HELIUM 10830 Å MEASUREMENTS OF THE SUN

R. BRAJŠA

Hvar Observatory, Faculty of Geodesy, University of Zagreb, Kačićeva 26,
HR-10 000 Zagreb, Croatia

S. POHJOLAINEN

Metsähovi Radio Research Station, Helsinki University of Technology, Otakaari 5A, 02150 Espoo,
Finland

V. RUŽDJAK

Hvar Observatory, Faculty of Geodesy, University of Zagreb, Kačićeva 26,
HR-10 000 Zagreb, Croatia

T. SAKURAI

Solar Physics Division, National Astronomical Observatory, Mitaka, Tokyo 181, Japan

S. URPO

Metsähovi Radio Research Station, Helsinki University of Technology, Otakaari 5A, 02150 Espoo,
Finland

B. VRŠNAK

Hvar Observatory, Faculty of Geodesy, University of Zagreb, Kačićeva 26,
HR-10 000 Zagreb, Croatia

and

H. WÖHL

Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, D-79104 Freiburg, Germany

Abstract. Measurements of the Sun in the near-infrared He I 10830 Å absorption line were performed using the echelle spectrograph with a dispersion of 6.71 mÅ per pixel at the Vacuum Tower Telescope (German Solar Telescopes, Teide Observatory, Izaña, Tenerife, Spain) on May 26, 1993. These measurements were compared with full-disc soft X-ray images of the Sun (Japanese solar satellite *Yohkoh*), full-disc solar images in Hα (Big Bear Solar Observatory), full-disc solar images in the He I 10830 Å line (National Solar Observatory, Kitt Peak) and with full-disc microwave solar maps at 37 GHz (Metsähovi Radio Research Station). In the He 10830 Å line the Sun displays a limb darkening similar to that in the visible part of the spectrum. Active regions and Hα filaments show a strong absorption in the He 10830 Å line, whereas the absorption is weak in coronal holes.

1. Introduction

The He I 10830 Å line is observed in emission outside the solar disc close to the limb, and in absorption on the disc (Mohler and Goldberg, 1956; Shcherbakov and Shcherbakova, 1991). However, under special conditions occuring during solar flares, the line can be seen in emission on the disc too (Zirin, 1992a). The He 10830 Å absorption line is weak in filament channels, but the filaments themselves show pronounced absorption. The helium absorption is enhanced above active regions, and reduced in coronal holes. Significant spatial and temporal vari-

ations of the line intensity on the disc were recorded on small scales (Fleck *et al.*, 1994), as well as on large scales (Harvey and Livingston, 1994).

The neutral helium atom (He I) emits/absorbs two sets of lines: the triplet series (orthohelium) and the singlet system (parahelium). The quantum selection rules forbid the transitions between triplet and singlet series, except in the case when collisional excitation/de-excitation are dominant. The orthohelium shows a fine structure, since the two electron spins are parallel, and the total spin equals unity, contrary to the parahelium with no fine structure, where the two spins are antiparallel and the tolal spin is zero. The He 10830 Å line originates in a transition between the two lowest metastable energy levels of orthohelium. The lowest metastable level of orthohelium behaves as a kind of a ground level for the triplet series, and can be populated in two ways, either by photoionization followed by a cascade to this level, or collisionally from the ground state of parahelium. The laboratory wavelengths of the He 10830 Å triplet are 10830.341 Å, 10830.250 Å, and 10829.081 Å respectively, where the first two components are so close together that they coalesce into the single, main line with a relative intensity 8 times stronger that the third component, which appears as a satellite line, 1.2 Å from the main line (de Jager, Namba, and Neven, 1966).

2. Observations, Data, and Reduction Procedures

The measurements of the intensity of the near infrared He 10830 Å absorption line were performed using the echelle spectrograph at the Vacuum Tower Telescope (VTT), German Solar Telescopes, in Izaña, Tenerife, Canary Islands, Spain, on May 26, 1993. Intensities of the helium line were recorded by a CCD camera and stored on an EXABYTE tape. A part of the solar spectrum around the helium line was taken every 4 s with an exposure time of 1 s. Binning of 2×2 was applied with the CCD camera, yielding an array of 512×512 pixels. The measurements on the solar equator and up to northern medium latitudes were performed in the east–west direction of the sky, defining velocity components in a rectangular system with one axis parallel to the celestial meridian. The scans were performed at about noon and in the afternoon during moderate weather conditions. The main observing parameters are given in Table I, where the dispersion refers to the number of pixels after the applied binning in the CCD camera, and the red filter mentioned in Table I transmits wavelengths longer than 7000 Å. Five solar scans of May 26, 1993 are presented in total in this work (Figures 1 and 2). The neighboring scans are displaced by 80″, which corresponds to the length of the spectrograph slit, so that the scanned stripes just touch each other, and subsequent scans were performed north from the solar equator (upper in Figure 2) respectively to the previous ones.

Each scan across the Sun performed with the VTT lasted for 50 min and contains 750 images, and each image represents a two-dimensional part of the spectrum whose dimensions are 80″ × 3.44 Å. The data reduction was performed on SUN

TABLE I

Parameters of the He 10830 Å line measurements of the Sun at the VTT, May 26, 1993

Width of the spectrograph slit	150 μm equals to 0.83″
Length of the spectrograph slit	80″
Exposure time	1 s
Scanning speed	1″ s^{-1}
Dispersion	6.71 mÅ pixel^{-1}
Spectral resolution	$\Delta\lambda = 16$ mÅ
Order separating filter at predisperser	red, RG 665, $\lambda > 7000$ Å
Spectral order	21
Binning in the CCD	2 × 2 yielding 512 × 512 pixels
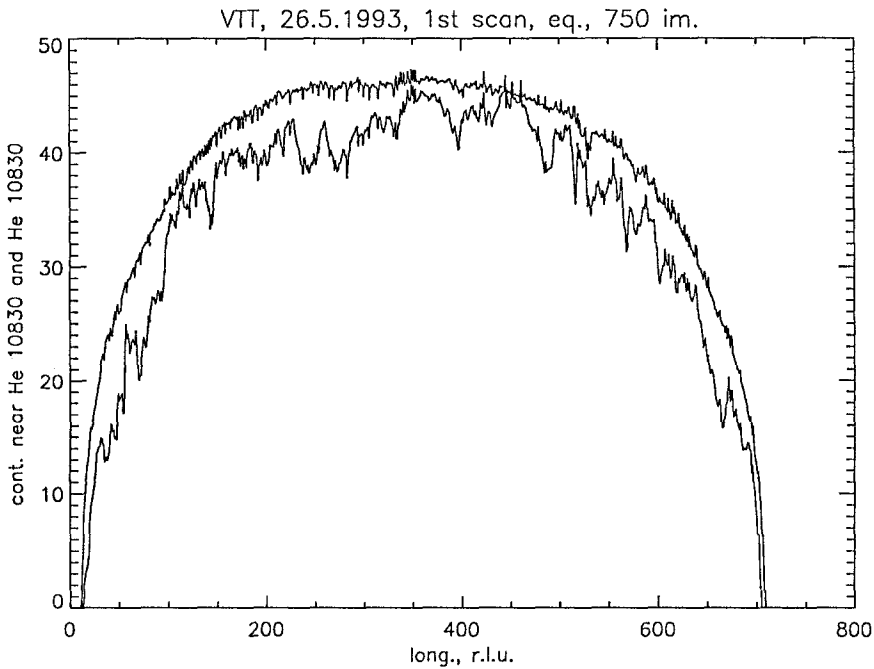
Fig. 1a.

workstations using codes written in the Interactive Data Language (IDL), and the first step was an averaging of all relative intensity recordings in the pixels along the slit. So, the noise was significantly reduced, and the He 10830 Å absorption line, which is generally of low intensity, was clearly detectable. Applying this procedure, small-scale (smaller than the length of the spectrograph slit of 80″) spatial changes of the He 10830 Å absorption line were averaged, allowing the
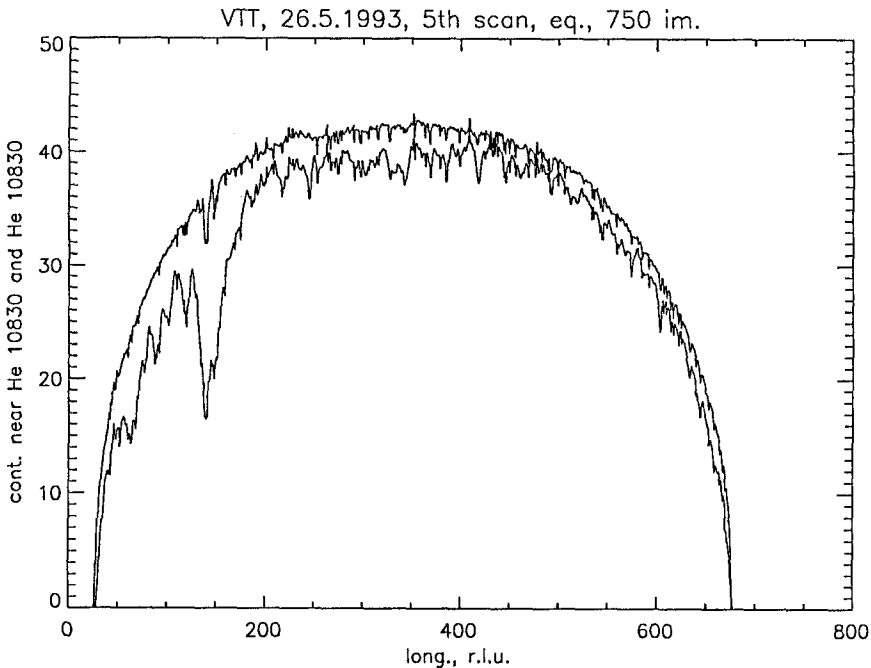
Fig. 1b.

Fig. 1a–b.   (a) The first solar scan performed on May 26, 1993 (the starting time was 11:05 UT) at the VTT along the line indicated in Figure 3. On the x-axis, the ordinal number of the exposure is indicated as being proportional to the position on the line of Figure 3. The scanning was performed from east (*left*) to west, so that the zero of the x-axis (where relative length units, r.l.u., are indicated and 1 r.l.u. equals 4 arc sec) of this frame is in the vicinity of the lower left corner of Figure 3, at the starting point of the line. On the y-axis are relative intensity units; the upper curve represents a part of the quasi-continuum near the He 10830 Å line, and the lower curve represents the He 10830 Å line. Each data point in this frame represents an exposure after averaging the measured data along the spectrograph 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). (b) The same as (a), but for the fifth scan of May 26, 1993, which started at 15:11 UT. This scan was performed along the line parallel to the line indicated in Figure 3, and is displaced north 320″ from the line indicated in Figure 3.

investigation of large-scale changes. As a measure of absorption, the sum of all relative intensities in the line divided by the number of data points was used. It can be assumed that the wavelength of the line does not change significantly during one scan. Indeed, the solar rotation causes a Doppler shift of the line amounting to 72 mÅ between slit positions near the centre of the solar disc and at the limb in the equatorial region, which is approximately 10 times smaller than the full width at half maximum intensity of the line. Hence, the 'borders' of the integration were fixed for one scan. The relative intensity of the helium line was compared with the intensity of the quasi-continuum located between the He 10830 Å line and the telluric H_2O 10832.1 Å line.
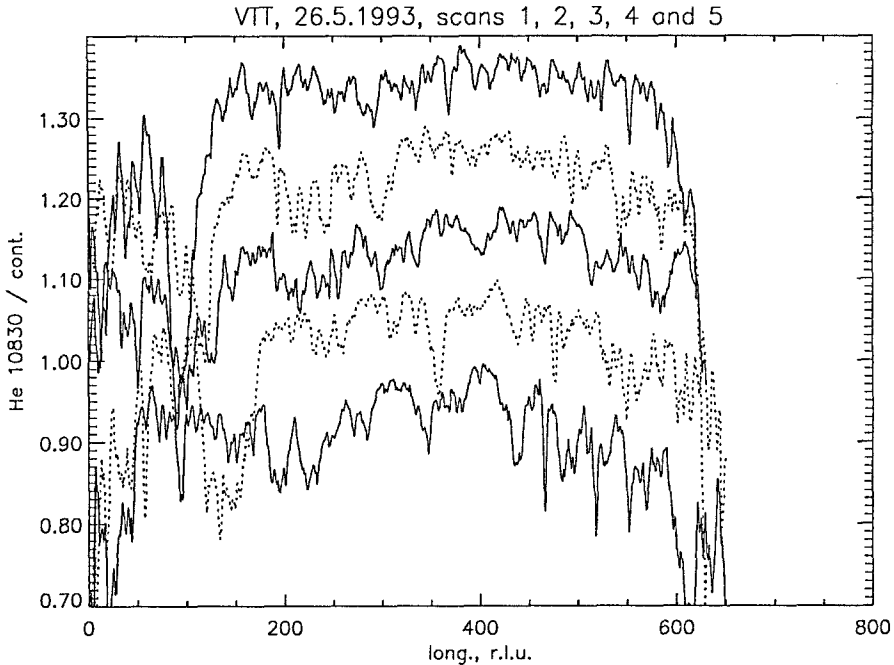
Fig. 2. Relative He 10830 Å line intensity divided by the relative intensity of the nearby quasi-continuum, for five solar scans of May 26, 1993. The start times of these scans were: 11:05 UT, 12:23 UT, 13:26 UT, 14:19 UT, and 15:11 UT, from the bottom to the top, and from the equatorial region to the north on the Sun. Minima in the plots represent a strong helium absorption and maxima a weak one. The scale on the y-axis represents the ratio of relative intensities for the first lower scan, and subsequent ratios are displaced in the y-direction by 0.1 relative units.

For comparison, the full-disc solar maps in Hα (Big Bear Solar Observatory – BBSO) and in the He 10830 Å line (National Solar Observatory, Kitt Peak – NSO/KP) were used. In the Hα case, the size of the image amounts to 512×481, or 640×481 pixels, and in the He-line case to 512×512 pixels. Full-disc He I 10830 Å spectroheliograms have been taken by NSO/KP since 1974 on a daily basis, using a 512-channel magnetograph (Harvey, 1994). These observations consist of four 512-arc-sec-wide scans of the solar image across the entrance slit of the spectrograph. It takes approximately 40 min to make these scans (Harvey and Livingston, 1994). The new NASA/NSO spectromagnetograph at the NSO/KP was described by Jones (1992) and by Jones *et al.* (1992). In addition, full-disc solar images at the wavelength of about 20 Å taken through the Al/Mg filter with the soft X-ray telescope on the Japanese solar satellite *Yohkoh* were analysed. The *Yohkoh* soft X-ray telescope was described by Tsuneta *et al.* (1991). It is sensitive in a band of wavelengths between 2 and 70 Å, full-disc solar images are taken daily, and the pixel size is 4.9″. All these data were transferred to the Kiepenheuer-Institute by the File Transfer Protocol (FTP), where full-disc solar images were produced using various IDL programs. The He I 10830 Å data from NSO/KP can be visualized in various
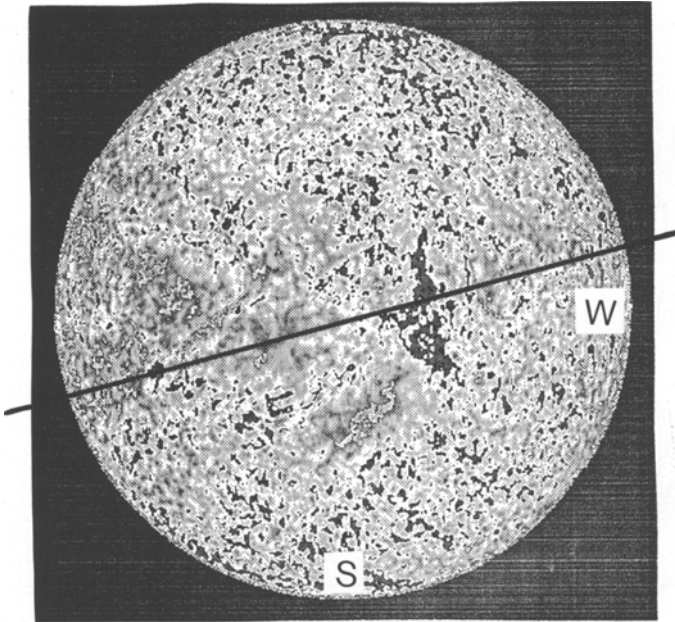
Fig. 3.   In this full-disc solar image, which was obtained at NSO/KP on May 26, 1993, the areas of strong He 10830 Å line absorption are shown gray and the areas of weak absorption, black. The solar equator is parallel to the x-axis of the frame, and north is up. The line across the solar disc indicates the scan explained in the caption of Figure 1(a).

representations. Here, we have used a representation described in the caption of Figure 3. The full-disc solar maps at 37 GHz (Urpo, Pohjolainen and Teräsranta, 1994), obtained by the 14-m radio telescope of the Metsähovi Radio Research Station (MRRS), were also compared with our He 10830 Å line measurements.

3. Results

The centre-to-limb function in the near-infrared region of the solar spectrum (two examples are shown in Figures 1(a) and 1(b), representing the 1st and the 5th solar scan) resembles the one in the visible part, showing a limb darkening. Figure 1(a) is based on a solar scan (VTT) in the vicinity of the He 10830 Å line, along the line shown in Figure 3, where a full-disc solar image in He 10830 Å (NSO/KP) is presented. This scan started on May 26, 1993, 11:05 UT at the VTT and lasted for 50 min. Since the scans were performed in the direction parallel to the celestial equator (i.e., in the Earth's coordinate system) from the east toward the west, the direction of scanning is not parallel to the solar equator (which is parallel to the x-axis of Figure 3). In Figure 1 the minima of the lower curve represent strong helium line absorption and the maxima represent weak absorption. In Figure 3 the

TABLE II

A short description of the observed phenomenology on the solar disc:
λ – wavelength; LTR (HTR) – low (high) brightness temperature region

Solar structure \ λ:	8 mm	He 10830 Å line	20 Å
Hα filament	LTR	strong absorption	–
Active region	HTR	strong absorption	emission
Coronal hole	LTR (HTR)	weak absorption	no emission

areas of strong He 10830 Å line absorption are shown gray and the areas of weak
absorption, black. It can be seen that our scans performed at the VTT reproduce
a part of the full-disc solar image (NSO/KP) in detail. Indeed, the maxima of the
He-intensities from Figure 1(a) correspond to black areas on, or in the vicinity of,
the line of Figure 3 indicating the regions of weak helium line absorption. On the
other hand, the minima correspond to gray regions in Figure 3, indicating strong
helium line absorption. The results of subsequent solar scans are shown in Figure 2,
together with the result of the first scan, as quotients of the He 10830 Å line and
the nearby quasi-continuum intensities. In this way the lower curve of Figure 2
was derived as the quotient of the two plots presented in Figure 1(a), representing
the first scan, and subsequent upper plots as the same quotients for other scans
performed north of the solar equator. Again, the minima of these curves represent
strong helium line absorption and the maxima weak helium line absorption. Since
in our measurements the ratio of relative intensities in the helium line and in the
nearby quasi-continuum was always lower than one, and in one case just equal to
one, the He 10830 Å line was not detected in emission on the solar disc.

Full-disc solar images in soft X-rays (*Yohkoh*), in Hα (BBSO), and in microwaves
(MRRS), for the day when the VTT measurements were performed, are presented
in Figures 4, 5, and 6, respectively. In Figure 4, a large equatorial coronal hole can
be seen, being also clearly detectable in the helium 10830 Å data from NSO/KP
(as the black area in Figure 3) and in the VTT registrations (the northern part of
the hole is cospatial with maxima in the scans of Figure 2). A comparison of the
He 10830 Å scans (VTT, Figure 2) with the Hα image (BBSO, Figure 5) reveals
that all filaments seen in the VTT spectrograph show strong absorption in the
helium line. Active regions, seen as bright areas in Figures 4 and 5, show also
pronounced He 10830 Å line absorption. The equatorial coronal hole detected in
the He 10830 Å line (Figures 2 and 3) and in soft X-rays (Figure 4) can also be
identified in microwaves (Figure 6). The coronal hole is characterized as a region
of lower microwave brightness temperature than the quiet-Sun level, spatially con-
nected with the north polar cap coronal hole. However, we have to point out an
enhancement of microwave radiation registered inside the north polar cap coronal
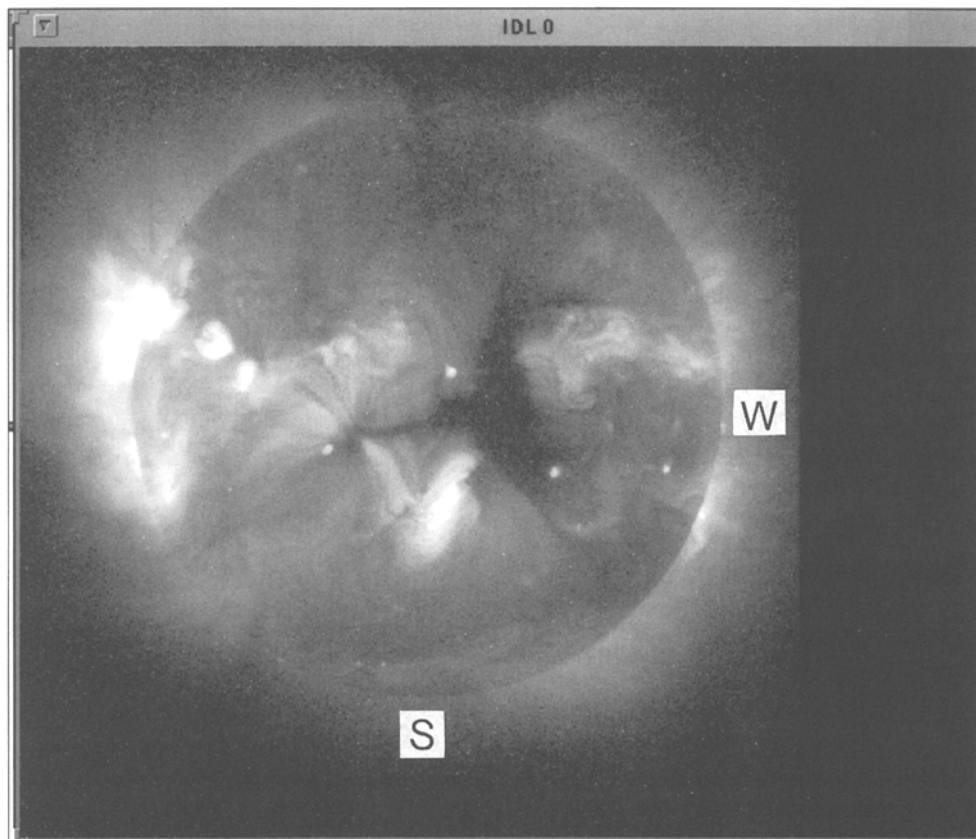hole (Figure 6).

Fig. 4.   Soft X-ray full-disc solar image at a wavelength of about 20 Å from the Japanese solar satellite *Yohkoh* taken on May 26, 1993, through the AlMg filter. The solar equator is parallel to the x-axis of the frame, with north up.

Although temporal and spatial variations are always present, the permanent characteristics of the observed features on the solar disc are given in Table II, presented in a preliminary form by Sakurai *et al.* (1994). Coronal holes can be noted in microwaves as low-temperature regions, which sometimes have a high-temperature region inside, as was the case in the north polar cap coronal hole mentioned above (Figure 6). This local enhancement of microwave radiation is cospatial with locations of a somewhat stronger helium 10830 Å line absorption (although weaker than in active regions and filaments), seen as white-gray regions on the full-disc He 10830 Å solar image in Figure 3.

4. Discussion

Let us first consider the reduction method of the He 10830 Å data (VTT) applied in this work. Similar to the method which is used for reduction of the NSO/KP
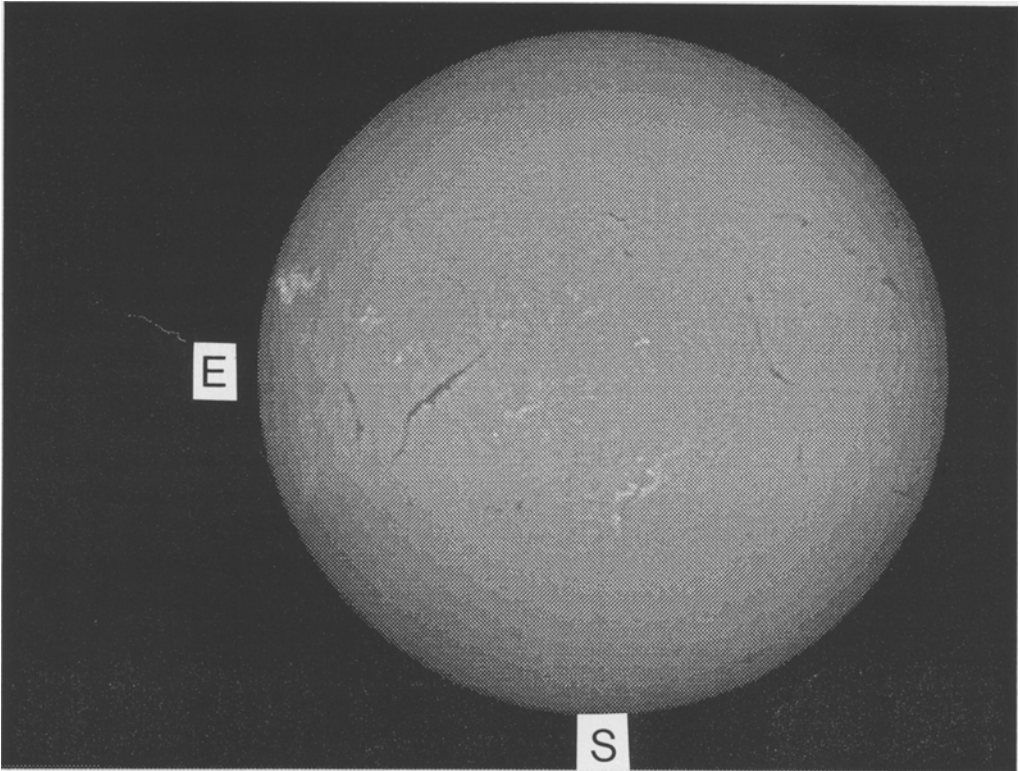
Fig. 5. Hα full-disc solar image from the BBSO taken on May 26, 1993. The solar equator is parallel to the x-axis of the frame and north is up.

He 10830 Å data (Harvey and Livingston, 1994), relative intensities in two spectral windows (in the line and in the nearby quasi-continuum) are measured. Contrary to the NSO/KP method, here the two windows were not equal in wavelength interval, and the final signal was calculated as a ratio of the two average values of relative intensity. The small-scale changes of the helium line, on scales smaller than the length of the spectrograph slit of $80''$, were averaged out in the present method. An example of changes of the line on smaller spatial scales than $80''$ is presented by Fleck *et al.* (1994), where in their Figure 1 changes between 0.93 and 0.98 of the line-to-continuum ratio were reported. In the present paper we are interested in the large-scale changes of the line, so that the small-scale changes were neglected.

In the He 10830 Å line and in the nearby quasi-continuum (Figure 1) the Sun shows a limb darkening similar to that in the visible part of the spectrum. It is well known that the curve of the centre-to-limb darkening becomes more and more flat as the wavelength increases from the visible to the infrared part of the spectrum, and for the 12 μm lines there is even a limb brightening (Zirin, 1992b). In the microwave part of the solar spectrum, either no significant centre-to-limb variations, or a limb
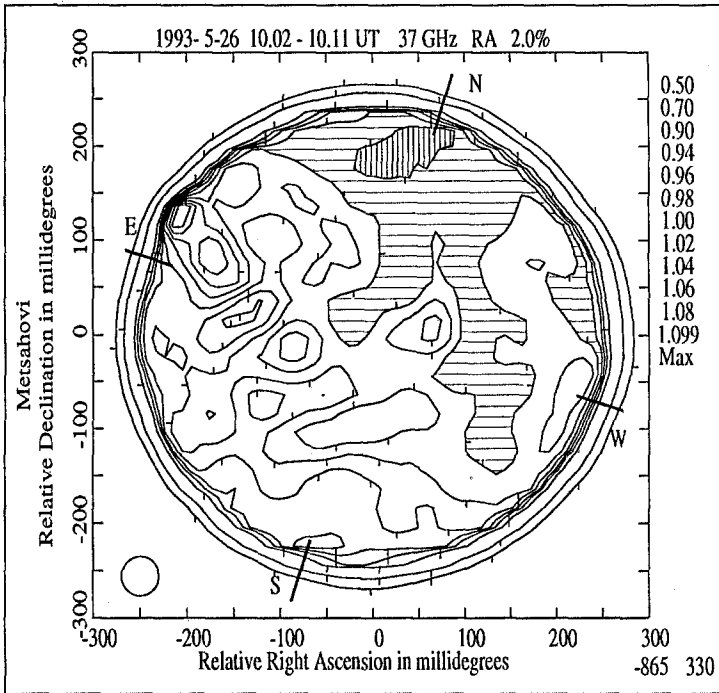
Fig. 6. Full-disc microwave solar image from the MRRS taken on May 26, 1993 at a frequency of 37 GHz. The solar axis and equator are indicated, as well as the scanning time (start and end time, above the image). The contours represent the iso-lines of the same brightness temperature, where a hatch inside a contour indicates a lower brightness temperature than the quiet-Sun level, and a hatch outside a contour a higher brightness temperature than the quiet-Sun level. The low brightness temperature microwave region related to the coronal hole in the northern hemisphere is indicated with horizontal hatching, whereas the local enhancement of microwave emission is denoted by vertical hatching.

brightening were observed, and the results are strongly dependent on the frequency (Brajša *et al.*, 1994).

The general appearance of coronal holes in microwaves is a region of lower brightness temperature, but slight enhancements of microwave radiation above the quiet-Sun level can be found inside such regions (Table III). Such an indication was also found in the present work (Figure 6). The temperature and density in coronal holes are depressed, leading to supressed emission in microwaves. However, at millimeter wavelengths, it is possible that weak depressions are easily counterbalanced or overcome by enhanced radio emission from the chromosphere, especially in regions of white-light faculae and/or intense magnetic fields (Kosugi, Ishiguro, and Shibasaki, 1986). So, in addition to the thermal bremsstrahlung, which is the dominant source of the quiet-Sun emission in microwaves (this emission

TABLE III

Coronal holes registered at centimeter and millimeter radio wavelengths: λ – wavelength; ν – frequency; T_B – brightness temperature; 'L' and 'H' stand for lower and higher brightness temperature relative to the quiet-Sun level

λ (mm)	ν (GHz)	T_B	Reference
80–320	3.8–0.9	L	Borovik and Kurbanov (1990)
63	4.8	L, H	Habbal and Gonzalez (1991)
28	10.7	L	Hirth und Fürst (1976)
8.3	36	L, H	Kosugi, Ishiguro, and Shibasaki (1986)
8.2	37	L, H	present work

is supressed in coronal holes), other radiation mechanisms, connected to faculae and magnetic fields possibly located inside the holes, should also be taken into account.

The lowest metastable energy levels of orthohelium are populated rather poorly in the solar photosphere. Therefore, the absorption occurs in chromospheric regions with low density and high temperature (Shcherbakov and Shcherbakova, 1991). The He 10830 Å absorption line is very shallow in coronal holes, since the population of the quasi-ground level for the absorption is at least in part dependent on the coronal back radiation, which is reduced in coronal holes. However, the coronal influences are rather subtle and helium images of the Sun are, in fact, excellent images of the chromosphere (Harvey and Livingston, 1994). The coronal line radiation is assumed to penetrate inward into the upper chromosphere, causing sufficient helium ionization to populate the lower level of the He I 10830 Å line, resulting in an optically thin absorption of the photospheric continuum at 10830 Å. The amount of absorption, which is proportional to the optical thickness of the upper chromosphere in the 10830 Å line, depends on the strength of the coronal lines at wavelengths in the He I 504 Å ionizing continuum, and on the density and geometrical thickness of the upper chromosphere (Avrett, Fontenla, and Loeser, 1994). The optical thickness of the line was also discussed by Ruedi, Solanki, and Livingston (1994), who stated that this He I line is in general optically thin, or at the most marginally optically thick.

Similar to the microwave radiation in the millimetric wavelength range (Brajša, 1993), the helium 10830 Å line originates at a height of about 2000 km above the photosphere. The calculated off-limb He 10830 Å line intesity distribution shows a minimum in the low chromosphere and a maximum at roughly 2000 km above the photosphere, in general agreement with observations (Avrett, Fontenla, and Loeser, 1994). On the basis of limb observations of the He 10830 Å line, Schmidt, Knölker, and Westendorp-Plaza (1994) found the maximum of the emission at 2400 km.

5. Conclusion

The He 10830 Å line is a very important indicator of the solar chromosphere and corona. In most circumstances this line is seen in absorption on the solar disc. In the present paper, large-scale spatial changes of the helium line intensity were studied (Figures 1 and 2), revealing a strong He 10830 Å line absorption at active regions and Hα filaments, and a weak He 10830 Å line absorption in coronal holes. Limb darkening was detected in the He 10830 Å line, as well as in the nearby quasi-continuum (Figure 1). A comparison of our He 10830 Å line recordings with full-disc solar images in various parts of the spectrum (Figures 3–6) depict the phenomenology presented in Table II. In this context, the detectability of coronal holes deserves special attention. Although the positions of coronal holes can be uniquely determined only by soft X-ray measurements, the He 10830 Å line and microwave (37 GHz) recordings, combined with Hα and magnetographic data, can provide information about coronal hole positions obtained from the ground.

References

Avrett, E. H., Fontenla, J. M., and Loeser, 1994, in D. M. Rabin *et al.* (eds.), 'Infrared Solar Physics', *IAU Symp.* **154**, 35.

Borovik, V. N. and Kurbanov, M. Sh.: 1990, *Astron. Nachr.* **311**, 371.

Brajša, R.: 1993, *Solar Phys.* **144**, 199.

Brajša, R., Ruždjak, V., Vršnak, B., Pohjolainen, S., Urpo, S., and Wöhl, H.: 1994, *Hvar Obs. Bull.* **18**, 9.

de Jager, C., Namba, O., and Neven, L.: 1966, *Bull. Astron. Inst. Netherlands* **18**, 128.

Fleck, D., Deubner, F.-L., Maier, D., and Schmidt, W.: 1994, in D. M. Rabin *et al.*, 'Infrared Solar Physics', *IAU Symp.* **154**, 65.

Habbal, S. R. and Gonzalez, R. D.: 1991, *Astrophys. J.* **376**, L25.

Harvey, K. L.: 1994, in D. M. Rabin *et al.* (eds.), 'Infrared Solar Physics', *IAU Symp.* **154**, 71.

Harvey, J. W. and Livingston, W. C.: 1994, in D. M. Rabin *et al.* (eds.), 'Infrared Solar Physics', *IAU Symp.* **154**, 59.

Hirth, W. and Fürst, E.: 1976, *Mitt. Astron. Ges.* **38**, 208.

Jones, H. P.: 1992, in K. L. Harvey (ed.), 'The Solar Cycle', *The NSO/Sac. Peak 12th Summer Workshop, ASP Conf. Ser.* **27**, 315.

Jones, H. P., Duvall, T. L., Jr., Harvey, J. W., Mahaffey, C. T., Schwitters, J. D., and Simmons, J. E.: 1992, *Solar Phys.* **139**, 211.

Kosugi, T., Ishiguro, M., and Shibasaki, K.: 1986, *Publ. Astron. Soc. Japan* **38**, 1.

Mohler, O. C. and Goldberg, L.: 1956, *Astrophys. J.* **124**, 13.

Rüedi, I., Solanki, S. K., and Livingston, W. C.: 1994, in M. Schüssler and W. Schmidt (eds.), *Solar Magnetic Fields*, Cambridge University Press, Cambridge, p. 363.

Sakurai, T., Wöhl, H., Brajša, R., Pohjolainen, S., Ruždjak, V., Urpo, S., Vršnak, B., and Ichimoto, K.: 1994, in J. Manninen and L. Kalliopuska (eds.), *Vth COSPAR Meeting of the Finnish Space Scientists*, University of Oulu, Department of Physics, Report 124, p. 53.

Schmidt, W., Knölker, M., and Westendorp-Plaza, C.: 1994, *Astron. Astrophys.* **287**, 229.

Shcherbakov, A. G. and Shcherbakova, Z. A.: 1991, in I. Tuominen, D. Moss, and G. Rüdiger (eds.), 'The Sun and Cool Stars: Activity, Magnetism, Dynamos', *IAU Colloq.* **130**, *Lecture Notes in Physics* **380**, 252, Springer-Verlag, Berlin.

Tsuneta, S., Acton, L., Bruner, M., Lemen, J., Brown, W., Caravalho, R., Catura, R., Freeland, S., Jurchevich, B., Morrison, M., Ogawara, Y., Hirayama, T., and Owens, J.: 1991, *Solar Phys.* **136**, 37.

Urpo, S., Pohjolainen, S., and Teräsranta, H.: 1994, *Solar Observations at Metsähovi in 1993*, Helsinki University of Technology, Metsähovi Radio Research Station, Series A, Report 16.

Zirin, H.: 1992a, in J. T. Schmelz and J. C. Brown (eds.), 'The Sun: a Laboratory for Astrophysics', *NATO ASI Ser.* **C373**, Kluwer Academic Publishers, Dordrecht, Holland, p. 449.

Zirin, H.: 1992b, in J. T. Schmelz and J. C. Brown (eds.), 'The Sun: a Laboratory for Astrophysics', *NATO ASI Ser.* **C373**, Kluwer Academic Publishers, Dordrecht, Holland, p. 175.