THE RATIOS $I(K_1)/I(H_1)$ AND $I(K_3)/I(H_3)$ OF Ca II AS DIAGNOSTICS OF THE CHROMOSPHERE ABOVE SUNSPOTS

I. P. TUROVA and S. A. GRIGORYEVA
Institute of Solar-Terrestrial Physics, Russian Academy of Sciences, Siberian Branch, P.O. Box 4026, Irkutsk, 664033, Russia

(Received 14 June 2000; accepted 31 July 2000)

Abstract. The ratios $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$ were calculated from four semi-empirical models of sunspot umbra. We determined the dependencies of both ratios of such parameters as temperature gradient and atmospheric opacity. A certain influence on the expected ratios $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$ can also come from the FIP effect provided it exists in the chromosphere above sunspot umbra. Theoretical and observed values of $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$ are compared. It is shown that for one of the sunspots we observed, the values obtained for the ratio $I(K_1)/I(H_1)$ cannot be explained in terms of existing umbra models.

1. Introduction

Inquiries into strong Fraunhofer lines, such as H and K Ca II, provide the observer with the clues to modeling the processes occurring in the solar chromosphere. Quantitative measurements of the profiles of these lines in sunspots were pioneered in a series of publications of Mustel and Tsap (see, for example, Mustel, 1955; Mustel and Tsap, 1960). Since then a great deal of work has been accomplished to study the various structural features of Ca II lines in different regions on the Sun (quiet region, plage, sunspot) depending on the position on the disk and on the time.

The intensity ratio of central reversals of the K and H Ca II lines, $I(K_3)/I(H_3)$, is known to be an important diagnostic tool for investigating the solar chromosphere. If the ratio $I(K_3)/I(H_3)$ is close to unity, then this indicates an optically thick medium; if, however, it approaches two, then this suggests an optically thin chromosphere.

Observational evidence has shown that for the quiet Sun the chromosphere can be thought of as an optically thick medium because in this case the ratio $I(K_3)/I(H_3) \approx 1$ (see, for example, Table III in a paper of Shine and Linsky, 1972). A different situation arises with sunspot umbra. Observations in sunspot umbrae that were carried out by several authors (Teplitskaya and Efendieva, 1976; Mattig and Kneer, 1978; Kneer *et al.*, 1981; Lites and Skumanich, 1982) show a significant spread in values of the ratio $I(K_3)/I(H_3)$. Although, according to the data of most authors, this ratio is close to one despite the difference of particular values, it can sometimes be significantly larger (see Table I). As regards the rea-

Solar Physics **197:** 43–56, 2000.

sons for the dissimilar values of the ratio $I(K_3)/I(H_3)$ in the umbra, it might be well to point out that the sunspot umbra is a very dynamic, variable feature. It is hardly probable that there would be two sunspot umbrae with identical spatial and temporal characteristics. In other words, the differences in the ratios $I(K_3)/I(H_3)$ for different sunspots and, as will be shown later in the text, for different portions of the umbra of a single sunspot are likely to reflect the dynamics of the umbra conditions.

Yet another ratio, $I(K_1)/I(H_1)$, measured at minimum intensities of nearby line wings, is known for strong Ca II lines. No active interest was expressed by researchers in this quantity, which is suggested by the paucity of published data. One reason for this neglect is that it is difficult to achieve accurate intensity measurements in the line wings as this requires careful corrections for the scattered light which can introduce significant distortions in these parts of the lines. Once these difficulties have been overcome we come up with a further useful diagnostic tool to provide information about thermodynamic parameters of umbra. Of a few published data on the ratio $I(K_1)/I(H_1)$ in sunspot umbra, it is worth to mention the publications of Mattig and Kneer (1978), Lites and Skumanich (1982), Kneer *et al.* (1981), and Teplitskaya and Efendieva (1976).

The most accurate measurements reported in Mattig and Kneer (1978) give the value of the ratio $I(K_1)/I(H_1)$ within 0.74–0.96.

The main objective of this paper is to estimate the diagnostic role of the ratios $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$, that is, to determine the particular chromospheric parameters on which these ratios depend. For this purpose, we resorted to the currently available semi-empirical static models of sunspot umbra (Avrett, 1981; Staude, 1982; Maltby *et al.*, 1986; Severino, Gomez, and Caccin, 1994).

Besides, when measuring a sunspot, Grigoryeva (1988) found a surprisingly low ratio $I(K_1)/I(H_1) = 0.48$. The question may well be raised about whether the ratio obtained reflects a real (while perhaps anomalous) state of the sunspot umbra or that is a result of inaccuracies committed in a photometric processing of a spectrogram. This brings up a more general problem. To date most observers of the solar spectrum, among them these authors, have turned to intensity measurements using CCD-matrices. At the same time extensive archives of photographs are still available, which can be indispensable when carrying out a variety of statistical studies. For example, when statistically significant ensembles of data on the H and K Ca II line profiles in sunspots are available, it is advantageous to use them in investigating the variations of the chromosphere over a cycle of activity or in comparing the chromosphere above the umbrae of sunspots of different magnetic configurations.

In the case under study, when considering the regions H_1 and K_1 of the H and K line profiles we have to handle the most complicated measurements. In the first place, a careful reduction for the scattered light must be performed. Secondly, densities of photographic material for H_1 and K_1 very frequently occur in the under-exposure region of characteristic curves, which calls for extreme care in

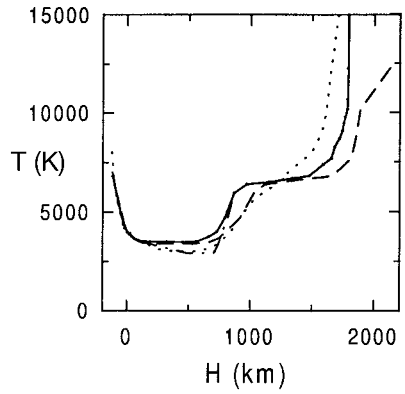


Figure 1. Temperature vs. height for four umbral models: (1) Staude (1982) model (*dots*); (2) Avrett (1981) model (*solid curve*); (3) Severino, Gomez, and Caccin (1994) model (*dash-dotted curve*); (4) Maltby *et al.* (1986) model (*dashes*). The height is measured outward from the level at which $\tau_{500} = 1$, where τ_{500} is the continuum optical depth at 500 nm wavelength.

monitoring the process of constructing them. This has motivated a further goal of this paper: to improve the accuracy of photographic photometry for weak densities by monitoring and correcting characteristic curves using some ‘reference’ intensity ratios. Results from updated photometry provide a means of assessing the reality of the anomaly in the above-mentioned sunspot.

2. The Expected Ratios $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$

To estimate the possibility of using the ratios $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$ as diagnostic tools when investigating the chromosphere, we now consider the question as to which values of the ratios are predicted by different sunspot umbra models. In doing this, we employed four above-mentioned semi-empirical static models of sunspot umbra. These models are one-dimensional and time-averaged, and take no account of dynamic effects; however, they can be very useful for our purposes. The models differ considerably from each other by their thermodynamic characteristics, such as the temperature variation and opacity. A brief comparison of the properties of the models may be found in a paper of Grigoryeva and Turova (1998). It should be noted that a modified variant of Avrett’s model was used in that paper which differs from the original model by the run of electron density n_e. The modified model gives a better agreement of calculated and observed profiles. Nevertheless, in this study we took the original Avrett’s model (1981). To illustrate the temperature run in these models we reproduce Figure 1 from Grigoryeva and Turova (1998).

When calculating the H and K Ca II line profiles in these models, we used the code MULTI (Carlsson, 1986), supplemented by Uitenbroek in order to include partial redistribution effects. Synthesized line profiles were used to calculate the ratios $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$. After that, we constructed the dependencies of these ratios on some typical model parameters, such as log τ_K and log τ_{500} in the temperature minimum (T_{min}); and log τ_K and log τ_{500} at the beginning of the upper chromosphere; their differences were also tested, i.e. the parameter was represented by, for example, the optical thickness of the chromosphere between (T_{min}) and $T = 8500$ K.

Of all model parameters that were considered, it was possible to determine a certain dependence of $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$, firstly, on the following factors: (a) opacity of the continuous spectrum in the temperature minimum (Figure 2(a)) and (b) opacity of the K Ca II line in the region of temperature rise immediately above the temperature minimum (Figure 2(b)). The fact that the opacity is a fundamental parameter determining the ratio $I(K_3)/I(H_3)$ is trivial. The surprising thing is, however, that the main influence comes from the lower chromosphere where the curves of response to a temperature variation do not yet reach their maximum value according to Grigoryeva, Turova, and Teplitskaya (1991). Furthermore, the same layer influences both $I(K_3)/I(H_3)$ and $I(K_1)/I(H_1)$. In this case the character of variation is the opposite: the largest ratios $I(K_3)/I(H_3)$, as would be expected, correspond to the most transparent Avrett and Staude models; for these same models, $I(K_1)/I(H_1)$ values are minimal.

Secondly, a certain influence on the ratios comes also from the temperature gradient (Figure 3), and only in those regions where it is large: immediately above the temperature minimum (Figure 3(a)), and at the transition from the temperature plateau to an abrupt rise in temperature (Figure 3(b)).

3. Observed Values of $I(K_1)/I(H_1)$ and $I(K_3)/I(H_3)$

3.1. Summary Data

As has been pointed out in the Introduction, there have been many measurements of the central intensity ratios $I(K_3)/I(H_3)$. They are presented in Table I, as well as less numerous measurements of $I(K_1)/I(H_1)$.

The mean ratios are:

$$I(K_3)/I(H_3) = 1.15 \pm 0.16, \qquad I(K_1)/I(H_1) = 0.79 \pm 0.185.$$

The authors themselves refer to some measurements as being questionable. For example, Lites and Skumanich (1982) suppose that their low values of $I(K_1)/I(H_1)$ are caused by an inadequately strict correction for the scattered light. Shine and Linsky (1972) who estimated the value of $I(K_3)/I(H_3)$ at 1.70 consider it also unreliable; furthermore, it differs from the above mean value by more than 3σ. An anomalously low value of $I(K_1)/I(H_1)$ (not included in Table I) that was obtained by these authors for one of the sunspots is discussed in detail in Section 3.2 of this paper. Omitting from the data in Table I the values of the ratios deviating from the mean values by more than 2σ (three points for $I(K_3)/I(H_3)$, and one point for $I(K_1)/I(H_1)$) we obtain the mean values

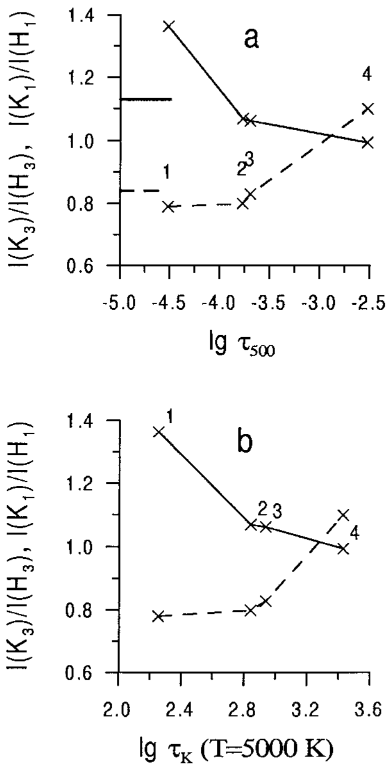


Figure 2. The ratios $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ (*solid curve*) and $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ (*dashed curve*) for four models as a function of (a) $\log \tau_{500}$ in the temperature minimum; short bars along the axis of ordinates correspond to the mean values of the ratios that were determined using published data, and (b) $\log\ \tau_\mathrm{K}$ at the temperature $T = 5000$ K (τ_K is the optical depth at the center of the K Ca II line). (1) Staude (1982) model, (2) Avrett (1981) model, (3) Severino, Gomez, and Caccin (1994) model, (4) Maltby *et al.* (1986) model.

$$I(\mathrm{K}_3)/I(\mathrm{H}_3) = 1.13 \pm 0.11, \qquad I(\mathrm{K}_1)/I(\mathrm{H}_1) = 0.84 \pm 0.11.$$

These values are shown by solid and dashed marks, respectively, along the axis of ordinates in Figure 2(a). It is evident that they are in very good agreement with the mean ratios predicted by the models, although the above standard deviations are relatively large.

Calculations from Section 2 predict an inverse correlation between $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ and $I(\mathrm{K}_1)/I(\mathrm{H}_1)$. Figure 4 shows the measured ratios for the cases where information is available for both ratios. Not counting all of the above-mentioned questionable and anomalous data for $I(\mathrm{K}_1)/I(\mathrm{H}_1)$, one can see a weak tendency for $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ to decrease at large values of $I(\mathrm{K}_3)/I(\mathrm{H}_3)$; however, the regression line plotted in the figure gives a negligible correlation coefficient $r = -0.494$.

Standard deviations include measurement errors and probable individual properties of sunspots. The error sources will be discussed below. As will be shown

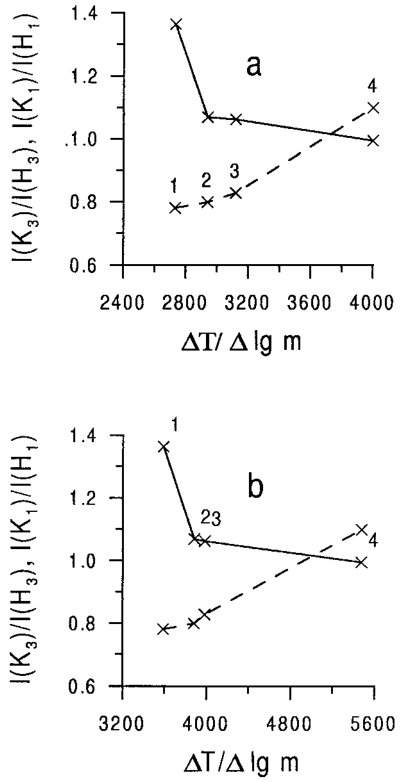


Figure 3. The ratios $I(K_3)/I(H_3)$ and $I(K_1)/I(H_1)$ vs. temperature gradient (a) in the region of an abrupt rise in temperature immediately above the temperature minimum, and (b) in the region of temperature rise just above the temperature plateau. The designations are the same as in Figure 2.

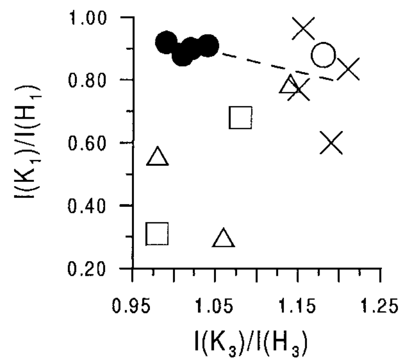


Figure 4. The ratios $I(K_1)/I(H_1)$ vs. $I(K_3)/I(H_3)$ according to published data: *dark circles* are the values from Mattig and Kneer (1978); the *open circle* is from Kneer *et al.* (1981); *crosses* are data from Teplitskaya and Efendieva (1976); *boxes* are data from Lites and Skumanich (1982), and *triangles* represent data from this paper. The *dashed curve* is a regression line constructed without taking into account the data from Lites and Skumanich (1982) and the data of this paper.

TABLE I

Observed ratios $I(K_3)/I(H_3)$ and $I(K_1)/I(H_1)$

Author	$I(K_3)/I(H_3)$				$I(K_1)/I(H_1)$
	Quiet	Plage	Penumbra	Umbra	Umbra
Goldberg *et al.* (1959)[1]	0.80				
Paciorek (1965)[2]				0.82	
Zirker (1965)[2]	1.23				
Teske (1967)[1]	0.90				
Mount (1968)[1]	1.00				
White and Suemoto (1968)	1.00				
Zirker (1968)[2]	1.075				
Linsky (1970)[1,2]	1.03	1.20		>0.97	
Shine and Linsky (1972)	1.00	1.06		1.70 :	
		1.12			
		1.06			
		1.05(?)			
		1.09			
		1.20(?)			
Efendieva (1973)		1.10	1.07	1.15	
		1.10	1.10	1.14	
		1.08	0.98	1.11	
		1.13	1.11	1.14	
		1.12	1.09	1.20	
		1.02	1.11	1.16	
		1.03	1.03	1.13	
		1.10	1.07	1.16	
		1.03	1.07	1.15	
		1.04	1.13	1.19	
			1.09	1.19	
Teplitskaya and Efendieva (1976)				1.06	0.88
				1.19	0.60
				1.155	0.965
				1.21	0.835
				1.15	0.77
				1.29	
				1.19	
				1.14	
				1.29	
				1.19	
				1.32	
				1.21	
	1.00	1.06	1.03	1.20	
Teplitskaja and Firstova (1976)				1.05	

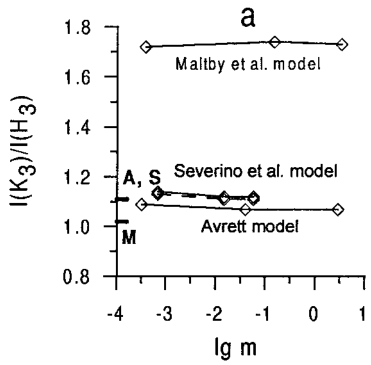
TABLE I

Continued

Author	$I(K_3)/I(H_3)$				$I(K_1)/I(H_1)$
	Quiet	Plage	Penumbra	Umbra	Umbra
Mattig and Kneer (1978)				1.01	0.88
				1.04	0.91
				0.99	0.92
				1.02	0.90
Firstova (1980)				1.00	
				1.165	
				1.11	
				1.54	
				1.44	
				1.14	
				1.36	
Lites and Skumanich (1982)				1.08	0.68:
				0.98	0.31:
				1.21	
				0.97	
Kneer *et al.* (1981)				1.18	0.88
Yun and Beebe (1982)	1.13		1.19	1.25	
Turova (1983)				0.96	
				0.97	
				1.01	
				0.99	

[1]From the paper of Shine and Linsky (1972).
[2]From the paper of Linsky and Avrett (1970).

later in the text, some of the anomalous values of the ratios cannot be explained by any errors at all. Of the physical factors influencing the individual properties of the chromosphere, we shall consider one ‘exotic’ (at first glance) factor. Nevertheless, it is known that the FIP phenomenon (that attracts considerable attention), a variation in chemical composition of the atmosphere depending on the first ionization potential, has its origins in the chromosphere. Grigoryeva, Ozhogina, and Teplitskaya (2000) calculated the H and K line profiles of calcium by assuming two possible variations in calcium abundance a_{Ca} in the chromosphere above sunspot umbra. If such an inconstancy of a_{Ca} is indeed the case, then it can be different for sunspots depending on the dynamics of their atmospheres, or on the magnetic field configuration, so that it manifests itself differently for different sunspots. Figure 5 shows the variation of the ratios $I(K_3)/I(H_3)$ and $I(K_1)/I(H_1)$ for three models of chromospheric umbra (Avrett (1981), Maltby *et al.* (1986), Severino, Gomez, and



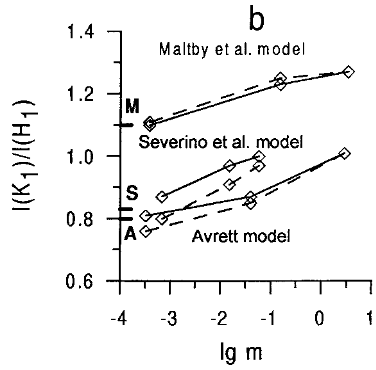


Figure 5. Dependence of the ratios $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ and $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ on the column mass m_0 at a variable $a_{\mathrm{Ca}}(m)$ for the models of Avrett (1981), Maltby *et al.* (1986), and Severino, Gomez, and Caccin (1994). The *solid* and *dashed curves* represent first and second variants of the behavior of the function $a_{\mathrm{Ca}}(m)$, respectively. *Diamonds* show three variants of the position of the point m_0: $m(x_{\mathrm{min}})$ indicates the deepest point, where x_{min} is the minimum degree of calcium ionization; $m(T_{\mathrm{min}})$ is the position of the temperature minimum point; m(plateau) is the point at the beginning of the temperature plateau. Short horizontal lines labeled 'A', 'M', 'S' mark the ratios $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ and $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ calculated, respectively, for the models of Avrett (1981), Maltby *et al.* (1986), and Severino, Gomez, and Caccin (1994) at a 'normal' (photospheric) value of a_{Ca}.

Caccin (1994)), with a different thickness of the layer where a_{Ca} is variable, and with two versions of the function $a_{\mathrm{Ca}}(m)$ (m being the column mass). In the first variant, a_{Ca} increases gradually from the photospheric value $(a_{\mathrm{Ca}})_{ph}$ at the point m_0 to the 'coronal' value of $(a_{\mathrm{Ca}})_{cor}$ at $T = 10\,000$ K. In the second variant (with the inversion of the variation of a_{Ca} in the photosphere) a_{Ca} initially decreases from the photospheric value $(a_{\mathrm{Ca}})_{ph}$ at the final point of the model atmosphere m_{end} to a certain minimum value at the point $m(\tau_{500} = 1)$, then increases to its 'normal' value at the point m_0, followed by an increase to the 'coronal' value at the point $m_{ch}(T \approx 10\,000$ K).

The figure suggests that the presence of the FIP effect in the chromosphere is indeed able to affect the intensity ratio of the K and H lines, and the character of this influence will be different for the ratios $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ and $I(\mathrm{K}_3)/I\mathrm{H}_3)$. As far as the ratio $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ (Figure 5(a)) is concerned, it should be noted that the three selected models gave a different response to the presence of the FIP effect. In the models of Avrett and Severino, Gomez, and Caccin, the ratios $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ were found to be close to their 'normal' values, i.e. to the values obtained for a standard (photospheric) a_{Ca}. For the Maltby *et al.* model, the presence of the FIP effect led to a significant increase of the ratio $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ – it was found to be >1.7. Such a value of $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ approaches to some published 'anomalously' high values, such as reported by Shine and Linsky (1972) (the ratio $I(\mathrm{K}_3)/I(\mathrm{H}_3) = 1.7$), Teplitskaya and Efendieva (1976) (1.32), and Firstova (1980) (1.54 and 1.36). At the same time the difference of the thickness of the layer where the abundance a_{Ca} varies, and also the presence or absence of the inversion of the function $a_{\mathrm{Ca}}(m)$ did not significantly affect the value of the ratio $I(\mathrm{K}_3)/I(\mathrm{H}_3)$.

For the ratio $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ (Figure 5(b)), the following remark is in order. The broader is the region where the abundance a_{Ca} varies with the height, the larger is the value of the ratio $I(\mathrm{K}_1)/I(\mathrm{H}_1)$, and for all models this ratio exceeds 'normal' ones. In only one case for the models of Avrett and Severino, Gomez, and Caccin (with the inversion of a_{Ca} run) are these ratios somewhat lower than 'normal' ones (0.76 and 0.8, respectively), but they are still higher than the ratio $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ as obtained by Grigoryeva (1988), and fit well the values calculated by, for example, Teplitskaya and Efendieva (1976).

As has been pointed out above, we used significantly different sunspot umbra models. In particular, the model of Maltby *et al.* spans a smaller temperature range when compared to the other models. In addition, it has a broader area of the temperature minimum; the temperature plateau is shifted to higher atmospheric layers; and there is no abrupt change in temperature in higher-lying layers. The model of Maltby *et al.* gives anomalously high values of the ratio $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ with a variable abundance a_{Ca} (by 70% larger than 'normal' values), but it does not seem to be able to reproduce the low values of the ratio $I(\mathrm{K}_1)/I(\mathrm{H}_1)$. We tried to verify how the temperature range encompassed by the model affects our results. For this purpose, we introduced the Avrett's model for the same temperature range as the model of Maltby *et al.*, into our calculations using the code MULTI. As would be expected, the ratios $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ remained unchanged. The ratios $I(\mathrm{K}_3)/I(\mathrm{H}_3)$, with a variable abundance a_{Ca} somewhat *decreased* (by 18% at most) in relation to 'normal' ratios. Thus the range of temperatures that is encompassed by the model does not seem to play a crucial role in the changes of the concerned parameters of the H and K Ca II line profiles.

To elucidate the reality of the anomalous values of the intensity ratio for the individual sunspots, we now consider in greater detail the H and K line profile measurements in one of them.

3.2. Measurements of H and K line profiles in the 'anomalous' sunspot

As has been mentioned above, in one of sunspots Grigoryeva (1988) measured anomalously low values of $I(K_1)/I(H_1)$. Spectrograms were taken with excellent seeing conditions and with only a moderate scattered light which was, nevertheless, carefully taken into account at the reduction stage. The only reason why the results could be put in doubt was the low density in the regions of H_1 and K_1. We undertook a reprocessing in order to assess the influence of this factor.

Pictures were taken on 10 August 1982 at the Sayan Solar Observatory with the automated solar telescope. The dispersion in the VI order of the grating was 37 mm nm^{-1}, the image at the slit was 190 mm in diameter, the diameter of the sunspot umbra was $\approx 15''$, and $\sin\theta = 0.16$. Both lines, H and K Ca II were present on every spectrogram.

A photometric reprocessing was carried out with a more sophisticated (than in Grigoryeva, 1988) instrument, microdensitometer AMD-1.

The sunspot showed an oscillatory process of the umbral flashes type. In order to appreciate whether the value of the ratio $I(K_1)/I(H_1)$ depends on the oscillation phase, we performed a photometric processing for two phases of the oscillatory process: a minimum and maximum of the intensity of $I(K_3)$ and $I(H_3)$. We had spectrograms at our disposal, which typically represented both phases of the oscillatory process. The spectrogram that was taken at the time of a maximum phase of the umbral flash will be referred to as spectrogram 1, and the spectrogram corresponding to a minimum of the umbral flash will be called spectrogram 2. The H and K line profiles were constructed for the sunspot umbra, penumbra, and for the quiet region on both sides of the sunspot. For each spectrogram we performed several tens of scans in the H and K lines, as well as in the area of the quasi-continuum near $\lambda = 395.4$ nm which intensity makes up $\approx 84\%$ of the continuum intensity near $\lambda = 400$ nm.

In the sunspot umbra of spectrogram 1, we made scans in the area of the umbra with a maximum intensity of the umbral flash, and in the quiet area of the umbra where no umbral flash process was observed. It will be recalled that the oscillatory process of the umbral flash is a local phenomenon occupying, according to some authors, 3–$4''$ in the sunspot umbra; therefore, it is an easy matter to select an area of the umbra free from this phenomenon. For spectrogram 2, sections were also made in the area of the umbral flash.

Particular attention was given to the accuracy of constructing the characteristic curve. We made a package of programs enabling us to automate the procedure of constructing the characteristic curve. Using a special-purpose program the steps of the photometric stepped wedge were scanned in some areas (≈ 15) on the photographic plate in order to encompass the entire range of densities which were present in the working scans. After that, we constructed a family of characteristic curves which were ranked according to a maximum density. Each curve of the family was approximated by a polynomial of degree n by the least-squares technique. We took the value of $n = 5$ as the most suitable. Thereafter the characteristic curves were combined in a single curve, and the curve which had maximum values of the density was taken to be the principal curve.The resulting characteristic curve thus obtained was also approximated by a polynomial of degree m. An optimum degree of the polynomial was chosen according to the value of the standard deviation of approximation errors, as well as to the behavior of this polynomial in the region of under-exposures and over-exposures. It turns out every so often that densities at the center of the H and K lines are in the region of under-exposures; therefore, particular care must be taken in the construction of this segment of the characteristic curve. The procedure of verifying the correctness of the construction of characteristic curves is described in a paper of Efendieva (1973). The photometric stepped wedge is photometered across the dispersion direction at several wavelengths in the wings of the H and K lines, as well as in the area of the quasi-continuum in order to cover, according to the densities, the entire characteristic curve. The scans obtained are processed using the resulting characteristic curve, and the intensities are expressed in fractions of the quasi-continuum. In the quasi-continuum, account is taken only of those steps of the photometric stepped wedge which are in the straight line portion. If the characteristic curve is properly constructed, then at each wavelength the residual intensity r_λ must be a constant value for all steps. If, however, there is a systematic deviation, then the characteristic curve needs to be corrected. The correction can be determined on the basis of the relationship $r_\lambda = f(D)$ (D being the density). It should be noted that although this correction method is very straightforward, it is not quite amenable to calculation; however, we have created such a program which has been and is used in correcting the characteristic curve.

To obtain the H and K line profiles in absolute units we made use the data from White and Suemoto (1968) and Houtgast (1970). Corrections for the scattered light were performed using the code of Staveland (1972) which was adapted to our purposes by Grigoryeva (1988).

Table II presents our measured ratios $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ and $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ for the umbra, penumbra and the quiet region obtained for two phases of the oscillatory process of the umbral flash. As is easy to see, the ratios $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ remain very low in both the maximum and minimum of the umbral flash. Furthermore, it can be pointed out that they are changing within the umbra. It is known that the ratio $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ in the quiet region is equal to unity (White and Suemoto, 1968). We obtained the value 0.96 for the ratio $I(\mathrm{K}_3)/I(\mathrm{H}_3)$. The value 0.04 can be regarded as an error of our measurements.

Thus a careful photometric reprocessing, and also a reduction for the scattered light left no doubt that very low values of the ratio $I(\mathrm{K}_1)/I(\mathrm{H}_1)$ with a ‘normal’ ratio $I(\mathrm{K}_3)/I(\mathrm{H}_3)$ are real.

TABLE II

Observed ratios $I(K_3)/I(H_3)$ and $I(K_1)/I(H_1)$ for the ‘anomalous’ sunspot

Region	$I(K_3)/I(H_3)$	$I(K_1)/I(H_1)$
Maximum phase of the umbral flash process		
Area of umbra with max. intensity	1.05	0.30
Quiet area of umbra	1.14	0.79
Penumbra	1.14	1.02
Quiet region	0.96	
Minimum phase of the umbral flash process		
Umbra	1.01	0.49
Penumbra	1.08	0.94
Quiet region	0.96	

4. Conclusions

(1) On the basis of calculations in terms of four currently available semi-empirical models of sunspot umbra it has been shown that the expected intensity ratios $I(K_3)/I(H_3)$ and $I(K_1)/I(H_1)$ are both determined by the opacity of the atmosphere in the temperature minimum region and just above it, as well as by temperature gradients in areas of a rapid rise above the temperature minimum and immediately above the temperature plateau.

(2) The models predict that the ratios $I(K_3)/I(H_3)$ and $I(K_1)/I(H_1)$ depend inversely on each other.

(3) In some cases the calculated ratios $I(K_3)/I(H_3)$ and $I(K_1)/I(H_1)$ are also significantly affected by the possible existence of the FIP effect in the chromosphere. For the ratio $I(K_1)/I(H_1)$, this influence increases with the increasing width of the region where the abundance of calcium varies with the height. The presence of the FIP effect for one of the models, Maltby *et al.* (1986) considerably increased the value of the ratio $I(K_3)/I(H_3)$, whereas for the other two models, Avrett’s (1981) and Severino, Gomez, and Caccin (1994), the ratio remained similar to a ‘normal’ one.

(4) The observed ratios agree closely, on average, with the mean ratios that are theoretically expected from models; however, the dispersion of some of the values is large and seems to be caused not only by measurement errors but also by imperfection of the static models themselves, as well as by individual properties of sunspot thermodynamics.

(5) We have carried out a careful photometric treatment of spectrograms for one of the sunspots with anomalously low ratios $I(\mathrm{K}_1)/I(\mathrm{H}_1)$. It has been shown that the 'anomaly' is quite real, and it can in no way be explained within the framework of existing static models.

Acknowledgements

We are grateful to R. B. Teplitskaya for an extensive discussion and useful remarks.

This work was supported by the Russian Foundation for Fundamental Research, project number 98-02-17726; a grant of governmental support for leading scientific schools of Russian Federation, project number 96-15-96733; the Governmental Scientific and Technical Program 'Astronomy'.

References

Avrett, E. H.: 1981, in L. Cram and J. H. Thomas (eds.), *The Physics of Sunspots*, Sacramento Peak Observatory, p. 235.
Carlsson, M.: 1986, *Uppsala Astron. Report*, No. 33, p. 1.
Efendieva, S. A.: 1973, *Issledovaniya po geomagnetizmu, aeronomii i fisike Solntsa*, Moscow, No. 26, 67.
Firstova, N. M.: 1980, *Astron. Zh.* **57** (3), 666.
Grigoryeva, S. A.: 1988, *Issledovaniya po geomagnetizmu, aeronomii i fisike Solntsa*, Moscow, No. 82, 33.
Grigoryeva, S. A. and Turova, I. P.: 1998, *Solar Phys.* **179**, 17.
Grigoryeva, S. A., Ozhogina, O. A., and Teplitskaya, R. B.: 2000, *Solar Phys.* **195**, 269.
Grigoryeva, S. A., Turova, I. P., and Teplitskaya, R. B.: 1991, *Solar Phys*. **135**, 1.
Houtgast, J.: 1970, *Solar Phys*. **15**, 273.
Kneer, F., Scharmer, G, Mattig, W., Wyller, A. Artzner, G., Lemaire, P., and Vial, J. C.: 1981, *Solar Phys*. **69**, 289.
Linsky, J. L. and Avrett, E. H.: 1970, *Publ. Astron. Soc. Pacific*. **82** (485), 169.
Lites, B. W. and Skumanich, A. A.: 1982, *Astrophys. J. Suppl. Ser.* **49**, 293.
Maltby, P., Avrett, E. H., Carlsson, M., Kjeldseth-Moe, O., Kurucz, R. L., and Loeser, R.: 1986, *Astrophys. J*. **306**, 284.
Mattig, W. and Kneer, F.: 1978, *Astron. Astrophys*. **65**, 11.
Mustel, E. R.: 1955, *Izv. Krymsk. Astrofiz. Obs*. **13**, 96.
Mustel, E. R. and Tsap, T. T.: 1960, *Izv. Krymsk. Astrofiz. Obs*. **22**, 75.
Severino, G., Gomez, M. T., and Caccin, B.: 1994, in R. J. Rutten and C. J. Schrijver (eds.), *Solar Surface Magnetism*, NATO ASI Series C 433, Kluwer Academic Publishers, Dordrecht, Holland, p. 169.
Shine, R. A. and Linsky, J. L.: 1972, *Solar Phys.* **25**, 357.
Staude, J.: 1982, *HHI-STP-Report*. No. 14, Category S, p. 24.
Staveland, L.: 1972, *Report Inst. Theor. Astrophys.*. Blindern-Oslo, No. 36, p. 32.
Teplitskaya, R. B. and Efendieva, S. A.: 1976, *Contr. Astron. Obs. Skalnaté Pleso*. **6**, 212.
Teplitskaya, R. B. and Firstova, N. M.: 1976, *Solar Phys*. **48**, 103.
Turova, I. P.: 1983, *Issledovaniya po geomagnetizmu, aeronomii i fisike Solntsa*, Moscow, No. 65, 86.
White, O. R. and Suemoto, Z.: 1968, *Solar Phys.* **3**, 523.
Yun, H. S. and Beebe, H. A.: 1982, *Solar Phys*. **78**, 347.