ON THE ORIGIN OF THE DISCRETE CHARACTER OF THE SOLAR DISK BRIGHTNESS IN THE 160 NANOMETER CONTINUUM

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ABSTRACT

Solar ultraviolet pictures with an effective resolution of 1' at 160 nm have been obtained during a flight on board a Black Brant rocket of the Transition Region Camera (TRC). The high spatial resolution photometry of the pictures has revealed very fine features (< 1 Mm) in the cells, the network, and active regions with excess brightness more than 5 times the average intensity of the solar background.

The procedure that was used in the reduction of the data, the results obtained, and a preliminary interpretation in terms of the Wilson effect in the bright network elements and of local energy dissipation in the cells are described.

Subject headings: Sun: chromosphere — Sun: corona — Sun: magnetic fields — ultraviolet: general

I. INTRODUCTION

High-resolution pictures of the Sun in the ultraviolet continuum near the level of the temperature minimum and the low chromosphere have been obtained by Brueckner (1979; see also Cook, Brueckner, and Bartoe 1983). They revealed the presence of numerous bright grains whose origin remained unexplained. In the course of the second flight of the Transition Region Camera (TRC), which occurred on 1980 September 23 (Bonnet et al. 1982), very high resolution pictures have also been obtained in the continuum around 160 nm, which again revealed similar structures, viz., grains in the interior of the cells and bright elements delineating the network. Our pictures provide a precise view of the fine structure of the solar atmosphere at the location between the dense photospheric layers, at the top of the convection zone, and the chromosphere, where magnetic pressure begins to overcome the gaseous pressure.

In this paper we evaluate first the performance of the TRC as far as spatial resolution is concerned in order to arrive at a more refined description of the 160 nm features. In the following sections we investigate the origins of the ultraviolet-bright grains which are observed in the interior of the supergranulation cells and of the bright elements which delineate the network.

II. ESTIMATION OF THE RESOLUTION ACHIEVED ON THE 160 NANOMETER PICTURES

The instrumentation is schematized in Figure 1. It has been described in Bonnet et al. (1980, 1982). Filtergrams of the Sun at Lyman-alpha and in the UV continuum at 160 nm are recorded on photographic film. Hereafter, we report on the results of the data reduction process of the 160 nm filtergrams, and only those instrumental characteristics that correspond to this wavelength are presented here.

a) Calculation of the Modulation Transfer Function of the TRC (MTF)

The Cassegrain telescope of 10.6 cm diameter and 2.5 m equivalent focal length acts as a spatial filter; its modulation transfer function (MTF1) is represented on Figure 2. The photographic film used during the flight is Kodak 104-07. The correct exposure time (i.e., that which covers the largest range of densities) is 1 s. The MTF of the film itself has been evaluated from the distribution of the grain sizes in the range of densities that correspond to the linear portion of the film characteristic, for 1 s exposure. It is shown as MTF2 on Figure 2.

The resulting MTF of the TRC is the product of the MTFs involved in the chain: telescope + emulsion × MTF1 × MTF2. It is represented on Figure 2 and shows the response of the TRC to the modulation of the contrast with spatial frequency.

The photographic pictures were analyzed with the PDS microphotometer of the Centre de Dépouillement des Clichés Astronomiques at Nice Observatory, using an area of analysis A = 10 × 10 μm², which corresponds to ~1 arcsec² on the solar disk. This introduces another degradation of the image, represented by MTF3:

MTF3 = |sine (dvₓ) × sine (dvᵧ)|,

where vₓ, vᵧ represent the spatial frequencies in x and y, d is the width of the spot, and

sine x = sin nx/ncy.

The sampling affects the Fourier spectrum of the image too, and convolutes it with a two-dimensional "sampling comb"

cb(avnₓ) × cb(avnᵧ),

where a is the sampling rate, and

cb(x) = ∑ₙ=−∞²δ(x - n)

is the comb function.

In order to evaluate the spatial information contained in the pictures, we compare the resulting MTF of the TRC with the statistical modulation introduced by the photographic noise.

b) Photographic Noise

The film calibration was performed after the launch on uniformly preexposed images recorded on the same piece of
film as that used for the flight. These images were scanned over square areas of 64 by 64 elements of $10 \times 10$ $\mu$m$^2$, and a Gaussian density histogram could be obtained for each frame. For each illumination, the peak value of the histogram provides a data point on the characteristic curve $D \log_{10} E$, at the selected exposure time for the 104-07 film. The root mean square width $\sigma_D$ of the histogram provides the film granularity $g$. According to Burton, Hatter, and Ridgeley (1973), the granularity is defined by $g = A \sigma_D$, where $A$ is the area of the microdensitometer slot. From the characteristic curve and the granularity we deduce the detector quantum efficiency (DQE) of the 104-07 film (Burton, Hatter, and Ridgeley 1973). The DQE is the square of the ratio between the signal-to-noise ratios ($S/N$)$_{out}$ after detection and ($S/N$)$_{in}$ due to the photon noise; i.e.,

$$DQE = \frac{(S/N)^2_{out}/(S/N)^2_{in}}{\gamma^2} = \frac{(dD/dE_p)E_p/g^2}{\gamma^2},$$

where $E_p$ is the exposure in photons cm$^{-2}$, and $E$ is expressed in ergs cm$^{-2}$, $\lambda$ is the wavelength in $\AA$, $\gamma$ is the gradient of the $D$-$\log_{10} E_p$ curve at density $D$ (i.e., the local contrast factor of the emission), and $g$ is the granularity in cm. Therefore, the relative variations of the DQE with $E$ can be represented by $\gamma^2/E^2$. Uncertainties in the granularity and in the evaluation of $\gamma$ generally limit the accuracy of the DQE to about $\pm 30\%$ (Burton, Hatter, and Ridgeley 1973). The characteristic curve, the variations of the granularity, and the quantity $\gamma^2/E^2 \propto$ DQE are plotted as a function of the exposure in Figure 3. The maximum value of the DQE is obtained near the “foot” of the characteristic curve, corresponding to an exposure time of 1 s, at a density $D = 0.1$. This value of $D$, where the maximum information can be extracted from the images, corresponds to the density we measure at the center of supergranules.

In terms of spatial frequencies, the photographic noise introduces a statistical density fluctuation, and features on the pictures cannot be actually resolved above spatial frequencies that correspond to a contrast which is lower than the statistical modulation. From the relation $D = \gamma \log_{10} E + D_0$, we deduce that fluctuations of density $\sigma_D$ create a statistical modulation

$$SM = \Delta E/e \approx 0.05 \text{ for } D = 0.1.$$
depends on the value of the density \( D \). The Rayleigh resolution obtained when the MTF is equal to 3 times the statistical modulation is then equivalent to 1" (Fig. 2), a resolution easily achieved on our images for most of the solar features that are present thereon.

III. THE DISCRETE CHARACTER OF THE 160 NANOmeter CONTINUUM BRIGHTNESS

Figure 4 is an enlargement of our best 1 s exposure. The fine structure of the chromospheric network clearly shows up on the picture, and bright grains can be seen everywhere, at the center of supergranules. A direct measurement reveals a typical width of these grains of 2" ~ 1.5 Mm and an average distance between them of 2 Mm. Similar features have been observed at various positions within the core of strong chromospheric lines such as Ca ii H and K, and H\( \alpha \) (Liu, Sheeley, and Smith 1972). The network shows up very clearly on the 160 nm pictures as a consequence of both the 1" resolution and the sensitivity to the temperature of the source function in the ultraviolet.

If the network can easily be described by only one type of bright element, inside the cells two scales of organization are combined, as shown by Foing (1983), i.e., a wavy modulation with a marked period of 8 Mm and features somewhat larger than the scale of the white-light granulation.

In the ultraviolet the solar brightness is very sensitive to temperature. If we assume that the Sun radiates like a blackbody, the brightness temperature difference between a feature and the neighboring background, \( \Delta T_b \), can be evaluated from the ratio \( I_b/I_c \) of their respective intensities:

\[
\Delta T_b = \left( \frac{kT_b^2}{\lambda} \right) \left( \log \frac{I_b}{I_c} \right) \approx 200 \log \frac{I_b}{I_c},
\]

for \( T_b = 4200 \, \text{K} \), and \( \lambda = \frac{hc}{v} = 160 \, \text{nm} \) (assuming that the 160 nm continuum originates near the temperature minimum as shown by Vernazza, Avrett, and Loeser 1981, hereafter VAL 81).

For a temperature difference of 200 K, the brightness is amplified by a factor 2.7, and all features appear with very high contrast. The photographic statistical modulation of 5% corresponds to a temperature brightness accuracy of 30 K, with a S/N ratio equal to 3, and sets the limit to the precision of our determinations.

The statistical study of a brightness scan (Fig. 5) provides an estimate of some of the characteristic parameters of the grains and network elements, such as their width and spatial distribution. The measured values of these parameters are given in Table 1 for (i) the center of supergranules, (ii) the chromospheric network, and (iii) an active region. The bright grains and network elements can also be seen on Figure 5: their contrast modulation is at least 4 times the statistical modulation due to photographic noise. Nevertheless, their characteristic width is close to the resolution of the TRC, and their measured profile yields only a lower limit to their excess brightness temperature since their dimensions may well be smaller.

Vernazza, Avrett, and Loeser have used the Harvard Skylab EUV observations to determine models of (A) a dark point within a cell, (B) the average cell center, (C) the average quiet Sun, (D) the average network, (E) a bright network element, and (F) a very bright network element (VAL 81). Following their analysis, we have constructed from our own data a histogram of the solar quiet-Sun intensity for features similar to their features A, B, C, D, E, and F and selected near Sun center. The corresponding distribution is shown on Figure 6, where the scale of intensities derived from the VAL 81 models is indicated for the sake of comparison. The two scales are adjusted in such a way that the intensities corresponding to features B (average cell center) coincide. If the FWHMs of the two distributions are in relatively good agreement, the distribution of TRC intensities extends over a range twice that of the VAL 81 intensities. In particular, the TRC distribution is skewed for intensities corresponding to features E and F, which
Fig. 4. Enlargement of a 100 nm picture (exposure time: 1 s). Note how the 100 nm network is resolved in bright elements; numerous bright grains are present inside the cells.
Fig. 5.—Two brightness scans across an average quiet-Sun area and an active region. The intensity scale is in arbitrary units. Note the spiky structure of the pictures and the apparent regular spatial organization of the bright "cell grains." The 2 sigma level due to photographic noise is indicated.

correspond to bright and very bright network elements. We attribute this difference to the difference in angular resolution between the Skylab data (5' x 5') and our data (1' x 1'), imposed by the microdensitometer slot, which means that features E and F have sizes smaller than the 5' x 5' resolution of the Skylab data. This conclusion is supported by the good agreement existing for features B, C, and D, which correspond to average features.

One may argue that the TRC 160 nm continuum is contaminated by emission from chromospheric lines within the spectral bandpass, which is not true for the Skylab data. In fact, as shown by Bonnet et al. (1982) on their Figure 1, the contribution of lines with respect to the continuum is negligible.

Our observations, together with those of Cook, Brueckner, and Bartoe (1983), show that the UV continuum emission occurs on a discrete spatial scale in the cells, the network, and active regions. We may therefore ask ourselves what the origin of this emission is.

Is it magnetic or is it the manifestation of a local energy dissipation? In the following we try to answer this question and show that although the network elements can probably be identified with cross sections of magnetic tubes, the cell grains most probably have a different nature.

IV. DO THE BRIGHT NETWORK ELEMENTS CORRESPOND TO HIGHLY CONCENTRATED MAGNETIC FIELDS?

High spatial resolution observations have shown that the photospheric magnetic fields are highly fragmented with strengths up to 2 kG and sizes less than 1". Dunn (1973) has discovered the existence of the so-called solar filigree, at a scale of 0.2 in loci of these concentrated fields. These magnetic elements are rooted in the intergranular lanes, tend to clump together, and form large magnetic features by interaction with photospheric motions. Do the bright network elements also correspond to these concentrated fields?

A straightforward answer to this question might be obtained through a direct analysis of the cospatiality between the grains and the field as measured on high-resolution magnetograms. Because such high-resolution, cotemporal magnetograms were not obtained during the flight of our rocket, we are forced to provide an indirect answer. For this we evaluate the magnetic field intensity in the network elements, assuming that they are the trace of magnetic flux tubes, and check whether the intensity is compatible with the intensity in these tubes as measured at the photospheric level.

The ratio of the light $I_e$ coming out of the network element (flux tube) to the light coming out in its vicinity $I_i$ is

$$\frac{I_e}{I_i} \approx \frac{S(\tau_i = 1)}{S(\tau_e = 1)} \approx \exp\left(\frac{h \nu}{k T_e} \Delta T_e\right).$$

where $S$ is the source function, $\tau$ is the optical depth, $T_e$ is the average brightness temperature at wavelength $\lambda = c/\nu$, and $\Delta T_e$ is the difference of brightness temperatures inside and outside the network element.
The quantity $\Delta T_B$ can be expressed as $\Delta T_B = (d T_B / d h) \Delta h$, where $d T_B / d h$ is the brightness temperature gradient, and $\Delta h$ is the height difference between two layers of equal optical depth in the network element and in its vicinity; $\Delta h$ can be expressed in terms of the magnetic field intensity of the flux tube.

In the Appendix we derive its expression, assuming that the greater brightness of the network element results from the Wilson effect:

$$\Delta h = H \log \left( 1 - \frac{1}{\beta_e} \right),$$

where $\beta_e$ is the ratio of the gaseous pressure outside the element, $P_e$, to the magnetic pressure in the flux tube, $B^2 / 8\pi$.

Relation (1) thus becomes

$$I_t / I_e \approx \exp \left[ \frac{h v}{k T_e^2} \left( \frac{d T_B}{d h} \right) \log \left( 1 - \frac{1}{\beta_e} \right) \right],$$

which relates the ratio of the intensity of the element and of the nonmagnetic quiet Sun to the magnetic field intensity $B$.

We have computed several values of the ratio $I_t / I_e$ using relation (2) for various values of $B$, taking

$$P_e = 1.31 \times 10^3 \text{ cgs},$$
$$H = 130 \text{ km},$$
$$d T / d h = 1.8 \text{ K km}^{-1},$$
$$T_e = 4470 \text{ K},$$

as given by VAL 81 near temperature minimum. The results are given in Table 2 and can be compared with the measured ratios $I_t / I_e$ at 160 nm (see Table 1). We see that our observations are consistent with fields of 120 G in the network near the temperature-minimum level and the low chromosphere and correspond to $\beta_e \approx 2$. This value is, in turn, consistent with photospheric fields of 1.5 kG (taking $P_e = 2B^2 / 8\pi$ in the photosphere), a value generally quoted for $B$ in flux tubes at the level of the photosphere.

Of course, our results are based on simplifying assumptions, the most critical of which being that the temperature is the same outside and inside the flux tube. If thermalization does not occur, certain other corrections would be needed, but our results qualitatively support the Wilson effect concept.

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>10 G</th>
<th>50 G</th>
<th>100 G</th>
<th>150 G</th>
<th>180 G</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^2/8\pi P_e = 1/\beta_e$</td>
<td>$3 \times 10^{-3}$</td>
<td>$7.7 \times 10^{-2}$</td>
<td>0.3</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>$h$ (km)</td>
<td>$0.39$</td>
<td>$10.4$</td>
<td>$-46$</td>
<td>$-150$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$I_t / I_e$</td>
<td>1.007</td>
<td>1.20</td>
<td>2.3</td>
<td>15.4</td>
<td>...</td>
</tr>
</tbody>
</table>

FIG. 6.—Intensity distribution of an average quiet-Sun area near the Sun center. Capital letters indicate the intensities of (A) a dark point within a cell, (B) the average cell center, (C) the average quiet Sun, (D) the average network, (E) a bright network element, and (F) a very bright network element, following the classification of VAL 81. The scale referring to capital letters with index c has been derived from the VAL 81 models. For the sake of comparison between the TRC and the VAL 81 distributions, the intensity of feature B on the VAL 81 scale arbitrarily coincides with the maximum of the TRC distribution. Notice that the correspondence of intensities between structures A, B, C, and D is quite good, while the TRC intensity distribution departs markedly from the bright features E and F corresponding to the bright UV network elements. A reference Gaussian distribution centered around the peak of the observed distribution (structure B) has been separated artificially from a brighter intensity distribution.
not apply in the chromosphere, it does indeed in the region extending between temperature minimum and 500 km above, which is precisely where the 160 nm continuum is formed. Different heating mechanisms may operate in the regions of greater magnetic fields and in the rest of the chromosphere, affecting the contrast of intensity between these regions and yielding slight overestimates of $B$. As noticed by Anzer (1983), a reasoning similar to the one used here bluntly applied to chromospheric lines formed in LTE above the temperature minimum would yield a magnetic flux tube brightness smaller than that of the nonmagnetic chromosphere, a result which is in contradiction to the observations, and which may well prove that these lines are not formed in LTE conditions.

We therefore conclude that our observations agree with the existence of highly concentrated magnetic fields in the network, corresponding to flux tubes with relatively small internal vertical velocities (see discussion in the Appendix). These tubes would show up as bright ultraviolet elements of size $\sim 10^3$ km and maximum average magnetic fields $\sim 120$ G.

V. ARE THE BRIGHT CELL GRAINS ALSO OF MAGNETIC ORIGIN?

The preceding discussion was concerned only with the ultraviolet network elements. The Wilson effect that we have invoked as a possible interpretation of their origin cannot explain the origin of the ultraviolet brightness excess inside the cells. In effect, with an excess brightness temperature of $\sim 80$ K, the intensity of the magnetic field that we derive, using the same method as above, is $\sim 60$ G (Table 2), which is much higher than the fields actually measured inside the cells.

Hence, we immediately give a negative answer to our question. (Of course, if magnetograms of higher spatial resolution than presently available reveal in the future the existence of highly concentrated magnetic fields in the cells that are co-spatial with the bright UV grains, this conclusion will be invalidated.) Therefore, in the context of today's observations, an alternative explanation must be proposed. As noticed by Bonnet et al. (1982), the ultraviolet-bright grains look very much like the cell points which are observed in the wings of the H and K lines (Liu, Sheeley, and Smith 1972). On spacetime-resolved K line profiles, Damé (1983) and Cram and Damé (1983) observe inside the cells periodic K2 brightenings which are coincident with downward motion of matter observed in K3. We suggest that the excess brightness of the grains at 160 nm results from a local dissipation of energy (whatever its origin might be). Our results allow us to evaluate how much energy would then be necessary to account for the excess brightness of the grains.

The increased continuum intensity $\Delta I_\lambda$ at wavelength $\lambda$ due to local energy dissipation processes which raise the temperature by $\Delta T$ is given by

$$\Delta I_\lambda = \int_{\Delta h} \Delta S_\lambda \exp \left( -\tau_\lambda \right) d\tau_\lambda ,$$

for directions of observation not too far from Sun center. Here $\Delta h$ is the thickness of the slab of the solar atmosphere in which the energy is dissipated. We will assume for the sake of simplicity that it is identical to the "height of formation" of the 160 nm continuum, which corresponds to the range of altitudes 350–550 km in VAL 81.

If all the deposited energy $E$ is radiated, we have

$$E = \pi \Delta L = \int_{\lambda} \Delta I_\lambda d\lambda,$$

$$= \int_{\lambda} \int_{\Delta h} \Delta S_\lambda \exp \left( -\tau_\lambda \right) K_\lambda (\tau_\lambda) \rho (\tau_\lambda) d\tau_\lambda d\lambda .$$

In the approximation of LTE, $\Delta S_\lambda (\tau_\lambda) = \Delta B_\lambda (T(\tau_\lambda))$, where $\Delta B_\lambda$ is the Planck function. Because $\Delta B_\lambda$ is nearly proportional to $B_\lambda$ and since $B_\lambda$ has its maximum in the visible, we see that the main contribution to $\Delta L$ comes from the visible around 500 nm. In addition, since the layer of thickness $\Delta h$ is located near temperature minimum, $\tau_\lambda (h)$ is very small in the visible and $\exp \left( -\tau_\lambda (h) \right) \approx 1$.

Assuming that the small change in $\Delta T$ affects only the emissivity $\epsilon_\lambda$ and not the opacity $K_\lambda$, we have

$$\Delta B_\lambda = \frac{\Delta \epsilon_\lambda}{K_\lambda}$$

and

$$\Delta L = \int_{\Delta h} \rho (h) dh \int_{\lambda} \Delta \epsilon_\lambda d\lambda,$$

$$= \int_{\Delta h} \rho (h) K_4 T^3 (h) \Delta T (h) dh ,$$

where $K$ is a “gray” absorption coefficient averaged over the visible wavelengths.

Since near temperature minimum $T(h)$ is nearly independent of $h$,

$$\Delta L = 4 \pi T^3 \Delta T \int_{\Delta h} K_4 (h) \rho (h) dh ,$$

or

$$\Delta L = 4 \pi T^3 \Delta T \Delta \tau ,$$

where $T$ refers to an average altitude $\bar{h}$ near temperature minimum ($\bar{h} = 450$ km), and $\Delta \tau$ is the range of optical depth near 500 nm which corresponds to altitudes between 350 and 550 km centered around $\bar{h}$.

According to VAL 81, $\Delta \tau = 3.10^{-4}$ around $\tau = 10^{-4}$. For $\Delta T = 80$ K and $T = 4470$ K, we find

$$E = \pi \Delta L = 8.8 \times 10^3 \text{ ergs cm}^{-2} \text{ s}^{-1} .$$

Altogether this crude calculation gives only an estimate of the observed dissipated energy. It is, however, very interesting to notice that it yields a value for $E$ which is in very good agreement with the amount of mechanical energy which is contained in acoustic waves in the region of temperature minimum (Mein 1981). A more refined computation should take into account the modification of opacity and density due to the increased temperature. Precise measurements of the ultraviolet brightness at several wavelengths in the continuum (instead of only one as here), together with the use of semi-empirical models, supplemented by spectroscopic data such as those of Cram and Damé (1983) would provide a good test of the validity of our conclusion: the filtergrams would yield the essential information on the dissipated energy, while the spectra would give the information on the dynamics involved through Doppler shift measurements and phase relationship.

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VI. CONCLUSION

Whole-Sun filtergrams as obtained by the Transition Region Camera at 160 nm allow a high-resolution overview of the region near temperature minimum and the low chromosphere. We have analyzed quantitatively the performance of the TRC and have evaluated the amount of information that one may expect from the pictures. They have a resulting resolution equivalent to 1" and yield an accuracy of 30 K on the brightness temperature at 160 nm, with a confidence interval of 3 σ. As of today, our pictures of the Sun appear to be the best ever taken from above the Earth’s atmosphere. The high sensitivity of the source function in the ultraviolet allows us to detect very faint brightness inhomogeneities and to resolve the network and active regions, and to observe spatial structures inside the cells.

Through a statistical analysis we have shown that the range of continuum intensities emitted by the features at 160 nm is twice that derived from the VAL 81 model, which puts constraints on the size of these features. Although the TRC 160 nm bandpass includes both continuum and chromospheric line emissions, the influence of lines which may explain the noted discrepancy is negligible (at least near the Sun center, where the comparison is made).

The ultraviolet-bright grains, which are observed everywhere in the cells, the network elements, and the active region elements have a characteristic size less than 1 Mm and a brightness temperature excess of 80–360 K.

We suggest that the network elements and the cell grains have different origins. The network elements may appear bright because of the Wilson effect at the top of concentrated magnetic flux tubes. The magnetic field intensity that we deduce assuming that the tubes are thermalized with their surroundings is 120 G, which corresponds to an intensity of 1.5 kG at the photospheric level. The cell grains cannot be of magnetic origin because the magnetic field intensity they would require would be too high, and we suggest that they are the trace of a local dissipation of energy contained in periodic motions. The amount of energy involved, which we estimate from the measured intensity at 160 nm, is very close to the amount of mechanical energy contained in acoustic waves at the temperature-minimum level. Longer time series of UV filtergrams might offer a useful way of checking the value of these two interpretations. The third flight of the TRC, which took place on 1982 July 13, may yield the necessary information. The results of this flight will be published in a forthcoming paper.

We would like to express our warmest acknowledgments to the Lockheed team (L. W. Acton, M. Bruner, W. Brown), who made it possible for us to fly the TRC, to NASA and to the SPARCS team, who offered the security of a safe launch and a perfect Sun pointing sequence, and to CNES, whose funds were used to build the TRC. The assistance of M. Décaudin of LPSP is especially acknowledged here as well as that of A. Bijaoui at Nice Observatory.

Dr. U. Anzer and the referee made very useful comments, which have been highly appreciated.

APPENDIX

COMPUTATION OF THE WILSON EFFECT IN THE BRIGHT UV NETWORK ELEMENTS

If we assume in a first approximation that the atmosphere is in hydrostatic equilibrium and isothermal, an assumption that we discuss below, the density can be expressed as

$$\rho(h) = \rho_0 e^{-h/H},$$

where $H$ is the scale height, and $\rho_0$ is the density at the base of the photosphere, and the optical depth $\tau$ is

$$\tau(h) = -\int_0^h K \rho(h) dh.$$

If we assume the opacity coefficient $K$ to be constant with $h$, which is valid in a first approximation in the region of the temperature minimum where $dT/dh$ is small, then

$$\tau(h) \approx K \rho_0 H e^{-h/H}, \quad \tau_{i}(h) \approx K \rho_0_i H e^{-h/H}, \quad \text{and} \quad \tau_{e}(h) \approx K \rho_{0e} H e^{-h/H}.$$

In the assumption of the grains corresponding to small magnetic flux tubes rooted deep in the photosphere, the equipartition of pressure $P$ outside and inside the tube can be written as

$$P_i + \frac{B^2}{8\pi} = P_e,$$

or

$$\rho_i = \frac{B^2}{8\pi RT} \frac{\mu}{\rho_e},$$

or, with $1/\beta_e = (B^2/8\pi)(\mu/RT)/(1/\rho_e)$:

$$\rho_i = \rho_e \left(1 - \frac{1}{\beta_e}\right),$$

where $B$ is the intensity of the magnetic field; $\beta_e$ is the ratio between the external pressure $P_e$ and the magnetic pressure and is always greater than 1.
From $\tau_\text{i}(h) = \tau_\text{e}(h)$, which yields $\rho_\text{oi} e^{-h/c} = \rho_\text{oe} e^{-h/cH}$, we deduce

$$\Delta h = h_\text{i} - h_\text{e} = H \log \left( \frac{1}{\beta_e} \right).$$

This expression of $\Delta h$ contains in itself several simplifying assumptions that had to be made, the most important of them being that of thermalization of the gas inside the tube with its surroundings. The assumption implies that both a spatial and temporal condition are met. The spatial condition is that the diameter of the tube be smaller than the distance of lateral thermalization. Assuming that the thermal exchange is dominated by the visible continuum, the distance of lateral thermalization can be approximated well with the photon mean free path. According to Stenflo (1977) (Fig. 4 in that paper), this condition is easily satisfied for all layers located 100 km above the photosphere. The temporal condition assumes that the thermal equilibrium of the tube is unaffected by any flow of matter which may be present in the tube. Such flows are generally observed (Beckers 1981) and have vertical velocities ranging from a few km s$^{-1}$ in the photosphere to a fraction of a km s$^{-1}$ at the temperature minimum.

The condition can be expressed as

$$t_{\text{Rad}} \ll t_{\text{Dyn}},$$

where $t_{\text{Rad}}$ is the radiative relaxation time, and $t_{\text{Dyn}}$ is a dynamic time constant:

$$t_{\text{Dyn}} = \frac{H}{V},$$

where $H$ is the scale height, and $V$ is the vertical velocity of matter inside the tube. According to Stenflo (1977) again, this condition is certainly satisfied in the photosphere and is less satisfied at higher levels if velocities in excess of 1 km s$^{-1}$ exist in the tube at the level of the photosphere. Therefore, our approximation is valid at temperature minimum only in the case of tubes which are pervaded with relatively low flow velocities. It is in general valid in the photospheric layers. For such layers $\beta_e = 2$, and the Wilson effect yields a substantial excess of brightness temperature in white light, which is consistent with what is observed in the filigree. For instance, if $\beta_e = 2$, $\lambda = 500$ nm, $T \sim 6200$ K, $H = 180$ km, $V T = -1600$ K/100 km, the brightness temperature excess could reach $\Delta T_B \sim 2000$ K.

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