ON THE VISIBILITY OF CORONAL HOLES IN MICROWAVES

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Abstract. Previous observations indicate that coronal holes generally appear as low brightness temperature regions in microwaves. However, within their borders local enhancements of radiation often occur. This is confirmed by comparing a full-disc solar image obtained at 37 GHz on 27 May 1993 with full-disc solar images obtained at various wavelengths. Microwave brightness temperatures of three coronal holes are determined and interpreted.

Key words: coronal holes - microwave measurements

1. Introduction

Regions of higher and lower brightness temperature (HTRs and LTRs, respectively) can be distinguished on full-disc solar images obtained at millimetre wavelengths. A general appearance of coronal holes at cm and mm wavelengths is that they can be seen as LTRs, inside which local HTRs often occur (Brajša et al., 1996; Pohjolainen et al., 2000; Pohjolainen, 2000 and references therein). In some cases HTRs can even prevail (e.g., Gopalswamy et al., 1999).

In the present paper we compare microwave measurements of the Sun performed at 37 GHz (full-disc solar images in different representations) with full-disc solar images obtained in soft X-rays (SXR) and in H\α. In addition, a corresponding solar magnetogram and scans over the solar disc
in the He I 1083 nm line are also used. A qualitative analysis of association of various features observed in different wavelengths and a quantitative estimate of brightness temperature of coronal holes are performed.

2. Measurements

All observations analysed in this paper were performed on May 27, 1993. In Figure 1 a full-disc solar image at the wavelength of about 2 nm taken through the Al/Mg filter with the soft X-ray telescope (SXT) on board the Yohkoh satellite is presented. The Yohkoh-SXT was described by Tsuneta et al. (1991), it is sensitive in a band of wavelengths between 0.2 and 7 nm and the pixel size is 4.9 arc seconds. At the SXR image in Figure 1 three coronal holes can be seen: the north and south pole coronal holes and an equatorial coronal hole. Five coronal bright points placed near the borders of the equatorial coronal hole can also be seen.
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Figure 2: Full-disc solar microwave map taken at 37 GHz (Metsähovi) on May 27, 1993. The intensities of the microwave radiation are denoted by iso-lines of the same brightness temperature. Regions with a brightness temperature above the quiet Sun are represented by thin iso-lines and regions with a brightness temperature below the quiet Sun by thick iso-lines. The first iso-line at the solar limb is at 0.50 \times qsI.

At Metsähovi Radio Observatory solar observations are performed with the 14 m dish radio telescope. At the frequency of 37 GHz (wavelength of 8 mm) the beam width of the telescope amounts to 2.4 arc minutes on the sky and the brightness temperature of the quiet Sun level is estimated to 7800 K. The sensitivity of the receivers is good enough for 0.1 sfu resolution. In the temperature scale this corresponds to better than 100 K and it is limited by short term changes in the atmospheric attenuation. Solar maps are measured by scanning the solar disc in right ascension and by changing the declination in small steps between the subsequent scans (e.g., Urpo et al., 1994; Pohjolainen et al., 2000). An example of a 37 GHz contour map is shown in Figure 2. The celestial equator is parallel to the x-axis of the image and the vertical line intersects the equatorial coronal hole.

For comparison, a full-disc solar image in H\alpha (Big Bear Solar Observatory - BBSO) and a full-disc solar magnetogram (National Solar Observa-
Figure 3: Hα full-disc solar image from BBSO taken on May 27, 1993. North is up and east is to the left.

tory - NSO at Kitt Peak) obtained on the same day are presented in Figures 3 and 4, respectively.

Finally, the He I 1083 nm scan along the Sun is presented in Figure 5. The measurements of the intensity of the near infrared He I 1083 nm absorption line were performed using the Echelle spectrograph on the Vacuum Tower Telescope at the Observatorio del Teide. The intensities of the helium line were recorded by a CCD camera. The measurements on the solar equator were performed in the east-west direction of the sky, defining the velocity components in a rectangular system with one axis parallel to the celestial meridian. So, the scan presented in Figure 5 was performed along the zero line of the relative declination in the microwave solar map presented in Figure 2. Further technical details about these measurements are given by Brajša et al. (1996; 2006).

The first step of He I 1083 nm data reduction was to average all of the intensity recordings in the pixels along the spectrograph slit. The length of the spectrograph slit amounted to 80 arc seconds. As a measure of absorption, the sum of all intensities in the line divided by the number of data points was used. Further, the relative intensity is determined as an aver-
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Figure 4: Full-disc solar magnetogram obtained on May 27, 1993 at NSO Kitt Peak. The orientation of the image is the same as in Figures 1 and 3.

age intensity in the He I 1083 nm line divided by the average intensity of the nearby quasi-continuum placed between the helium line and the telluric water-vapour line at 1083.21 nm. Such a scan is presented in Figure 5, where it can be seen that the He I 1083 nm line was observed only in absorption on the solar disc (relative intensity smaller than 1). The two peaks with relative intensity greater than 1 mark the solar limb.

We also note that the vertical border lines in Figure 5 (at the numbers 517 and 561 of the arbitrary units of relative right ascension) mark the locations where the northern part of the equatorial coronal hole is crossed.

3. Results

On May 27, 1993 three large coronal holes can be seen on the full-disc solar image obtained in SXR (Figure 1). These are the North pole coronal hole
Figure 5: He I 1083 nm scan along the Sun passing through the disc centre obtained with the VTT on May 27, 1993 with the line-to-continuum ratio plotted. The scan was performed parallel to the celestial equator, so the relative right ascension in arbitrary units is plotted on the x-axis.

(NpCH), the South pole coronal hole (SpCH) and the equatorial coronal hole (EqCH). For the best estimate of the brightness temperature of coronal holes we used two colour-coded microwave maps recorded at 06:42-06:51 and 15:09-15:18 UT on May 27, 1993, not reproduced here.

Taking into account the two solar microwave maps mentioned above, we have measured the following brightness temperatures $T_b$ of these three coronal holes relative to the quiet Sun level ($qsl$) estimated to 7800 K:

- **NpCH**: $0.98 \times qsl < T_b < 1.02 \times qsl$
- **SpCH**: $0.96 \times qsl < T_b < 1.02 \times qsl$
- **EqCH**: $1.00 \times qsl < T_b < 1.06 \times qsl$.

The borders of these coronal holes were determined from the SXR image presented in Figure 1. We note that we have not found any significant centre-to-limb intensity variation in full-disc solar maps obtained at 37 GHz in agreement with Brajša et al. (1994).

The average brightness temperature of the EqCH is higher than the average brightness temperature of the two polar CHs, probably due to the presence of stronger magnetic field inside the EqCH, as can be seen by comparing the solar magnetogram (Figure 4) with SXR and microwave images (Figures 1 and 2, respectively). The polar coronal holes have brightness temperatures approximately at or just below the quiet Sun level and the equatorial coronal hole has the background radiation at the quiet Sun level.
with some areas of enhanced emission up to 6% above it.

We also note that no pronounced chromospheric plages, which could contribute to enhanced emission in microwaves, were observed within the borders of the three coronal holes. This can be seen by comparing the full-disc solar image obtained in Hα (Figure 3) with the full-disc solar images in SXR and in microwaves (Figures 1 and 2, respectively).

In Figure 5 the scan across the Sun depicting the relative intensity of the He I 1083 nm line is plotted. The vertical border lines in Figure 5 (at the numbers 517 and 561 of the arbitrary units of relative right ascension) mark the locations where the northern part of the equatorial coronal hole is crossed. The relative intensity of the He I 1083 nm line in the equatorial coronal hole is between 0.973 and 0.991. The relative intensity of 0.991 is the highest value on the solar disc for this scan implying the weakest He I 1083 nm line absorption. In Figure 2, the horizontal line through 0 millidegrees of relative declination indicates the scan across the Sun in the He I 1083 nm line presented in Figure 5, and the intersection with the vertical line (placed at 140 millidegrees of relative right ascension) indicates the central position in the northern part of the equatorial coronal hole. The local minimum of the relative intensity of the He I 1083 nm line at 497 arbitrary units of relative right ascension in Figure 5, implying enhanced He I 1083 nm absorption, represents the He I 1083 nm dark point underlying the SXR bright point placed eastward from the main body of the equatorial coronal hole (Figure 1).

4. Summary and Discussion

As we have seen in the present paper, observations indicate that coronal holes generally have brightness temperatures not very much different from the quiet Sun level at mm wavelengths. They often appear asLTRs with local enhancements of microwave radiation above the quiet Sun level (HTRs) inside themselves. The measured brightness temperature inside the observed equatorial coronal hole is up to 6% higher than the quiet Sun level. Further, the equatorial coronal hole is on the average brighter in microwaves than the polar coronal holes. This is very probably due to the presence of stronger magnetic fields measured inside the equatorial coronal hole in agreement with the study by Gopalswamy et al. (1999).

The chromospheric plages could contribute to enhanced emission in mi-
crowaves, due to locally higher chromospheric temperature. However, within the borders of the three analysed coronal holes, no distinct chromospheric plages in Hα were observed.

To interpret the visibility of coronal holes in microwaves we have developed theoretical models of the thermal bremsstrahlung radiation originating in the solar chromosphere, transition region and corona for the quiet Sun and coronal holes (Brajša et al., 2007). We have found that the most important contribution to the microwave brightness temperature variation comes from density changes in the transition region and low corona, i.e. at the altitudes where the temperature is below 1 million K. This can explain both the LTRs and HTRs associated with coronal holes (Brajša et al., 2007). According to the models presented in that paper, the brightness temperature of the coronal hole region at 37 GHz amounts to 7841 K. This corresponds roughly to the estimated quiet Sun level of the microwave full-disc solar images recorded at the Metsähovi Radio Observatory at that frequency, \( T_b = 7800 \) K (e.g., Urpo et al., 1994). It is in a good agreement with the observations which indicate that the average background radiation of coronal holes does not depart much from the quiet Sun level. According to our models, the differences in brightness temperature between the coronal hole regions and non-hole quiet Sun areas amount to 73 – 510 K (0.9 – 6.5 %).

The He I 1083 nm line is formed by electron transitions between the two lowest energy levels of orthohelium, i.e., the triplet state of the helium atom. The lowest state of orthohelium is metastable, since the transitions from the triplet states to singlet states (parahelium) are forbidden. So, the lowest state of the orthohelium is acting as a "ground level" for the 1083 nm line. To have the He I 1083 nm absorption, an electron must be in the lowest state of the orthohelium. This state can be populated in two ways. The first is the photoionisation by UV and EUV radiation from the corona and subsequent cascading back, called the photoionisation-recombination (PR) mechanism. The other possibility is the direct excitation by collisions from the ground state of parahelium. The PR mechanism is effective only in regions with temperatures less than 10000 K, while the collisions become important at temperatures higher than 20000 K. Further details can be found in papers by e.g., Brajša et al. (1996), Andreotta and Jones (1997) and Vršnak et al. (2002), although the role of different processes in the solar chromosphere, transition region, and corona in the excitation of the neutral He atoms is still not fully resolved.
The He I 1083 nm line absorption was suppressed in the equatorial coronal hole, although in the microwaves a local peak in emission occurred there. This is consistent with the increased density in the transition region, i.e., at the altitudes where the temperature is below 1 million K. The increased density in the transition region and low corona is the most important contribution to the microwave brightness temperature. The material is however not visible in SXR observed by Yohkoh-SXT and does not produce much He I absorption, which can be explained by the above mentioned PR mechanism, i.e., by it’s reduced effectivity in coronal holes.

Finally, we have also found an association of a coronal bright point, observed in SXR, and a He I 1083 nm dark point, measured as local pronounced absorption in the He I 1083 line, in agreement with Golub et al. (1989) and Harvey-Angle (1993).

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