

On the metallicity gradient in the Galactic disk

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Abstract The problem of the chemical composition gradient in the Galactic disk is studied based on a sample of metallicity estimates of open star clusters, using Gaia DR2-improved distance estimates. A clearly non-monotonic variation was observed in the average metallicity of clusters with increasing Galactocentric distance. One can clearly see the metallicity jump of 0.22 in $[\text{Fe}/\text{H}]$ at a Galactocentric distance of about 9.5 kpc, which appears to be linked to the outer boundary of the thinnest and youngest component of the Galactic disk. The absence of a significant metallicity gradient in the internal ($R < 9$ kpc) and external ($R > 10$ kpc) regions of the disk demonstrates the absence of noticeable metal enrichment at times of the order of the ages corresponding to those of the disk regions under consideration. Observational data show that the disk experiences noticeable metal enrichment only during the starburst epochs. No significant dependence was identified between the average metallicity and the age of the clusters.

Key words: Galaxy: general — Galaxy: disk — (Galaxy:) open clusters and associations: general

1 INTRODUCTION

High-precision photometric and astrometric data from the Gaia Data Release 2 (DR2) catalog (Gaia Collaboration et al. 2018) have heavily influenced research in a number of Galactic astronomy fields. One such study examines the spatial gradient of the chemical composition in the Galactic disk. Another rather interesting subject is the time gradient of the chemical composition as it relates to the rate of heavy element enrichment in the disk. These gradients have been studied previously (Magrini et al. 2017; Marsakov et al. 2016; Huyen et al. 2015; Kubryk et al. 2015; Mikolaitis et al. 2014; Marsakov et al. 2014; Gozha & Marsakov 2013). References to earlier studies on the metallic gradient of the Galactic disk can be found in Gozha et al. (2012a). Lépine et al. (2011) provide a detailed analysis of influence of the spiral structure of the Galactic disk on its chemical structure. The Gaia DR2 has facilitated more precisely defining the distances to many stellar objects, giving impetus to our research on this matter. We decided to study the gradients of the chemical composition based on open star cluster (OCL) data, as these objects are observed at large distances from the Sun, and therefore at a greater range of Galactocentric distances. Their ages cover the entire range of Galactic disk ages, which distinguishes these objects as compared to, for example, classical Cepheids, whose ages are, to a certain ex-

tent, unreliable, as the age range of these massive, obviously young stars is quite small.

2 SAMPLE OF OCL DATA

The “Homogeneous Catalog of Open Cluster Parameters” (Loktin & Popova 2017) provided the data on the open clusters. Cluster metallicities are from the catalogs of Gozha et al. (2012b), Kharchenko et al. (2013) and Dias et al. (2002). For those clusters with a known metallicity not found in the “Homogeneous Catalog of Open Cluster Parameters,” the ages of the OCLs were taken from the catalog of Kharchenko et al. (2013). Figure 1 (left) displays a comparison of OCL ages referenced from the “Homogeneous Catalog of Open Cluster Parameters” and those from the catalog of Kharchenko et al. (2013). The points are positioned close to the 45° line, an unsurprising observation due to the similarities in the age determination methods and theoretical isochrone sets applied, and therefore support the inclusion of the ages from the catalog of Kharchenko et al. in our sample. Not all clusters with metallicity estimations have distance estimates in the “Homogeneous Catalog of Open Cluster Parameters.” To ensure greater uniformity in the initial data, the distances to the OCLs in our sample were calculated using parallaxes from the catalog of Cantat-Gaudin et al. (2018), which is based on Gaia DR2. Figure 1 (right) depicts a comparison of the OCL distances from the Sun, determined

by trigonometric parallaxes, to the distance estimates obtained primarily through diagram fitting and adopted from the “Homogeneous Catalog of Open Cluster Parameters.” The figure demonstrates that the distance estimates from both are close for most clusters located within 1.5 kpc from the Sun, but the same cannot be said for more distant clusters. At the same time, however, errors in the estimates from both the trigonometric parallaxes and photometry increase at farther distances, as distant clusters require deep photometry. Errors in determining color excesses and interstellar absorption also increase as distance from the Sun increases. The final sample includes clusters with a deviation from the Galactic plane that did not exceed ± 1.5 kpc. In total, the sample included 322 OCl and contains clusters with decimal logarithms of age ($\log T$) ranging from 6.6 to 9.8, which covers the entire age interval for Galactic disk objects. The Galactocentric distances of the sample cover the interval 5 – 17 kpc, and the metallicities $[\text{Fe}/\text{H}]$ of these OCls fall within the range of $-1.54 - +0.46$.

3 METALLICITY GRADIENTS

Figure 2 (left) shows the metallicity estimate dependence on the Galactocentric distances, R , for the OCls in our sample. Galactocentric distances are calculated using the Galactocentric distance of the Sun, 8.3 kpc (Gerasimenko 2004). To present the available data, we tested the following regression models:

(1) the simplest model, with no gradient. That is, the metallicity is equal to the average metallicity of the sample clusters $\langle [\text{Fe}/\text{H}] \rangle = -0.147(\pm 0.270)$. In Figure 2 (left), a horizontal dashed line signifies this model, which is clearly inadequate for extreme Galactocentric distance values.

(2) linear dependence of metallicity on Galactocentric distances, with the coefficient values determined by the least squares method

$$[\text{Fe}/\text{H}] = 0.241(\pm 0.065) - 0.041(\pm 0.007)R.$$

In Figure 2 (left), the corresponding regression line is represented as a solid line. The coefficient of R is the linear gradient of metallicity in the Galactic disk. The standard deviation of residuals from the regression model is equal to 0.25. The average error in the catalog values for $[\text{Fe}/\text{H}]$ is 0.1, however, we use heterogeneous material, making it difficult to examine the reasons for the large dispersion in OCl metallicities. Testing the statistical significance of the inclusion of a linear R term in the model yields a dispersion ratio of 1.14 for models (1) and (2), which, according to the Fisher distribution, indicates that the linear term is significant for our sample size at a 95% significance level.

(3) quadratic model for Galactocentric distance

$$[\text{Fe}/\text{H}] = 0.300(\pm 0.242) - 0.053(\pm 0.048)R + 0.001(\pm 0.002)R^2.$$

The ratio of the coefficient of the squared Galactocentric distance and its error hints at the statistical insignificance of this regression model term. Indeed, the dispersion ratio is 1.003 for models (2) and (3), and, according to the Fisher distribution value, the quadratic term is not significant at any reasonable value of the significance level.

(4) linear model, adjusted for the dependence on time (OCl age)

$$[\text{Fe}/\text{H}] = -0.258(\pm 0.167) - 0.049(\pm 0.007)R + 0.069(\pm 0.021)\log T.$$

The dispersion ratio is equal to 1.03 for models (2) and (4), indicating that the time term in the model is statistically insignificant.

(5) purely time dependent metallicity

$$[\text{Fe}/\text{H}] = -0.264(\pm 0.174) + 0.014(\pm 0.021)\log T.$$

Figure 2 (middle) illustrates this dependence. The standard deviation of residuals from the regression model is equal to 0.27. The dispersion ratio is 1.001 for models (1) and (5), and the dependence is statistically insignificant.

(6) linear dependence on the absolute value of the distance from the Galactic plane, $|Z|$

$$[\text{Fe}/\text{H}] = -0.109(\pm 0.019) - 0.214(\pm 0.065)|Z|.$$

This model was considered due to the fact that some of the oldest OCls may belong to the thick disk of the Galaxy and have, on average, less metallicity than clusters in the thin disk. Figure 2 (right) demonstrates the dependence of metallicity on the OCl distance from the Galactic plane. The standard deviation of residuals from the regression model is equal to 0.26. The dispersion ratio is 1.04 for models (1) and (6), that is, the regression of $|Z|$ is statistically insignificant.

4 NONLINEARITY OF DEPENDENCE OF METALLICITY ON GALACTOCENTRIC DISTANCE

We established that the quadratic term in the regression model of the dependence of metallicity on the Galactocentric distance is not statistically significant. In previous studies, instances of nonlinearity in this dependence appear regularly (see the references above). Figure 3 shows the smoothed dependence between the metallicity of all the sample clusters and the Galactocentric distance,

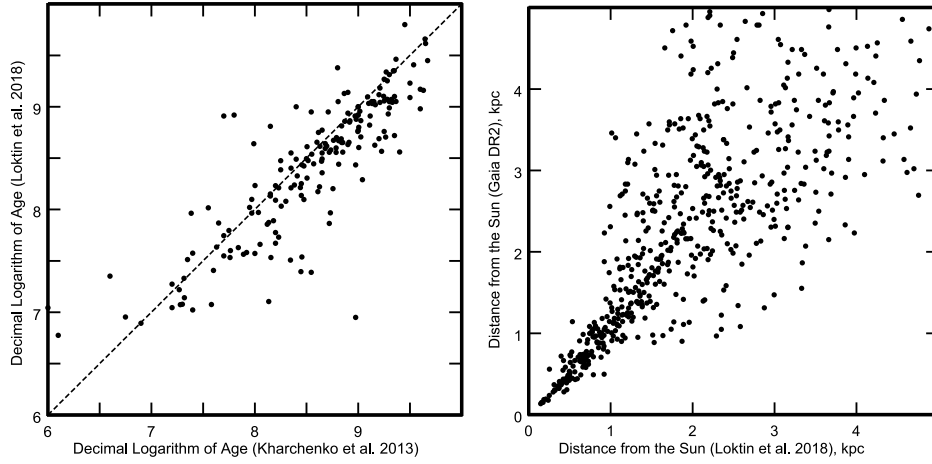


Fig. 1 Comparison of OCl ages from the “Homogeneous Catalog of Open Cluster Parameters” and the catalog of Kharchenko et al. (2013) (*left*). Comparison of heliocentric distances of OCl from the “Homogeneous Catalog of Open Cluster Parameters” and Gaia DR2 (*right*).

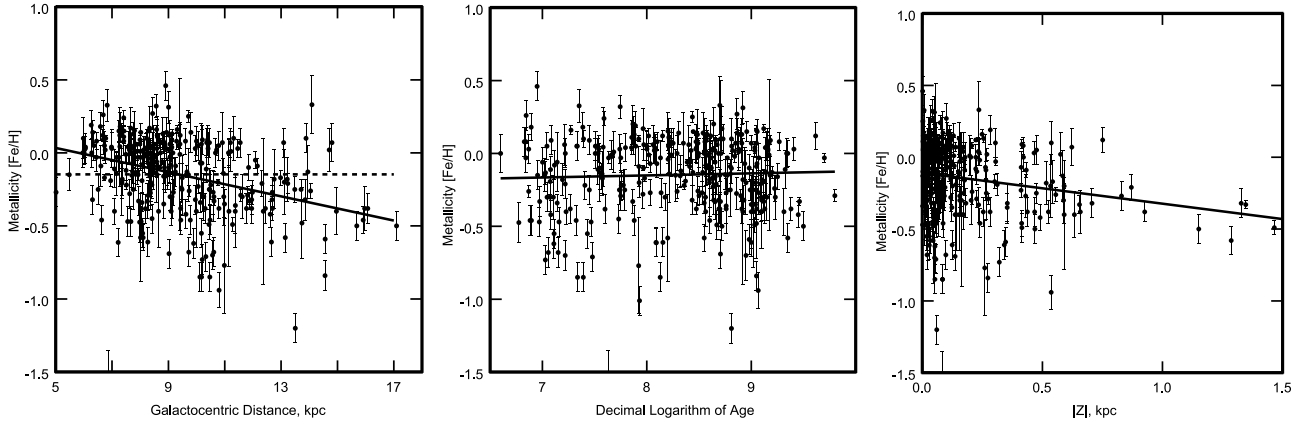


Fig. 2 Dependencies of OCl metallicity on the Galactocentric distances (*left*), decimal logarithm of age (*middle*) and the distance from the Galactic plane (*right*). *Solid lines* represent regression models (2), (5) and (6), from left to right respectively. *Vertical bars* signify the errors of metallicities in the catalogs referenced.

with points representing individual clusters. Smoothing was performed in two steps: (1) smoothing with a 9-point digital low-pass filter; (2) and sliding interval averaging for groups of 20 points. The stepwise nature of the resulting dependence is clearly visible: a distinct jump in the average OCl metallicity is observed in the region of $R = 9 - 10$ kpc. Figure 3 in Twarog et al. (1997) also clearly demonstrates this jump, as does figure 2a in Gozha et al. (2012c). Interestingly, this jump is practically unobservable in the corresponding dependence for classical Cepheids. The reasons for this jump are difficult explain, but it must be taken into account when building models of the chemical evolution of the Galaxy.

We decided to examine the internal and external regions of the Galaxy, with respect to the jump, separately. Of all the clusters in the sample, we selected two groups of clusters according to their distances from the center of the Galaxy, $R < 9$ kpc and $R > 10$ kpc. For both groups,

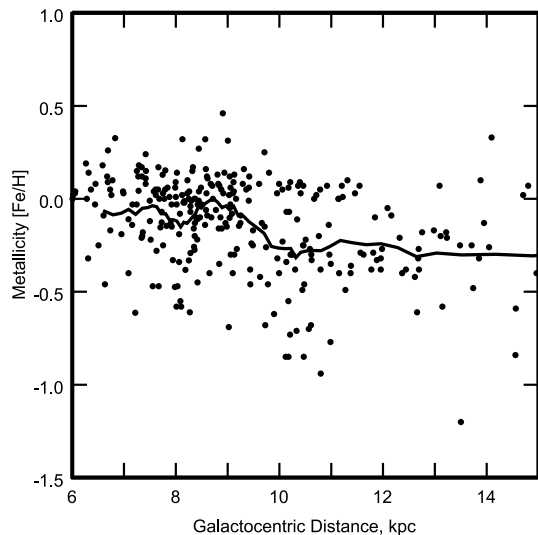
regression lines were obtained for the linear dependencies between metallicities and Galactocentric distances, the results of which are presented in the third column of Table 1 (first and third lines). The last column of Table 1 lists the corresponding dispersion ratios. We found that the slopes of the lines are statistically insignificant. Therefore, the ratio of metallicity dispersion to the deviation dispersion from the approximating straight line is 1.018 and 1.006 for clusters in the inner region of the Galaxy ($R < 9$ kpc) and in the outer ($R > 10$ kpc) region, respectively.

Thus, as previously noted by Twarog et al. (1997), the dependence of metallicity on the Galactocentric distance is represented as two horizontal line segments spaced along $[\text{Fe}/\text{H}]$ at intervals of 0.22, with average metallicities of $-0.065(\pm 0.019)$ for $R < 9$ kpc and $-0.284(\pm 0.028)$ for $R > 10$ kpc.

We decided to reexamine the dependence of metallicity on the distance of OCl from the Galactic plane sep-

Table 1 Regression Lines for the Dependence of OCl Metallicity on the Galactocentric Distance and Distance from the Galactic Plane

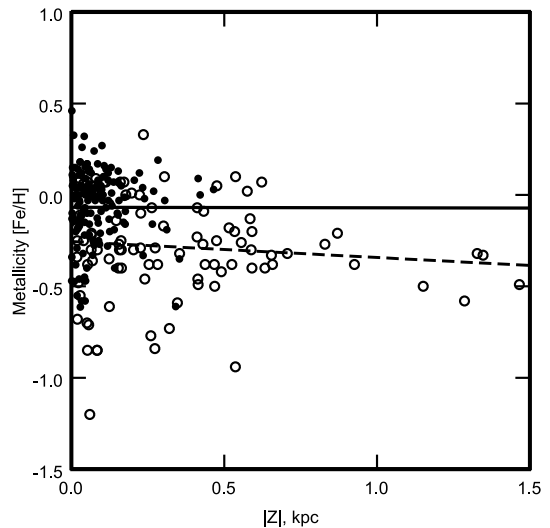
	Sample size	[Fe/H]	Dispersion Ratio
$R < 9$ kpc	153	$-0.067(\pm 0.177) + 0.0002(\pm 0.023) \cdot R$	1.018
		$-0.068(\pm 0.026) - 0.003(\pm 0.215) \cdot Z $	1.007
$R > 10$ kpc	99	$-0.144(\pm 0.201) - 0.012(\pm 0.017) \cdot R$	1.006
		$-0.255(\pm 0.040) - 0.087(\pm 0.087) \cdot Z $	1.001

**Fig. 3** The smoothed dependence of OCl metallicities on the Galactocentric distances.

arately for the internal and external regions, with respect to the metallicity jump. Table 1 (second and fourth lines) and Figure 4 show the results of attempts to approximate by straight lines. The last column of Table 1 indicates the insignificance of the slopes of these dependencies, therefore, we did not get any statistically significant metallicity dependencies for $|Z|$. If the absence of this dependence is expected for $R > 10$ kpc, since there are practically no metal-rich thin disk clusters in this region, then its absence for $R < 9$ kpc most likely indicates insufficient data, as thick disk clusters growing in proportion with $|Z|$ could lead to the occurrence of such a dependence.

5 GENERATIONS

Above, we examined the average metallicity dependency on cluster age and found that both the inclusion of an age-dependent term in the general model (see model (5) above) and a separate analysis of the age dependence yielded no definite results. We decided to try a slightly different approach to resolve this issue. In Popova & Loktin (2008), we identified the individual generations of OCl that belong to regions of different spiral arms. It can be assumed that the metallicities of different OCl within the volume of one space and one generation should be close. In this case, we can average the OCl metallicities of one generation and one space volume, which should lead to more reli-

**Fig. 4** Dependence of OCl metallicities on distance from the Galactic plane, with regression lines for distances of $R < 9$ kpc (filled circles, solid line) and $R > 10$ kpc (open circles, dashed regression line).

able estimates in regard to random errors. Our sample clusters were divided into groups according to their spiral arms and generations: the Carina-Sagittarius Arm (Car-Sag) with R about 7.03 kpc, three generations; the Orion Arm (Ori) with R about 8.80 kpc, three generations; the Perseus Arm (Per) with R about 10.49 kpc, two generations. Arm positions were taken from Popova & Loktin (2005). For each generation of each arm, the average $\log T$ and average metallicity [Fe/H] were determined along with the corresponding standard errors. The results are displayed in Table 2.

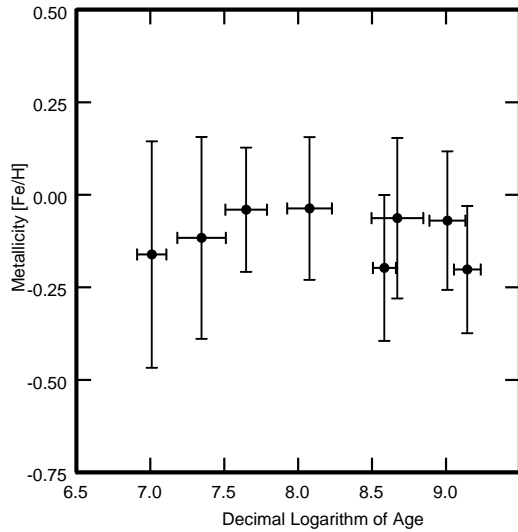
The values from Table 2 are plotted in Figure 5. Each point represents a separate generation for each of the spiral arms. This figure does not manifest any noticeable age trend in the average OCl metallicity, which leads us to acknowledge the fact that the present data do not allow us to discuss not only the rate of heavy-element enrichment of the Galactic disk, but even the observability of the enrichment itself.

6 SUMMARY AND CONCLUSIONS

The chemical composition gradient of the Galactic disk was examined based on a sample of OCl with available metallicity estimates and improved distance estimates

Table 2 Dependence of the Average OCl Metallicity on the Average Decimal Logarithm of Age

Spiral Arm	Generation	$\langle \log T \rangle$	$\langle [\text{Fe}/\text{H}] \rangle$	Sample size
Car-Sag	1	7.35 ± 0.16	-0.116 ± 0.273	10
Car-Sag	2	8.08 ± 0.15	-0.037 ± 0.193	17
Car-Sag	3	9.01 ± 0.12	-0.070 ± 0.187	9
Ori	1	7.01 ± 0.10	-0.161 ± 0.306	9
Ori	2	7.65 ± 0.14	-0.040 ± 0.168	19
Ori	3	8.67 ± 0.17	-0.063 ± 0.217	37
Per	1	8.58 ± 0.08	-0.198 ± 0.197	8
Per	2	9.14 ± 0.09	-0.202 ± 0.172	11

**Fig. 5** Dependence of the average OCl metallicity on the average logarithm of age. Each point represents a separate generation of an individual spiral arm.

provided by Gaia DR2. As reported by Twarog et al. (1997), we did not see a monotonic variation in the average OCl metallicity as the Galactocentric distance increased. This dependence clearly exhibits a jump in the metallicity $[\text{Fe}/\text{H}]$ of 0.22 at a Galactocentric distance of about 9.5 kpc, which appears to be linked to the outer boundary of the thinnest component of the Galactic disk. This supports the idea of Gozha et al. (2012c) that OClS in the solar vicinity are two subsystems that differ in kinematics and chemical composition. The absence of a significant metallicity gradient in the inner ($R < 9$ kpc) and external ($R > 10$ kpc) regions of the disk signals the absence of a noticeable metal enrichment during the ordering of the ages that correspond to those of the disk regions under consideration. Observational data indicate that a noticeable metal enrichment of the disk occurs only during the starburst epochs, when the Galactic disk components, such as a thick and thin disk, and maybe other not so clearly visible components form. Unsuccessful attempts to obtain a dependence of average metallicity on age also point to-

ward this conclusion. Errors, both systematic and random, in the estimates of distances naturally lead to changes in the gradient of the chemical composition of the Galaxy. Obviously, random errors in distance estimates on average cause an overstatement of distances, which means an underestimation of the chemical composition gradients. An attempt to introduce statistical corrections to the influence of random errors on distances (Loktin & Popova 2019) did not lead to noticeable changes in the results, so we did not apply these corrections in this paper.

Unfortunately, the data on OClS metallicities are still rather unreliable. One would expect that a large number of uniform metallicity estimates would become available after implementation of the RAVE project (Kordopatis et al. 2013). Unfortunately, most OClS are concentrated near a plane of the Galaxy for which the RAVE Data Release 5 (DR5) catalog has no information. Data from the LAMOST survey (Deng et al. 2012; Zhao et al. 2012), especially the recently created DR5, show great promise.

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