INVESTIGATION OF He I 10 830 Å 'DARK POINTS' AT THE SAYAN SOLAR OBSERVATORY AND THE BAIKAL ASTROPHYSICAL OBSERVATORY

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Abstract. A new two-bandpass birefringent filter has been produced at ISTP, Irkutsk for the investigation of the fine structure of the chromosphere. One filter passband is centered on the He I 10 830 Å line, the second one is centered on Hα. The FWHM of the He I 10 830 Å passband is 0.46 Å and of the Hα passband is 0.3 Å. A large number of filtergrams were obtained with the filter at the Sayan observatory. At the same time, spectral observations with high spatial and spectral resolution were carried out by the large solar vacuum telescope at the Baikal Observatory. We selected 29 'dark point' spectra with sizes from $2''$ to $13''$, as well as 'dark points' on the filtergrams. Comparison of spectrograms and filtergrams has shown a good agreement of their size and intensity in relation with the surrounding chromosphere as well as the absence of primary line-of-sight velocities in both observation types. From spectral observations, the depth of 10 830 Å is over 30% for some 'dark points', and the FWHM is more than 1 Å. He I 10 830 Å line profiles in 'dark points' are more deep and wide than in quiet regions. The optical depth of the chromosphere in 'dark points' is estimated. Comparison with the unperturbed chromosphere showed that 'dark points' in He I 10 830 Å are more optically thin than the nearby chromosphere.

1. Introduction

Infrared observations in the solar astrophysics have become more and more urgent, because they open absolutely new prospects. The He I 10 830 Å line is the most interesting line triplet of neutral helium that allows us to research the physical characteristics of the upper chromosphere and the transition region between the chromosphere and corona. It is possible to expect that monochromatic observations of the Sun in the 10 830 Å line will result in similar breakthroughs for understanding the upper layer solar atmosphere nature as they have been made with birefringent filters (BF) using the Hα line.

In 1998, a two-bandpass BF made by ISTP was put into operation (Kushtal and Skomorovsky, 1998). The filter allows to get an image of the Sun in both the He I 10 830 Å and Hα lines. In summer 1998 the first observations by using this filter were obtained using the non-eclipse solar coronagraph at the Sayan solar observatory.

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About 400 filtergrams of active regions, the quiet chromosphere near the equator and at the poles, prominence and flares in both the He I 10 830 Å and Hα lines were obtained. The fine structures of the solar chromosphere at the level of the line formation and their comparison with chromosphere structure in He I 10 830 Å and Hα were prioritized. It was also important for observers to test new equipment for solar fine structure investigation. In particular, we investigated 'dark points' in the line He I 10 830 Å. They are often associated with bright points in X-rays and in C IV. Hypothetically, they are the result of local magnetic field reconnection (Golub *et al.*, 1977; Sheeley and Harvey, 1977; Harvey, Tang, and Gaizauskas, 1986; Porter *et al.*, 1986).

Investigation of 'dark points' by using filtergrams and spectroheliograms are widely presented in the literature, (for example, Golub *et al.*, 1977; Sheeley and Harvey, 1977; McCabe and Mickey, 1981; Harvey, Tang, and Gaizauskas, 1986; Porter *et al.*, 1986; Ikhsanov and Parfinenko, 1987; Parfinenko, 1989; Parfinenko and Parfinenko, 1990; Harvey *et al.*, 1997). These investigations describe in detail the morphological feature of 'dark points', their relationship with bright points and associations with magnetic bipole fields. Many publications are devoted to the He I 10 830 Å line profile investigation in the quiet chromosphere, active regions, coronal holes, also the Sun as a star (Giovanelli and Hall, 1977; Shcherbakova *et al.*, 1983; Shcherbakov and Shcherbakova, 1983; You Jian-qi *et al.*, 1989; Bukach *et al.*, 1990; Levkovsky, Papushev, and Salakhutdinov, 1994; Singh, Jain, and Venkatakrishnan, 1994; Brajša *et al.*, 1996; Dupree, Penn, and Jones, 1996; Kozlova *et al.*, 1996; Shcherbakov *et al.*, 1996; Muglach, 1997; Penn and Allen, 1997; Somov and Kozlova, 1998). At the same time, we have found only one publication (Li Hui, Fan Zhongyu, and You Jianqi, 1996) in which the He I 10 830 Å line profiles of 'dark points' were researched. So at the same time the 'dark point' investigation by means of BF at the Sayan observatory as well as the spectral observations of 'dark points' in He I 10 830 Å lines using the large solar vacuum telescope at the Baikal Observatory were conducted. About 300 spectrograms with the help of a CCD-camera were obtained.

Unfortunately the weather conditions were different, because of the remoteness of the two observatories (about 400 km). Therefore, we had no possibilities for simultaneous observations of the same 'dark points'. However, this did not prevent us from getting some peculiarities and also estimating physical parameters of 'dark points' (DPs) in the He I 10 830 Å line.

In Section 2 we present a brief description of the new birefringent filter and give observational results obtained with its help. In Section 3 features of the He I 10 830 Å line profiles are presented on the basis of spectral data. Information about DP obtained by filtergrams and spectrograms is summarized in Section 4.

2. DP Observation by Means of BF

The birefringent filter with two passbands is developed and manufactured in ISTP for solar atmosphere investigation. The crystal filter plates of optical calcite are collected in four wide-angle splitted regulated elements and one wide-angle unregulated element. One of the bands is centered on the He I 10 830 Å line. The band halfwidth is 0.46 Å, shift along the spectrum ± 2 Å , angular field ± 1.17°. For the second band, centered on Hα, these parameters are 0.3 Å, ± 0.9 Å, ± 0.9° respectively. We use as polarizers efficient in both wave lengths birefringent prisms of calcite glass. The half-wave and quarter-wave plates of the tunable elements have a high interference order that allows a proper phase-shift value in both bands and eliminates a need for superachromatic plates. A band separation system allows carrying out simultaneous observations in both lines.

The solar image was recorded with the help of a 512 × 512 CCD camera. Average exposure in He I 10 830 Å is 0.4 s on the disk and 1–1.2 s for prominences and it is 0.1–0.2 s in the Hα line. The image scale is 0.4″ pixel^{-1}. For chosen solar regions with size 200″ × 200″ temporal image series were registered in the center and wings of He I 10 830 Å and Hα lines with a step of 0.2 Å to ± 0.6 Å from the line center.

On our filtergrams we considered DPs, i.e., localized darkening with time parameters corresponding to Harvey’s definition (Harvey, Tang, and Gaizauskas, 1986). To separate such structures from longer lived plages which also appear in He I 10 830 Å as localized darkening, we had compared He I and Hα filtergrams. We eliminated from the consideration small dark structures in He I corresponding to Hα plage. Thus six image series were chosen in the He I 10 830 Å and Hα line. In each series, we obtained images in the center and wings of lines, and the interval between images was 15–20 s.

The characteristic size of DP on the filtergram is mainly 12–16″ which agrees with results of Harvey, Tang, and Gaizauskas (1986). But on the filtergrams of the northern polar region He I 10 830 Å DP size is 8–10″ after correction for the projection effect. We found that the DP’s intensity relative to the intensity of the surrounding atmosphere was about 0.67. In the northern polar region this ratio reached approximately 0.9.

On most filtergrams we did not note an intensity asymmetry of DPs in blue and red wings of the He I 10 830 Å line. Only in one case we observed a blue asymmetry of 0.2 Å and in one a red asymmetry of 0.2 Å.

According to Harvey, Tang, and Gaizauskas (1986), DPs have a characteristic lifetime of 10–30 min or several hours. In the second case they can show large intensity variations. Li Hui, Fan Zhongyu, and You Jianqi (1996) found that the evolution time is about 40 min. Our observational estimations did not disagree with these conclusions. So, at 10:40 UT we observed an active region with three DPs. We obtained several images in He I 10 830 Å over 2 min and did not note any evolution. Then the observations were interrupted due to weather conditions and were resumed at 12:05 UT. In the same active region we observed two DPs. Their size was $12.5'' \times 12.5''$, the distance between their centers was $16.5''$. After 25 min these DPs showed a change of the surrounded region intensity ratio from 0.68 to 0.61. The relative location did not change.

3. Spectral Investigation of DPs in He I 10 830 Å Line

Spectral observations of DPs in He I 10 830 Å line were obtained at the Large Solar Vacuum Telescope by means of the CCD camera. All instrumental parameters are presented in Table I.

In total 222 spectrograms in the 10 830 Å region were obtained. In practice a line shape looks irregular along the slit in all of the spectrograms. As DPs, we selected only those objects where, together with ordinary weak absorption, there was a region with a sufficiently deep 10 830 Å line. We selected 29 such DP regions.

Selected DPs had a size from $2''$ to $13''$, their average size (taking 29 events into account) was $4.8'' \pm 2.5''$. Rust and Bridges (1975) consider that $1''$-size DPs are associated with spicules. In papers by Shcherbakov and Shcherbakova (1983) and Ikhsanov and Parfinenko (1987) the authors have supposed that DPs present themselves as a conglomerate of spicules. However, this occurs very often when distances between DPs are sufficiently large (Figure 1). This seems to us to contradict such a DP interpretation.

Spectrogram processing was done by the standard method for CCD-camera observations. There were measured values of dark current and flat field. Then these values were used to correct the working frames. To obtain the He I 10 830 Å triplet profile the Si I wing blend was excluded. Figure 2 shows He I 10 830 Å triplet profiles in DPs and undisturbed chromosphere.

Depth values of 10 830.3 Å and 10 829.1 Å triplet lines were obtained, and their depth ratio $r(\mu)$, where $\mu = \cos\theta$. We have obtained a full width at half maximum (FWHM), center shift for the 10 830 Å line, and calculated a line-of-sight velocity. All listed parameters were also obtained for several regions of undisturbed chromosphere. Average values of all parameters for DPs and the undisturbed chromosphere are presented in Table II. The 10 830 Å triplet profile parameters for the quiet chromosphere obtained in previous papers (Kozlova *et al.*, 1996; Shcherbakova *et al.*, 1983) are also given there.

In DPs Li Hui, Fan Zhongyu, and You Jianqi (1996) found a blue line shift corresponding to a velocity of 5–17 km s^{-1}. In DPs we obtained shifts with a maximum line-of-sight velocity ± 7 km s^{-1} both to the red and the blue. Herewith, as can be seen from Table II, we did not find primary motion upwards or downwards. We have compared material velocities in DPs with their size, spectral parameters of profiles, also with value of $\cos\theta$, and we did not find any dependency of line-of-sight velocity on these parameters.

TABLE I
Observation parameters

Spectrograph slit width	100μm $\approx$ 0.5$''$
Spectrum order	1 (left)
Theoretical spectral resolution	0.08 Å
Spectrum length	$\sim$13 Å
Spectral dispersion	0.027 Å pixel^{-1}
Time of exposure	1–2 s
Spectrum detector	CCD detector TEK 512 $\times$ 512

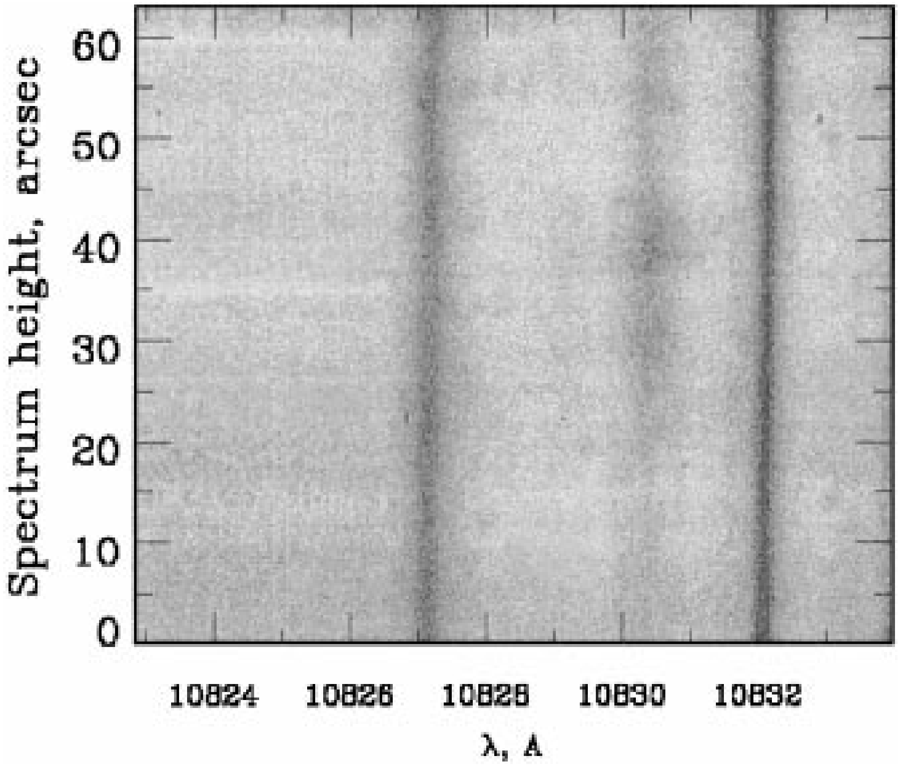

Figure 1. DP image.

We have found that the He I 10 830.3 Å and 10 829.1 Å line in DPs is deeper than in a quiet chromosphere and this agrees with Li Hui, Fan Zhongyu, and You Jianqi (1996). In some DPs, the depth of the two unsplit components is more than 30%, and halfwidth exceeds 1 Å. On the whole, the He I 10 830 Å line profiles are deeper and wider in DPs than in the undisturbed chromosphere.

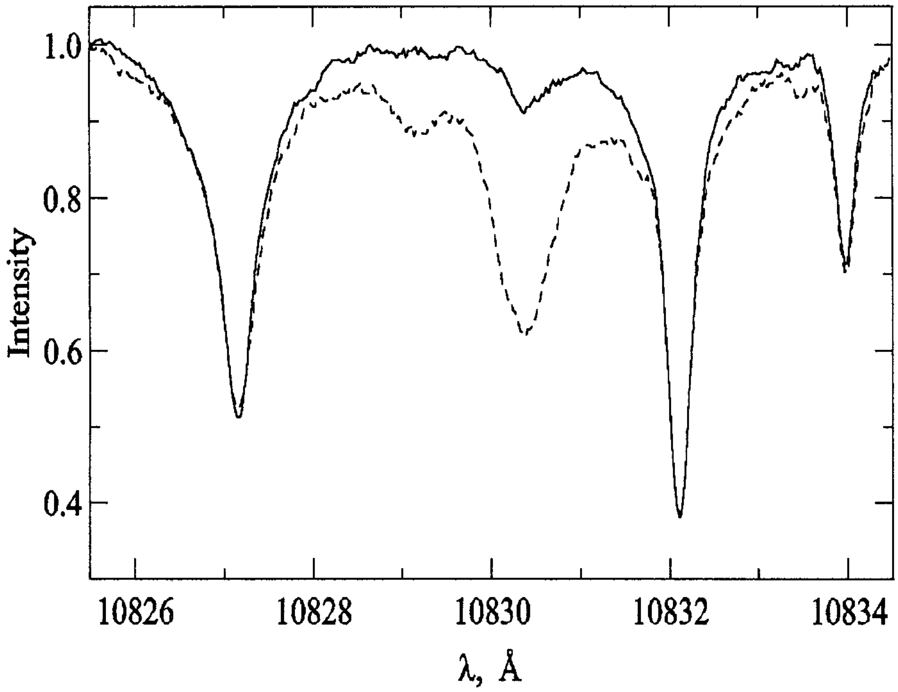

Figure 2. DP and undisturbed region profiles (*dashed* and *solid lines*, respectively).

TABLE II
Parameters of DPs and undisturbed chromosphere.

	DPs	Present paper	Undisturbed region (Shcherbakova *et al.*, 1983)	Kozlova *et al.* (1996)
R (10 830)	0.264 ± 0.047	0.10 ± 0.02	0.12 ± 0.04	0.047
R (10 829)	0.080 ± 0.025	0.05 ± 0.01	0.03 ± 0.01	0.020
$r(\mu)$	3.30 ± 1.19	2.00 ± 0.57	4.1 ± 1.0	
τ_0 (10 830)	1.70 ± 0.35	2.74 ± 0.21	2.0 ± 0.7	4.35
	(2.0 ± 0.9)	(4.75 ± 0.70)		
τ_0 (10 829)	0.21 ± 0.05	0.34 ± 0.03	0.26 ± 0.07	
	(0.25 ± 0.11)	(0.59 ± 0.09)		
FWHM	0.77 ± 0.13	0.56 ± 0.06	0.55 ± 0.08	0.33
ξ_D (km s^{-1})	−0.8 ± 2.6	0.2 ± 1.7	7.2 ± 1.4	9.1

Using the He I 10 830 Å triplet it is possible to obtain the optical depth of the chromosphere by the ratio of the depths of the two non-split components to the third component (Giovanelli and Hall, 1977; Shcherbakova *et al.*, 1983):

$$r(\mu) = \frac{1 - e^{-8\tau_0/\mu}}{1 - e^{-\tau_0/\mu}} \tag{1}$$

or

$$r(\mu) = \frac{R_0^{\text{obs}}(10830)}{R_0^{\text{obs}}(10829)}, \tag{2}$$

where $R_0^{\text{obs}}(10830)$ = integral depth of two non-split components (10 830.34 Å and 10 830.25 Å) and $R_0^{\text{obs}}(10\,829)$ = depth of the 10 829.08 Å component.

In an optically thin atmosphere, the value $r(\mu)$ is about 8. Penn and Jones (1996) obtained this ratio in the entire emission shell and in a quiescent prominence close to 8. Their method is the fitting of both component by double Gaussian and calculation of integral intensity. The authors had fitted the ‘main’ He 10 830.3 Å spectral feature and then the ‘blue’ spectral feature at 10 829.1 Å. $r(\mu)$ was obtained as the ratio of the integrated intensity in the ‘main’ to the ‘blue’ features. We have not used such a method because of the strong influence of the blue wing of the water vapor line (the telescope is situated on the shore of Lake Baikal). As can be seen from Figure 2, the 10 830 Å line features are broadened by the thermal and Doppler velocities and they are nearly fully resolved. So it can be supposed that our observed 10 830 Å line profiles nearly correspond to the integrated absorption strength of both components.

Furthermore, it is known that UV coronal radiation influences the He 10 803 Å triplet formation. This mechanism was taken into consideration by Pozhalova (1988) in solving the statistical equilibrium and radiation transfer equation system in the chromosphere. She derived an approximate analytical expression for depth of He I 10 830 Å line:

$$R_0^{\text{obs}}(\tau_0, \mu) = 1 - e^{\tau_0/\mu} - D(\tau_0, \mu), \tag{3}$$

where

$$D(\tau_0, \mu) = \frac{1}{2\Phi(\mu)}\{(1 - e^{-\tau_0/\mu})[\beta - \mu(\delta + \alpha(\ln\, \tau_0 + 1))] + \tau_0[\delta + \alpha(\ln\, \tau_0 + 1)]\},$$

$\Phi(\mu)$ is the solar limb darkening; $\alpha = 0.407$, $\beta = 0.823$, $\delta = -0.648$ are the coefficients calculated by the author.

In Table II we presented averaged optical depth values, calculated by formula (2), where expression (3) is used for the central depth. The values τ_0 enclosed in brackets are calculated by formula (1).

In spite of some uncertainty of the obtained results, this data can be used for estimation of DP physical parameters in comparison with the undisturbed chromosphere. We can conclude that optical depth in the chromospheric DPs is more transparent than in the undisturbed chromosphere.

4. Conclusion

The comparison of filtergrams and spectrograms has shown that the same phenomena (DPs) were observed at both observatories: their size and intensity in relation to the surrounding chromosphere agree. Systematic line-of-sight velocities are not revealed in either observation type.

On the basis of spectral observations, it is possible to conclude that He I 10 830 Å line in DPs is deeper and wider than in the surrounding chromosphere. DPs are optically thinner in comparison with the surrounding atmosphere. Line-of-sight velocity values vary from -7 km s^{-1} to $+7$ km s^{-1}.

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