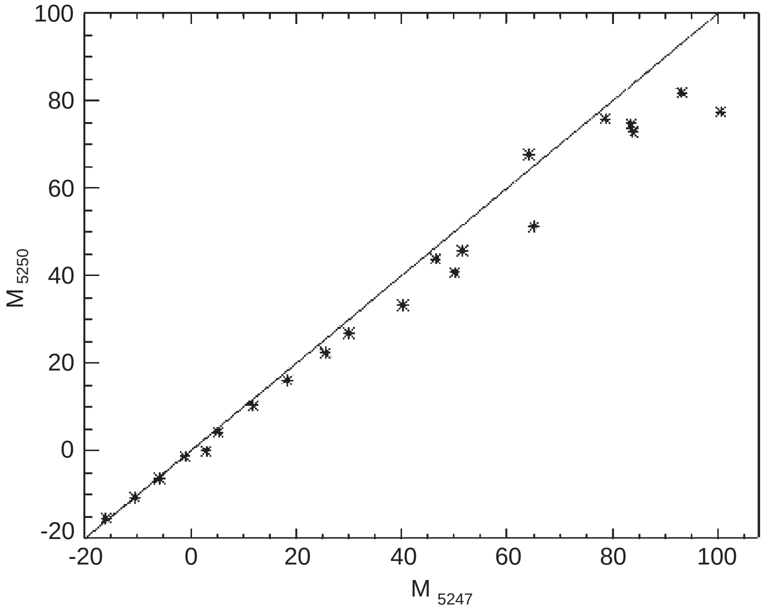

Fig. 3. – Plot of the signal for 5250 *vs.* 5247, corected for the g-factor. The scale corresponds to 8 gauss per unit.

the linear approximation is no longer adequate (the line with the larger g-value becomes magnetically saturated) producing a slope different from unity. In fig. 3, each entry represents all of the spectra with the chosen value, hence hundreds of measurements.While Stenflo's found $M_{5247}/M_{5250} > 1$ for the stronger elements, we find it (fig. 3) tracks unity perfectly, below 300 gauss (40 on the abscissa), above which saturation begins. The vast majority of our measurements are below this value, comfortably within the linear portion of this curve. This simply establishes that the fields are less than 300 gauss. But the measures cannot fall on this line by accident, and the close correspondence between the fields derived from each line tells us there is little error in the determination from fields > 25 gauss.

While the data in a single profile cannot distinguish between models, we can combine large numbers of profiles to do this. Figure 4 shows the difference $V_{5250}(\Delta\lambda)/3 - V_{5247}(\Delta\lambda)/2$ for $\Delta\lambda = \pm 90$ mÅ. Here we have averaged all spectra for which M_{5250} corresponds to a flux between 100 and 200 gauss and for which the line deviates from symmetry by less than 5%. For comparison we have also plotted what we would expect to see if the field were 1000 gauss with a filling factor between 10.1 and 0.2. The observed profile is closer to zero (which is the expected weak field limit) than to what we would expect if the field were 1000 G, demonstrating again that the field is sub-kiloGauss. Lastly, note that we have plotted the difference between the two lines, not the ratio. This difference has the property that the error bars across the domain are approximately constant. The quality of the data can be judged by the close tracking of 45 degrees.

When we average the absolute values of field strength along the slit, we find 38 gauss, the median value is 23.5 G, showing the strong influence of the strongest elements. If we confine the averaging to fields less than 50 gauss, we find 17 gauss. 93% of the

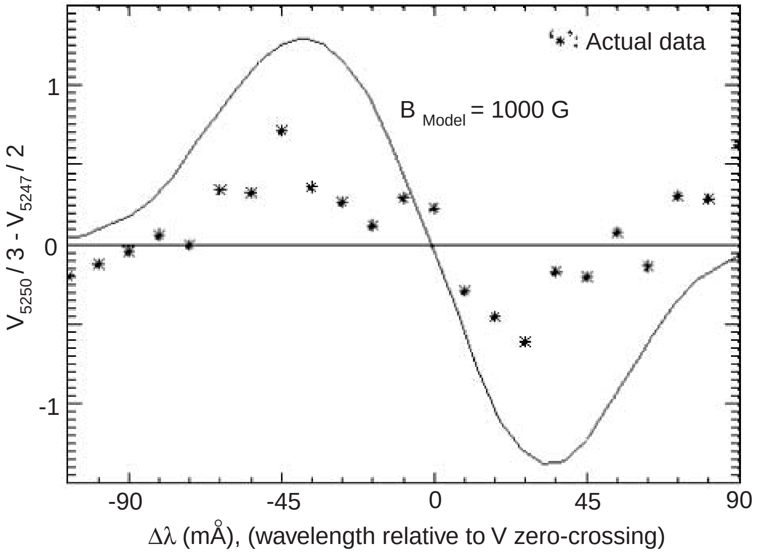

Fig. 4. – The difference between the two lines as a function of wavelength. For no saturation, we should get the horizontal line, for kilogauss, we get the sine-like function. The actual value is closer to the weak-field fit.

flux is weaker than 500 G and 7% stronger. Calibration of field strength is possible from splittings, which we can measure for 1000 gauss and comparison with calibrated videomagnetograms. In any event the close adherence to the proper g-factor ratio tells us that saturation does not occur and fields are below 300 gauss. In all cases where we can measure splittings accurately, the fields from splitting correspond to those derived from M within 20%. We calibrate M by slopes obtained from line profiles in the KPNO atlas. Because the profile in magnetically enhanced regions is flatter, the observed value is decreased, a weakness inherent in all measurements. Despite these warnings, the derived values are in good agreement.

5. – Discussion

Why are our quiet-Sun results different from those of previous workers? Mainly, we think, because their lower sensitivity led to missing the weak fields. This can be judged by published spectra, which give fields only for the strong elements and show nothing in between. We find that with the spatial and temporal resolution of the BBSO SPVMG system 93% of the flux in the quiet Sun is due to fields weaker than 500 G. There are no kilogauss fields in the intranetwork elements, but there are non-zero (0–20 gauss) fields everywhere. We find the typical field strengths for network elements to be 200–500 G. Using Stenflo's line ratio test, we find excellent correspondence to the g-factor down to 25 gauss, with no sign of saturation below 300 gauss.

Another result of our work: while fig. 1 shows a conventional image, with magnetic elements about $2''$ in diameter, separated by 4–$5''$, the deepest SPVMG-grams show essentially continuous field with little interruption. This background field is < 20 gauss; measurements of the two lines are less accurate below 20 gauss.

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We acknowledge help from the Big Bear observers and Mr. T. Spirock in instrument setup and thank Dr. P. Goode for allocating time for renewed observations. This work has been supported by the NSF under ATM-9726147.

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