INFRARED PHOTOMETRIC RESULTS OF A SUNSPOT

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ABSTRACT

We obtained simultaneously recorded time series of broadband images of a sunspot close to the disk center at the German Vacuum Tower Telescope, Tenerife, in two wavelength bands at 0.56 μm and 1.55 μm. Maps of brightness difference images T_b(1.55 μm) and T_b(0.56 μm) were computed for the best image pairs. Furthermore, a scatter plot of the brightness temperatures was made where five different magnetic and non-magnetic regions — quiet region (QR), faculae, pores, penumbra, and umbra — in the field of view can be clearly distinguished. Pores as well as the penumbra are surrounded by the facular regions consisting of several single facular elements. However, facular regions are also found in non-magnetic vicinity.

1. INTRODUCTION

Information about the thermal structure of magnetic and non-magnetic configurations in the photospheric layers provide hints in understanding the development from small facular regions to pores and possibly farther to sunspots. It was shown by Zayer et al. (1990) that the internal temperature of magnetic elements depend on the amount of magnetic flux. In addition, augmenting magnetic features increase in size and filling factor, the lateral radiative heating becomes less efficient (Knölker & Schüssler 1988), and the photospheric layers become cooler then the surroundings at all heights.

Observations at the minimum of opacity (around 1.6 μm) allow us to investigate the deepest layer in the photosphere. At this wavelength many faculae have dark contrast at disk center (Foukal et al. 1989, 1990; Foukal & Moran 1994; Sobotka et al. 2000) and change to bright faculae when observed on distance from the disk center (Auffret & Muller 1991; Topka et al. 1997, e.g.). Sánchez Cuberes et al. (2002) obtain a value of μ ≤ 0.5 – 0.6 where the change from dark to bright faculae takes place.

Table 1. Effective continuum formation heights z_c [km]

<table>
<thead>
<tr>
<th>Model</th>
<th>z_c(0.56 μm)</th>
<th>z_c(1.55 μm)</th>
<th>Δz_c</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSRA</td>
<td>29</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>Penumbra</td>
<td>27</td>
<td>-1</td>
<td>28</td>
</tr>
<tr>
<td>Umbral Cores</td>
<td>20</td>
<td>-47</td>
<td>67</td>
</tr>
<tr>
<td>Spot</td>
<td>19</td>
<td>-48</td>
<td>67</td>
</tr>
</tbody>
</table>

2. OBSERVATION AND DATA REDUCTION

Time series of broadband images of the solar photosphere including a spot with associated pores were obtained at the German Vacuum Tower Telescope (VTT, Observatorio del Teide, Tenerife) during 1998 June 16–22. They were taken simultaneously in two channels:

1. \( \lambda_1 = 0.56 \pm 0.0025 \text{μm} \)

2. \( \lambda_2 = 1.55 \pm 0.0046 \text{μm} \)

These wavelengths form in different photospheric layers and thus provide information about this layers. With the help of response functions the temperature contribution in each wavelength and heliocentric angle can be estimated. These functions have been computed by applying the 3D radiative transfer code of Fabiani Bendicho & Trujillo Bueno (1999) to the models of a mean quiet photosphere HSRA (Gingerich et al. 1971), of a penumbra (del Toro Iniesta et al. 1994), of a sunspot (Collados et al. 1994) and of umbral cores (Maltby et al. 1986).

The response functions have different shapes for each model and wavelength. In order to interpret the results, we define the effective formation heights of the continua, \( z_c \), as the positions of the centroid of the response functions. Table 1 presents the \( z_c \) values obtained for our time series, where \( z = 0 \) corresponds to \( \tau_{0.5} = 1 \). The last column gives the difference in formation heights: \( \Delta z_c = z_c(0.56) - z_c(1.55) \). It can be seen that \( \Delta z_c \) is larger for the sunspot and the umbral cores than for the penumbra and the quiet photosphere. This is because sunspots have lower mean temperature atmospheres than their penumbra and the photosphere.
In Figure 1 an image of the observed region NOAA 8243 at 0.56 μm is shown. Black contours mark facular regions which can occur as small isolated structures or show up as extended regions at the borders of pores and the penumbra, respectively. Nevertheless, there are extended facular regions which do not belong to other magnetic structures, but exist seemingly isolated.

The data reduction was similar to that described in Sobotka et al. (2000). In this paper we will summarize only the main steps of the image reconstruction. After standard flat-field and dark current correction all images were normalized to the mean intensity of the undisturbed photosphere. The noise filtering and the correction for the theoretical point spread function (PSF) of the telescope were performed simultaneously by means of a Wiener filter following Sobotka et al. (1993). The frames were aligned and destretched to minimize seeing distortions. Solar acoustic waves and residual seeing-induced jitter were removed applying a subsonic filter (cut-off phase velocity 4 km s\(^{-1}\)). Finally, all frames were rescaled to a unique image scale of 0\(^{\prime\prime}\)1 pixel\(^{-1}\) in both channels. Thus the resulting field of view is 70" × 70". This procedure gives us the possibility to obtain simultaneous information coming from different layers of the solar atmosphere.

3. THERMAL STRUCTURE

In analogy to Sobotka et al. (2000) and Sánchez Cuberes et al. (2002) we computed difference images of the best image pairs. In order to compare the intensities at different positions in each pairs we carefully matched the 1.55 μm images to the 0.56 μm ones using a destretching algorithm.

3.1. Difference Images

Since the contrast of infrared images is lower than the white-light contrast, a simple subtraction would give no significant information. Hence, the difference images have been computed according the following formula:

\[ I_{\text{diff}} = F \cdot [I(1.55) - 1] - [I(0.56) - 1], \]

where 1 stands for the mean intensity of the quiet photosphere and the factor \( F \) is defined by

\[ F = \frac{\Delta I_{\text{RSR}}(0.56)}{\Delta I_{\text{RSR}}(1.55)}, \]

which enhances the lower infrared contrast by means of the white light contrast. The quiet regions were identified visually.

Sobotka et al. (2000) showed that dark faculae are caused by an intensity deficit in the infrared band. In the brightness difference images dark faculae are defined as regions where \( I_{\text{diff}} < -0.039 \) (empirically determined). Areas of pores were set to an isointensity level of \( 1 - \Delta I_{\text{RSR}} \approx 0.9 \) in the 0.56 μm frames. The threshold to identify the penumbra was set to the pores' intensity level, whereas the border of umbra-penumbra was found at \( I(0.56 \mu m) \leq 0.55 \).

Figure 2 exhibits a brightness difference image of the best image pair. Just as for Figure 1 it was overplotted with the contours of the facular regions which now in contrast to the intensity image reveal the faculae. This is due to the nearly equal heating to comparable temperatures of these features and their surroundings at the 0.56 μm layer. Moreover, they environ pores partially or – in
some few cases — totally and are also found at the edge of the outer penumbra boundary. However, extended facular regions can exist autonomously without visual link to other magnetic features. Nevertheless there is a smooth transition between faculae and pores as can be seen in Figure 3 where the pixel cloud of faculae are extended to that of pores (cf. Section 3.2).

### 3.2. Brightness Temperature

In order to study the temperature distribution within the field of view in both bands, the brightness temperatures $T_b(\lambda)$ have been computed according to Planck’s law:

$$T_b(\lambda) = \frac{c_2}{\lambda \ln[(c_1/\lambda^5 I_{\text{abs}}(\lambda)] + 1},$$

where $c_1$ and $c_2$ are the constants of the Planck formula. To transform the normalized intensities to absolute intensities, i.e., in physical units, we used the calibration factors $I_{\text{pho}}(1.55) = 0.043 \text{ W cm}^{-2} \text{ ster}^{-1} \text{ Å}^{-1}$ (Makarova et al. 1994) as well as $I_{\text{pho}}(0.56) = 0.335 \text{ W cm}^{-2} \text{ ster}^{-1} \text{ Å}^{-1}$ (Neckel & Labs 1984) which were computed for positions at the disk center.

Brightness temperature maps were computed (not shown) applying Formula 3 to every pixel of the best image pairs. Quiet region, facular, and pore areas as well as umbra and penumbra were separated in the field of view in the same manner as described in Section 3.1. Average temperature values of $T_b$ in each regions are presented in Table 2. The temperature of the quiet photosphere is the reference value that depends on $I_{\text{abs}}$.

A pixel-to-pixel scatter plot of $T_b(1.55)$ versus $T_b(0.56)$ is shown in Figure 3. The temperature difference, $\Delta T_b = T_b(1.55) - T_b(0.56)$, is an important parameter depending on the temperature stratifications in different photospheric structures. It can be seen that pixels of the quiet region are separated from facular regions, whereas pores continue these pixel areas and overlap partially with the penumbra. The umbra is attached to the penumbra and the tail of this cloud deviates from the remaining pixels. The straight line in Figure 3 marks the constant temperature difference of $\Delta T_b(\text{QR}) = 479 \text{ K}$ of the quiet region on average. In facular regions $T_b(1.55)$ is generally shifted by about -76 K with respect to the QR and furthermore $\Delta T_b(\text{QR}) > \Delta T_b(\text{Faculae})$ holds for all facular pixels. As for pores, the bigger part of the pixels is situated below $\Delta T_b(QR)$, i.e. the temperature differences are similar to those in facular regions. Only a minor fraction lies above the line with $\Delta T_b(\text{QR})$, so these have temperature differences like QR pixels. In the penumbra the situation is divided into areas brighter and darker than the mean photospheric temperature difference $\Delta T_b(\text{QR})$. This describes the fact of the bright and dark filamentary structure of the penumbra. These could correspond to two umbral dot (UD) populations found e.g. in Tritischer & Schmidt (2002) which are not evenly distributed but the hot UD's are rather located where the brightness temperature of the local background is enhanced or shows a gradient. In the case of the other population (cool UD) their preferred locations are the regions of the umbral nuclei.

### 4. DISCUSSION AND CONCLUSIONS

From simultaneous time series observed in two wavelength bands (1.55 μm and 0.56 μm) we computed brightness difference maps of a sunspot and its surrounding. A pixel-to-pixel scatter plot is presented which provides information about the temperature stratification in the photosphere. The pixel cloud of the umbra shows an increase of $\Delta T_b$ with decreasing $T_b$ as well as an additional decrease of $\Delta T_b$ with decreasing $T_b$ for the coolest parts of the umbral core. This implies an increase of the formation height difference for the hotter parts of the umbra and a decrease for their coolest regions. However, the values of $\Delta z$ listed in Table 1 do not indicate this result. The brightness temperatures (see Table 2) of granulation and faculae differ little in the white light band but in the infrared wavelength there is a temperature difference of about 70 K. Therefore faculae cannot be seen in higher photospheric layers whereas they can be identified visually in the deepest layers. Moreover, a similarity of pores and their facular surrounding to the penumbra and its faculae is obvious in the brightness difference image given in Figure 2. This confirms that the magnetic radii of pores and sunspots are larger than their brightness radii (Kepens & Martinez Pillet 1996; Skumanich 1999).
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