Iron abundance in the atmosphere of Arcturus

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Abstract

Abundance of iron in the atmosphere of Arcturus has been determined from the profiles or regions of the profiles of the weak lines sensitive to iron abundance. The selected lines of Fe I and Fe II were synthesized with the MARCS theoretical models of the atmosphere. From the observed profiles of lines available with a high spectral resolution in the atlas by Hinkle and Wallace (2005), the values of the iron abundance \( A = 6.95 \pm 0.03 \) and the radial-tangential macroturbulent velocity \( 5.6 \pm 0.2 \) km/s were obtained for Arcturus. The same physical quantities were found for the Sun as a star; they are \( 7.42 \pm 0.02 \) and \( 3.4 \pm 0.3 \) km/s, respectively. For Arcturus, the iron abundance relative to the solar one was determined with the differential method as \([\text{Fe/H}] = -0.48 \pm 0.02\).

1 Introduction

The abundance of chemical elements in the atmosphere of a star is traditionally determined from the values of equivalent widths of spectral lines with the use of completely computer-aided methods. Such methods allow a large number of lines of different elements to be quickly processed. They are convenient and widely used in practice. For example, in the recent paper by Scott et al. [31], new estimates of the abundance of chemical elements in the solar atmosphere were obtained from the values of the equivalent widths. However, for many stars, this approach sometimes yields unreliable results. In those cases when the stellar spectrum looks like a paling of many lines, a specified interval of the spectrum is synthesized, and the profiles of the selected lines rather than the equivalent widths are analyzed. Such a synthesis requires the data on the atomic parameters of all of the lines in the interval; however, as a rule, they are far from always well known. Moreover, not all of the weak lines have been identified so far. If individual spectral lines can be isolated in the observed spectrum, the synthesis of their profiles may yield reliable results in the analysis of the chemical composition of stars.

As was shown in our previous study [33], to determine the abundance, only those regions of the profile that are most sensitive to it rather than the whole line profile can be used. Such an approach is especially urgent in those cases when one wing of the profile is strongly blended, or the intensity in a red wing of the line is obviously insufficient, or the continuum cannot be unambiguously determined due to the absorption in many weak lines, or there is a strong deviation from the local thermodynamic equilibrium (LTE) in the line core. The new approach suggested by Sheminova and Cowley [33] allows the abundance to be accurately obtained when the equivalent widths of lines and their complete profile cannot be reliably measured.

The purpose of the present paper is to determine the abundance of iron in the atmosphere of Arcturus with a high accuracy from those parts of the profiles of spectral lines that are most sensitive to the abundance.
To determine the abundance as accurate as possible from adjusting the shapes of the profiles of spectral lines, it is very important to select proper lines from the stellar spectrum. It is stressed in [33] that the weak lines with the central depths \( R = 1 - F_\lambda / F_c \leq 30\% \) (where \( F_\lambda \) and \( F_c \) are the radiation fluxes in the line and continuum, respectively) are most suitable for determining the abundances. It is well known that the weaker the absorption line, the less sensitive its profile to the microturbulent velocity \( \xi_{\text{mic}} \). As a rule, this parameter can be estimated with a poor accuracy, and the uncertainty in its value directly influences the abundance estimate. The tests showed that the profiles of weak lines with \( R \) less than 10% are practically indifferent to the change of the velocity \( \xi_{\text{mic}} \). They are most suitable for determining the abundance. The use of the line profiles with the central depths of 10–20% and 20–30% may yield the error in the abundance of approximately \( \pm 0.01 \) dex and \( \pm 0.02 \) dex, respectively, if \( \xi_{\text{mic}} \) changes by \( \pm 0.5 \) km/s. The profiles of moderate lines (\( R \) varies from 30 to 60%) are most sensitive to \( \xi_{\text{mic}} \), because of which their synthesis requires accurate values of the microturbulent velocity for each of the lines. Note that the profiles of weak lines are also less sensitive to the damping effects. Due to this, the selection of lines with \( R < 30\% \) may substantially reduce the influence of the ambiguity in the parameters \( \xi_{\text{mic}} \) and damping constant.

The profiles of weak lines are substantially influenced by such parameters as the macroturbulent velocity \( \xi_{\text{mac}} \), the rotation velocity of a star \( V \sin i \), the abundance of the element \( A \), and the oscillator strengths \( \log gf \) of a specified line. Among the listed parameters, except the abundance, the parameter \( \log gf \) is most crucial. The oscillator strengths influence the line profiles in the same way as the abundance does, and it is difficult to separate their effects. The only way to obtain a correct value of the abundance is to choose the lines for which this parameter is known as accurately as possible. Naturally, it is desirable that the oscillators’ strengths are obtained from laboratory experiments.

It is of particular importance that the lines used in the synthesis have at least one wing or a large part of a wing that is free of blending. If there are no obvious blends in the wings, though the line is strongly asymmetric, this asymmetry may be caused by the influence of very weak blends. Only experience may show what lines can be used for determining the exact value of the abundance and what lines cannot.

Thus, to select the absorption lines of Fe I and Fe II, we used the following criteria:
1. the depth \( R \) in the center of a line should be less than 0.3;
2. the profiles should contain the regions that are free of blends;
3. the parameters \( \log gf \) should be measured in laboratory with a high accuracy.

To determine the value of the iron abundance in the atmosphere of Arcturus relative to the solar one as exactly as possible, the same lines in the spectra of Arcturus and the Sun were selected. In this case, the accuracy in the oscillator strengths will produce no effect on the relative abundance. First, the lines in the spectrum of Arcturus were chosen from the spectral atlas of Hinkle and Wallace [23]; then, the same lines were checked in the spectrum of the Sun as a star. The spectral atlas [23] contains the normalized spectrum of the flux of Arcturus and the Sun as a star that was measured with a high signal-to-noise ratio and a high spectral resolution (150000 and 300000 for Arcturus and the Sun, respectively) in the visible range.

To retrieve the value of the absolute abundance of iron in the atmosphere of Arcturus as accurately as possible, the data on the oscillator strengths of the weak lines of Fe I were taken from a paper of Fuhr and Wiese [10] that contains only the experimental data divided into five ranges by accuracy (\( \pm 3, 10, 25, 50, \) and \( > 50\% \)). We used only the data with the accuracy of \( \pm 3 \) and \( \pm 10\% \). The oscillator strengths for the Fe II lines were taken from a paper of Mele'ndez and Barbuy [29] that contains the most reliable data currently available.

Note, in the spectrum of Arcturus, many weak lines are partially blended or subjected to the “line haze” effect more strongly than those in the solar spectrum. To take this into consideration, at least partly, in the synthesis of the profile of a specified line, we calculated all of the blends.
Table 1: Selected weak lines and the values of the iron abundance obtained for the atmospheres of Arcturus and the Sun

| λ, nm | EP, eV | log gf | R, km/s | ξ_{mac}, km/s | χ², 10^{-5} | [Fe/H] |
|-------|--------|--------|---------|--------------|-------------|--------|
|       |        |        | Arcturus |          |             |        | Sun     |          |             |             |         |
| 541.2786 | 4.35 | -1.72 | 0.19 | 6.95 | 5.82 | 0.2 | 0.19 | 7.44 | 3.35 | 0.2 | -0.49 |
| 566.1345 | 4.28 | -1.76 | 0.30 | 6.89 | 5.86 | 5.4 | 0.20 | 7.39 | 3.13 | 0.4 | -0.50 |
| 585.5077 | 4.61 | -1.48 | 0.25 | 6.91 | 5.70 | 2.9 | 0.20 | 7.41 | 3.21 | 0.7 | -0.52 |
| 672.5357 | 4.10 | -2.10 | 0.23 | 6.91 | 5.69 | 6.1 | 0.14 | 7.39 | 3.32 | 0.2 | -0.48 |
| 679.3259 | 4.28 | -1.81 | 0.15 | 6.91 | 5.70 | 2.9 | 0.20 | 7.41 | 3.21 | 0.7 | -0.47 |
| 680.4271 | 4.56 | -1.48 | 0.25 | 6.91 | 5.69 | 6.1 | 0.14 | 7.39 | 3.32 | 0.2 | -0.52 |
| 683.7008 | 4.59 | -1.69 | 0.18 | 6.96 | 5.46 | 0.9 | 0.14 | 7.44 | 3.11 | 0.6 | -0.48 |
| 685.4823 | 4.59 | -1.66 | 0.10 | 6.96 | 5.17 | 1.2 | 0.10 | 7.48 | 3.16 | 0.7 | -0.52 |
|        |       |        | Average | 6.94 | 5.57 | 2.2 | 7.43 | 3.22 | 0.4 | -0.49 |
|        |       |        | ±0.03 | ±0.24 | ±2.4 | | | | | | ±0.02 |

Table 1 presents a list of the weak lines selected for determining the iron abundance in the atmospheres of Arcturus and the Sun.

3 Synthesis of the spectra of Arcturus and the Sun

The synthesis of spectral lines, which is fundamental for the analysis of the chemical composition of stars, was performed with our programming code called SPANSAT [13]. The local thermodynamic equilibrium (LTE) is assumed in all of the calculations. One-dimensional (1D) models of the atmosphere were built from the MARCS database of Gustafsson at al. [22]. For Arcturus, we assumed the effective temperature T_{eff} = 4286 K, the acceleration of gravity log g = 1.66, the metallicity [M/H] = -0.33, and the abundance of α-elements (O, Ne, Mg, Si, S, Ar, Ca, and Ti) [α/Fe] = +0.4 dex, which corresponds to the data of Ramírez and Allende Prieto [30]. The reliability of these data has been recently confirmed in our paper [32]. To obtain the atmospheric model with these fundamental parameters, we used six corresponding models from the MARCS database and interpolated them.

The atmospheric model for the Sun as a star was also taken from the MARCS database; its parameters are T_{eff} = 5777 K, log g = 4.44, and [M/H] = 0. The chemical composition...
of the solar atmosphere corresponds to the data of Asplund et al. [2]. The rotation velocity was $V \sin i = 1.5 \text{ km/s}$ [20] and $1.85 \text{ km/s}$ [8] for Arcturus and the Sun, respectively. The van der Waals constant of dumping was calculated with the Anstee-Barklem-O’Mara method. The required dumping parameters $\sigma$ and $\alpha$ were taken from papers [5, 6].

The 1D atmospheric models of Arcturus and the Sun require the micro- and macroturbulent velocities to be introduced. We investigated their influence on the line profile in the stellar spectrum. The most optimal version is the isotropic model of microturbulence and the radial-tangential model of macroturbulence. Moreover, the micro- and macroturbulent velocities do not change with depth in the atmosphere. The radial-tangential model of macroturbulence suggested by Gray [16] is a sum of two Gaussians:

$$ G = G(\xi_{\text{mac}}^R)S^R + G(\xi_{\text{mac}}^T)(1 - S^R), $$

where $S^R$ of the surface area on the disk of a star occupied by the radial component. We assumed the simplest case, where $S^R = 0.5$ and the radial component $\xi_{\text{mac}}^R$ is equal to the tangential one $\xi_{\text{mac}}^T$. In this case, the velocity of radial-tangential macroturbulence is usually designated as $\xi_{\text{mac}}^{RT}$. The yielded accuracy of the agreement between the synthesized and observed profiles is two times higher than that in the isotropic model of macroturbulence.

4 Determining the iron abundance

To determine the iron abundance, the standard fitting procedure of the synthesized and observed profiles was used. The profiles or their abundance-sensitive regions should be free of blending. The free parameters were only the abundance $A$ and the macroturbulent velocity $\xi_{\text{mac}}^{RT}$. The remaining parameters were fixed. According to Ramírez and Allende Prieto [30], the microturbulent velocity for Arcturus is $\xi_{\text{mic}} = 1.74 \text{ km/s}$, while the standard value of $\xi_{\text{mic}} = 1 \text{ km/s}$ was chosen for the Sun as a star in accordance with the value assumed in the MARCS model of the solar atmosphere. The Doppler shift of the observed lines relative to the standard wavelength was determined for each of the lines. The observed (obs) profiles were fitted with the synthesized (syn) ones by minimization of

$$ \chi^2 = \frac{1}{N} \sum_{k=1}^{N} (R_{k,\text{syn}} - R_{k,\text{obs}})^2, $$

where $N$ is the number of profile points chosen for fitting. The procedure was automatically performed with visual checking. The final result (in our case, the iron abundance, macroturbulent velocity, and the minimization accuracy) depends on the initial values chosen for free parameters. This choice is of particular importance, since it influences the accuracy of determining the abundance. The closer the initial values to the supposed actual ones, the higher the fitting accuracy. Because of this, it is necessary to find the optimal values of the free parameters $A$, and $\xi_{\text{mac}}^{RT}$ for each of the lines. Note that these free parameters produce different effects on the line profile. Our experience showed that $\xi_{\text{mac}}^{RT}$ mostly influences the external wings of lines, while $A$ influences the internal ones. From this, we may suppose that the well-chosen initial conditions will yield the reliable fitting by two free parameters.

In those cases, when the continuum contains very weak unidentified blends that cannot be taken into account in the synthesis, the fitting of the profiles in the wing is restricted to approximately 5%. One more cause of probable uncertainties in the fitting is the asymmetry of profiles. Sometimes we had to choose only one wing (more frequently, a blue one) of the line for fitting. Our experience showed that the blue wing is less deflected by photospheric convective motions than the red one. Gehren et al. [15] also noted that the intensity in a red wing of the lines is often insufficient (the red deficit of intensity). This fact can be noticed when comparing the observed, usually asymmetric, profiles to the symmetric synthesized profiles obtained in the frames of the 1D atmospheric models. The observed line profile results from the averaging by space and time. It can be hypothesized that the lines formed in different parts of the disk, where the temperatures and velocities along the line of sight are different, will differ in shift, width, and shape. Because of this, the resultant profile, which is averaged over the disk, will be asymmetric and shifted by the wavelength. The shape and the shift of the profile may also be influenced by other factors, such as spots, oscillations, and pulsations. However, the main cause of the asymmetry of absorption lines in the stars of the FGK spectral classes is the convection...
penetrating into the photosphere. The influence of convective motions on the profile was studied in detail in many papers [1, 9, 35], explaining how and why the asymmetry of lines and the red deficit of intensity appear.

Figures 1 and 2 show the results of adjusting the synthesized and observed regions of the profiles for some lines of Fe I and Fe II. As is seen, the differences between the synthesized and observed profiles within the fitted intervals are less than 1%. At the same time, for the whole profile, these differences often exceed 1% due to either the very weak unidentified lines near the continuum or the inaccurate atomic parameters of the identified blends or the asymmetry of the observed profiles caused by convective motions.

The results of determining the iron abundance for each of the lines in the atmosphere of Arcturus are presented in Table 1. We obtained the mean value of the iron abundance for Arcturus as \( A_{\text{Fe}} = 12 + \log(N_{\text{Fe}}/N_{\text{H}}) = 6.94 \pm 0.03 \) and \( 6.96 \pm 0.02 \) by the Fe I and Fe II lines, respectively. On average, the fitting accuracy in the abundance-sensitive regions of the profiles of the Fe I and Fe II lines is \( \chi^2 = 2.2 \cdot 10^{-5} \) and \( 1.1 \cdot 10^{-5} \), respectively. The mean value of the relative abundance of iron (or metallicity) was obtained as the difference between the values of the iron abundance in the atmospheres of Arcturus and the Sun retrieved from the same lines; it is \( [\text{Fe/H}] = A_{\text{Fe}}^\star - A_{\text{Fe}}^\odot = -0.49 \pm 0.02 \) and \( -0.46 \pm 0.02 \) by the Fe I and Fe II lines, respectively.

Figures 3a and 3c present the individual values of the iron abundance and metallicity for Arcturus obtained by each of the lines. The average values from all of the Fe I and Fe II lines for the iron abundance \( A = 6.95 \pm 0.03 \) and \( [\text{Fe/H}] = -0.48 \pm 0.02 \) are shown by dashed lines.

The values of the radial-tangential macroturbulent velocity in the atmosphere of Arcturus obtained from adjusting the synthesized and observed profiles of the selected lines are shown in Fig. 3d. A dashed line indicates the average value of the macroturbulent velocity \( v_{\text{mac}}^{\text{RT}} = \).
5.59 ± 0.22 km/s, while the values of 5.57 ± 0.25 and 5.60 ± 0.22 were obtained from the Fe I and Fe II lines, respectively. Figure 3f presents the values of velocity relative to the solar ones, i.e., $\Delta \xi_{\text{mac}} = \xi^*_{\text{mac}} - \xi^\odot_{\text{mac}}$.

The analogous calculations were performed for the Sun (Table 1). The mean values of the abundance obtained from the Fe I and Fe II lines are $A = 7.43 \pm 0.03$ and $7.42 \pm 0.02$, respectively, and the values of the macroturbulent velocity are $\xi^{\text{RT}}_{\text{mac}} = 3.22 \pm 0.09$ and $3.69 \pm 0.11$ km/s, respectively. The fitting accuracy in the abundance-sensitive regions of the profiles averaged $\chi^2 = 0.4 \cdot 10^{-5}$ and $0.3 \cdot 10^{-5}$ for the Fe I and Fe II lines, respectively. These values are almost an order of magnitude higher than those for Arcturus, because the spectral resolution of the solar spectrum is two times higher. Figure 3b shows the individual values of the abundance obtained from each of the lines in dependence on the excitation potential $E_P$. The individual values of the macroturbulent velocity are shown in Fig. 3e. A dashed line indicates the mean value of the macroturbulent velocity $\xi^{\text{RT}}_{\text{mac}} = 3.46 \pm 0.26$ km/s.

5 Discussion

In general, the estimates obtained in the present paper satisfactorily agree with the recently published values of the iron abundance for Arcturus and the Sun (Tables 2, 3). All the data for Arcturus (except our estimates) presented in Table 2 were obtained with the methods based on the adjustment of the equivalent widths of the Fe I and Fe II lines within the atmospheric models from the database of Kurucz and their different modifications. The values of [Fe/H] were found with the differential method, except those from a paper of Gustafsson et al. [22], where the value of $A = 7.45$ was used for the Sun. As is seen, the parameters of the used models weakly differ from those of our model. For example, the parameters of the models of Ramírez and Allende Prieto [30] completely coincide with ours, though their models differ from ours in
the same degree as the models by Kurucz differ from the MARCS models. It is known from a paper [22] that these models are practically analogous. The MARCS models are somewhat cooler, and the maximum at 80 K is for \( \tau < 0.01 \).

Ramirez and Allende Prieto [30] found the value of \([\text{Fe/H}] = -0.52 \pm 0.02\) and \(-0.40 \pm 0.03\) from the lines of neutral iron and ions, respectively. They recommend the final value \(-0.52 \pm 0.04\). They additionally tested their result with the MARCS model (i.e., the same as ours) and obtained \(-0.54 \pm 0.05\). This means that the difference in the abundances obtained with different atmospheric models of Arcturus is 0.02, while the difference from our result (\([\text{Fe/H}] = -0.48 \pm 0.02\)) within the same model is substantially higher (0.06). We suppose that, as compared to the method of equivalent widths, the use of the method of sensitive points favored, first, the decrease of \( \sigma \) (the root mean square deviation) by 0.03 dex and, second, the increase of the relative value of the iron abundance by 0.06 dex.

In addition, we will pay attention to the known fact (especially for the Sun) that the results for the iron abundance obtained from the lines of neutral and ionized iron are different. Rather large differences can be seen in the data of the other studies (Table 3), from 0.05 to 0.12. In our case, this difference is 0.03. The large difference can be caused by both the effects connected with the deviation from LTE and the differences in the models for the temperature distribution in the photosphere. Note that our method used weak lines, which allowed us to avoid the errors caused by the LTE approximation.
The reliability of our results is also evidenced by the fact that the individual values of [Fe/H] obtained for each of the lines show no substantial dependence on the excitation potential EP (Fig. 3c). This means that the chosen atmospheric model is correct and the lines demonstrate no noticeable deviations from LTE, i.e., the lines with high and low excitation potentials yield close values. We tend to believe that the value we obtained for the iron abundance in Arcturus relative to the Sun [Fe/H] = −0.48 ± 0.02 contains no considerable systematic errors in the frames of the MARCS model of the atmosphere.

Our purpose was also to obtain, as accurately as possible, the absolute value of the iron abundance for Arcturus in the usual hydrogen scale. Such data are not so widely available in the literature. For the recent years, we have found the data on the absolute abundance of iron that slightly differ because of the difference in the list of spectral lines selected for analyzing the abundance in these studies [11, 12]. As is seen from Table 2, the agreement with our data is rather good, within the error of analysis. We obtained the mean value from all of the lines $A = 6.95 ± 0.03$; the values of $\Delta A = A(\text{Fe I}) − A(\text{Fe II}) = −0.02$ and $\sigma$ are substantially smaller than those in papers [11, 12]. This confirms the reliability of our data.

With the MARCS model, we also analyzed the iron abundance for the Sun as a star and obtained $A = 7.43 ± 0.03$ and $7.42 ± 0.02$ from the same lines of Fe I and Fe II, respectively. We used the same method of sensitive points. The value of the abundance averaged over all lines was $7.42 ± 0.02$. This analysis was required in order to derive, as exactly as possible, the relative abundance for Arcturus [Fe/H] with the differential method, i.e., line by line. From the comparison of our results with the others obtained for the Sun as a star, one may notice that the value of the iron abundance for the Sun still substantially varies (from 7.41 to 7.56) in spite of a large number of new researches (some of them are presented in Table 3). In principle, it is clear that such results are connected with some differences in different procedures analyzing the iron abundance. The main differences may arise due to the following causes:

1. different atmospheric models;
2. an error in the gf values;

Table 2: Values of the iron abundance in the atmospheres of Arcturus obtained after 2006 from the LTE analysis of the Fe I and Fe II lines. $T_{\text{eff}}/\log gf/\xi_{\text{mic}}$ are the parameters used in the 1D theoretical models of the atmosphere

| [Fe/H] (Fe I) | A(Fe I) | [Fe/H] (Fe II) | A(Fe II) | $T_{\text{eff}}/\log gf/\xi_{\text{mic}}$ | Source |
|--------------|---------|---------------|---------|-----------------------------------|--------|
| −0.50 ± 0.07 | 6.95 ± 0.07 | −0.55 ± 0.05 | 6.99 ± 0.05 | 4285/1.55/1.61 | Fulbright et al. [11] |
| −0.54 ± 0.04 | 6.91 ± 0.04 | −0.45 ± 0.11 | 7.00 ± 0.11 | 4285/1.55/1.62 | Fulbright et al. [12] |
| −0.52 ± 0.02 | −       | −0.40 ± 0.03 | −       | 4286/1.66/1.74 | Ramirez et al. [30] |
| −0.49 ± 0.07 | −       | −0.40 ± 0.04 | −       | 4290/1.60/1.60 | McWilliam et al. [28] |
| −0.49 ± 0.02 | 6.94 ± 0.03 | −0.46 ± 0.02 | 6.96 ± 0.02 | 4286/1.66/1.74 | This study |

Table 3: Iron abundance obtained after 2009 from the analysis of the Fe I and Fe II lines for the Sun as a star [3, 7, 27] and for the center of the solar disk [29, 31]
(3) the use of the LTE or non-LTE approximations;
(4) different base lists of lines;
(5) selection of atomic or ion lines;
(6) selection of lines observed in the disk center or for the Sun as a star;
(7) an accuracy of measurements of equivalent widths;
(8) a way of determining the micro- and macroturbulent velocities;
(9) a choice of the parameters of damping due to collisions;
(10) different computer codes.

Each of the listed causes of the appearing differences contributes its effect to the result. For example, from the data of [31] (Table 3), it is seen that the difference in the models yields the difference between the abundance values from 0.04 to 0.11 dex. The large scatter of the values of \( A \) is produced by the uncertainty in the oscillator strength. From the data of [27], the iron abundance is 7.41–7.56 depending on the oscillator strength, i.e., the maximum difference is 0.15 dex. The non-LTE effects reduce the abundance by 0.01 dex (the data from [7] in Table 3). As is shown by Holzreuter and Solanki [25], the accounting for the combined effect of the horizontal radiation transfer and the non-LTE approximation on the iron lines in the realistic 3D atmospheres will reduce the iron abundance by approximately 0.012 dex. The choice of the list of lines may cause a difference of 0.04 dex (the data from [11, 12] in Table 2).

It is also seen from Table 3 that the difference between the values of the iron abundance derived from the analysis of the Fe I and Fe II lines may be rather large, from 0.01 to 0.09 dex. It depends on both the choice of the spectral lines and the atmospheric model. In the cooler photospheres (e.g., MARCS), this difference is 0.01–0.02 dex, while it reaches 0.05 dex in the hotter ones (e.g., HM [24]). In our case, the difference between the values obtained from the Fe I and Fe II lines is minimum (0.01 dex). The iron abundance obtained from the observations of the disk center and for the Sun as a star may differ to a little degree. For example, it follows from paper of Caffau et al. [4] that, for the Sun as a star, the 3D models yield the abundance 0.02 dex lower than for disk center.

The abundance derived from the equivalent widths and 1D models depends on the choice of the parameter of microturbulence. The uncertainty in this parameter may lead to different equivalent widths of the synthesized lines and, consequently, to different values of the abundance.

Figure 4 demonstrates how the equivalent widths of the synthesized lines (weak, moderate, and strong) may differ if the value of the microturbulence parameter 1 km/s is changed within the limits of \( \pm 0.5 \) km/s. As is seen, the equivalent widths of very weak lines are practically constant under such variations of microturbulence. The situation becomes more problematic for moderate lines (partially saturated lines). To choose the microturbulence parameter properly is of key importance for calculations of these lines in the analysis of the abundances. For example,

![Figure 4: Change of the equivalent width \( W \) in dependence on the parameter of microturbulence \( \xi_{\text{mic}} \) for artificial absorption lines of different strengths calculated for the Sun as a star.](image-url)
if a moderate line with the equivalent width \( W \approx 5 \) pm for the Sun as a star is synthesized with the value of 0.7 km/s instead of the standard value of 1 km/s, the derived abundance will be 0.09 dex higher, and the difference will be even larger for a moderate line with \( W \approx 10 \) pm.

The uncertainty in the microturbulence parameter, together with the rotation velocity of the star, influences the shape of the profiles and may introduce an error to the abundance value obtained from the line profiles. According to our calculations for weak lines, the increase of the macroturbulent velocity \( \xi_{\text{mac}} \) from 3.0 to 3.5 km/s makes the abundance higher by 0.02 dex, while the twofold increase of the classic damping constant due to collision processes yields a small increase of the abundance, 0.01 dex. In the 3D models of the atmospheres, there is no problem with micro- and macroturbulent velocities, though they have their own problems and complexities. Moreover, it is not easy to apply the 3D models to the analysis of the abundance in stellar atmospheres, and their use for synthesizing the spectral lines is time consuming.

If we sum (with no sign) the above-listed possible errors in the estimate of the iron abundance, we will find the maximally possible total error, 0.4–0.5 dex. This error is very large, and it may appear only in rare cases when the base list of lines and the atomic and atmospheric parameters are poorly selected. In real practice, some errors are compensated, which results in a lower total error.

Recently, Scott et al. \cite{31} have redefined the chemical composition for the Sun with the use of the solar spectrum in the disk center and the 3D models accounting for the correction for deviation from LTE. For iron, they obtained the value \( A = 7.47 \pm 0.04 \), and they recommend that it should be used as the most reliable value currently available. They also report the abundance value of 7.41 ± 0.04 obtained with the MARCS models. In fact, both our and their values of the iron abundance obtained with the 1D MARCS models of the atmosphere are the same within the analysis errors. This confirms the reliability of our result. Moreover, this allows us to estimate the correction for horizontal inhomogeneity of the atmosphere that is ignored in our analysis. Note, our method of analyzing the abundance excludes systematic errors caused by inaccuracy in the equivalent widths, non-LTE effects, and uncertainties in the micro- and macroturbulent velocities and damping constant. To transform the abundance found by Scott et al. \cite{31} (\( A = 7.47 \) for the solar center) to the abundance for the Sun as a star, we introduce the correction of −0.02 dex and subtract our abundance value (7.42). The result yields the highest possible systematic error for atmospheric horizontal inhomogeneity, which amounts to 0.03 dex. This means that the iron abundance determined for the Sun as a star with the MARCS theoretical models of the atmosphere is underestimated by 0.03 dex due to the 1D approximation.

As regards the macroturbulent velocity derived in the present analysis for Arcturus, the values \( \xi_{\text{mac}} = 5.57 \pm 0.24 \) and 5.60 ± 0.2 km/s (from the Fe I and Fe II lines, respectively) do not contradict the data obtained earlier in the Fourier analysis (Table 4). Gray \cite{18} found the value \( \xi_{\text{mac}} = 5.25 \) km/s. The fact that our estimate is somewhat higher can be explained by two causes.

The first cause is that we used weaker lines. In the atmosphere of Arcturus, the macroturbulent velocities decrease with height, while the micromagnetic velocities increase due to defragmentation of large elements, lifting up. In the analysis of strong lines, the retrieved velocities \( \xi_{\text{mac}} = 4.8 \) km/s \cite{18} and 4.6 ± 0.3 km/s \cite{34} are lower than ours.

The second cause is that we used a new value for the rotation velocity of Arcturus \( V \sin i = 1.5 \) km/s \cite{20}, while the other studies (see Table 4) are based on the higher velocity \( V \sin i = 2.4 \) km/s \cite{19}. In the procedure of adjusting the spectra, the decrease of the rotation velocity should influence the parameter \( \xi_{\text{mac}} \) by raising its value to some extent. If the new value of the rotation velocity is correct, we may recommend that the new value of macroturbulence \( \xi_{\text{mac}} = 5.6 \) km/s, together with the new value of rotation \( V \sin i = 1.5 \) km/s, be used in the analysis of weak lines of Fe I and Fe II.

Since the rotation velocity is a reliable parameter for the Sun, the differences between the values of macroturbulent velocity obtained by different researchers may be caused by the discrep-
Table 4: Macroturbulent velocity in the atmosphere of Arcturus and the Sun as a star from the analysis of the Fe I and Fe II line profiles

| Source                | ξ<sub>RT</sub><sup>mac</sup>, km/s |
|-----------------------|-----------------------------------|
| **strong lines**      |                                   |
| Arcturus              | 4.8 ± 0.2                         |
|                      | 4.6 ± 0.3                         |
|                      | 5.0                               |
| Sun as a star         | 3.1 ± 0.1                         |
|                      | 2.6 ± 0.2                         |
|                      | 2.3 ± 0.4                         |
|                      | 3.2                               |
|                      | 2.6                               |
| **weak lines**        |                                   |
| Arcturus              | 5.25 ± 0.2                        |
|                      | 5.2 ± 0.2                         |
|                      | 5.6 ± 0.2                         |
| Sun as a star         | 3.8 ± 0.2                         |
|                      | 4.0                              |
|                      | 3.8                               |
|                      | 3.45 ± 0.3                        |
|                      | 3.5 ± 0.3                         |
| **Source**            |                                   |
|                       | Gray [18]                         |
|                       | Sheminova & Gadun [34]            |
|                       | Gray & Brown [20]                 |
|                       | Tsuji [38]                        |
|                       | This study                        |
|                       | Gray [17]                         |
|                       | Sheminova & Gadun [34]            |
|                       | Takeda [37]                       |
|                       | Gehren et al. [14]                |
|                       | Gehren et al. [15]                |
|                       | Mashonkina et al. [27]            |
|                       | Steffen et al. [36]               |
|                       | This study                        |

The table contains the values of ξ<sub>RT</sub><sup>mac</sup> taken from different papers. As is seen, the values of ξ<sub>RT</sub><sup>mac</sup> obtained from strong lines are smaller than those from weak lines. This is a well-known fact indicating the decrease of ξ<sub>RT</sub><sup>mac</sup> with height in the photosphere. For all of the weak lines, we obtained the mean value ξ<sub>RT</sub><sup>mac</sup> = 3.5 ± 0.3 km/s. Gray [17] found ξ<sub>RT</sub><sup>mac</sup> = 3.8 ± 0.2 and 3.1 ± 0.1 km/s for the lower and upper photosphere, respectively. The decrease of ξ<sub>RT</sub><sup>mac</sup> with height is also confirmed by our data acquired from the Fe I (3.22 ± 0.09 km/s) and Fe II (3.69 ± 0.11 km/s) lines. From the data for the center of the solar disk contained in the tables by Gurtovenko and Sheminova [21], we estimated the mean height where these lines are formed. On the average, the weak lines of Fe II are effectively formed at the level of 146 km, while the weak lines of Fe I are formed at the level of 182 km. Because of this, the values of macroturbulent velocity in the solar photosphere derived from the Fe I and Fe II lines differ. Note that Arcturus does not show such difference in the values of macroturbulent velocity obtained from the same weak lines of Fe I and Fe II, since the formation conditions for these lines on Arcturus differ from those on the Sun.

## 6 Conclusions

Arcturus is often used as a standard for studying the chemical composition of the other similar giant stars. Fortunately, for Arcturus, the spectrum of extremely high quality, from the UV range to the IR one, is available together with the spectrum of the Sun as a star (the atlas by Hinkle and Wallace [23]). Since Arcturus is a relatively close star, the parameters of its atmosphere are known better than those of any other RGB star. Because of this, it was of particular interest to apply the method of sensitive points exactly to Arcturus in order to estimate the iron abundance in its atmosphere more accurately.

From the synthesis of weak spectral lines of Fe I and Fe II with the MARCS models of the atmosphere, we determined the absolute value of the iron abundance for Arcturus (A = 6.95 ± 0.03) and the Sun as a star (A = 7.42 ± 0.02) in the usual logarithmic scale relative to hydrogen. We also applied the differential method to determining the iron abundance relative to the Sun and derived [Fe/H] = −0.48 ± 0.02 on average.

It is especially important to know a high-accuracy value of the absolute abundance of iron for the application of the differential method to the analysis of the abundance in the other stars. As Fulbright et al. [11] note, not only the compensation of errors in the oscillator strength is an advantage of the differential analysis. In a first approximation, the errors caused by different
unaccounted effects in the atmospheric models, such as 3D hydrodynamics, granulation, non-LTE, magnetic fields, chromospheric effects, etc., may compensate each other when the analysis is performed with this method relative to the similar stars having rather close parameters of the atmosphere. Thus, for many stars, the differential abundances can be obtained more reliably than the absolute abundances based on the atmospheric models.

For Arcturus, we recommend using the absolute value of the iron abundance $A = 6.95 \pm 0.03$. We also recommend that the sensitive points of the profiles of preferably weak lines should be used instead of the full profile, especially in the cases when the standard method of equivalent widths cannot be applied.

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