Oxygen abundance distribution in Galactic disc.

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ABSTRACT

We have performed a NLTE analysis of the infrared oxygen triplet for a large number of cepheid spectra obtained with the Hobby-Eberly telescope. These data were combined with our previous NLTE results for the stars observed with Max Planck Gesellschaft telescope with the aim to investigate oxygen abundance distribution in Galactic thin disc. We find the slope of the radial (O/H) gradient value to be equal $-0.058$ dex/kpc. Nevertheless, we found that there could be a hint that the distribution might become flatter in the outer parts of the disc. This is also supported by other authors who studied open clusters, planetary nebulae and H\textsc{ii} regions. Some mechanisms of flattening are discussed.

Key words: stars: abundances – stars: variables: Cepheids – Galaxy: abundances – Galaxy: disc – Galaxy: evolution.

1 INTRODUCTION

From the astronomical point of view oxygen is among the most interesting elements in the Universe. This is because it is the third most abundant element, it constitutes the base of the life (at least on the Earth), and it is used as a proxy of the global metal content in several astronomical objects, thus, when measured in objects with different ages, it is a tracer of the temporal evolution of the chemical content of our Galaxy. General information about the oxygen abundance distribution in Galactic substructures comes from spectroscopic study of sources such as stars, planetary nebulae, H\textsc{ii} regions, and interstellar matter. Comparison of the data on oxygen abundance provided by these sources shows that there are discrepancies that affect our understanding of those processes that are responsible for the production and distribution of this element in our Galaxy and other galaxies. At present, new accurate oxygen abundance data from a large homogeneous sample of objects at the different Galactocentric distances are urgently necessary.

Since oxygen and other \textit{α}-elements are produced in explosive processes in SNe II, it is of particular interest to study the distribution of this element in Galactic thin disc. Characteristics of such a distribution may reveal the spatial dependence of the SNe II activity that, as we believe, is caused by the interstellar gas density distribution in the disc, the efficiency of the Galactic spiral arms’ influence on the gas, and the local metallicity level.

The current status of the abundance gradient studies with Galactic cepheids indicates growing evidence that elemental distributions in the disc require, for their description not a single slope gradient, but instead a bimodal (or even multimodal) structure with different slopes in each region. For instance, [Andrievsky et al. (2002b)] using a sample of cepheid stars demonstrated that among other \textit{α}- and iron-group elements, oxygen and iron show a steeper increase of their content toward the Galactic centre. This increase at about 6.6 kpc changes the flat distribution in the solar vicinity to the much steeper one in the range of about 4-7 kpc. This is also supported by the results of Pedicelli et al. (2009) and Genovali et al. (2013) (both studies deal with iron distribution).

Later, [Luck et al. (2003)] reported about a clear separation in elemental abundance distributions of the outer Galactic disc from its middle part. This separation is associated with Galactocentric distance of about 10 kpc. This finding was confirmed by [Andrievsky et al. (2004)] with a larger sample of stars. They concluded that "the wriggle feature in the metallicity distribution, which is associated with Galactocentric distance of about 11 kpc can be interpreted as a change of metallicity level in vicinity of the Galactic corotation resonance".

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In contrast, Kozyukik, Wallerstein & Andrievsky (2002) and Luck et al. (2006) did not find any strong reason to not use a simple linear gradient to describe the spatial abundance distributions obtained with even more expanded sample of the cepheid stars. The latter conclusion was reached by [Luck et al. (2011)] and [Luck & Lambert (2011)] (but proposed an increased scatter of the abundance data outward the distance of 10 kpc). In part, this conclusion may be affected by including the new cepheids covering more distant parts of the disc in Galactocentric longitude, that could clean up any specific features in the radial abundance distribution.

Genovali et al. (2014) have also used a single gradient value to describe the iron abundance distribution over a broad range of Galactocentric distances from 5 to 19 kpc. Lemasle et al. (2013) also do not support the flattening of the abundance distribution for some elements in the outer Galactic disc, but at the same time they do not provide the corresponding data for oxygen and iron.

As we can see, the situation with characteristics of the abundance distribution in Galactic disc of such astrophysically important elements as oxygen and iron is far from being clear. All the data on oxygen distribution from the giant and supergiant stars F-G-K stars come from analysis of either forbidden oxygen lines at 630.03 and 636.38 nm, or 615.6-615.8 nm triplet, but there are known problems of the reliable oxygen abundance determination from this restricted sample of the lines. For example, two forbidden lines can hardly be detected in the supergiant spectra if the effective temperature of the star is higher than 5500 K, but this is the case for a large amount of cepheids. Moreover, these lines are often polluted with terrestrial absorptions. Since this region is dominated by terrestrial bands, the additional measures of the spectra cleaning are needed. Among the triplet lines, only the line 615.8 nm is more or less detectable in the supergiant spectra. It cannot be detected in the medium-to-high resolution spectra of the stars with effective temperature lower than 5500-6000 K. Thus, in some cases, in order to derive oxygen abundance for a large sample of the cepheid stars one needs to use either forbidden lines (for cooler stars, or for phases of minimum with lower temperature), or triplet lines (for the hotter stars).

A good solution would be to use of the 777.1-777.4 nm triplet. It affords the most suitable opportunity to derive oxygen abundance in F-G-K supergiant stars because: 1) its lines are quite strong and very well shaped over a wide range of the effective temperature, 2) these lines are practically not blended, 3) they are reachable with many spectrograph even for the faintest cepheids. The most significant obstacle, which prevents a wide use of this triplet in spectroscopic analyses, is an obvious necessity to apply sophisticated NLTE approximation in order to get correct oxygen abundance. This is a well known problem (see e.g. a very instructive example about extremely strong dependence of the derived oxygen abundance on the effective temperature provided by the LTE study of Schuler et al. (2006)).

The main goal of the present paper was to derive correct NLTE oxygen abundance for a large homogeneous sample of cepheids using the IR oxygen triplet, and then to construct on this basis the oxygen abundance distribution in the Galactic thin disc.

The paper is organized as follows. Our sample of cepheids is presented in Sect. 2. The NLTE approximation that was used to derive oxygen abundance from the strong IR triplet is detailed described in Sect. 3. The oxygen abundance distribution in the disc is the subject of Sect. 4. The Discussion and Conclusion summarize our results from the point of view of the recent observational and theoretical works on abundance gradients in the Galactic disc.

2 OUR SAMPLE OF STARS

Continuing our program of the Galactic abundance gradient investigation (Andrievsky et al. 2002a,b,c; Luck et al. 2003; Andrievsky et al. 2004; Luck et al. 2006; Lépine et al. 2011), we study the oxygen distribution in the thin disc with a large sample of Galactic cepheids. Our sample consists of two subsamples. One contains the Hobby-Eberly Telescope (HET) data described in detail by Luck & Lambert (2011). The second is composed by the MPG Telescope data, which are described in [Luck et al. (2013)]. The observational data for both samples were collected by one of the authors (REL).

The list of the studied stars (only HET data) and their spectra can be found in Table [II] (electronically available in its full form).

3 METHOD OF ANALYSIS

The NLTE approximation was used to derive oxygen abundance in our stars. For this we used the OI triplet at 777.4 nm. Study of the NLTE deviations in the IR oxygen triplet was initiated by many authors in the past (e.g. Kiselman 1991; Takeda 1992; Carlsson & Judge 1993; Paumzen et al. 1996; Reetz 1999; Mischenina et al. 2000; Przybilla et al. 2004; Fabbian et al. 2009; Sitnova et al. 2012). As shown by those authors NLTE effects significantly strengthen these lines. At the same time available OI atomic models were not always able to reproduce observed triplet profiles. For instance, Przybilla et al. (2004) found different oxygen abundance in A and F stars derived from IR lines and lines in visual part of the spectrum.

The most complete atomic models published by Sitnova et al. (2013) and Fabbian et al. (2009) take into account the most recent collisional rate values between atoms and electrons (Barklem 2007). Nevertheless, the lack of detailed calculations describing collisions with hydrogen atoms force the use of Drawin’s formula (Drawin 1969) with a very uncertain correcting factor varying from 0 to 1.

In this work we modified our oxygen atomic model first presented in Mischenina et al. (2000) and then updated in Dobrovolskas et al. (2014). Our present model consists of 51 OI levels of singlet, triplet and quintet systems and the ground level of OII ion. An additional 24 levels of neutral oxygen and 15 levels of ions of higher stages were added for particle number conservation. The Grotian diagram of our model is shown in Fig. I Fine-splitting was taken into account only for the ground level and 3p5P level (the upper level for 777.4 nm triplet).

Two-hundred and forty eight bound-bound transitions were included in the detailed analysis. Photoionization cross-sections were selected from TOPBASE (Cunto et al. 1993). Accurate quantum-mechanical calculations were employed.
for the first 19 levels to find collisional rates with electrons (Barklem 2007). Using spline interpolation the collision rates can be interpolated against temperature. The remaining allowed collisional transitions were approximated by the van Regemortel (1962) formula, while for the forbidden transitions we applied the Allen’s (1973) formula with the collision strength set equal to 1.0. Collisions with hydrogen atoms were described using Drawin’s formula (Drawin 1963), as modified by Steenbock & Holweger (1984). An oscillator strength of \( f = 0.001 \) was used for the forbidden transitions. Thus, we decreased by a factor of two the rates that correspond to the IR triplet 777.4 \( \text{nm} \) and increased by four times the rates that correspond to 884.6 \( \text{nm} \) triplet. We also strengthened the coupling between 3p3p3P (the upper level for the 844.6 \( \text{nm} \) triplet lines) and levels of the quintet system 4s5S\(^0\) and 3d5D\(^0\) due to collisions with hydrogen atoms. For the forbidden transitions we used \( f = 1.0 \) in Drawin’s formula. With these modifications, we were able to adjust theoretical and observational profiles of oxygen lines of different multiplets in the spectra of the rather hot A-F stars, the solar-type stars, as well as the cooler stars. For the cooler stars we used correcting factor \( S_H = 1 \), in agreement with Barklem (2007), as done by Sitnova et al. (2013), and Sitnova et al. (2013). Table 2 lists the source of observed spectra and stellar parameters.

We consider that a decrease of all collisional rates calculated by Barklem (2007) is not appropriate, therefore we decided to change the collisional rates only for some transitions. Thus, we decreased by a factor of two the rates that correspond to the IR triplet 777.4 \( \text{nm} \) and increased by four times the rates that correspond to 884.6 \( \text{nm} \) triplet. We also strengthened the coupling between 3p3p3P (the upper level for the 844.6 \( \text{nm} \) triplet lines) and levels of the quintet system 4s5S\(^0\) and 3d5D\(^0\) due to collisions with hydrogen atoms. For the forbidden transitions we used \( f = 1.0 \) in Drawin’s formula. With these modifications, we were able to adjust theoretical and observational profiles of oxygen lines of different multiplets in the spectra of the rather hot A-F stars, the solar-type stars, as well as the cooler stars. For the cooler stars we used correcting factor \( S_H = 1 \), in agreement with Barklem (2007), as done by Sitnova et al. (2013), and Sitnova et al. (2013).

In Fig. 2 we show a comparison between observed and synthetic profiles for the lines of different multiplets for Vega and Procyon. Note that a single oxygen abundance value was used to synthesize all the lines for each star. Good agreement is seen both for 615.7 \( \text{nm} \) triplet lines that are not affected significantly by NLTE effects, and for IR triplets, which are significantly affected. Another test was applied to the solar spectrum. We used solar atmosphere model of Castelli & Kurucz (2003) that was supplemented by VAL-C chromosphere model (Vernazza et al. 1981) with an explicit distribution of the microturbulent velocity. (Note that the influence from the chromosphere on the lines of IR triplets is very small, no more than 1.5% in their equivalent widths). Observed profiles were taken from Solar flux atlas (Kurucz et al. 1984). We also made a comparison for the solar disc center using the Solar atlas of Delbouille et al. (1974). A comparison of the theoretical profiles for 630 \( \text{nm} \) line, the lines of 777.4 \( \text{nm} \) and 844.6 \( \text{nm} \) triplets with observed profiles in the solar spectrum is shown in Fig. 3. To synthesize all the lines we used a single oxygen abundance log \( e(O) = 8.71 \) (the same value as proposed by Scott et al. 2009).

Table 1. Parameters and Abundances for Program cepheids (only header of the table is showed. The full table is available in electronic form)

| Object  | Phase | \( T_{\text{eff}}, \text{K} \) | \( \log g \) | \( V_t, \text{km s}^{-1} \) | (Fe/H) | (O) | \( R_C \) (kpc) |
|---------|-------|-----------------|-------------|-----------------|--------|-----|-------------|
| AA Gem  | 0.422 | 5141            | 1.23        | 3.92            | 7.34   | 8.51 | 11.55       |
| AA Gem  | 0.658 | 5190            | 1.45        | 5.85            | 7.38   | 8.51 | 11.55       |
| AA Mon  | 0.841 | 5797            | 2.26        | 4.90            | 7.41   | 8.51 | 11.36       |

Figure 1. The Grotrian diagramme for O I.
Table 2. Stellar parameters

| Star     | $T_{\text{eff}}$, K | $\log g$ | [Fe/H] | $V_t$, km s$^{-1}$ | (O/H) | Res. | Source                  |
|----------|---------------------|----------|--------|--------------------|-------|------|-------------------------|
| Sun      | 5777                | 4.44     | 0.0    | 1.0                | 8.71  | 35000 | Kurucz et al. (1984)    |
| Procyon  | 6590                | 4.00     | 0.0    | 1.8                | 8.73  | 80000 | Bagnulo et al. (2003)  |
| Vega     | 9550                | 3.95     | -0.5   | 2.0                | 8.59  | 10000 | Takeda et al. (2007)   |
| Sirius   | 9850                | 4.30     | 0.4    | 1.8                | 8.42  | 80000 | Bagnulo et al. (2003)  |

Figure 2. Profile fitting of the O I line in the Vega and Procyon spectrum.

Figure 3. Profile fitting for the oxygen lines in the solar spectrum.

Figure 4. Profile fitting of the O I line in the cepheids spectrum. Open circles - observed profiles, continuous line - NLTE profiles, dashed line - LTE profiles calculated with derived NLTE oxygen abundance.

4 OXYGEN ABUNDANCE DISTRIBUTION IN THE DISC

In Fig. 5 we show NLTE oxygen distribution vs. Galactocentric distance for the combined sample of HET and MPG Telescope stars.

The region 5-13 kpc is quite well sampled by our oxygen data and the distribution is rather tight. At larger distances the data are more dispersed. Samples observed with different telescopes produce results that agree well.

The data in Fig. 5 can be interpolated linearly. In this case we have the slope $\Delta(O/H)/\Delta R_G = -0.058$ with $R^2 = 0.61$. The slope derived by Luck & Lambert (2011) is quite similar: $-0.056$ with $R^2 = 0.47$. Those authors did not discuss the possible bimodal character of the gradient.

Nevertheless, despite the less populated outer disc region, it seems that abundance distribution here could be more flat. In Fig. 6 we show the same data as in Fig. 5 but assuming a bimodal distribution. We formally adopted position of the possible break in the distribution at 11 kpc taking into account that in many studies, which report about gradient flattening, the distances of 10-12 kpc are mentioned (see references in Introduction and Discussion).
Figure 5. NLTE oxygen abundance vs. Galactocentric distance. Open circles - HET data, crosses - MPG Telescope data.

Figure 6. Bimodal distribution of oxygen abundance. The break position is close to 11 kpc.

More robust confirmation of this conclusion follows from Fig. 6. In this figure all cepheids were binned with a step of 0.5 kpc. For each bin we show error of the mean. If only one star falls in a bin, then error of the mean was adopted to be equal 0.2. A clear change of the general trend at about 12 kpc and a local increase of the oxygen abundance in vicinity of 15 kpc is seen.

5 DISCUSSION

As shown by Barros et al. (2013), the specific action of the corotation resonance results in orbital trajectory migration of stars and also in the formation of a gas density minimum in the corotation. For instance, their Fig. 7 demonstrates how a star situated initially inside the corotation circle after some time appears outside it. The star from outside the corotation circle, on contrary, migrates inside it. The typical time of this change is about 2 Gyr. The star migration process itself may disturb the observed radial metallicity distribution at present time.

More massive stars (like cepheid progenitors) have insufficient time to migrate far from their birth places, therefore this mechanism is not efficient in modifying the metallicity distribution obtained from these objects. Their position should be approximately associated with their parent gas clouds. Since the gas component flows in opposite direction from the corotation circle (with respect to stars) due to the influence of angular momentum loss and gain in vicinity of the corotation circle (Barros et al. 2013) and references therein, one can expect some increase in the metallicity outwards of the corotation circle, which reflects a local increase in the gas density, the star formation rate, and therefore the metallicity production. An element such as oxygen, being produced by massive short-lived stars, may show an abundance distribution that reflects the instantaneous mass density distribution in the Galactic disc. In our Fig. 6 a peculiar region could be associated with $R_G \approx 11$ kpc. Barros et al. (2013) find an evidence of the mass density gap at Galactocentric distance of about 9 kpc. This is somewhat less that 11 kpc, but qualitatively conclusion remains the same.

If we turn to iron abundance distribution using the most complete data for cepheids provided by Luck & Lambert (2011), their Fig. 1, then we have to state that it is difficult to detect any peculiar point in this distribution. Iron is efficiently produced by SNe Ia stars, whose progenitors have a typical lifetime of about 1 Gyr, or slightly more (Iben & Tutukov 1984), which is comparable to the characteristic crossing time of particular region in vicinity of the corotation circle. The movement of the slightly larger number of the SNe Ia progenitors from the inner part of corotation circle towards the outer part, and opposite movement of the smaller number of such stars from the outer part could increase the gas pollution with iron at the corotation circle itself and in vicinity of it, and therefore veil any “instantaneous” distribution picture of this element created by SNe of type II.

It should be noted that Daflon & Cunha (2004), based on observations of OB stars, found a different behaviour of the oxygen gradient compared to the present work, with a strong step near the solar radius (taken as 8.5 kpc). The OB stars are much younger (a few million years) than the cepheids, so that in principle, their abundance is really that
of the surrounding gas. Costa et al. (2004) derived some flattening at Galactocentric distances larger than 10 kpc on the basis of a set of Galactic planetary nebulae, and a previous work in this series (Andrievsky et al. 2004, 2013) led to the same conclusion based on cepheid variables. More recent results by Lemasle et al. (2013) suggest a constant slope along the Galactic radius, although their own data are not inconsistent with some flattening at large Galactocentric distances. More recent results of the same group based on accurate iron abundances of a large sample of Galactic cepheids (Genovali et al. 2014) are consistent with a linear gradient over a broad range of Galactocentric distances given by -0.06 dex/kpc, very similar to the results shown in Figure 5.

Open cluster data seem to indicate the same tendency. In particular, a recent study based on Yong et al. (2012) based on a- and iron-group element abundances of new sample of objects in the outer Galactic disc. For instance, the plot for representative a-element magnesium shows a break of the distribution at 13 kpc with some flattening of the distribution at larger radii (see their Fig. 31a). In principle, similar behaviour is inherent to the cepheid (Mg/H) distribution (Fig. 31d).

The same conclusion was also made earlier by Magrini et al. (2009), who claimed that there is a flattening of the iron and a-element distribution (or even plateau) at the radii larger than 12 kpc. Cescutti et al. (2007) succeeded to model the flattening of the gradients produced by open clusters, as well as by cepheids, hot stars and red giant stars.

Lépine et al. (2013) performing an average of abundances of several alpha elements in order to decrease the effect of individual errors on measurements, suggest (their Figure 6) that there are two distinct levels of alpha abundances, with some overlap in Galactic radius. A recent study based on Galactic H II regions and featuring the outer disc object NGC 2579 (Esteban et al. 2013) is also consistent with a flattened gradient at large distances from the Galactic center.

The flattening of the gradients at large Galactocentric distance seems to be an universal property of disc galaxies. For example Stasinska et al. (2013) considered PNe and H II regions in the spiral galaxy NGC 300 and found that oxygen and other element abundance gradients from PNe are significantly shallower than those from H II regions, and this may indicate a steepening of the metallicity gradient in NGC 300. Very clear flattening of the oxygen abundance distribution in the outer parts of the spiral galaxy M83 was reported by Bresolin et al. (2009) (see their Fig. 9). Recently, Sanchez et al. (2014) presented the largest and most homogeneous catalog of H II regions in several hundreds of galaxies from CALIFA survey. Many of these galaxies show a flattening in the oxygen abundance.

These results may in principle be affected by the time variation of the radial abundance gradients in the Galactic disc, but some recent work based on four different sample of Galactic planetary nebulae suggest that this variation was probably very small during the past 4 to 5 Gyr, so that the gradients indicated by these different objects are essentially indistinguishable (Maciel & Costa 2013). Therefore, the planetary nebula gradient is not expected to be very different from the gradient observed in H II regions and cepheid variables, which is supported by recent additional observational data on these objects (Fu et al. 2009; Pedicelli et al. 2009). Dynamical calculations valid for the Milky Way disc over a time span of about 6 Gyr seem to confirm these results (Curir et al. 2014).

Additionally, some recent work on the time variation of the abundance gradients as a function of the redshift suggest that the variations are indeed very small for $z < 0.5$ (cf. Gibson et al. 2013; Pilkington et al. 2012), which comprise the age bracket of most of the objects mentioned above.

Alternatively, the data at galactocentric distances larger than 14 kpc in principle may become more scattered. In such a case, the outer parts of the Galaxy may show abundances that reflect local events that influence the abundances more than coherent evolution as implied by a gradient. Unfortunately, this type of analysis is not really possible with cepheids (the natural lack of the cepheid stars at large distances). Perhaps in the future giants might be used to continue the project.

6 CONCLUSION

Summarizing our present study, one can note that there is a growing observational evidence about the flattening of a-element distributions (including oxygen) in the discs of different galaxies including our Galaxy. These data come from spectroscopic analyses of the open clusters, planetary nebulae, H II regions, hot stars, red giant stars, and now, from cepheids.

Since oxygen is produced by massive short-lived stars, its abundance distribution should follow an instantaneous gas distribution in the Galactic disc. As recently concluded by Barros et al. (2013) based on several previous theoretical studies, the radial gas density profile has a gap at the corotation circle, and an increased density on both sides of it. Our observational data comprising a large sample of cepheids, analysed taking into account NLTE effects on oxygen abundance determinations, seem to support this assumption, and show that the corotation resonance in the Galactic disc can have really significant impact on the abundance gradients in its vicinity. In particular, our oxygen abundance distribution reveals a clear change of the general trend at about 12 kpc with the subsequent flattening in the range from 12 to 15 kpc, or even small increase of the oxygen abundance toward 15 kpc.

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