Influence of Inelastic Collisions with Hydrogen Atoms on Non-LTE Oxygen Abundance Determinations

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Abstract—We present the results of our modeling of the O I line formation under non-LTE conditions in the atmospheres of FG stars. The statistical equilibrium of O I has been calculated using Barklem’s quantum-mechanical rates of inelastic collisions with hydrogen atoms. We have determined the non-LTE oxygen abundance from atomic O I lines for the Sun and 46 FG stars in a wide metallicity range, $-2.6 < [\text{Fe/H}] < 0.2$. The application of accurate atomic data has led to an increase in the departures from LTE and a decrease in the oxygen abundance compared to the use of Drawin’s theoretical approximation. The change in the non-LTE abundance from the infrared O I 7771-5 Å triplet lines is $0.11$ dex for solar atmospheric parameters and diminishes in absolute value with decreasing metallicity. We have revised the $\text{[O/Fe]} - [\text{Fe/H}]$ relationship derived by us previously. The change in $\text{[O/Fe]}$ is small in the $\text{[Fe/H]}$ range from $-1.5$ to $0.2$. For stars with $\text{[Fe/H]} < -1$ the $\text{[O/Fe]}$ ratio has increased so that $\text{[O/Fe]} = 0.60$ at $\text{[Fe/H]} = -0.8$ and rises to $\text{[O/Fe]} = 0.75$ at $\text{[Fe/H]} = -2.6$.

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1. INTRODUCTION

The oxygen abundance in the atmospheres of the Sun and other stars is an important quantity that is needed to test the Galactic chemical evolution scenarios and the theory of stellar structure and evolution.

The infrared (IR) O I 7771-4 Å triplet lines are the only set of atomic lines that is observed in the spectra of metal-poor stars. Previously, many authors have shown that the IR O I lines are formed under conditions far from local thermodynamic equilibrium (LTE). The oxygen abundance was first determined by abandoning LTE by Kodaira and Tanaka (1972) and Johnson (1974) for stars and by Shchukina (1987) for the Sun. Subsequently, more complex oxygen model atoms were constructed by Kiselman (1991), Carlsson and Judge (1993), Takeda (1992), Paunzen et al. (1999), Reetz (1999), Mishenina et al. (2000), and Przybilla et al. (2000). Non-LTE effects lead to a strengthening of lines and, consequently, to a decrease in the abundance derived from these lines.

Having considered atomic and molecular lines in the solar spectrum, Asplund et al. (2004) achieved agreement between the abundances from different lines using a three-dimensional (3D) model atmosphere based on hydrodynamic calculations and the non-LTE corrections calculated for a classical ID model atmosphere. In Asplund et al. (2004) the mean abundance from atomic and molecular lines is $\log \varepsilon = 8.66 \pm 0.05$; subsequently, Asplund et al. (2009) obtained $\log \varepsilon = 8.69$ by the same method. Here, $\log \varepsilon = \log (n_{\text{elem}}/n_{\text{H}}) + 12$. This value turned out to be lower than $\log \varepsilon = 8.93 \pm 0.04$ obtained previously by Anders and Grevesse (1989) from OH molecular lines using the semi-empirical HM74 model atmosphere (Holweger and Mueller 1974). It should be noted that the models of solar internal structure constructed with the chemical composition from Anders and Grevesse (1989) described well the sound speed and density profiles inferred from helioseismological observations. A revision of the oxygen abundance by 0.27 dex led to a discrepancy between the theory and observations up to 15σ (Bahcall and Serenelli 2005). This problem still remains unsolved.

In our previous paper (Sitnova et al. 2013), based on the model atom from Przybilla et al. (2000) improved by including the cross sections for the excitation of O I transitions in collisions with electrons from Barklem (2007), we derived the mean oxygen abundance from atomic O I lines for the Sun and 46 FG stars in a wide metallicity range, $-2.6 < [\text{Fe/H}] < 0.2$. The application of accurate atomic data has led to an increase in the departures from LTE and a decrease in the oxygen abundance compared to the use of Drawin’s theoretical approximation. The change in the non-LTE abundance from the infrared O I 7771-5 Å triplet lines is $0.11$ dex for solar atmospheric parameters and diminishes in absolute value with decreasing metallicity. We have revised the $\text{[O/Fe]} - [\text{Fe/H}]$ relationship derived by us previously. The change in $\text{[O/Fe]}$ is small in the $\text{[Fe/H]}$ range from $-1.5$ to $0.2$. For stars with $\text{[Fe/H]} < -1$ the $\text{[O/Fe]}$ ratio has increased so that $\text{[O/Fe]} = 0.60$ at $\text{[Fe/H]} = -0.8$ and rises to $\text{[O/Fe]} = 0.75$ at $\text{[Fe/H]} = -2.6$. 

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abundance $\log \varepsilon = 8.74 \pm 0.05$ from the O I 6300, 6158, 7771–5, and 8446 Å lines in the solar spectrum using a classical plane-parallel solar model atmosphere and $\log \varepsilon + 3D = 8.78 \pm 0.03$ by applying the 3D corrections taken from the literature.

There exist a huge number of works in which the [O/Fe] ratio was determined for samples of stars; here, we mention some of them. It is well known from an analysis of observations that stars with [Fe/H]$^1 < 0$ show an excess of [O/Fe], which increases with decreasing metallicity approximately to [Fe/H] $\approx -1$ and then remains almost constant at [Fe/H] $< -1$. The [O/Fe] ratio as a function of [Fe/H] is understandable qualitatively and quantitatively, and, in general, the Galactic chemical evolution models describe the observational data for [O/Fe]. Almost the same [O/Fe] ratio for stars with [Fe/H] $< -1$ stems from the fact that at the epoch of their formation the interstellar gas was enriched with metals by massive stars exploded as type II supernovae (SNe II) or hypernovae. By the formation epoch of stars with [Fe/H] $\approx -1$, type Ia supernovae began to contribute to the enrichment of the medium with heavy elements, where the iron production efficiency is higher than that in the explosions of massive stars, which led to a reduction in [O/Fe]. At present, attempts are being made to establish subtler features in the behavior of [O/Fe], for example, to understand what the actual spread in [O/Fe] is for stars with a similar metallicity, from which the conclusion about the mixing of matter in the Galaxy can be drawn. Such an attempt was made by Bertran de Lis et al. (2016), who determined the oxygen abundance from IR OH lines in red giants with metallicity $-0.65 < [\text{Fe/H}] < 0.25$. Ramirez et al. (2013) determined the oxygen abundance by taking into account the departures from LTE from the OI 7771–5 Å lines for a sample of several hundred FGK dwarfs with $-1.2 < [\text{Fe/H}] < 0.4$. Bensby et al. (2014) performed a detailed analysis of 13 elements from oxygen to barium in several hundred nearby dwarf stars with $-2.6 < [\text{Fe/H}] < 0.4$. The oxygen abundance was inferred from the OI 7771–5 Å lines in non-LTE. In these papers particular attention is given to the chemical peculiarities of stars in various Galactic subsystems (the thin and thick disks, the halo, the Hercules and Arcturus streams). Amarsi et al. (2015) collected data from the literature on oxygen abundance determinations over 2000–2015 for dwarf stars with $-3.3 < [\text{Fe/H}] < 0.5$, determined their atmospheric parameters using the temperatures measured by the IR flux method, and corrected the derived abundance by applying the corrections for the hydrodynamic and non-LTE effects. As a result, the authors found a linear increase in [O/Fe] from $-0.3$ to $0.6$ as [Fe/H] decreased from $0.5$ to $-0.7$ and then a constant [O/Fe] down to [Fe/H] $\approx -2.5$; an increase in [O/Fe] to 0.8 is possible at a lower metallicity. The question of whether there is an increase in [O/Fe] at [Fe/H] $< -1$ is not completely clear. There are different opinions on that score in the literature. For example, Israelian et al. (1998) found a linear increase in [O/Fe] from 0.6 to 1 for [Fe/H] from $-1.5$ to $-3$ from their analysis of OH lines. Fulbright and Johnson (2003) also found an increase in [O/Fe] from 0.6 to 0.8 as [Fe/H] decreased from $-1$ to $-2.5$ using the forbidden 6300 Å line and the IR 7771–5 Å triplet lines. However, the results of Tomkin et al. (1992), Gratton et al. (2000), Nissen et al. (2002), Cayrel et al. (2004), Fabbian et al. (2009), and Sitnova (2016), which are also based on an analysis of atomic O I lines, suggest a constant [O/Fe] ratio at [Fe/H] $< -1$.

For the Sun and cool stars the abundance derived from atomic lines can be inaccurate due to the uncertainty in calculating the statistical equilibrium of oxygen related to the lack of knowledge of the excitation and ionization efficiencies in inelastic collisions with neutral hydrogen. Quantum-mechanical calculations of collisions with hydrogen atoms are available for a number of atoms: for Li I (Belyaev and Barklem 2003), Na I (Belyaev et al. 1999, 2010; Barklem et al. 2010), Mg I (Barklem et al. 2012), Al I (Belyaev 2013), Si I (Belyaev et al. 2014), K I (Belyaev and Yakovleva 2017), and Ca I (Belyaev et al. 2016; Barklem 2016; Mitruschenkov et al. 2017). Since there are no accurate calculations and laboratory measurements, the rates of inelastic collisions with H I are calculated from the formula derived by Steenbock and Holweger (1984) using the formalism of Drawin (1968, 1969). The authors themselves estimate the accuracy of the formula to be one order of magnitude. A scaling factor ($S_{\text{HI}}$) that can be found by reconciling the abundances from lines with strong and weak departures from LTE is usually introduced in this formula. For oxygen Allende Prieto et al. (2004) and Pereira et al. (2009) obtained $S_{\text{HI}} = 1$ by investigating the changes of the O I line profiles in different regions of the solar disk; Takeda (1995) obtained the same result from O I lines in the solar spectrum in fluxes. For the Sun and cool stars agreement between the abundances determined from different O I lines can be achieved by choosing the scaling factor. Caffau et al. (2008) performed non-LTE calculations for O I with $S_{\text{HI}} = 0, 1/3,$ and 1. The higher the efficiency of the collisions with hydrogen atoms, the smaller the departures from LTE.

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1 We use the standard notation for the elemental abundance ratios $[X/H] = \log(N_X/N_H)_{\text{star}} - \log(N_X/N_H)_{\text{Sun}}$. 

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and the higher the abundance. For example, for the IR O I 7771 Å line the abundance derived with $S_{H} = 1$ is higher than that with $S_{H} = 0$ by 0.12 dex. It is important to note that Belyaev and Yakovleva (2017) proposed a simplified but physically realistic method of estimating the rates of inelastic collisions with hydrogen atoms that is recommended to be applied instead of Drawin’s approximation for those elements where there are no accurate data so far.

This paper was motivated by the appearance of quantum-mechanical calculations of the cross sections for inelastic processes in collisions of O I with hydrogen atoms performed by Barklem (2017). In this paper we check how the use of data from Barklem (2017) will affect the oxygen abundance determination for the Sun and a sample of FG stars with metallicity $\sim -2.6 < [\text{Fe/H}] < 0.2$ and on the [O/Fe]–[Fe/H] relationship derived by us previously (Sitnova 2016). The model atom and the methods and codes used are described in Section 2. The O I lines in the Sun are analyzed in Section 3. The stellar parameters, the observations, and the derived oxygen abundance are presented in Section 4. Our results are presented in the Conclusions.

2. THE METHOD OF OXYGEN ABUNDANCE DETERMINATION

In this paper we determined the oxygen abundance from O I lines in the non-LTE case where the population of each level in a specified model atom is calculated by simultaneously solving the system of statistical equilibrium (SE) and radiative transfer equations. We solved this system of equations in a specified model atmosphere with the DETAIL code developed by Butler and Giddings (1985) based on the accelerated $\Lambda$-iteration method. The opacity calculation was improved, as described by Mashonkina et al. (2011). The level populations obtained in DETAIL were then used to compute the line profiles with the synthV_NLTE code (Ryabchikova et al. 2016), which is an improved version of the code developed by Tsymbal (1996). We use O. Kochukhov’s binnag code to compare the theoretical spectrum with the observed one.

The technique of calculations and the mechanism of departures from LTE for O I were described in detail by Sitnova et al. (2013). We use the multi-level model atom constructed from the most up-to-date atomic data. We took the model atom from Przybilla et al. (2000) as a basis; it consists of 51 O I levels and the O II ground state. The level energies were taken from NIST (Kramida et al. 2015); the transition oscillator strengths and photoionization cross sections were calculated within the Opacity Project (Seaton et al. 1994) and are accessible in the TOPbase database. To calculate the rates of bound–bound transitions in collisions with electrons, we use the quantum-mechanical calculations from Barklem (2007) for 153 transitions. For the remaining transitions, where there are no accurate data, we use the formulas from van Regemorter (1962) and Wooley and Allen (1948) for optically allowed and forbidden transitions, respectively. To calculate the rates of bound–free transitions in collisions with electrons, we use the formula from Seaton (1962) with the threshold photoionization cross section from TOPbase. The resonant charge exchange (O I $+ p \leftrightarrow$ O II $+ H I$) was taken into account as prescribed by Arnaud and Rothenflug (1985).

In this paper we take into account the excitation/deexcitation and ion-pair formation/mutual neutralization processes in collisions with hydrogen atoms according to the data from Barklem (2017). Previously, we used Drawin’s approximation (Drawin 1968, 1969; Steenbock and Holweger 1984) due to the absence of accurate data.

Figure 1 shows the transition rates in inelastic collisions with hydrogen atoms and electrons under conditions typical for the solar atmosphere at the O I line formation depths. According to the data from Barklem (2017), the O I $+ H I$ excitation rates are systematically lower than those calculated from Drawin’s formula. On average, the difference between the rates is about two orders of magnitude. For transitions with energies $\Delta E = E_u - E_l < 1.5$ eV Barklem’s rates for O I $+ H I$ collisions are of the same order of magnitude as the rates of collisions with electrons, while for transitions with higher energies the electron collisions are much more efficient than the hydrogen ones. The collisions with H I form an ion pair much more efficiently than the collisions with electrons ionize an atom in the entire range of ionization energies. However, this does not affect the results, because the statistical equilibrium of O I in the range of parameters under consideration is determined by the bound–bound transitions. We performed a test calculation for the Sun without any allowance for the ion-pair formation and mutual neutralization processes in collisions with hydrogen atoms and obtained very small changes in level populations that led to changes in the non-LTE abundance within 0.003 dex for the O I 7771–5 Å lines.

2 http://www.astro.uu.se/~oleg/download.html

3 http://cdsweb.u-strasbg.fr/topbase/topbase.html
3. ANALYSIS OF O I LINES IN THE SOLAR SPECTRUM

The solar abundance was determined using the spectrum of the Sun as a star (Kurucz et al. 1984). The model atmosphere has an effective temperature $T_{\text{eff}} = 5780$ K, surface gravity $\log g = 4.44$, and microturbulence $\xi = 0.9$ km s$^{-1}$. We use the classical 1D models from the MARCS grid (Gustafsson et al. 2008).

The list of lines and the derived oxygen abundance are given in Table 1. The atomic data for transitions, i.e., the wavelength $\lambda$, the oscillator strength ($\log gf$), and the lower-level excitation energy ($E_{\text{exc}}$), were taken from the VALD database (Kupka et al. 1999; Ryabchikova et al. 2008).

The application of accurate data for collisions with hydrogen atoms led to an enhancement of the departures from LTE and a strengthening of the IR lines. We obtained the mean non-LTE oxygen abundance $\log \epsilon(O) = 8.70 \pm 0.08$, which is lower than that derived in non-LTE with approximate data by 0.06 dex. For the IR triplet lines in the Sun the non-LTE abundance decreased by 0.11 dex. For the 8446 Å line the change is slightly smaller, 0.07 dex. In comparison with our previous results (Sitnova et al. 2013), the difference between the non-LTE abundances from the 7771–5 and 8446 Å lines increased from 0.02 to 0.05 dex. For the weak 6158 and 6300 Å lines in the visible range the departures from LTE are still negligible, irrespective of the method of calculating the inelastic collisions with hydrogen atoms. The difference of 0.07 dex between the non-LTE abundances from the forbidden [O I] 6300 Å line and the 7771–5 Å lines obtained in our previous paper decreased to 0.04 dex. The difference in non-LTE abundances from the 6158 and 7771–5 Å lines increased from 0.07 to 0.18 dex. It should be noted that the abundance from the 6158 Å line is systematically higher than that from the IR triplet not only for the Sun but also for GF dwarfs. According to the data from Sitnova (2016), the mean difference $\Delta = 0.12 \pm 0.07$ is obtained by comparing the absolute non-LTE abundances from these two lines for 17 GF stars in the [Fe/H] range from $-0.8$ to 0.2. With the classical MARCS model atmosphere Asplund et al. (2004) obtained a difference of 0.13 dex in non-LTE abundance between these two lines for the Sun. The systematic difference is probably caused by the inaccuracy of the oscillator strengths calculated theoretically by Hibbert et al. (1991).

4. THE OXYGEN ABUNDANCE IN THE SAMPLE STARS

In this section we redetermine the non-LTE oxygen abundance based on an improved model atom for 46 FG stars investigated by us previously (Sitnova 2016).

4.1. The Sample of Stars, Observations, Atmospheric Parameters

The sample of stars includes 46 unevolved stars from dwarfs to subgiants. The stars are uniformly distributed in metallicity over a wide range, $-2.6 < [\text{Fe/H}] < 0.2$. High-resolution ($\lambda/\Delta \lambda > 45,000$) spectra with a signal-to-noise ratio $S/N > 60$ were obtained at the 3-m telescope of the Lick Observatory with the Hamilton spectrograph and were taken from the UVES$^4$ and ESPaDOnS$^5$ archives. We also used the spectra obtained at the 2.2-m telescope

$^4$ http://archive.eso.org/eso/eso_archive_main.html
$^5$ http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/search/
of the Calar Alto Observatory with the FOCES spectrograph and provided by K. Fuhrmann. The observations and their reduction were described in detail by Sittnova et al. (2015), Pakhomov and Zhao (2013), and Zhao et al. (2016). We use the atmospheric parameters carefully investigated by various methods by Sittnova et al. (2015). For most stars there are effective temperature measurements by the infrared flux method (Alonso 1996; Casagrande et al. 2010, 2011); the effective temperature for each star can be estimated from its color indices. The final temperatures agree with the photometric ones within the measurement error limits and were chosen so as to achieve agreement between the non-LTE abundances from Fe I and Fe II lines. The stars occupied the positions on the evolutionary tracks from the grid of Yi et al. (2001) corresponding to their mass and metallicity. For ten stars from our sample there is a $T_{\text{eff}}$ determination based on the bolometric flux and the angular diameter measured with the CHARA interferometer (Boyajian et al. 2012, 2013; North et al. 2009; von Braun et al. 2014). Our temperatures are systematically higher than the interferometric ones by 78 $\pm$ 81 K. However, this difference does not exceed the error in $T_{\text{eff}}$, which we estimate to be 80 K. For two other stars, HD 140283 and HD 103095, the interferometric temperatures measured previously by Creevey et al. (2012, 2015) and Boyajian et al. (2013) differ from those adopted by us by more than 250 K. Karovicova et al. (2018) redetermined the angular diameters and bolometric fluxes for these two stars, which led to an increase in $T_{\text{eff}}$ and agreement with our determinations within 10 K.

The Hipparcos trigonometric parallaxes (van Leeuwen et al. 2007) are known for all sample stars, which allows log $g$ to be calculated by a spectroscopy-independent method. For the stars where the parallax error, according to the Hipparcos data, exceeded 10% we refined log $g$ by analyzing the non-LTE abundances from Fe I and Fe II lines. The statistical equilibrium of Fe I–II was calculated with the model atom developed by Mashonkina et al. (2011) with the scaling factor to the Drawin rates of inelastic collisions with hydrogen atoms $S_H = 0.5$. It is worth noting that new Gaia6 parallaxes have appeared (Brown et al. 2016) for 22 stars from our sample. We achieved good agreement between our spectroscopic log $g$ and those calculated from the new Gaia DR1 parallaxes: $\Delta \log g (\text{Spec - Gaia}) = -0.01 \pm 0.07$, despite the fact that for the same 22 stars the spectroscopic log $g$ differ noticeably from those derived from the Hipparcos data, $\Delta \log g (\text{Spec - Hipparcos}) = -0.15 \pm 0.12$. The differences in log $g$ concern the stars that are 100 pc or more away from the Sun. For the nearest stars the spectroscopic log $g$ agree well with those calculated from both Hipparcos and Gaia DR1 data.

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Table 1. The list of O I lines with atomic parameters and LTE and non-LTE solar abundances. The non-LTE abundance is given for the cases where the inelastic collisions with hydrogen atoms were calculated from the approximate formula (S13) and based on the quantum-mechanical calculations (S17).

| $\lambda$, Å | $E_{\text{exc}}$, eV | log($gf$) | Transition | LTE | non-LTE, S13 | non-LTE, S17 |
|--------------|---------------------|----------|------------|-----|--------------|--------------|
| 6158.146     | 10.741              | -1.841   | $3p^5P - 4d^5D^o$ | 8.83| 8.82         | 8.82         |
| 6158.176     | 10.741              | -0.996   | $3p^5P - 4d^5D^o$ | 8.83| 8.82         | 8.82         |
| 6158.186     | 10.741              | -0.409   | $3p^5P - 4d^5D^o$ | 8.83| 8.82         | 8.82         |
| 6300.304     | 0.000               | -9.7201  | $2p^3P - 2p^3D$  | 8.68| 8.68         | 8.68         |
| 7771.941     | 9.146               | 0.369    | $3s^5S^o - 3p^5P$ | 8.91| 8.74         | 8.63         |
| 7774.161     | 9.146               | 0.223    | $3s^5S^o - 3p^5P$ | 8.91| 8.76         | 8.65         |
| 7775.390     | 9.146               | 0.001    | $3s^5S^o - 3p^5P$ | 8.87| 8.75         | 8.66         |
| 8446.250     | 9.521               | -0.463   | $3s^3S^o - 3p^3P$ | 8.87| 8.77         | 8.70         |

1 The data from Froese Fisher et al. (1998).
When fitting the [O I] $\lambda 6300$ Å line, we took into account the blending Ni I $\lambda 6300.34$ line with log($gf$) = -2.11 (Johansson et al. 2003) and the abundance log ε(Ni) = 6.23.
The microturbulence $\xi_t$ and [Fe/H] were derived from Fe I and Fe II lines, respectively. Additionally, $T_{\text{eff}}$, log $g$, and [Fe/H] were checked using a grid of evolutionary tracks from Yi et al. (2001).

4.2. Influence of Inelastic Collisions with Hydrogen Atoms on the Non-LTE Oxygen Abundance Depending on Atmospheric Parameters

The non-LTE and LTE oxygen abundances for this sample of stars were derived by Sitnova (2016). Here, we redetermined the non-LTE oxygen abundance from the IR 7771-5 Å triplet lines using the quantum-mechanical data for inelastic collisions with hydrogen atoms. The mean difference between the non-LTE abundances from the triplet lines obtained in this and previous (Sitnova 2016) papers is shown for each of 46 stars in Fig. 2 as a function of metallicity, effective temperature, and gravity.

Just as for the Sun, the application of accurate data for the sample stars leads to a lower non-LTE oxygen abundance. The difference in non-LTE abundance ranges from 0.02 to 0.15 dex, depending on the atmospheric parameters. The difference between the non-LTE abundances derived with accurate and approximate data diminishes with decreasing metallicity, because in metal-poor stars the O I lines are weak and the non-LTE corrections are small in absolute value.

4.3. The Galactic [O/Fe] Trend

Figure 3 shows the [O/Fe] ratio that we derived in this and previous papers. In the metallicity range $-1 < [\text{Fe/H}] < 0.2$ the [O/Fe] ratio for each of the stars changed by no more than 0.03 dex compared to the previous results, because the change in the non-LTE oxygen abundance for these stars turns out to be approximately the same as that for the Sun. For stars with $[\text{Fe/H}] < -1$ the [O/Fe] ratio turns out to be higher than its previous value, with [O/Fe] increasing with decreasing [Fe/H].

Out of the present-day Galactic chemical evolution models, our previous data for [O/Fe] were best described by the model of Kobayashi et al. (2011) without allowance for rapidly rotating metal-poor massive stars. This model predicts a slow decrease in [O/Fe] from 0.7 to 0.6 as [Fe/H] increases from $-3$ to $-1$ and then a drop in [O/Fe] to 0.1 at [Fe/H] = −0.17 (the values were recalculated by taking into account the difference between our solar oxygen and iron abundances and those adopted by Kobayashi et al. (2011)). Our revision of the oxygen abundance led to an increase in [O/Fe] with decreasing metallicity at [Fe/H] < −1. This behavior of [O/Fe] can be described by the model of Kobayashi et al. (2011), where rapidly rotating metal-poor massive stars were taken into account. This model predicts an increase
in [O/Fe] from 0.6 to 0.85 as [Fe/H] decreases from −2 to −3, while at [Fe/H] > −2 the behavior is the same as that in the previous model. It should be noted that allowance for rapidly rotating massive stars improved fundamentally the description of the behavior of [C/Fe] and [N/Fe] at [Fe/H] < −1.5, but does not affect the behavior of heavier elements.

5. CONCLUSIONS

We performed non-LTE calculations for O I using the data from Barklem (2017) for collisions with hydrogen atoms. The oxygen abundance was determined from atomic lines for the Sun and 46 FG dwarfs in a wide metallicity range, −2.6 < [Fe/H] < 0.2.

The application of accurate data leads to an enhancement of the departures from LTE and a decrease in the abundance from the IR lines. The changes in the non-LTE abundance are biggest for the IR 7771-5 Å triplet lines. For example, for the Sun the non-LTE abundance from these lines decreases by 0.11 dex compared to what is obtained with approximate data for collisions with hydrogen atoms. Our new calculations do not affect the non-LTE abundance from weak lines in the visible range (6158, 6300 Å).

For the Sun we obtained the mean non-LTE oxygen abundance log ε(O) = 8.70 ± 0.08, which is lower than that inferred in non-LTE with approximate data for collisions with hydrogen atoms by 0.06 dex. This value is even farther from what is required to reconcile the theoretical and observed density and sound speed profiles.

For 46 stars from the sample the changes in the non-LTE abundance vary from 0.02 to 0.13 dex, depending on the atmospheric parameters. The change in the solar oxygen abundance and the oxygen abundance for individual stars led to a change in the behavior of the Galactic [O/Fe] trend with [Fe/H] in the range −2.6 < [Fe/H] < −1: the increase in [O/Fe] with decreasing [Fe/H] became more noticeable. For stars with −1 < [Fe/H] < 0.2 the changes in the non-LTE abundance for the sample stars are close to what was obtained for the Sun. Therefore, the [O/Fe] ratio barely changed.

The refined dependence can be used to test the Galactic chemical evolution models.

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