ON THE CONTINUUM INTENSITY-MAGNETIC FIELD RELATION ALONG THE DECAY PHASE OF SUNSPOTS*†

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Abstract. We present continuum intensity-magnetic field distributions for a decaying sunspot. It is shown that a very simple model accounts for the observed correlation. The Wilson depression is determined.

1. Introduction

The two basic sunspot properties are the darkness and the strong magnetic fields found on these structures. We have studied the relation between the continuum intensity (I) and magnetic field strength (B) at different positions along the umbra of a slowly decaying sunspot (NOAA/USAF 5012) during two consecutive days. In the literature there exists a number of papers which analyse the relation between both magnitudes at the sunspot centers (Deinzer, 1965; Dicke, 1970; Yun, 1970; and more recently, Chou, 1987). In general, they found that sunspots with the highest central magnetic field are the cooler ones. Here, we are interested in the continuum intensity-magnetic field distributions at *different positions* on the same umbral structure. Previous results have been presented by Abdussamatov (1971) and Gurman and House (1981). The main conclusion is the existence of a clear – negative – correlation between both magnitudes. In very simple terms, this can be understood through the inhibition of convective energy transport by the magnetic field: independently of the precise mechanism, we could expect a lower continuum intensity in places of stronger magnetic fields. In this work we present new observations confirming the existence of such a correlation and stress the fact that the observed $I - B$ distribution provides information about one of the most problematic sunspot parameters, the Wilson depression, defined as the geometrical distance between the surfaces $\tau = 1$ in the quiet photosphere and the sunspot.

In principle, there are two ways to proceed. One can obtain the Wilson depression by taking photographs of the sunspot passage across the disc. Then the $I - B$ distribution provides information about the normal pressure and temperature in those hidden layers of the Sun. Alternatively, if a model of the convection zone is assumed to be valid, then the $I - B$ distribution allows us to estimate the value of the Wilson depression. In this work we follow this second method. Finally, it must be noted that, for the above-

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described procedure to work, an additional assumption concerning the role of magnetic tension on sunspot equilibrium has to be made. We will show that this is not a serious restriction to our conclusions.

2. Observations and Data Reduction

Stokes I and V photographic spectrograms were taken at the V.G.T. at Izaña in the 6302 Å regions. The film was Kodak 2415 emulsion, the slit width was 170 μm (corresponding to 16 mÅ or 1.36″ on the Sun) the exposure time 20 s. For the polarimetric analysis we used the Meudon analyzer (Semel, 1980). The magnetic field was measured via the centroid differences between the two lobes in the V profile (in this way we avoid the influence of stray light in the field evaluation). The identification of the slit position was made with the help of the Slit-Jaws photographs taken simultaneously with the spectrograms.

In order to avoid, or at least to reduce, the instrumental polarization effects on the magnetic measurements we symmetrized the V profile by taking its Fourier transform and returning only the imaginary parts (i.e., the antisymmetric ones). The results of the symmetrization procedure agree with estimates from the telescope Muller matrix (Sánchez Almeida, 1988).

The continuum intensity was obtained from white-light pictures (5500 Å, FWHM = 180 Å) taken with the V.N.T. (Izaña). The film was Kodak AHU and the exposure times varies between $\frac{1}{60}$–$\frac{1}{30}$ s. The continuum images were rebinned in order to adjust the different spatial scales of both telescopes.

Finally, with a pinhole photometer, aureole scans were taken in order to derive the stray-light correction following Mykland (1970). The instrumental set-up is described in Martínez Pillet *et al.* (1990).

We present here results for 9 May, when the spot radius was 4.5″ and the stray-light correction 20% of the photospheric intensity and for 10 May with corresponding values of 4.0″ and 25%, respectively.

3. Results: $I - B$ Distribution

In Figure 1 we have plotted the observed values of the intensity and magnetic field averages over each pixel (1″ × 1″). We have considered the stray-light as a constant level superimposed on the white-light pictures. Although this is acceptable for the umbra, this procedure tends to overestimate the stray-light correction on the penumbra and the corresponding values should be too low. This effect is not important for contrast values smaller than, say, 0.4.

The uncertainty on the magnetic field measurements is given mainly by the signal-to-noise ratio on the Stokes V spectrum (5–10). For the contrast values the main source of error is the stray-light correction. Other sources of error like the density–intensity calibration are negligible.

It is evident from Figure 1 that, in our sunspot, the regions with lower intensities are

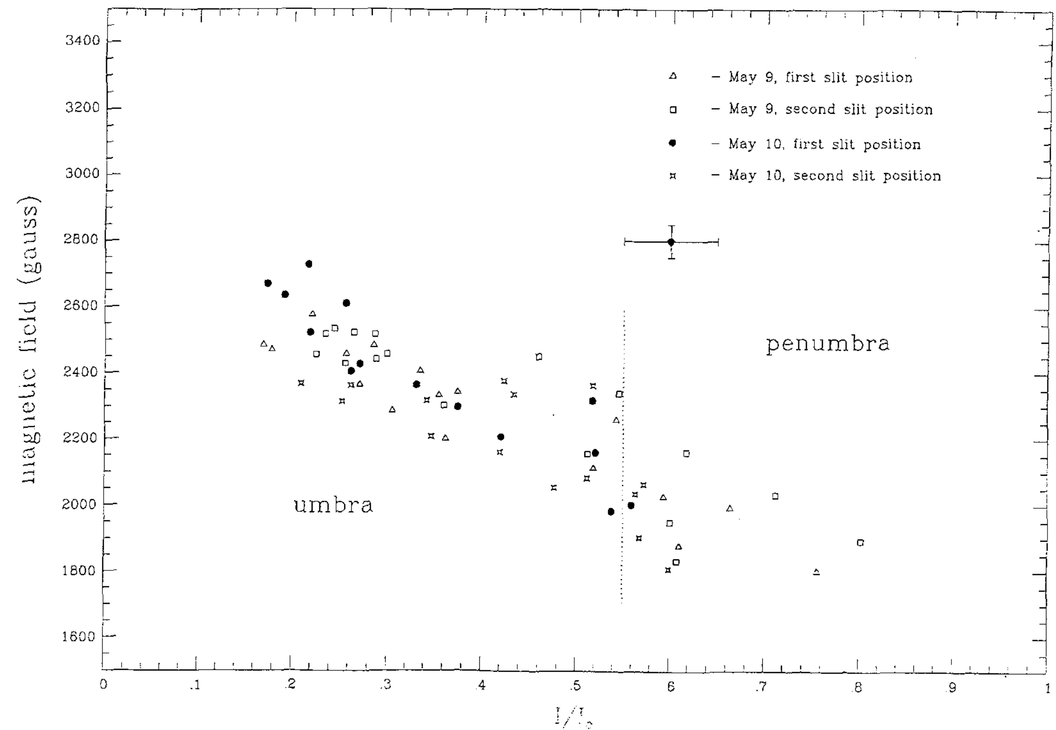

Fig. 1. Continuum intensity-magnetic field distributions for our sunspot on two slit positions and for two consecutive days. The intensity values are corrected for stray-light. This effect is overestimated for the penumbral values. The error bar on the intensity measurements is due to the stray-light correction. For the magnetic field the error is estimated from the signal-to-noise ratio on the Stokes V spectrograms.

associated with the highest magnetic field. This strong correlation agrees well with those found by Abdussamatov (1971, Figure 4) and Gurman and House (1981, Figure 4).

In order to understand the observed correlation between continuum intensity and magnetic field, we need a model for the magnetic configuration. To that end, let us write the horizontal component of the magnetostatic equation

$$\frac{\partial P}{\partial r} = \frac{B_z}{\mu}\left(\frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r}\right). \tag{1}$$

B_r and B_z are the two components of the (axially-symmetric and untwisted) magnetic field. If we integrate Equation (1) between the undisturbed photosphere (at a distance a from the spot axis) and a particular point on the sunspot at a distance r from the center and making use of the ideal gas equations results in

$$\frac{T(r, z)}{T_0(z)} = \frac{m(r, z)}{m_0(z)}\,\frac{\rho_0(z)}{\rho(r, z)} \times$$

$$\times\left[1 - \frac{1}{2\mu P_0(z)}\left(B_z^2(r, z) + 2\int^{a} B_z(r', z)\,\frac{\partial B_r(r', z)}{\partial z}\,\mathrm{d}r'\right)\right], \tag{2}$$

m is the average molecular weight. The other symbols have their usual meanings. The subscript '0' refers to the normal convection zone. Equation (2) shows the relation between the local temperature in the sunspot and the (local) magnetic field as well as the thermodynamic conditions in the quiet photosphere at the same height. The magnetic term in Equation (2) is the sum of two components. The first one (B_z^2) is associated with the magnetic pressure, the second with horizontal tension forces due to the bending of the field lines. We need some assumption concerning this second term. For a pure vertical field this is equal to zero (this was used by Solov'ev, 1984; and by Sobotka, 1985), giving a magnetic contribution of $B^2(r)$. For a particular topology of the Schlüter and Temesváry spot, Low (1980) shows that the two terms equal $\frac{3}{2}B^2(r)$.

On the other hand, we can translate our continuum intensity values to temperature on the sunspot by assuming LTE:

$$\frac{I}{I_0} = \frac{e^{hc/\lambda k T_0} - 1}{e^{hc/\lambda k T} - 1} \, . \tag{3}$$

In Figure 2 we show temperature, from (3), and B^2 for the same observations as for Figure 1. This figure strongly suggests a linear relationship between the sunspot temperature and the square of the magnetic field. The above-cited theoretical considerations and the correlation on Figure 2, allow us to simplify the magnetic part of Equation (2) as

$$\frac{T(r, z_1)}{T_0(0)} = \frac{m(r, z_1)}{m_0(z_1)} \frac{T_0(z_1)}{T_0(0)} \frac{\rho_0(z_1)}{\rho(r, z_1)} \left[1 - \frac{1 + f_T}{2\mu P_0(z_1)} B^2(r, z_1) \right] . \tag{4}$$

The value of f_T is 0 for a pure vertical field and $\frac{1}{2}$ for the field configuration of Low (1980). $z_1 = z_{WD}$ is the Wilson depression (i.e., $\tau_0^{5500}(0) = 1$ and $\tau^{5500}(z_1) = 1$).

From Equation (4) it is easy to see how the ratio between the slope and the regression constant gives information about f_T and $P_0(z_1)$. We have

$$\frac{P_0}{1 + f_T} = (0.83 \pm 0.07) \times 10^6 \text{ dyn cm}^{-2} . \tag{5}$$

It should be remarked that our procedure does not depend on the concrete values of the quantities outside of the square brackets on the right-hand side of (4) as long as we only make use of the *ratio* between the slope and the regression constant. Finally, giving plausible values to f_T and if we take Spruit's (1977) convection zone model we can obtain

$$z_{WD} = \begin{cases} 720 \pm 40 \text{ km} , & f_T = 1.0 ; \\ 630 \pm 40 \text{ km} , & f_T = 0.5 ; \\ 470 \pm 30 \text{ km} , & f_T = 0.0 . \end{cases} \tag{6}$$

The 'standard' value of this parameter is 600 ± 200 km (Gokhale and Zwaan, 1972), which agrees well with our estimates but, at the same time, does not allow us to ascertain

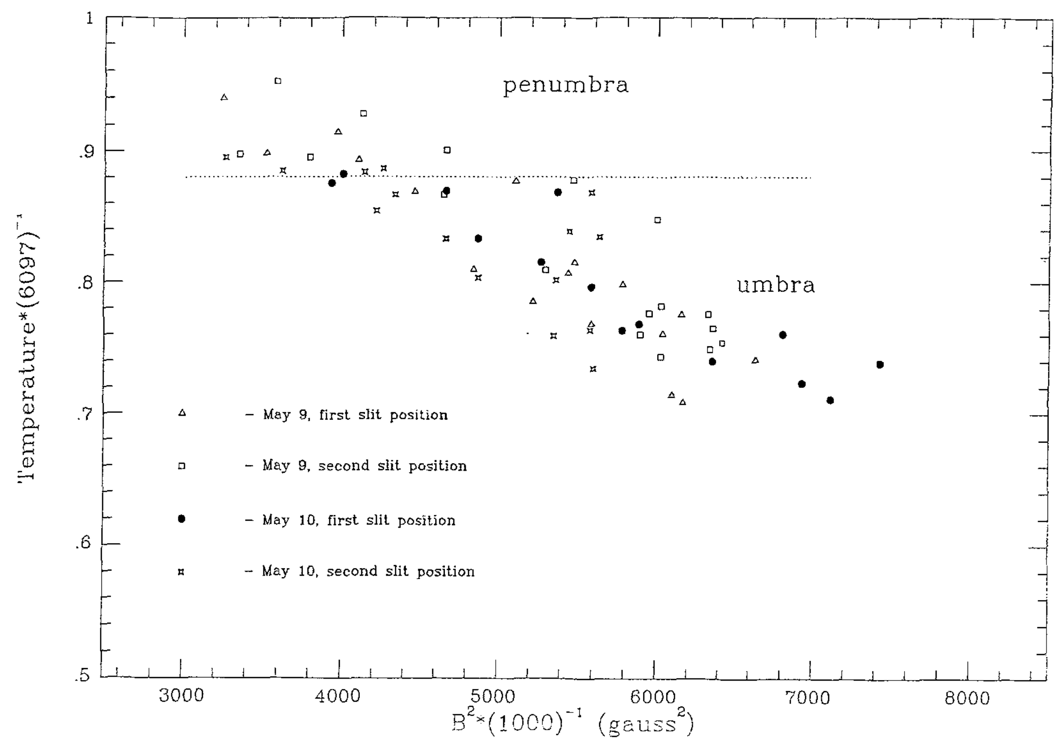

Fig. 2. The linear relationship observed between the square of the magnetic field and the temperature deduced from Equation (3). The data come from Figure 1.

a precise value for f_T. In order to develop a self-consistent method we must supply it with another 'input' like the measure of the spot Wilson depression from its center-to-limb variation. Work is in progress in this direction.

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