SOLAR CENTRE-TO-LIMB INTENSITY FUNCTIONS IN OPTICAL AND RADIO WAVELENGTH RANGES

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Abstract. Centre-to-limb intensity functions in the Hα line, He I 10830 Å line, the nearby continuum and in microwaves (37 GHz) are investigated and compared with the corresponding intensity functions in different wavelength intervals ranging from 1.4 GHz to 12 μm. The "quiet Sun" limb-darkening function flattens with increasing wavelength from the visible to the infrared part of the spectrum, and even exposes a limb brightening in some parts of the micrometer, submillimeter and centimeter wavelength ranges.

1. Introduction

The investigation of centre-to-limb intensity variations on the solar disc is important for various reasons, such as the analysis of the structure of the solar atmosphere at different heights, as well as the study of solar irradiance and solar diameter variations. Depending on the part of the spectrum under consideration,
and on the radiation process involved, a limb darkening, limb brightening or no change in intensity from the centre toward the limb is recorded. The centre-to-limb intensity functions were investigated in segments of the ultraviolet (Greve, 1978) and visible wavelength range (Mattig and Schröter, 1961), in the infrared part of the spectrum (Deming et al., 1991; Zirin, 1992), as well as in the submillimeter (Bastian, Ewell and Zirin, 1993), millimeter (Kosugi, Ishiguro and Shibasaki, 1986) and centimeter wavelength ranges (Fürst, Hachenberg and Hirth, 1974; Hurford, 1992). In this paper we study the centre-to-limb behaviour in the Hα line, in the near infrared (He I 10830 Å line and nearby continuum) and in the microwave (8 mm) part of the solar spectrum. A comparison with the corresponding functions in wavelength ranges from 1.4 GHz to 12 μm is made.

2. The Measurements and Data Reductions

The measurements in the microwave part of the spectrum were performed at 37 GHz (8 mm) using the 14-m radio telescope of the Metsähovi Radio Research Station (MRRS), Helsinki University of Technology, Finland. The quiet Sun level is estimated to have a brightness temperature of 7800 K, and the resolution of recordings in the brightness temperature scale is better than 100 K. The radio telescope beam size, at 37 GHz, amounts to 2.4 arc min. A full-disc microwave measurement of the Sun consists of 91 x 29 data points, and the recording used in our study was performed on June 26, 1992.

The intensity measurements of a part of the solar spectrum around the near infrared He I 10830 Å absorption line were performed with the echelle spectrograph at the Vacuum Tower Telescope (VTT), German Solar Telescopes, Izaña, Tenerife, Canary Islands, Spain. East-west scans of the Sun were performed, and each particular scan was 80" broad containing 750 exposures. The measurements recorded on May 26, 1993 are analysed here.

The full-disc solar observations in the Hα line originate from the Big Bear Solar Observatory (BBSO), California Institute of Technology, USA. These were used in a digital form, so that the number of data points allow a spatial
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resolution of about 5'' . In this paper the image of the whole Sun taken on June 27, 1992 is analysed.

While the measurements from the VIT were recorded on an EXABYTE tape, the measurements from the MRRS and from the BBSO were transferred to the Kiepenheuer-Institut für Sonnenphysik (KIS), Freiburg, Germany, by the File Transfer Protocol (FTP). All these data were further reduced using codes written in the Interactive Data Language (IDL) at the KIS. The reduction procedures were described in Brajića et al. (1994) and in Brajića, Ruždjak and Wöhl (1994), where also the radius of the Sun and the centre-to-limb function at 37 GHz were discussed.

3. Centre-to-Limb Functions in the Hα and He I 10830 Å Lines, and at 37 GHz

In Figure 1 the full-disc solar image in Hα is presented. The performance of the reduction procedure can be seen in Figure 2a, where relative intensities surrounding the largest filament from Figure 1 were plotted in two spatial dimensions. The low intensity contours at the filament's position are clearly exposed. In Figure 2b a scan along the solar disc in the equatorial region is plotted, revealing the limb darkening and a notably lower intensity at the filament's position.

The centre-to-limb intensity variation in the He I 10830 Å absorption line (lower curve) and in the nearby continuum (upper curve) is presented in Figure 3, showing a limb darkening similar as observed in the Hα line. Different structures in the solar atmosphere expose either a strong (filaments and active regions) or a weak absorption (coronal holes) in the helium line (Brajića et al., 1994). However, both scans, in the line and in the adjacent continuum, show the same general behaviour. Figures 3a and 3b represent two scans displaced by 80'' in the northern direction.
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Fig. 1. Image of the whole Sun in the Hα line (Big Bear Solar Observatory, California Institute of Technology) taken on June 27, 1992.

The full-disc solar image in the microwave part of the spectrum, at the frequency of 37 GHz, is presented in Figure 4. The relative intensities across the solar disc in the equatorial region are plotted in Figure 5a. We would like to mention that the Solar activity was rather low on June 26 and 27, 1992 and on May 26, 1993. The microwave source at the west limb exposed in Figure 4 was connected to a 2B, X4 two ribbon flare which occured at 19:47 UT on June 25, 1992, at the position n09 w70 and generated a post-flare loop system. A dozen of such microwave limb sources have been studied in the paper by Urpo et al. (1986). To exclude this post-flare effect, a plot of the centre-to-limb intensity function was performed also at the angle of 45° respectively to the x-axis of Figure 4. Such a plot is presented in Figure 5b. At the frequency of 37 GHz the centre-to-limb function is nearly constant, and the variation, if it exists at all, is very small.
Fig 2. a) A two-dimensional plot of the relative intensity $i$ as a function of the relative coordinates $x$ and $y$ in the vicinity of the large filament from Fig. 1.
b) The relative intensity $i$ across the solar disc presented in Fig. 1. The limb darkening and the depression due to the large filament are seen.
Fig. 3. Solar scans performed on May 26, 1993 (the starting times were: a) 12:23 UT; b) 13:26 UT) at the Vacuum Tower Telescope (German Solar Observatories, Observatorio del Teide, Izaña). On the x-axis the ordinal number of the exposure is indicated. The scanning was performed from east to west, and the relative length units, rlu are indicated, and 1 rlu equals to 4 arc seconds. On the y-axis are relative intensity units; the upper curve represents the scan in a part of the quasi-continuum near the He I 10830 Å line, and the lower curve the scan in the He I 10830 Å line. Each data point in this frame represents an exposure after averaging the measured data along the spectrograph's slit, and after averaging a part of the data in the direction of the dispersion (in the part of the quasi-continuum for the upper plot, and in the helium line for the lower plot, always keeping the "borders" unchanged).
Fig. 4. Full-disc solar image taken in the microwave part of the spectrum at the frequency of 37 GHz on June 26, 1992 (Metsahovi Radio Research Station, Helsinki University of Technology).

4. Interpretation of the Observed Phenomenology

The Sun observed in the Hα line shows a centre-to-limb intensity function as in the optical continuum (Figures 1 and 2) whereas the Sun observed at 37 GHz exposes a different behaviour (Figures 4 and 5). The measured centre-to-limb intensity variation at 37 GHz (MRRS) is very small, in accordance with previous results (Fürt, Hachenberg and Hirth, 1974; Kosugi, Ishiguro and Shibasaki, 1986). The intensity variation at the solar limb is smeared (Figure 5), primarily because of the radio telescope resolution.
Fig. 5. a) The relative intensity $i$ across the solar disc in the equatorial region of the frame presented in Fig. 4.

b) The relative intensity $i$ measured at the angle of $45^\circ$ to the equator in the 1st quadrant of the frame presented in Fig. 4.
In the He I 10830 Å line and in the nearby quasi-continuum the solar radiation exposes a limb-darkening effect (Figure 3) similar as in the optical part of the spectrum. It is well known that the curve of the centre-to-limb darkening flattens as the wavelength increases from the visible to the infrared part of the spectrum, and for the spectral lines in the 12 μm wavelength range there is even a limb brightening (Deming et. al., 1991; Zirin, 1992). In the microwave part of the solar spectrum, either no significant centre-to-limb variations, or a limb brightening were observed, and the results are strongly dependent on the frequency (Table I).

The solution of the radiative transfer problem in the radio wavelength range gives for the brightness temperature, $T_B$ (Rohlfs, 1986):

$$T_B(l) = T_B(0) e^{-\tau_v(0)} + T (1 - e^{-\tau_v(0)})$$

where $\tau_v$ is the optical depth, defined by $d\tau_v = -kd/\epsilon$ ($k$ - opacity; $dl$ - a unit path element), $T$ is the thermodynamic temperature at the level positioned at "l", and the radiation passes first through the level denoted by "0". According to the model, given by Zirin, Baumert and Hurford (1991), the microwave emission from the quiet Sun originates dominantly from the optically thick chromosphere and from the optically thin corona. In that case the level denoted by "0" is placed in the chromosphere, the level denoted by "l" in the corona, and after neglecting higher order terms in the expansion of Equation (1) one obtains (Zirin, 1988):

$$T_B = T_{CH} e^{-\tau_C} + T_C \tau_C$$

where the subscript "CH" denotes the chromospheric values and "C" the coronal ones. Since $\tau_C << 1$, one finds:

$$T_B = T_{CH} + T_C \tau_C$$

Substituting the free-free absorption coefficient (Chiuderi Drago, 1990) into the expression for the optical thickness, one finds in SI units (assuming that the opacity does not depend on the path):

$$\tau_C = 15 \cdot 10^{-12} l_C N_e^2 v^{-2} T^{-3/2}$$

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Table I

<table>
<thead>
<tr>
<th>λ</th>
<th>ν</th>
<th>centre-to-limb function</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>white light</td>
<td></td>
<td></td>
<td>Tandberg-Hanssen, 1977</td>
</tr>
<tr>
<td>Hα 6563 Å</td>
<td>457 THz</td>
<td></td>
<td>Tandberg-Hanssen, 1977</td>
</tr>
<tr>
<td>He I 10830 Å</td>
<td>277 THz</td>
<td></td>
<td><em>present work</em></td>
</tr>
<tr>
<td>12 μm</td>
<td>25 THz</td>
<td></td>
<td>Zirin (1992)</td>
</tr>
<tr>
<td>0.85 mm</td>
<td>353 GHz</td>
<td>12-16%</td>
<td>Bastian <em>et al.</em> (1993)</td>
</tr>
<tr>
<td>8.1 mm</td>
<td>37 GHz</td>
<td>&lt; ±1.5%</td>
<td><em>present work</em></td>
</tr>
<tr>
<td>8.3 mm</td>
<td>36 GHz</td>
<td>&lt; ±1%</td>
<td>Kosugi <em>et al.</em> (1986)</td>
</tr>
<tr>
<td>1 - 3 cm</td>
<td>30-10 GHz</td>
<td>&lt; ±1%</td>
<td>Fürst <em>et al.</em> (1974)</td>
</tr>
<tr>
<td>6 cm</td>
<td>5 GHz</td>
<td>several 10%</td>
<td>Fürst <em>et al.</em> (1974)</td>
</tr>
<tr>
<td>21 cm</td>
<td>1.4 GHz</td>
<td></td>
<td>Hurford (1992).</td>
</tr>
</tbody>
</table>

where \( l_C \) denotes the length of the path in the corona, \( N_e \) the number electron density and \( \nu \) the frequency. Finally, one receives for the brightness temperature in the microwave wavelength range:

\[
T_B = T_{CH} + 15 \cdot 10^{-12} l_C N_e^2 T_C^{-1/2} \nu^{-2}
\]  

(5)

From this expression one can see that the contribution to the brightness temperature from the optically thin corona depends on the path \( l_C \). Since this path is larger towards the solar limb, the model predicts a limb brightening in microwaves. However, as can be seen from Table I, this limb brightening was observed only at particular microwave frequencies so far.
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RASPOĐJELA INTENZITETA ZRAČENJA U OPTIČKOM I RADIOVALNOM PODRUČJU NA SUNČEVOM DISKU

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Sažetak. Istraživana je ovisnost intenziteta zračenja o udaljenosti od središta Sunčevog diska na valnoj duljini spektralne linije Hα te linije He I 10830 Å i obližnjeg kontinuuma, kao i u mikrovalnom području (37 GHz). Rezultati su uspoređeni s odgovarajućim funkcijama za zračenje u raznim spektralnim intervallima u području od 1.4 GHz do 12 μm. Rubno zatamnjenje na "mirnom" Sunčevom disku sve je manje izraženo od vidljivog prema infracrvenom dijelu spektra, te čak prelazi u pojačanje intenziteta zračenja pri rubu diska u nekim dijelovima mikrometarskog, podmilimetarskog, milimetarskog i centimetarskog spektralnog područja.

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