Asymmetry of Lines in the Spectra of the Sun and Solar-Type Stars

V. A. Sheminova

Main Astronomical Observatory, National Academy of Sciences of Ukraine,
Akademika Zabolotnoho 27, Kyiv, 03143 Ukraine
e-mail: shem@mao.kiev.ua

Abstract

We have analysed the asymmetry of lines Fe I and Fe II in spectra of a solar flux using three FTS atlases and the HARPS atlas and also in spectra of 13 stars using observation data on the HARPS spectrograph. To reduce observation noise individual line bisectors of each star have been averaged. The obtained average bisectors in the stellar spectra are more or less similar to the shape C well known to the Sun. In stars with rotation speeds greater than 5 km/s the shape of the bisectors is more like /. The curvature and span of the bisectors increase with the temperature of the star. Our results confirm the known facts about strong influence of rotation velocity on the span and shape of bisectors. The average convective speed was determined based on the span of the average bisector, which shows the largest difference between the velocity of cold falling and hot rising convective flows of the matter. It’s equal to −420 m/s for the Sun as a star. In solar-type stars, it grows from −150 to −700 m/s with an effective temperature of 4800 to 6200 K, respectively. For stars with greater surface gravity and greater metallicity, the average convective velocity decreases. It also decreases with star age and correlates with the speed of micro and macroturbulent movements. The results of solar flux analysis showed that absolute wavelength scales in the FTS atlases used coincide with an accuracy of about −10 m/s, except for the atlas of Hinkle, etc., whose scale is shifted and depends on the wavelength. In the range from 450 to 650 nm, the scale shift of this atlas varies from −100 to −330 m/s, respectively, and it equals on average of −240 m/s. The resulting average star bisectors contain information about the fields of convective velocities and may be useful for hydrodynamic modeling of stellar atmospheres in order to study the characteristic features of surface convection.

Keywords: line asymmetry, line profiles, solar-type stars, velocity field, granulation.

1 Introduction

In stellar spectra asymmetry of absorption lines may arise due to dark spots, bright points, and bright plages, as well as due to oscillations, pulsations, granulation, and line blending. The main cause of asymmetry in solar-type stars is granulation [14]. It is directly observed in images of the solar surface as a granulation pattern. For main-sequence stars direct observation of granulation is impossible, however, signatures of stellar granulation can be studied by analyzing the asymmetries of the absorption line profiles. By studying the asymmetry of many lines, we can obtain information about the characteristics of surface convection in stars. The observation of spectral lines in stars, as compared with the Sun, has a number of limitations. Firstly, in cases of stars we observe a disk-integral flux, which leads to the weakening of the Doppler shifts. Secondly, the absolute line shifts cannot be measured due to the lack of data on the exact radial velocities of many stars. Thirdly, the rotation of the stars affects the shape of the line profiles and alters the asymmetry. Fourthly, spectral lines become weaker in low-resolution stellar spectra, and profile distortions increase. This should be borne in mind when studying the asymmetry of lines in stars.

The appearance of granulation on the stellar surface is caused by convection in the surface layers, which creates wide upward flows of hot matter, so-called granules, and cold downward flows, or intergranules. Granules make a blue contribution to the spectral line due to the matter’s ascent velocity. Cold intergranules are narrow because of the smaller area and they make a red contribution
due to the matter’s descent velocity. The combined effect of all contributions integrated over the stellar surface creates asymmetric line profiles [14]. Photospheric velocities that are directly caused by convection and affect the asymmetry of lines are called convective or granulation velocities. According to [22], the average velocity of the distribution of granulation velocities is the average ascent velocity of granules \( V = V_{\text{col}} - V_{\text{hot}} \), where \( V_{\text{col}} \) and \( V_{\text{hot}} \) velocity of granules are the velocities of cold and hot matter, respectively; the dispersion of this distribution is the so-called macroturbulent velocity \( V_{\text{mac}} \). Simple modeling showed that the average granulation velocity affects the asymmetry, while the velocity dispersion affects the line width, and always \( V < V_{\text{mac}} \). As noted in [18], asymmetry is controlled by three parameters: (1) average velocity of granules and intergranules, (2) brightness contrast between granules and intergranules, and (3) the fraction of the stellar disk area occupied by granules in relation to intergranules. For a star, (2) and (3) are combined into a flux contrast \( (F_{\text{hot}} - F_{\text{col}})/(F_{\text{hot}} + F_{\text{col}}) \), where \( F_{\text{hot}} \) is the flux emitted by all granules, and \( F_{\text{col}} \) is the flux emitted by all intergranules on the stellar disk. The higher the degree of correlation between the velocity and temperature in the granules and in the intergranules, the stronger the asymmetry of the observed line. The rotation velocity \( v \sin i \) also affects the asymmetry when it is higher than \( V_{\text{mac}} \). According to [38], the asymmetry is to a lesser extent influenced by the abundance of chemical elements and the activity of stars, and the latter decreases the line asymmetry in comparison with inactive stars.

The asymmetry of the profiles is quantitatively characterized by the bisector, which represents the dependence between convective shifts and the relative flux of radiation at each point of the line profile. The most complete picture of convective shifts is seen for strong lines. This is due to a significant difference in physical conditions at different effective formation depths of each segment of the line where the bisector is measured. Early studies of the solar spectrum [7, 14, 29, 32] established that the bisector has a typical shape similar to the letter C. The upper part of the profile near the continuum has a small blue shift due to significant contributions of radiation from intergranules in the deep layers of the photosphere. The largest blue shift occurs closer to the middle of the profile due to the predominant fraction of radiation from hot rising granules. The core of a strong line has a smaller blue shift because the radiation contrast between granules and intergranules decreases in the upper photospheric layers of the core formation. The asymmetry of the line profile varies depending on the line depth and atomic parameters, such as chemical composition, excitation and ionization potential, wavelength, oscillator strength, i.e., the parameters that determine the effective depth of line formation in the atmosphere.

Stellar bisectors show significant differences both in the shape and the magnitude of the blue span with variations in effective temperature, luminosity class, or gravity. According to the results of stellar spectra studies [3, 11, 12, 13, 18, 19, 21, 22, 38], the bisector does not show the C-shape in all cold FGK stars of the main sequence; this shape is often slightly distorted, and sometimes only the upper part of the letter C is visible. The differences in shape from one star to another depend on the strength of granulation and the structure of the atmosphere. The span or shift of the bluest point of the bisector, which characterizes the average granulation velocity of the star, decreases from F- to K-stars. For giants, the span is larger than for dwarfs. The brighter the star (or the greater the luminosity, or the smaller the gravity), the lower the height of the bluest point of the bisector, and the higher the granulation penetrates into the atmosphere. The spectra of stars with a very low metal abundance reveal a significantly greater line asymmetry and a wider range of velocities than stars of the same class with solar metallicity [2]. This fact is interpreted as a signature of a low metal abundance and, therefore, a low opacity in convective atmospheres. There is also another feature of asymmetry: if we proceed along the main sequence towards higher temperatures, the line bisectors in the F0 zone change their tilt to the opposite direction. This boundary separating the two modes is called the granulation boundary [21, 23]. It is assumed that convection in hot F0V stars is qualitatively different: granules are small and quickly rise upward, while intergranules are large and descend slowly.

To better understand stellar granulation and its effect on the observed spectra, hydrodynamic modeling of the solar and stellar atmospheres is performed, which takes into account atmospheric inhomogeneities associated with the granulation phenomenon. The first studies on granulation modeling [3, 6, 15] predicted that the energy flux passing through the atmosphere is the most important parameter that affects the magnitude of blue shifts and, therefore, the span of the bisector. The correlation between temperature, velocity, and density is weaker in cold dwarfs than in hotter stars. Subsequent
studies on modeling the convective envelopes of stars, e.g., [1, 4, 9, 39], confirmed and explained many observational features of bisectors. Despite the great progress in modeling, theoretical calculations were carried out only for some FGK stars using a limited set of spectral characteristics and were verified against a limited set of observations. It is necessary to study a larger number of stars with hotter and colder temperatures. Careful validation of the models on high-quality observed spectra is required. It is especially important to verify the models for coincidence with the bisectors of many observed lines. This should be done so that the granulation properties predicted by the models can be guaranteed to be fully reliable. Therefore, obtaining new data on the asymmetry of the observed lines and on their bisectors for stars with different characteristics remains an important problem in the physics of stellar atmospheres. Solving this problem requires high quality stellar spectra and careful selection of absorption lines to reduce the bisector errors.

The aim of this study is to measure the line bisectors in the spectra of solar-type stars with different characteristics and to trace the change in their shape with the variations in the stars’ parameters. In other words, this study is dedicated to the second signature of stellar granulation, i.e., line asymmetry. The first signature of granulation is the broadening of the line profiles by macroturbulent motions, and the third signature of granulation is the blue shift of lines due to the dominant contributions of hot granules. The well-known parameter of classical macroturbulence shows the strength of granulation in one or another star. In our previous study [42], we already investigated the first signature of granulation in the stars that are analyzed here. This enables us to perform a comparison of convective and macroturbulent velocities and confirm the existing understanding of granulation processes and its effect on spectral lines.

2 Initial data and methods

Observation data. Table 1 shows the basic data for the stars whose spectra we will analyze. These stars are from the Calan-Hertfordshire Extrasolar Planet Search (CHEPS) sample. The main characteristics of the stars, such as effective temperature $T_{\text{eff}}$, surface gravity $\log g$, and metallicity $[M/H]$, were taken from [27], the data on mass $m$ and age from [36], and the data on macroturbulent velocity $V_{\text{mac}}$ and rotational velocity $v\sin i$ from [42]. The spectral types correspond to the data from the SIMBAD database (http://cdsportal.u-strasbg.fr). All the stars are single and inactive ($\log R_{\text{HK}} \leq -4.5$ dex). The $T_{\text{eff}}$ range is small, from 4800 to 6200 K. Some of the stars are slightly enriched in metals with $[M/H]$ from 0.06 to 0.34, while others have a small metal deficit from $-0.05$ to $-0.15$.

| HD     | Type     | $T_{\text{eff}}$ (K) | $\log g$ | $[M/H]$ | $M/M_\odot$ | Age (Gy) | $V_{\text{mac}}$ (km/s) | $v\sin i$ (km/s) | $n$ | $V$ (m/s) |
|--------|----------|----------------------|----------|---------|-------------|----------|------------------------|-----------------|------|---------|
| 189627 | F7 V     | 6210                 | 4.40     | 0.07    | 1.244       | 4.0      | 5.52                   | 5.93            | 31   | -606    |
| 92003  | F0 V     | 6158                 | 5.10     | 0.27    | 1.087       | 7.2      | 2.20                   | 2.09            | 37   | -573    |
| 93849  | G0/1 V   | 6153                 | 4.21     | 0.08    | 1.268       | 3.5      | 2.92                   | 3.05            | 41   | -696    |
| 158469 | F8/G2 V  | 6105                 | 4.19     | -0.14   | 1.223       | 2.0      | 3.61                   | 3.10            | 44   | -686    |
| 127423 | G0 V     | 6020                 | 4.26     | -0.09   | 1.107       | 3.1      | 2.90                   | 2.53            | 34   | -442    |
| 6790   | G0 V     | 6012                 | 4.40     | -0.06   | 1.098       | 3.5      | 3.16                   | 2.94            | 32   | -511    |
| 102196 | G2 V     | 6012                 | 3.90     | -0.05   | 1.395       | 3.0      | 4.26                   | 3.56            | 36   | -630    |
| 102361 | F8 V     | 5978                 | 4.12     | -0.15   | 1.250       | 2.0      | 5.62                   | 5.03            | 47   | -600    |
| 147873 | G1 V     | 5972                 | 3.90     | -0.09   | 1.493       | 2.6      | 5.95                   | 6.51            | 34   | -586    |
| Sun    | G2 V     | 5777                 | 4.44     | 0.00    | 1.000       | 4.6      | 2.11                   | 1.84            | 61   | -456    |
| 38459  | K1 IV-V  | 5233                 | 4.43     | 0.06    | 0.882       | 9.0      | 3.20                   | 1.85            | 37   | -220    |
| 42936  | K0 IV-V  | 5126                 | 4.44     | 0.19    | 0.881       | 12.0     | 3.14                   | 0.97            | 26   | -338    |
| 221575 | K2 V     | 5037                 | 4.49     | -0.11   | 0.823       | 6.0      | 2.79                   | 1.89            | 36   | -152    |
| 128356 | K2.5 IV  | 4875                 | 4.58     | 0.34    | 0.824       | 15.5     | 1.74                   | 1.01            | 19   | -220    |

The spectra of the stars were obtained with the HARPS (High-Accuracy Radial Velocity Planetary Searcher) spectrograph at La Silla in Chile [28]. The signal-to-noise ratio is above 100. The spectral resolution $R \approx 120000$ is rather low for this problem; however, according to [19], this is sufficient,
since the nominal spectral resolution should be at least 100000.

**List of spectral lines.** The lines were selected visually using a graphic solar atlas \[44\] with a high resolution \( R \approx 700000 \). To reduce uncertainties due to noise, bisectors were measured in the \( F_\lambda/F_c \) range from 0.1 to 0.95. Here, \( F_\lambda \) and \( F_c \) are the radiation fluxes in the line and the continuum, respectively. The selected lines were in the wavelength range from 450 to 650 nm. The number of lines varied from star to star, because new blends appeared in the line profiles with decreasing \( T_{\text{eff}} \). The presence of subtle blends in the profiles was checked by analyzing the bisectors and comparing them with the mean bisector. As a result of this selection, the final lists of lines in different stars mainly differed in the range of very weak and strong lines. The number of lines \( n \) is given in Table 1.

**Measurement of the central wavelength of a line.** To accurately determine the wavelength of a line in the spectrum of a star is only possible for a symmetrical profile. In reality, stellar spectral lines are always asymmetric and distorted by blends and noise, which makes it impossible to accurately and unambiguously calculate their central wavelength. There are various procedures for measuring the line wavelength \[25\]. In most cases, the wavelength of the line is determined by fitting polynomials of the 2–4 order by the number of points nearest to the minimum. We have chosen, in our opinion, a more error-tolerant method using the center of gravity of the line core \[10\]. The accuracy of this method is not affected by a strong or weak, wide or narrow line in the core. Mainly what matters is the interpolation step of the profile. In our case, it was equal to 0.1 pm.

**Calculation of the convective line shifts.** For stars, it is difficult to determine convective line shifts because the true radial velocity of the stellar center of mass is not known accurately enough. To exclude the influence of the radial velocity, the zero point of the shifts is established using absolute solar shifts, as was done in \[20\], or an arbitrary zero point is adopted using the shifts of the core wavelengths of the strongest lines. In \[32\], to determine the convective line shifts observed in magnetic formations on the solar surface, the strong line \( \text{Mg I} \) \( \lambda 517.27 \) nm was used (hereinafter referred to as the “Mg line”) based on the assumption that the core of this line forms high in the atmosphere, where the brightness contrast nearly disappears and its convective shift will be almost zero. This line was also used in \[10\] along with a group of strong iron lines to determine the zero point of the shifts of the observed lines in magnetic formations. In the study of K-dwarfs \[38\], the shifts of the cores of the strongest lines of iron were also used on the basis of the assumption that they are equal to zero, which was based on the results obtained for the solar spectrum in \[2\].

In this study, we used the Mg line. This allowed us to eliminate Doppler shifts due to the radial velocity of the star relative to the observer on the Earth, gravitational displacement, and other displacements if they were not taken into account in the calibration of the observations as well as errors in the method of measuring the central wavelength. Such a zero point of the shift scale will contain an error that is equal to the intrinsic convective shift of the Mg line. Such a scale for stellar spectra will henceforth be called the Mg scale. In this scale, the convective shift of the spectral line is easily calculated relative to the laboratory wavelength in units of velocity using the following formula

\[
V = c(\lambda_{\text{obs}} - \lambda_{\text{lab}})/\lambda_{\text{lab}} - c(\lambda_{\text{Mg}}^{\text{Mg}} - \lambda_{\text{lab}}^{\text{Mg}})/\lambda_{\text{lab}}. \tag{1}
\]

Here \( \lambda_{\text{obs}} \) is the measured central wavelength of the observed line in the spectrum of the star, \( \lambda_{\text{lab}} \) is the laboratory wavelength. The superscript Mg indicates the Mg line. We have applied this formula to all stars and tested it using the Sun’s spectrum.

**Laboratory wavelengths.** To measure convective shifts, we used the results of laboratory studies of wavelengths \[34\]. The catalog of laboratory wavelengths presented in \[34\] is currently one of the most accurate and contains a complete list of iron lines. All the line wavelengths are divided into four categories depending on their errors (0.04 to 1 pm and larger). Most lines have an error below 0.05 pm, and approximately half of them are below 0.1 pm (or 60 m/s for a wavelength of 500.0 nm). For weaker lines \( (F_\lambda/F_c > 0.7) \), the error of laboratory wavelengths is approximately 2.5 times larger than for stronger lines.

**Plotting of the bisectors.** To obtain a bisector, we first interpolate the line profile using a cubic spline with a step of 0.01 pm. We then calculate the midpoints of the horizontal lines drawn from the measured point on the blue side of the line profile to the interpolated point on the red side of the profile. By connecting the resulting series of midpoints, we obtain a curve that is the bisector of the line. The ordinate axis on the bisector plots is the radiation flux \( F_\lambda/F_c \) normalized to the continuum,
and the abscissa axis is the wavelength shifts of the measured profile points calculated according to the above formula and converted to velocity units.

Since more and more blends appear in the spectra when proceeding to cooler stars, the line profiles become more noisy, their bisectors are more distorted, and the number of blendless lines decreases. For this reason, reliable results cannot be obtained by analyzing individual bisectors in the spectra of many stars. There is a practice to remove any noise by averaging the bisectors. For example, it was shown [3, 13] that it is possible by averaging bisectors to obtain a statistically reliable result by discarding points that deviate sharply from the mean bisector. We applied this method as well. All abrupt outliers were considered erroneous and removed from the averaging or the top and/or bottom parts of the bisector were cut off if they contained a large outlier. In such cases, there is inevitably some degree of subjective judgment, so we acted with caution. The mean bisector was calculated as the arithmetic mean of the positions of those bisectors that contribute at each absorption depth with a step of 1% of the intensity of the continuum. For each star, we averaged the individual bisectors in the Mg scale and then smoothed the mean bisector.

3 Line bisectors in the solar flux spectrum

**Individual and mean bisectors.** We performed an analysis of solar line bisectors to add the Sun to our sample of solar-type stars to ensure the validity of our results. For this purpose, we used the solar atlas [33], that represents the spectrum of the Moon-reflected solar flux obtained at HARPS in 2010 with a resolution $R \approx 120000$ in the spectral range from 476 to 585 nm and with a small gap in the range of 530–534 nm. We will refer to this atlas as HARPS. This atlas was calibrated using an ideal laser frequency comb (LFC) calibrator. The authors of this atlas claim that the wavelength solution is the most accurate of all currently possible and requires no other correction. We will use the HARPS atlas for the comparison with the results of the analysis of stellar spectra obtained with the same spectral resolution.

In addition, three more high-resolution solar flux atlases obtained with FTS (Fourier-Transform Spectrometers) were used. The HINKL FTS atlas [26] provides convenient access to the KURUCZ atlas [31] with a resolution $R \approx 340500, 521360, \text{and } 522900$ for the wavelength ranges of 401.9–473.8, 473.8–576.5, 576.5–753.9 nm, respectively. The NECKL FTS atlas [35] provides a high-quality spectrum with $R \approx 400000$ for the center of the disk and averaged spectrum over the entire disk. The IAG FTS atlas [40] has a very high resolution $R \approx 5 \times 10^6$ and an accurate wavelength scale. Its systematic deviation from the HARPS scale is approximately $-5 \pm 5 \text{ m/s}$ and it has no significant trend in the range of 480–580 nm. We will further use the IAG atlas as a reference for the comparison with the other atlases of the solar spectrum.

We have measured bisectors for 61 lines. All the bisectors of these lines, as well as the mean bisector, are shown in Fig. 1 in the absolute scales of each atlas. As can be seen, the range of blue shifts is the same for the IAG and NECKL atlases, while that for HARPS is narrower, and it is significantly broadened and shifted towards the blue part of the spectrum for the HINKL atlas. Figure 2a shows the mean bisectors of the four atlases in absolute scales. The average convective velocity was determined from the span of the mean bisector. For NECKL and IAG, it is $-418$ and $-423$ m/s, respectively. For the HARPS atlas, it is slightly lower ($-395$ m/s) due to the lower spectral resolution. The lower-resolution solar spectrum weakened by the reflection from the Moon shows smoother line profiles with less pronounced asymmetry. The authors of the HARPS spectrum provided the solar radiation flux that was not normalized to the continuum, so we used the local continuum for each individual line. This may partially affect the shape of the bisector near the continuum. For the HINKL atlas, the bisector span turned out to be the largest and, accordingly, the average convective velocity turned out to be large ($-636$ m/s). The shape of this bisector is also different from the IAG. The bend in the upper part of the bisector is smaller due to increased blue shifts of the weakest lines with wavelengths greater than 600 nm. Based on the comparison results, we came to the conclusion that the wavelength scales in the IAG, NECKL, and HARPS atlases nearly coincide within the analysis errors and are quite accurate. The average convective velocity in the photosphere of the Sun as a star measured from the data of these atlases is approximately $-420$ m/s. There appears to be an issue with the wavelength scale in the HINKL atlas, which will be discussed below.
Errors of the absolute scales of solar atlases. We compared the absolute shifts of the mean bisectors of each atlas with the IAG and, thus, estimated the error of the absolute scales in the wavelength range from 450 to 650 nm. The NECKL and HARPS atlases have an insignificant error of approximately $-10$ m/s (Fig. 2a), while the error in the HINKL atlas is $-240$ m/s. This infers that the absolute scales of the IAG, NECKL, and HARPS atlases can be considered to be reliable, while the HINKL scale cannot. The analysis of the shifts of individual bisectors showed that the scale shift in the HINKL atlas relative to IAG depends on the line wavelength. Figure 3 demonstrates this dependence for the HINKL atlas, while the IAG, NECKL, and HARPS atlases show only an insignificant trend, which is a consequence of this line selection. In the HINKL atlas, blue line shifts increase with wavelength. The greater the wavelength, the greater the bisector shift. The difference between the shifts in HINKL and IAG is approximately $-100$, $-220$, and $-330$ m/s for 450, 550, and 650 nm.
Figure 3: Absolute convective shifts of the iron lines in the solar flux spectrum according to the IAG, HINKL, NECKL, and HARPS atlases depending on the wavelength (the squares show the line shifts from the IAG atlas for comparison).

650 nm, respectively. The growth of the blue shifts with wavelength contradicts the physical sense. Just the opposite should be the case, since opacity increases with wavelength, the contrast between the granules and intergranules decreases, and the blue shift should decrease. As shown in [25], there is hardly any dependence of blue shifts on wavelength for lines of different strengths. However, if we select lines of equal strength, the blue shifts of these lines decrease with wavelength. That being said, weak lines show less dependence than strong lines. We used lines of different strengths, so there should be no dependence on the wavelength in our case. This suggests that the wavelength scale of the spectrum in the HINKL atlas is, apparently, not accurate enough. It was noted in [20] that the zero point in the HINKL atlas was reset, apparently in order to align the average positions of the Fe I lines with laboratory values [34]. According to the data presented [20], the shift between HINKL and IAG in the range 600–630 nm is $-336$ m/s. This agrees with our estimates for that particular range.

**Verification of the Mg scale.** Using the solar data, we can verify the Mg scale plotted with respect to the Mg line. Since all the solar atlases have absolute scales, we can trace possible uncertainties in the Mg scale. Figure 4 shows the mean bisectors in this scale (dashed line) and the bisectors in the absolute scale for each atlas (solid line). The bisectors in the Mg scale are shifted by the corresponding absolute shift of the Mg line in each atlas, the value of which depends on the calibration accuracy of the atlas. In absolute scales, this shift is $-204$ m/s (HINKL), 64 m/s (IAG), 60 m/s (NECKL), and 61 m/s (HARPS). The close values obtained for three atlases allow us to conclude that the Mg line in the solar spectrum has a small red shift of $\approx 60$ m/s. When comparing the mean bisectors of four atlases in the Mg scale (Fig. 2b), the difference between HINKL and IAG is significantly reduced. Almost all the mean bisectors are in satisfactory agreement within the analysis error. Therefore, we

Figure 4: Mean bisectors of the lines according to the data of the IAG, HINKL, NECKL, and HARPS atlases in the absolute scales (solid lines) and Mg scales (dashed lines).
can conclude that the use of the Mg line for constructing the wavelength scale allows reducing possible errors in the central wavelengths of the lines but introduces an additional error equal to the intrinsic shift of the Mg line core.

![Figure 5:](image)

It is interesting to note that this intrinsic Mg line shift turned out to be red. In general, the reddening effect of shifts of very strong lines was previously known both for solar lines [43] and stellar lines [3]. It is possible that this small red shift is caused in part by convective currents penetrating into the region between the upper photosphere and lower chromosphere. Doppler images obtained in the core of this line show that the granulation structure still exists, but it differs markedly from the granulation pattern seen in the wings of this line [11]. According to [3, 30], the structure of granulation is preserved up to heights of approximately 500–700 km, while its characteristics vary with height. The temperature inversion in granules and intergranules almost always occurs, on average, at heights of 200–300 km, while the inversion of vertical velocities occurs in most cases at heights > 500 km. At heights of approximately 700 km, 20% of the granulation structures are still observed. These are the heights between the upper photosphere and lower chromosphere where the core of the Mg line should form. According to [37], the formation height of the core of this line calculated for the center of the solar disk is approximately 600 km. The maximum sensitivity to temperature variations is manifested at a height of approximately 550 km, and that to vertical velocity variations is at approximately 800 km. We calculated the formation height of the Mg line core in the solar flux spectrum with the aid of the SPANSAT software [17] using the depression contribution functions [24]. Figure 5 shows the observed and calculated profiles of the Mg line core and the profiles of effective heights. As can be seen, in the range $F_\lambda/F_c = 0.1–0.2$, the core forms at heights of 600–800 km, i.e., in the region where granulation structures are weakened but still visible on Doppler images. It can be assumed that the altered structure of granulation in the lower chromosphere is one of the causes for the reddening of shifts in the cores of strong lines. It is possible that the red contributions to the line from the downward flows slightly prevail over the blue contributions from the upward flows, and the shift of the core of the velocity-sensitive Mg line may be red.

4 Line bisectors in stellar spectra

**Bisector noises and errors.** Individual bisectors in the spectra of the stars are distorted by noise to a greater or lesser extent. Note that a slight tortuosity of the bisectors is visible even at very high
resolution in the IAG solar flux atlas (Fig. 1). The tortuous character is even more pronounced in the stars with $v \sin i \geq 3$ km/s. In principle, radiation at any given point of the line profile comes from a wide range of depths in the photosphere and total disk. This should lead to averaging and smoothing of all possible oscillations and to a smoother shape of the bisectors. However, we see large observational noise in the line profiles and their bisectors, which does not allow obtaining reliable results for individual bisectors. Small noise of rotationally broadened profiles leads to even larger errors in the bisectors. In addition, if we proceed from the fact that the tortuosity is more pronounced in stars with $v \sin i > 5$ km/s, it can be assumed that another cause for this may be the redistribution of Doppler shifts caused by rotation in the surface regions near the limb, as was noted in [22]. In colder, slowly rotating stars, one can also see the chaotic appearance of the bisectors. In addition to noise, there is uncertainty with blends, which also introduces additional scatter and affects the reliability of the results. Averaging the bisectors makes it possible to remove noise; for this reason, all the results of the analysis of stellar spectra were obtained based on the averaged bisectors.

Figure 6: (a) Individual bisectors are shown on the Mg scale for the Fe I (thin solid lines) and Fe II (dashed lines) lines and the mean bisector (thick solid lines) for the star HD 102361; (b) the same bisectors taking into account the correction for wavelength dispersion.

Figure 7: Convective line shifts are shown on the Mg scale in the spectrum of the star HD 102361 depending on the wavelength (crosses) and shifts of the same lines taking into account the correction for wavelength dispersion (squares).

For stars, we will consider all bisectors on the Mg scale. This means that their position has already been corrected for the gravitational displacement and radial velocity of the star, and it corresponds to the convective shift of the line core with an error equal to the convective shift of the Mg line in this star. The magnitude of this convective shift is unknown, but it should be presumably small within the accuracy of this analysis for solar-type stars.

Line bisectors in the spectrum of the star HD 102361 F8V. Our preliminary analysis of individual bisectors showed a very wide range of bisector shifts in the spectrum of HD 102361, which is sharply different from other stars. In addition, the magnitude of the shifts depends on the line wavelength (Fig. 6a). Blue shifts reach approximately $-2000$ m/s in the 538–643 nm range, and red shifts reach almost 500 m/s in the 441–460 nm range, i.e., the line shifts become bluer with increasing wavelength. This is clearly seen in Fig. 7, which shows the dependence of the shifts of the individual lines on the wavelength. This dependence resembles the dependence found in the HINKL atlas (see
Figure 8: Individual bisectors of the Fe I (thin solid lines) and Fe II (dashed lines) lines as well as the averaged bisectors (bold solid lines) in the Mg scale for solar-type stars with the indicated main parameters $T_{\text{eff}}/\log g/[\text{N/H}]/v\sin i$.

Fig. 3). In this regard, we introduced a dispersion correction to the wavelength scale for this star. Figure 7 shows the corrected line shifts, and Fig. 6b shows the positions of the bisectors of these lines in the corrected shift scale for the star HD 102361.
Changes in the bisectors with star temperature. Figure 8 shows the bisectors of the lines of all the stars and the Sun as a star (HARPS atlas) in order of decreasing effective temperature from left to right and from top to bottom on the same scale. We see no significant differences in the bisectors of the Fe I and Fe II lines, although it is known that the bisectors of strong Fe II lines for the Sun have a more pronounced C shape than the bisectors of Fe I lines of the same strength. Apparently, this is a consequence of the lower resolution, higher noise, and a small number of Fe II lines. If we consider the bisector of the strong line from the top near the continuum to the bottom near the core, we can get an idea of the variation in the total velocity of upward and downward flows from bottom to top in the photosphere of a particular star. Any point on the bisector reflects the average velocity of convective flows at photospheric heights from which radiation is emitted at the corresponding point of the line profile. To more accurately tie this velocity to the height, it is necessary to calculate the profile of the line formation heights. However, even one bisector can tell a lot.

Figure 8 shows that, in general, the individual bisectors of the weakest lines are most blue-shifted on the shift scale, since these lines form in deep layers, where the convective velocities of ascending granules are large. The strong lines are less displaced because their cores form in the high layers of the photosphere, where granulation is significantly weaker. The placement of the bisector shifts on the scale from the weakest to the strongest lines shows a certain range of convective velocities inherent in a particular star. The width of this range increases with effective temperature and with decreasing surface gravity and metallicity. We can say that this range of shifts is one of the signatures of the efficiency of convection in the stellar photosphere.

![Diagram showing changes in the shape of the mean bisectors with effective temperature of the star.](image)

Figure 9: Changes in the shape of the mean bisectors with the effective temperature of the star. The horizontal arrangement of the bisectors on the shift scale is arbitrary but ordered by the effective temperature. Star parameters $T_{\text{eff}}/\log g/[N/H]/v\sin i$, as well as the type of star, are noted under each bisector.
The mean bisectors, as seen in Fig. 9, have a C shape for most stars, same as in the case of the Sun, but with different bulge in the middle of the bisector, the size of which depends on the main parameters of the star. Among all the bisectors, the bisectors for the stars HD 189627 F7V, HD 102361 F8V, and HD 147873 G1V with a rotation velocity $v \sin i \geq 5$ km/s stand out the most. The shape of these three bisectors resembles a greatly elongated top of the letter C or even a slash symbol (/). This shape is caused by the effects of rotation on the line profiles. As is known from [22], the lower part of the bisector compresses or contracts with an increase in the rotation velocity and deviates more and more towards the blue part of the spectrum; for this reason, the shifts of the line cores in such stars become bluer.

Mean bisectors differ in length. In the spectra of hotter stars, absorption lines are significantly weakened as compared to cooler stars; their bisectors become shorter and their cores more displaced since they form in deeper layers. As a rule, the hotter the star, the faster it rotates. The length of the mean bisector depends not only on temperature but also on the star’s rotation velocity and metallicity. This is especially noticeable for stars with large $v \sin i$, e.g., the mean bisector in the star HD 189627 is much shorter than the others and the shift of its lower part is bluer.

![Figure 10: Average convective velocities derived from the bisector span depending on the effective temperature, gravity, metallicity, age of the star, rotation velocity, and micro- and macroturbulence velocities (the dashed lines show the linear approximation).](image)

An important characteristic of the bisector is its span or shift of the bluest point. It can be seen from Fig. 9 that the span depends on the temperature. The higher the effective temperature, the greater the curvature or span of the bisector and the greater the average convective velocity. In
addition, the span depends on the surface gravity, which tends to weaken the motion of the ascending granules and, due to this, the span decreases in stars with higher gravity. In metal-rich stars, the opacity of the photosphere increases, the motion of the ascending granules slows down, and the span becomes smaller. For example, in the stars HD 93849 and HD 158469 with close \( T_{\text{eff}} \), \( \log g \), and \( v \sin i \) values, the mean bisectors differ due to different metallicities. In this regard, we cannot expect a clear dependence of the span of the bisectors on temperature in our sample of stars, since the other parameters vary from star to star, albeit not much. In general, we can say that the span of the bisector depends on the structure of the atmosphere, which is determined by the main parameters of the star.

The height of the span of the mean bisector is also a characteristic feature. As can be seen from Fig. 9a, the hotter the star, the smaller the span height. This means that effective granulation in hot stars extends into the higher layers of the photosphere. In colder stars (Fig. 9c), the span height is large and this indicates that the effective ascent of matter in the granules occurs in deeper layers than in the case of hot stars. Hence, it follows that the higher the temperature, the higher the convective flows of hot matter rise into the atmosphere.

**Convective velocities in stellar photospheres.** We measured the shift of the bluest point on the mean bisector, i.e., the span of the bisector, and obtained the average convective velocity in the photosphere for each star. The results are presented in Table 1 and Fig. 10 depending on the parameters of the star. It is clearly seen that the closest correlation exists between the average convective velocity or the ascent velocity of granules and the effective temperature of the star. The rest of the dependences shown in Fig. 10 have a greater scatter of values; however, a certain tendency is observed everywhere in accordance with the physical sense. We would like to note the existence of a correlation between the convective velocity and the micro- and macroturbulence parameters. It is not without reason that the macroturbulence velocity is often called the first signature of granulation in a star’s atmosphere. The higher the ascent velocity of granules, the more efficient the granulation and the stronger the micro- and macroturbulence in stars, i.e., the stronger the dispersion of convective velocities. The influence of the star’s rotation on the line bisectors is also confirmed. The higher the rotation velocity, the higher the ascent velocity of the granules. The correlation between the mean convective velocity and the age of the star should also be noted. It is obvious that granulation efficiency should decrease with age. Thus, none of the dependences presented in Fig. 10 contradict the physical sense and they confirm the reliability of observational data on stellar asymmetry.

## 5 Conclusions

In this study, we have analyzed the asymmetry of lines in the spectra of solar-type stars obtained with the HARPS spectrograph with a resolution of approximately 120000 and a signal-to-noise ratio above 100. Bisectors, which are chains of convective blue shifts in the photospheric layers where the corresponding points of the spectral line profile are formed, were measured for the selected lines. The main findings are as follows.

In solar-type stars, the bisectors of very weak lines show blue shifts in the deepest layers of the photosphere, and their shape resembles the upper part of the letter C. The bisectors of strong lines carry information about the convective velocities of almost all the photospheric layers, and they have a shape similar to the letter C for most stars, which becomes more like the / symbol if the rotation velocity of the star \( v \sin i \geq 5 \) km/s.

With an increase in the effective temperature, the curvature of the bisector systematically increases. This is confirmed by the clear dependence of the magnitude of the bisector span on the effective temperature. The mean convective velocities derived from the magnitude of the bisector span increase from \(-150\) to \(-700\) m/s in stars with an effective temperature of \(4800\) to \(6200\) K, respectively. With increasing surface gravity and metallicity, convective velocities become lower. As the star ages, convective velocities decrease, as expected. The photospheric macroturbulent velocity, which is the dispersion of convective velocities, directly depends on the magnitude of these velocities.

The line bisectors in the solar flux spectrum presented in the HARPS atlas fit well into the general picture of the bisectors of solar-type stars. The comparative analysis of the bisectors measured in the absolute scales of four solar flux atlases showed that the wavelength scale in the FTS atlases IAG, NECKL, and the HARPS atlas is set with an accuracy of \(\pm 10\) m/s in the range of \(450–650\) nm. The
wavelength scale in the HINKL atlas is shifted relative to the IAG atlas by an average of $-240 \text{ m/s}$. In addition, the HINKL scale shift changes with wavelength from $-100$ to $-330 \text{ m/s}$ in the range of 450–650 nm, respectively. In this regard, it is undesirable to use the HINKL atlas to determine the convective blue line shifts.

The above conclusions confirm the known facts regarding the nature of the line bisectors in the spectra of solar-type stars and show that, in general terms, the stellar line bisectors are similar to the solar line bisectors but with their own characteristic features. When we compare the shape of the bisectors and the magnitude of the blue shifts of the lines of different strengths in the stellar spectrum with solar data, it is possible to obtain preliminary estimates of the average convective velocity, height of penetrating convection, rotation velocity, and macroturbulent velocity in the stellar photosphere. By the magnitude of the bisector span, it is possible to estimate the layers of the maximum effect of granulation on the profiles of spectral lines and the energy of granulation in the photosphere.

Observation noise, blends, and insufficiently high spectral resolution distort the shape of the bisectors. This affects the bisectors of rapidly rotating stars to a greater extent. Due to these reasons, the individual bisectors are not reliable enough, so all the conclusions were drawn on the basis of the mean bisectors. The mean convective velocities derived from the bisector span are only the lower limit since insufficiently high resolution reduces this span. In addition, convective velocities in the scale of shifts relative to the Mg line may contain the Mg line shift itself if it turns out to be nonzero. The values of the obtained average convective velocities do not exceed the accuracy of laboratory wavelengths, which is 30–60 m/s at best. To improve the analysis results, it is necessary to have more accurate laboratory wavelengths and stellar spectra with higher resolution and signal-to-noise ratio.

ACKNOWLEDGMENTS

I am sincerely grateful to Ya. Pavlenko and A. Ivanyuk for providing the observed spectra of stars and would also like to thank the reviewer for important remarks.

References

[1] Allende Prieto C., Asplund M., Garcia Lopez R. J., Lambert D. L. Signatures of Convection in the Spectrum of Procyon: Fundamental Parameters and Iron Abundance. ApJ 2002. 567. P. 544–565.

[2] Allende Prieto C., Garcia Lopez R. J. Fe i line shifts in the optical spectrum of the Sun. A&A Suppl. 1998. 129. P. 41–44.

[3] Allende Prieto C., Garcia Lopez R.J., Lambert D. L., Gustafsson B. Spectroscopic Observations of Convective Patterns in the Atmospheres of Metal-poor Stars. ApJ 1999. 526. P. 991–1000.

[4] Allende Prieto C., Koesterke L., Ludwig H. -G., Freytag B., Caffau E. Convective line shifts for the GAIA RVS from the CIFIST 3D model atmosphere grid. A&A 2013. 550. id.A103, 13 pp.

[5] Asplund M., Nordlund A., Trampedach R., Allende Prieto C., Stein R. F. Line formation in solar granulation. I. Fe line shapes, shifts and asymmetries. A&A 2000. 359. P. 729–742.

[6] Atroshchenko I. N., Gadun A. S. Three-dimensional hydrodynamic models of solar granulation and their application to a spectral analysis problem. A&A 1994. 291. P. 635–666.

[7] Balthasar, H. Asymmetries and Wavelengths of Solar Spectral Lines and the Solar Rotation Determined from Fourier-Transform Spectra. Sol. Phys. 1984. 93. P. 219–241.

[8] Baran O. A., Stodilka M. I. Convection structure in the solar photosphere at granulation and mesogranulation scales. Kinematics and Physics of Celestial Bodies 2015. 31. P.65–72.

[9] Beeck B., Cameron R. H., Reiners A., Schussler M. Three-dimensional simulations of near-surface convection in main-sequence stars. II. Properties of granulation and spectral lines. A&A 2013. 558. id.A49, 18 pp.
[10] Brandt P. N., Gadun A. S., Sheminova V. A. Absolute shifts of Fe I and Fe II lines in solar active regions (disk center). *Kinem. Phys. Cel. Bod.* 1997. 13. N5, P. 65–74.

[11] Dravins D. Stellar granulation. II. Stellar photospheric line asymmetries. A&A 1987. 172. P. 211–224.

[12] Dravins D. Stellar Surface Convection, Line Asymmetries, and Wavelength Shifts ASP Conference Series, IAU Colloquium 170. Eds. J. B. Hearnshaw and C. D. 1999. 185. P. 268–276.

[13] Dravins D. Ultimate information content in solar and stellar spectra. Photospheric line asymmetries and wavelength shifts. A&A 2008. 492. P. 199–213.

[14] Dravins D., Lindegren L., Nordlund A. Solar granulation – Influence of convection on spectral line asymmetries and wavelength shifts. A&A 1981. 96. P. 345–364.

[15] Dravins D., Nordlund A. Stellar granulation. V. Synthetic spectral lines in disk-integrated starlight. A&A 1990. 228. P. 203–217.

[16] Fontenla J. M., Avrett E. H., Loeser R. Energy Balance in the Solar Transition Region. III. Helium Emission in Hydrostatic, Constant-Abundance Models with Diffusion. ApJ 1993. 406. P. 319–345.

[17] Gadun A. S., Sheminova V. A. SPANSAT: the Program for LTE Calculations of Absorption Line Profiles in Stellar Atmospheres. Preprint No. ITF-88-87P (Institute for Theoretical Physics of the Ukrainian SSR Academy of Sciences, Kiev, 1988).

[18] Gray D. F. Observations of spectral line asymmetries and convective velocities in F, G and K stars. ApJ 1982. 255. P. 200–209.

[19] Gray D. F. Shapes of Spectral Line Bisectors for Cool Stars. Publications of the Astronomical Society of the Pacific 2005. 117. P. 711–720.

[20] Gray D. F. Solar-flux Line-broadening Analysis. ApJ 2018. 857. Id. 139. 8 p.

[21] Gray D.F., Nagel T. The Granulation Boundary in the H-R Diagram. ApJ 1989. 341. P. 421–426.

[22] Gray D. F., Toner C. G. Inferred properties of stellar granulation. ApJ 1985. 97. P. 543–550.

[23] Gray D. F., Toner C. G. The remarkable spectral line asymmetries of F and G Ib supergiant stars. Publications of the Astronomical Society of the Pacific 1986. 98. P. 499–503.

[24] Gurtovenko E. A., Sheminova V. A. Formation depths of Fraunhofer lines // eprint arXiv:1505.00975

[25] Hamilton D., Lester J. B. A Technique for the Study of Stellar Convection: The Visible Solar Flux Spectrum. The Publications of the Astronomical Society of the Pacific 1999. 763. P.1132–1143.

[26] Hinkle K., Wallace L. The Spectrum of Arcturus from the Infrared through the Ultraviolet in Astronomical Society of the Pacific Conference. Series. 336. Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, eds. T. G. Barnes, F. N. Bash. 2005. 321 p.

[27] Ivanyuk O. M., Jenkins J. S., Pavlenko Ya. V., et. al. The metal-rich abundance pattern – spectroscopic properties and abundances for 107 main-sequence stars. MNRAS. 2017. 468. P. 4151–4169.

[28] Jenkins J. S., Jones H. R. A., Gozdiewski K. First results from the Calan-Hertfordshire Extrasolar Planet Search: exoplanets and the discovery of an eccentric brown dwarf in the desert. MNRAS. 2009. 398. P. 911–917.

[29] Kostik R. I., Orlova T. V. On the asymmetry of selected Fraunhofer lines. Sol. Phys. 1977. 53. P. 353–358.
[30] Kostyk R. I., Shchukina N. G. Fine Structure of Convective Motions in the Solar Photosphere: Observations and Theory. Astronomy Reports 2004. 48. P. 769–780.

[31] Kurucz R. L., Furenlid I., Brault J., Testerman L. Solar flux atlas from 296 to 1300 nm. National Solar Observatory Atlas, Sunspot, New Mexico, National Solar Observatory, 1984.

[32] Livingston W. C. Magnetic fields and convection – New observations. Solar and stellar magnetic fields: Origins and coronal effects; Proceedings of the Symposium, Zurich, Switzerland. 1983. P. 149–152.

[33] Molaro P., Esposito M., Monai S., Lo Curto G., et al. A frequency comb calibrated solar atlas. A&A 2013. 560. id.A61, 9 pp.

[34] Nave G., Johansson S., Learner R. C. M., Thorne A. P., Brault J. W. A New Multiplet Table for Fe i. ApJS 1994. 94. p.221.

[35] Neckel H. Announcement Spectral Atlas of Solar Absolute Disk-averaged and Disk-Center Intensity from 3290 to 12510 A (Brault and Neckel, 1987). Sol. Phys. 1999. 184. P. 421–422.

[36] Pavlenko. Y. V., Kaminsky B. M., Jenkins, J. S., Ivanyuk O. M., Jones, H. R. A., Lyubchik Y. P. Masses, oxygen, and carbon abundances in CHEPS dwarf stars. A&A 2019. 621. id.A112, 13 pp.

[37] Quintero Noda C., Uitenbroek H., Carlsson M., Orozco Suarez D., Katsukawa Y., et al. Study of the polarization produced by the Zeeman effect in the solar Mg I b lines. MNRAS. 2018. 481. P. 5675–5686.

[38] Ramirez I., Allende Prieto C., Lambert D. L. Granulation in K-type dwarf stars. I. Spectroscopic observations. A&A 2008. 492. P. 841–855.

[39] Ramirez I., Allende Prieto C., Koesterke L., Lambert D. L., Asplund M. Granulation in K-type dwarf stars. II. Hydrodynamic simulations and 3D spectrum synthesis. A&A 2009. 501. P. 1087–1101.

[40] Reiners A., Mrotzek N., Lemke U., Hinrichs J., Reinsch K. The IAG solar flux atlas: Accurate wavelengths and absolute convective blueshift in standard solar spectra. A&A 2016. 587. id.A65, 8 pp.

[41] Rutten R. J., Leenaarts J., Rouppe van der Voort L. H. M., de Wijn A. G., Carlsson, M., Hansteen V. Quiet-Sun imaging asymmetries in Na I D1 compared with other strong Fraunhofer lines. A&A 2011. 531. id.A17, 16 pp.

[42] Sheminova V. A. Turbulence and Rotation in Solar-Type Stars. Kinematics and Physics of Celestial Bodies 2019. 35. P.129–142.

[43] Sheminova V. A., Gadun A. S. Convective shifts of iron lines in the solar photosphere. Kinematika i Fizika Nebesnykh Tel 2002. 18. N1, P.18–32.

[44] Wallace L., Hinkle K. H., Livingston, W. C., Davis S. P. An Optical and Near-infrared (2958–9250 A) Solar Flux Atlas. ApJS 2011. 1. id. 6, 8 pp.