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On the quantitative method for measurement and analysis of the fine structure of Fraunhofer line profiles

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The methods of measurement and analysis of the fine structure of weak and moderate Fraunhofer line profiles are considered. The digital spectral materials were obtained using rapid scanning high dispersion and high resolution double monochromators. The methods of asymmetry coefficient, bisector method and new quantitative method proposed by the author are discussed. The new physical values of differential, integral, residual and relative asymmetries are first introduced. These quantitative values permit us to investigate the dependence of asymmetry on microscopic (atomic) and macroscopic (photospheric) values. It is shown that the integral profile asymmetries grow appreciably with increase in line equivalent width. The average effective depths of the formation of used Fraunhofer lines in the photosphere of the Sun are determined. It is shown that with the increasing of the effective formation depths of the lines integral and residual asymmetries of the lines profiles noticeably decrease. It is in fine agreement with the results of intensity dependence of asymmetry. The above-mentioned methods are critically compared and the advantages of author's method are shown. The computer program of calculation of the line-profile asymmetry parameters has been worked out.

Keywords: Solar spectrum; Fraunhofer line profile; fine structure; quantitative method

1 Introduction

As far back as the 1960s, it turned out that the profiles of a majority of weak and moderate Fraunhofer lines in Utrecht photometric atlas [1] of the normal solar spectrum are asymmetric. However, it was revealed that this asymmetry was produced by the asymmetry of the instrumental profile. Asymmetry of Fraunhofer line profiles in the spectrum of the disk center of the Sun was first discovered by Voight [2] in 1955 by observation of the oxygen infrared triplet (λ7771.954 Å, λ7774.177 Å, λ4775.395 Å). However, the asymmetric nature of Fraunhofer line profiles in the solar spectrum was

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finally established in 1960–62 by Higgs [3] on the basis of observations with higher spectral resolution.

Since the 1960s, in the Main Astrophysical Observatory of the Russian Academy of Sciences the study of Fraunhofer line-profile asymmetry using a double monochromator with photoelectric registration of the spectrum was started [4–7]. In 1979 in the Main Astrophysical Observatory of the Ukrainian Academy of Sciences a more perfect double monochromator with photoelectric registration of the spectrum using digital registration was created. This instrument was intended for investigation of the fine structure of weak and moderate Fraunhofer lines and their change along the solar disk [9]. The Kostik's group investigations of this problem deserve particular attention [10–18].

Weak Fraunhofer line-profile asymmetry in the spectrum of the Sun was convincingly proved only after application of new rapid scanning double monochromators and Fourier spectrometers with higher dispersion and higher resolution. Usual photographic observations cannot provide the necessary accuracy for revealing and study of the asymmetry of weak Fraunhofer line profiles in the spectrum of the Sun and stars.

The digital spectral atlases of the disk center of the Sun by Delboille, Neven and Roland [19] and Beskers, Bridges and Gilliam [20] on a full flux from the entire disk of the Sun, obtained by use of rapid scanning double monochromators with high dispersion, as well as the digital atlas by Kurucz, Furgenlid, Brault and Testerman [21], obtained by a Fourier spectrometer with high dispersion for full fiux of the Sun have considerably extended the possibility of investigation of the asymmetric nature of weak and moderate Fraunhofer lines in the wide spectral range. The digital atlas by Griffin [22] also obtained using double monochromators permits us to study the Fraunhofer line profile asymmetry in the spectrum of Procyon.

In study of Fraunhofer line profiles structure the problem of choice of the spectral lines is of great importance. The lines selected for this purpose should be free from blending by the lines of solar and telluric ones. In addition, they should possess the minimum isotopic shifts and be free from superfine structures. Iron lines, in this sense, are the most proper ones. The list of the selected spectral lines for measurement of the line profile asymmetry in the spectrum of the Sun was recommended by Kostik [16]. The selection of spectral apparatuses is also important. It is obvious that the spectral device must have strictly symmetric instrumental profiles.

For the first time Fraunhofer lines' asymmetry was described by a simple comparison of the violet and red wings of line profiles. A little later, the profile asymmetry was characterized by the bisector method.

Further, the most extended research into the asymmetry properties of weak and moderate Fraunhofer line profiles in the spectrum of the disk center of the Sun was accomplished by Dravins et al. [23–26] by the bisector method of Fe I and Fe II lines, as well by Kostik [10–18], Fe, Ti, Cr and Ni lines; then Balthasar [27–30], Fe, Ti, Cr, Ni, Ca, Sc, Si and Na lines; Gadun and Kostik [31], Fe, Ti, Cr and Ni lines; Atrashenko et al. [32–34] and Gasanalizade [8], λ698.979 Å K I line; Braundt and Shreter [35–36], λ7699 Å K I line; Cavallini et al. [37], λ6301.515 Å line; Pirs [38] and Cavallini et al. [40–45], Fe lines in the region of the spectrum $\lambda\lambda$5500–6400 Å.

However, the bisector method is not qualitative and therefore cannot be used for considering the change of sign asymmetry inside a line profile as well the dependence

of asymmetry on microscopic (atomic) and macroscopic (photospheric) values.

Asymmetry of Fraunhofer line profiles may be also characterized by the method of asymmetry coefficient. Many researchers applied this method in their investigations and we will note the work done by Kostil [11–16] and his group in Ukrainian Main Astrophysical Observatory where the profile asymmetry coefficients of about 130 weak and moderate intensity Fraunhofer lines were determined. They also considered the dependence of the asymmetry coefficient on intensity, the excitation potential of a low level, as well as its change along the disk of the Sun. The principal drawbacks of the above-mentioned methods are as follows:

1. Asymmetry of the absorption line profile was qualitatively described.
2. There was no definite parameter characterizing the asymmetry of line profiles quantitatively.
3. There was no parameter characterizing the whole Fraunhofer line profile asymmetry.
4. It was not possible to investigate the statistic dependence of Fraunhofer line profile asymmetry on atomic and photospheric values.

To solve the problem of the dependence of Fraunhofer line profile asymmetry on the atomic and photospheric values it is necessary to introduce a quiet definite parameter characterizing asymmetry of a whole line profile. To solve this problem Kuli-Zade [49–51] for the first time offers a new qualitative method for description and measurement of the Fraunhofer lines profile asymmetry. For this objective he introduced the new dimensional quantities with definite physical meaning. These values enable one to characterize the asymmetric property of line absorption profile in the solar and stellar spectra in detail and, which is important, quantitatively.

The new values introduced by us are as follows:

1. Differential asymmetry – determines a value of asymmetry in the given depth of line profile qualitatively. It shows a change of the asymmetry inside a line profile by value and sign as well.
2. Integral asymmetry – defines asymmetry of the whole line profile.
3. Residual asymmetry – defines a dominance of the violet or red asymmetry for the whole line profile quantatively.
4. Relative asymmetry – defines the fixed integral asymmetry of the whole line profile in units of equivalent widths.

These values permit us to investigate asymmetry of the Fraunhofer line profiles in detail as well as their dependence on atomic and photospheric parameters.

2 The method of asymmetry coefficient

In theoretical studies, in particular, in the theory of elementary particles the value

$$k = \frac{R_{vi} - R_{ri}}{R_{vi} + R_{ri}}$$

is called the asymmetry coefficient, where R_{vi} and R_{ri} are the depths of the violet and red wings, located at the same distance from the center of distribution. Applying this formula to the special line it can be rewritten as follows:

$$k = \frac{R(-\Delta\lambda_i) - R_(+\Delta\lambda_i)}{R(-\Delta\lambda_i) - R_(+\Delta\lambda_i)},$$

where R is the depth of a profile at a distance $\Delta\lambda$ from the center of a line. Here $\Delta\lambda_i$ corresponds to the violet wing, and $+\Delta\lambda_i$ to the red wing of a line profile.

However, in experimental studies, the asymmetry coefficient in such form is not convenient to use, because it cannot characterize the asymmetry of a line profile. Besides, it can differ greatly for different depths and this makes its application inappropriate.

The strictly mathematic asymmetry coefficient of the function describing the spectral line profile is defined as [68–69]:

$$k = \frac{M_3}{(\sqrt{M_2})^3}, \tag{1}$$

where

$$M_2 = \sum_{i=1}^{N} (\Delta\lambda_i - \overline{\Delta\lambda})^2 p_i, \tag{2}$$

$$M_3 = \sum_{i=1}^{N} (\Delta\lambda_i - \overline{\Delta\lambda})^3 p_i \tag{3}$$

are the central moments of a function of the second and third orders.

In (2) and (3), $\Delta\lambda_i$ are the current values of an accidental $\Delta\lambda$ (the distance from the center to the given point of a line profile); $\overline{\Delta\lambda}$, mathematical expectation of an accidental value $\Delta\lambda$ and p_i is the probability of an accidental value $\Delta\lambda$ in point i.

The profile of Fraunhofer lines is usually expressed as dependence of residual intensity $r(\Delta\lambda)$ on $\Delta\lambda$. We will express it as dependence of fixed depth of the profile $R\prime(\Delta\lambda) = \dfrac{R(\Delta\lambda)}{R_0}$ on $\Delta\lambda$ as it is shown in Fig. 1.

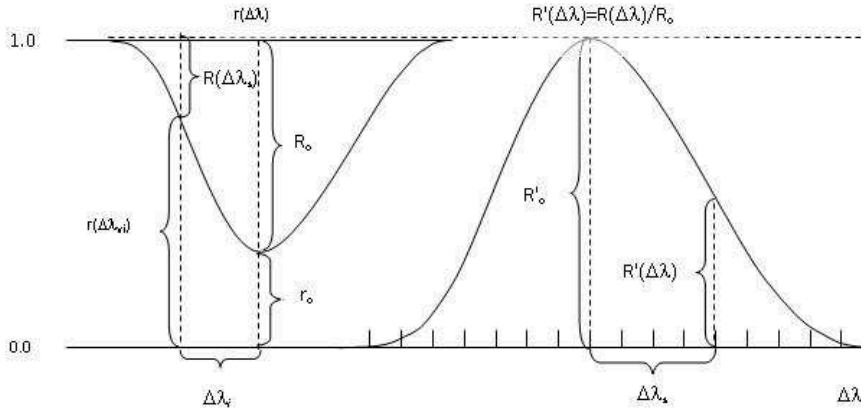


Figure 1 To determination of asymmetry coefficient of the line profiles.

To find the values of $\Delta\lambda_i$, p_i and $\overline{\Delta\lambda_i}$, let us divide the range of values $\Delta\lambda$ into N equal intervals. If we designate the depth of the profile in the point i corresponding to the distance from the center of the profile of line as $\Delta\lambda_i$ by $R(\Delta\lambda_i)$ then we may write:

$$\overline{\Delta\lambda} = \sum_{i=1}^{N} \Delta\lambda_i p_i, \tag{4}$$

$$p_i = \frac{R(\Delta\lambda_i)}{\sum\limits_{i=1}^{N} R(\Delta\lambda_i)}. \tag{5}$$

It is obvious that

$$\sum_{i=1}^{N} p_i = 1. \tag{6}$$

Kuli-Zade and Shabanova [71, 72] have calculated the central moments M_2 and M_3, as well as asymmetry coefficient k of 100 weak and moderate Fraunhofer lines in the resolved and unresolved spectrum of the Sun on the basis of modern spectral materials with high dispersion. The calculations were carried out using an original computer programme.

It turned out that the asymmetry coefficients k for diverse lines can be positive (a positive excess) and negative (a negative excess).

For the resolved spectrum of the Sun, 76 lines out of 95 lines considered are characterized by a positive excess ($k > 0$), and 13 lines by a negative excess ($k < 0$). In the unresolved spectrum of the Sun, 64 lines out of 95 are characterized by a positive excess ($k > 0$) and 31 lines by a negative excess ($k < 0$).

In Figs 2 and 3 the dependence of asymmetry coefficient k on the equivalent widths of the lines W for the resolved and unresolved spectrum of the Sun, respectively, is shown. As it is seen, in both cases the modulus of asymmetry coefficient $|k|$ noticeably decreases with increase of the equivalent widths of the lines and at $W \approx 120$ mÅ approaches zero. It should be emphasized that previous studies paid no attention to the sign of the asymmetry coefficient and therefore we found that it decreases with increase of lines equivalent widths.

Kostik [16] studied the change of the asymmetry coefficient along the disk of the Sun. He found that on approach to the limb of the Sun k considerably decreases. He determined the distance from the center of the disk of the Sun, where the sign of asymmetry changes. It turned out to depend on lines intensity. For weak lines (equivalent width $W < 25$ mÅ) it takes place at $\cos\vartheta = 0.35$ and for strong lines (equivalent width $W > 100$ mÅ) at $\cos\vartheta = 0.65$. He found that asymmetry changes its sign, on average, at $\cos\vartheta = 0.50$. Kuli-Zade and Shabanova [71, 72] have shown for the first time that not k, but its absolute value, i.e. $|k|$, decreases with an increase of lines intensity. So, positive and negative values of k with increase of the equivalent widths approach zero on both sides.

The changes of positive ($k > 0$) and negative ($k < 0$) coefficients of asymmetry of Fraunhofer lines profiles with increase of their equivalent widths in the unresolved spectrum of the Sun (where the number of lines with a negative excess almost three times than in the resolved spectrum) become apparent more distinctly. The change

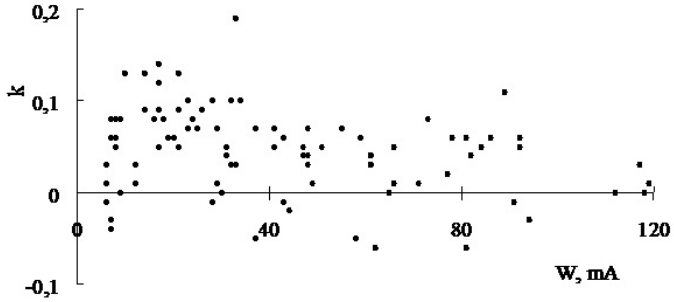


Figure 2 The dependence of asymmetry coefficient on the equivalent width for the resolved spectrum of the Sun (disk centre).

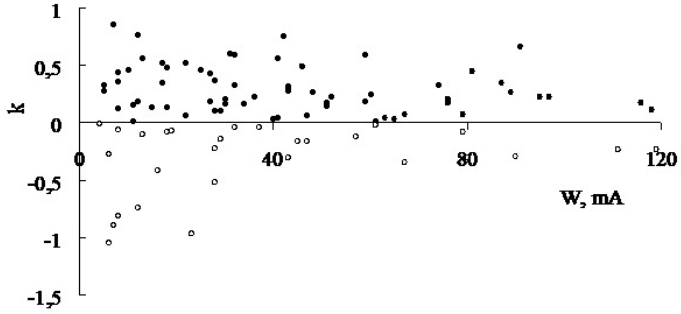


Figure 3 The dependence of the asymmetry coefficient on the equivalent width for the unresolved spectrum of the Sun (flux).

of negative k ($k < 0$) with the increase of line intensity looks like an almost mirror reflection of the change of positive k ($k > 0$).

However, later we will show that the decrease of asymmetry coefficient with growth of lines intensity is physically not explicable and most likely is an error of the method of asymmetry coefficient for lines profiles.

3 The bisector method

It should be noted that the bisector method for discovery and analysis of the fine structure of the weak Fraunhofer lines profiles in the spectrum of the Sun was first proposed by Dravins et al. [24, 25]. This method is not qualitative but should be mentioned, though in its time it played a definite role in Fraunhofer lines profiles asymmetry study.

Bisector is a geometrical place of the middle of the chords connecting the points on the violet and red wings of the lines profiles having the identical residual intensity or the same depths.

Balthasar divides the lines into three classes by depths of formation of their cores in the photosphere of the Sun [27]. According to Balthasar, for lines formed on the higher layers, i.e. comparatively high lines, bisector recalls "C", with decrease of the height of formation of the lines the lower part of "C" disappears, but for weak lines it turns into "═══". Bisector of the lines profiles most of all depends on intensity of the lines, which was noted in the works of Kostik [16] and Dravins et al. [25].

Kostik and Orlova [14, 15] showed that for the weak lines the curvature of the bisector increases with increasing of the excitation potential of the low level lines.

The curvature of bisector decreases somewhat according to the wavelength which was studied for the first time by Kostik [16] and Dravins at al. [25]. In addition, Dravins et al. [23, 26] showed that for comparatively strong lines the curvature of bisector grows a little from arc lines of iron to ores.

The change of asymmetry of Fraunhofer lines profiles in the disk of the Sun has not been studied yet in detail. It is connected with the fact that bisector of a profile is not sensitive to the changes of a physical state of photosphere of the Sun. On other hand, for the study of the change of asymmetry by the disk of the Sun it is necessary to measure the absolute shifts of the considered lines in the spectrum of the disk limb.

Stathopoulou and Alissandrakis [70] studied the profiles of 75 Fe I lines in the center of the disk of the Sun ($\mu = 1.0$), near the edge of the Sun disk ($\mu = 0.2$) and in the full flux on the basis of the spectral materials obtained at the Kitt Peak National Observatory. They determined the depths of formation of the centers of the lines in these three cases and qualitatively showed that asymmetry decreases with optic depth.

4 The Kuli-Zade method

To describe the asymmetric property of lines profiles, Kuli-Zade has proposed a new qualitative method and introduced new dimensional physical values characterizing the asymmetric property of Fraunhofer line profiles quantitatively [49–51].

The method consists of the following:

Let us determine the mean of the line profile on the height of half width of $\Delta\lambda_{1/2}$ and draw a line perpendicular to X axis through it. We will determine the points with the identical residual intensity.

It is obvious that

$$r(\Delta\lambda_{vi}) = r(\Delta\lambda_{ri}). \tag{7}$$

If a line profile is symmetrical on the given depth, then

$$\Delta\lambda_{vi} = \Delta\lambda_{ri}, \tag{8}$$

but if a line profile is asymmetric, then

$$\Delta\lambda_{vi} \neq \Delta\lambda_{ri}. \tag{9}$$

Here $\Delta\lambda_{vi}$ and $\Delta\lambda_{ri}$ are the distances from the center of the lines profiles on the arbitrary depth R_i for the violet and red wings, correspondingly. Then the difference

$$\delta(R_i) = \Delta\lambda_{vi} - \Delta\lambda_{ri} \tag{10}$$

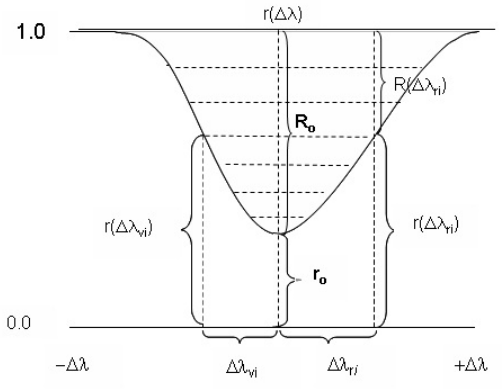


Figure 4 To determine the differential asymmetry of line profile.

may characterize the asymmetric nature of a line profile on the depth $R(\Delta\lambda_i)$.

We will call this value differential asymmetry. Both the value and sign of the differential asymmetry change with the profile depth.

If

$$\delta(R_i) > 0$$

let us call this asymmetry violet, but if

$$\delta(R_i) < 0$$

we will call it red. If

$$\delta(R_i) = 0$$

the line profile on the given point will be symmetric.

Let us assume that the dependence of differential asymmetry $\delta(R)$ on the depth of the profile R for some Fraunhofer lines looks as illustrated in Fig. 5.

Then we find that inside a line profile the differential asymmetry changes its sign three times: at $R = 0.20$, $R = 0.58$ and $R = 80$. In the ranges $R = 0.0$–0.20 and $R = 0.58$–0.80

$$\delta(R_i) > 0,$$

i.e. violet asymmetry takes place. In the ranges $R = 0.20$–0.58 and $R = 0.80$–0.94

$$\delta(R_i) < 0,$$

i.e. red asymmetry takes place.

We will name the field formed by the dependence $\delta(R_i)$ on R (hatched field in Fig. 5) integral asymmetry. It is obvious that integral asymmetry may be expressed as follows:

$$\Lambda = \int_0^{R_0} |\delta(R_i)| dR = \sum_i |\delta(R_i)| \Delta R_i, \tag{11}$$

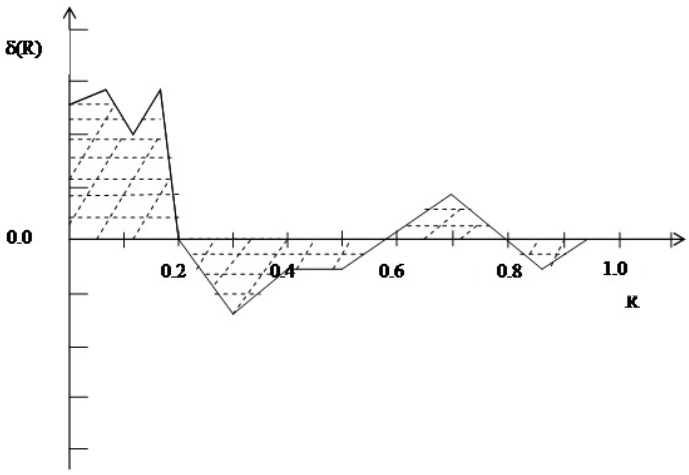


Figure 5 To determine the differential asymmetry of line profile.

where R_o is the central depth of a profile. The difference of positive and negative fraction of integral asymmetry

$$\Delta\Lambda = \sum_{\delta(R)>0} |\delta(R_i)|\Delta R_i - \sum_{\delta(R)<0} |\delta(R_i)|\Delta R_i \tag{12}$$

we will call residual asymmetry. It shows a predominance of violet and red asymmetries.

If

$$\Delta\Lambda > 0,$$

then violet asymmetry predominates; if

$$\Delta\Lambda < 0,$$

then red asymmetry predominates; and if

$$\Delta\Lambda = 0,$$

then both asymmetries have equal weights.

Let us call the value

$$\Lambda_0 = \frac{\sum\limits_i |\delta(R_i)|\Delta R_i}{W} \tag{13}$$

relative asymmetry where W is the equivalent width of a line profile.

It is obvious that if to designate positive share of integral asymmetry Λ through

$$\Lambda_+ = \sum_{\delta(R)>0} |\delta(R_i)|\Delta R_i \tag{14}$$

and negative through

$$\Lambda_- = \sum_{\delta(R)<0} |\delta(R_i)|\Delta R_i, \tag{15}$$

at

$$\Lambda_+ = \sum_{\delta(R)>0} |\delta(R_i)|\Delta R_i = 0 \tag{16}$$

a line profile is entirely characterized by red asymmetry and, at

$$\Lambda_- = \sum_{\delta(R)<0} |\delta(R_i)|\Delta R_i = 0 \tag{17}$$

the line profile is characterized by violet asymmetry.

Thus, the new method proposed by us permits us to make a more detailed depiction and study the asymmetry of Fraunhofer lines profiles in the spectrum of the Sun and stars. In contrast to the bisector method, in our method the asymmetry of absorption lines profiles is characterized by the qualitative values having a definite physical sense.

Indeed, it turned out that inside the given line profile $\delta(R)$ can change its sign several times from $\delta(R) > 0$ to $\delta(R) < 0$, i.e. from violet to red asymmetry and vice versa.

The original program for the values characterizing line profile asymmetry has been worked out [52].

In Fig. 6 as an example the dependence of the differential asymmetry $\delta(R)$ on the depth of R profile for the lines of oxygen infrared triplet in the resolved and unresolved spectrum of the Sun is presented. As it is seen in all the cases, with the distance from the center of the lines increasing towards to the wings, the values of differential asymmetry (violet $[\delta(R) > 0]$ and red $[\delta(R) < 0]$) decrease considerably.

Both in resolved and unresolved spectrum of Sun the character and sign for some lines remain. However, for other lines the asymmetry changes its sign to the opposite.

As it is seen in Fig. 6 in both resolved and unresolved spectrum of the Sun for all three lines of triplet almost in all the depths of profiles

$$\delta(R) > 0,$$

i.e. the profiles of all three lines are characterized by obvious violet asymmetry. Only in the nucleus itself an inconsiderable red asymmetry is observed. However, it should be noted that in the central parts of the profiles the accuracy of determining $\delta(R)$ is less than that in the wings.

From the resolved spectrum (center of the disk) to the unresolved (the full flux from the whole disk) for all three lines the value of asymmetry considerably decreases. The character of the change of differential asymmetry with increase of profile depth does not change practically.

Applying the above-mentioned Kuli-Zade method [57, 58] Λ_+, Λ_-, Λ, $\Delta\Lambda$ and Λ_o for 95 weak and moderate non-blending Fe I, Ni I, Ti I, Cr I, Fe II, Ti II, Cr II Fraunhofer lines and others in the resolved and unresolved spectrum of the Sun have determined. They found that in the resolved spectrum for 49 lines out of 95 studied lines, violet asymmetry predominates, and for 46 lines the predominant asymmetry is red. In the unresolved spectrum for 28 lines, violet asymmetry predominates, but for 67 lines red asymmetry does. So, in the resolved spectrum of the Sun for majority of the lines violet asymmetry, and in the unresolved spectrum red asymmetry, is typical.

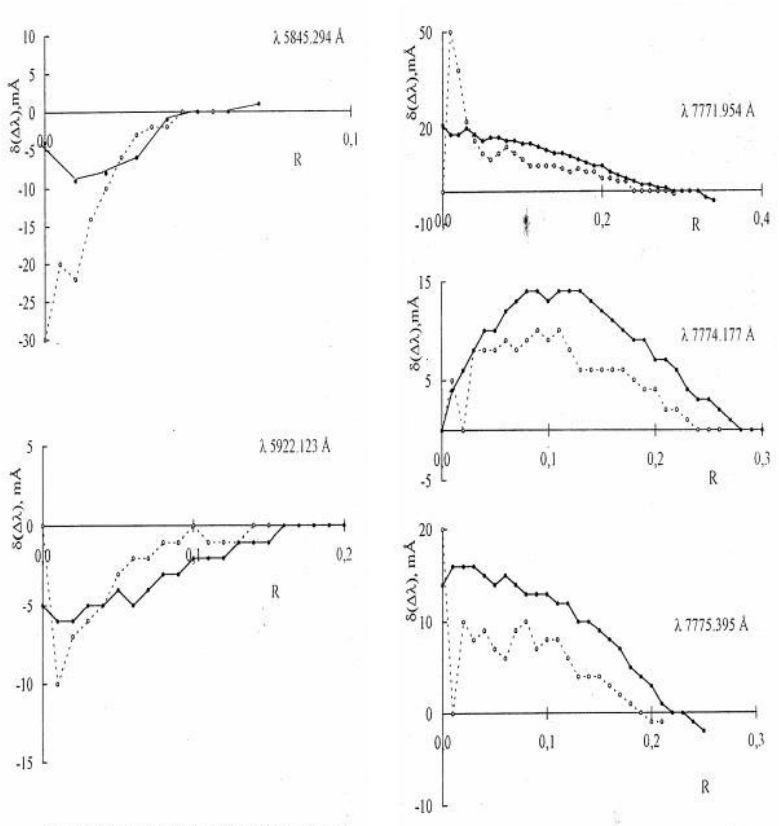


Figure 6 Dependences of differential asymmetry on line profile depths. ∘∘ unresolved spectrum of the Sun; •• resolved spectrum of the Sun.

In Fig. 6, the dependences of differential asymmetry on line depths for lines λ5845.294 Å and λ5922.123 Å are also given.

In the resolved spectrum of the Sun (the center of the disk) for lines λ5293.375 Å Cr I, λ5295.321 Å Fe I, λ5386.340 Å Fe I, λ5661.354 Å Fe I, λ5677.695 Å Fe I, λ5719.828 Å Cr I, λ5811.919 Å Fe I, λ5844.668 Å Cr I, λ5844.933 Å Fe I, λ5845.294 ÅFe, λ5969.578 Å Fe I, λ6098.250 Å Fe I, λ6098.664 Å Ti I, λ6159.382 Å Fe I, λ6226.740 Å Fe I, λ6330.852 Å Fe I, λ6446.400 Å Fe II, λ6608.044 Å Fe I, λ7540.444 Å Fe I, λ7719.460 Å Fe I

$$\Lambda_+ = \sum_{\delta(R)>0} |\delta(R_i)|\Delta R_i \approx 0,$$

i.e. their profiles are completely characterized by red asymmetry, and for lines λ5342.708 Å Cd, λ5648.279 Å Cr I, λ6176.816 Å Ni I, λ6186.717 Å Ni I, λ6252.563 Å Fe I, λ6303.767 Å Ti I

$$\Lambda_- = \sum_{\delta(R)<0} |\delta(R_i)|\Delta R_i \approx 0.$$

i.e. their profiles are fully characterized by violet asymmetry.

In the resolved spectrum of the Sun (fall flow from the whole disk) for lines λ5197.942 Å Fe I, λ5223.190 Å Fe I, λ5293.375 Å Cr I, λ5305.866 Å Cr II, λ5320.040 Å Fe I, λ5608.981 Å Fe I, λ661.354 Å Fe I, λ5778.463 Å Fe I, λ5844.608 Å Cr I, λ5845.294 Å Fe I, λ5922.123 Å Ti I, λ5929.682 Å Fe I, λ6098.250 Å Fe I, λ6098.644 Å Ti I, λ7540.444 Å Fe I.

$$\Lambda_+ = \sum_i |+\delta(R_i)|\Delta R_i \approx 0,$$

i.e. the profiles of the lines are completely characterized by red asymmetry, for lines λ5367.476 Å Fe I, λ5522.454 Å Fe I, λ6246.36 Å Fe I, λ6303.461 Å Fe I, λ6430.856 Å Fe I

$$\Lambda_- = \sum_i |-\delta(R_i)|\Delta R_i \approx 0,$$

i.e. the profiles of the lines are completely characterized by violet asymmetry.

Hence it follows that in the resolved and unresolved spectrum of the Sun the number of Fraunhofer lines with red asymmetry is much more than that of the lines with violet asymmetry.

5 The dependence of asymmetry on power and depth of formation of Fraunhofer lines

As it was noted in the beginning, the previous methods did not permit us to characterize the asymmetric property of the profiles of weak and moderate Fraunhofer lines quantitatively.

Therefore it was impossible to study the dependence of asymmetry of the profiles of Fraunhofer lines from atomic and photospheric values. The new quantative method proposed by Kuli-Zade introduced new physical parameters such as integral, residual and relative asymmetry and permits us to study the dependence of asymmetry of

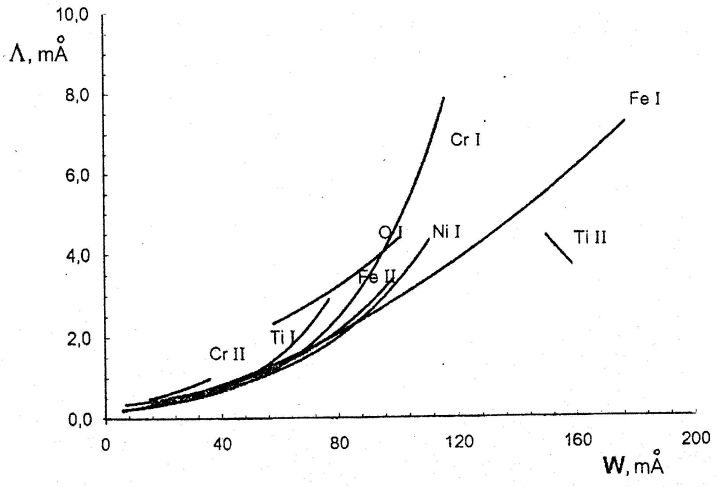


Figure 7 The dependence of integral asymmetry on the equivalent widths of the lines.

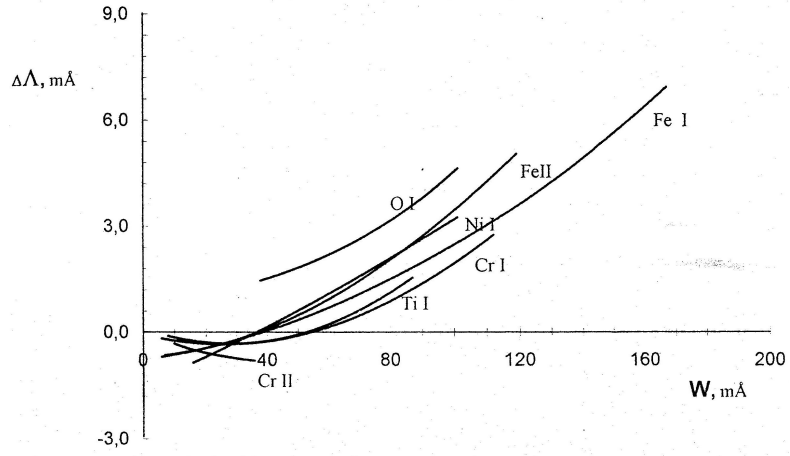


Figure 8 The dependence of residual asymmetry on the equivalent depths.

the Fraunhofer line profiles on their intensity (equivalent widths), efficient depths of formation in the photosphere of the Sun and etc. Thus we can obtain new information which can be useful in the analysis of physical processes leading to the observed asymmetries of the profiles of absorption lines in stellar atmospheres.

The dependence of integral, residual and relative asymmetry of the profiles of the weak and moderate Fraunhofer lines on their intensity and on formation depths in the photosphere of the Sun has been studied in detail in works of Kuli-Zade [52, 55, 56, 60, 62, 63, 65]. The lines of different chemical elements are considered separately.

In Fig. 7 the dependence of integral asymmetry Λ on the equivalent widths of W of the individual chemical elements is shown. As it is seen, there is obvious and considerable increase of Λ with growth of W for the lines of all the considered elements. Let us recall that according to the data of the different authors the coefficient of asymmetry, on the contrary, abruptly decreases with intensity of the lines. In Fig. 8 the dependence of residual asymmetry $\Delta\Lambda$ on the equivalent widths W of lines is given. As it is seen for all lines the considerable increase of $\Delta\Lambda$ with growth of W is observed.

In Fig. 9 the dependence of relative asymmetry Λ_o on the equivalent widths of the lines W is shown. It is clearly seen that with increase of line intensity, Λ_o first decreases somewhat, approximately at $W \approx 35$ mÅ it has minimum value, and then at $W > 35$ mÅ it slightly increases.

In Figs 10–11 the dependence of the integral Λ and residual $\Delta\Lambda$ asymmetries on the average effective depth of formation of the lines τ_o in the photosphere of the Sun for lines of various chemical elements is presented.

As it is seen with increase of τ, the integral, residual and relative asymmetries considerably increase. It was to be expected as weak lines are efficiently formed in deeper layers of photosphere than moderate ones. In general, with an increase of lines intensity their effective depth formations decrease.

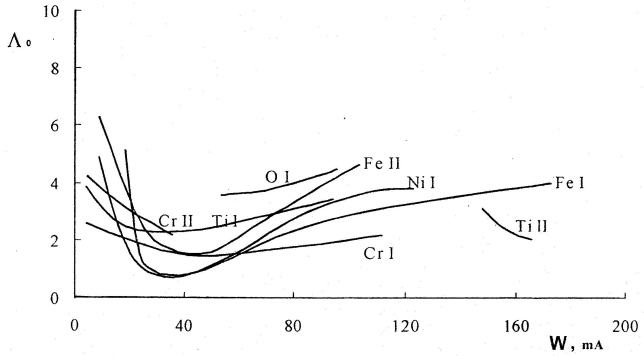


Figure 9 The dependence of relative asymmetry on the equivalent widths of the lines.

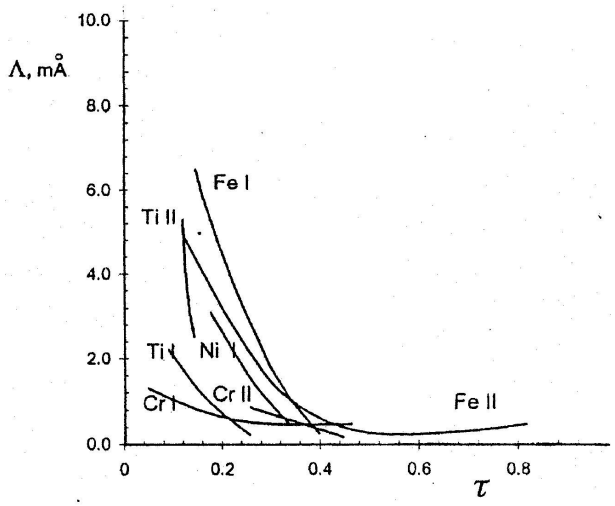


Figure 10 The dependence of integral asymmetry on the effective depth of lines formation.

6 Discussion

At present, it is supposed that Fraunhofer line profiles asymmetry in the solar spectrum is connected with dynamical processes in the photosphere. If it is so in reality, then intense lines should be more affected by dynamical processes than weak lines. This is due to the fact that intensive Fraunhofer lines are formed in the whole photosphere and, in particular, even in the lower part of the chromosphere. As to weak lines, they are formed in the fine layer of the low layers of the photosphere. Consequently, the asymmetry should indeed strengthen with increase of lines power just what is established by applying the new qualitative method proposed by us.

We consider the result about the decreasing of the coefficient k with the increase of equivalent line widths, obtained by application of the asymmetry coefficient method to be errors. To be more accurate, it is the error of the method that can not take into consideration the changes of asymmetry sign inside a line profile. Indeed, within

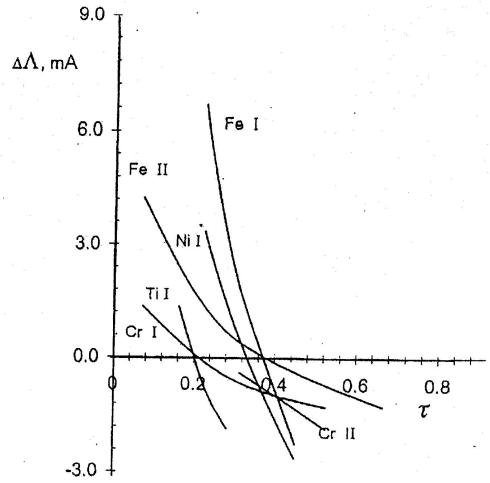


Figure 11 The dependence of residual asymmetry on the effective depth of lines formation.

the profile of a given line, asymmetry may repeatedly change its value and sign. Therefore, red asymmetry in one depth of a line profile can be compensated by violet asymmetry in other depths. As a result, line profile asymmetry decreases and even asymmetric intense lines may become almost symmetric.

In the method proposed by Kuli-Zade this fact is taken into account, i.e. when determining the summary asymmetry of Fraunhofer line profiles, the modules of its positive and negative fraction are summed up.

This method enables one to characterize weak and moderate Fraunhofer line profiles asymmetry in the spectrum of the Sun and stars in detail and qualitatively. Asymmetry of line profiles is characterized by dimensional parameters having a definite physical sense.

Integrated asymmetry of line profiles, as it was to be expected, considerably increases with the growth of line intensity. At that both residual and relative asymmetries of line profiles increase as well. On the other hand, with the increase of the average effective depth of formation the integral, residual and relative asymmetries of a line heavily decrease. This is in full agreement with the result of line intensity dependence.

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