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V. V. Kovtyukh, S. A. Korotin, S. M. Andrievsky, N. Matsunaga, K. Fukue. Chemical properties of the central part of the Galactic nuclear stellar disc. Abundances in four classical Cepheids revisited. Monthly Notices of the Royal Astronomical Society, 2022, 516, pp.4269-4275. 10.1093/mnras/stac2468 . insu-03849369

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **516,** 4269–4275 (2022)
Advance Access publication 2022 September 3

https://doi.org/10.1093/mnras/stac2468

Chemical properties of the central part of the Galactic nuclear stellar disc. Abundances in four classical Cepheids revisited

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Accepted 2022 August 26. Received 2022 August 23; in original form 2022 June 24

ABSTRACT

This paper is a revised abundance analysis of four yellow supergiant stars Cepheids which are located in the Galactic nucleus. The results are based on the spectra secured with the help of *Subaru* telescope, which are of the better quality comparing to previously analysed spectra taken with the *Infrared Telescope Facility*. A significantly improved method of the effective temperature determination of program stars, which is based on the calibrating relations between the temperature and line depth ratios, was applied. The present results confirmed our previous finding about the solar metallicity level at the Galaxy centre. It is very likely that the four stars of our program were born from an interstellar medium having homogeneous chemical properties, since all the stars are located close to each other, have close pulsation periods, and hence the age. However, one of the stars has a somewhat increased abundance of all studied elements compared to the abundance in the other three stars. A possible reason of this fact is discussed.

Key words: Galaxy: centre – stars: abundances – stars: variables: Cepheids.

1 INTRODUCTION

Today we can state that generally we are well aware of the fundamental structure of our Galaxy and its chemical properties. Less explored parts of our stellar system are located, e.g. at the far periphery of the Milky Way disc. Additionally, the region on the other side on Galactic centre in the Galactic disc plane for many years was considered as the ‘zona Galactica incognita’ (Vallée 2002). In the recent years, thanks to the efforts of the observational astronomy and significant progress in the observational technology, it has become possible to observe Galactic objects located at the very centre and behind the centre of the Galaxy.

The thin Galactic disc consists of the Galactic objects that are younger than halo and thick disc. In our series of papers (Andrievsky et al. 2002a,b,c; Andrievsky et al. 2004; Luck et al. 2003; Kovtyukh, Wallerstein & Andrievsky 2005b; Lemasle et al. 2013; and other papers), we investigated elemental abundance distribution in the Galactic disc using spectroscopic study of the relatively young stars Cepheids. The general trend of abundance distributions (iron, for instance) in the range of Galactocentric distances 5–16 kpc is well reproduced in theoretical simulations (see e.g. Andrievsky et al. 2004; Cescutti et al. 2007; Minchev, Chiappini & Martig 2013, their fig. 2, look-back time 1 Gyr; and others). At the same time, the chemical properties of the near-central region of the Galaxy are still quite poorly known. The overall picture built on mapping the chemical properties of the Galaxy will, of course, be incomplete without consideration of the region close to its centre.

Recently, several attempts have been made to determine the elemental abundances in this region. Martin et al. (2015) studied one Cepheid SU Sct, which is located at the rather close distance to the Galactic centre. Later, Andrievsky et al. (2016) derived the abundances of 36 chemical elements in one Cepheid star, ASAS 181024−2049.6, also located at close distance (the authors adopted the Galactocentric distances for these two stars to be 3 and 2.5 kpc, respectively). The abundance results for these stars showed for the first time that at this distance, a plateau-like structure can exist in the radial elemental abundance distribution across the disc (it is also possible that we may not be dealing with a plateau, but instead with some kind of maximum in the abundance distribution; better statistics for this zone should make this clear). It should be noted that Bailer-Jones et al. (2009) list in their catalogue the *Gaia* parallaxes for these two stars, which support the larger distances from Galactic centre; about 5 kpc. Finally, Kovtyukh et al. (2019) have made the first attempt to derive the chemical properties of the Galactic disc at its nuclear part using the high-resolution infrared (IR) spectroscopic observations of four classical Cepheids. Those stars are located at Galactocentric distance smaller than 1 kpc (Matsunaga et al. 2016). These four stars were discovered and discussed by Matsunaga et al. (2011, 2015): $GCC-a$, $GCC-b$, $GCC-c$, and $GCC-d$.

Combining our data on the abundances in the studied Cepheids from the three papers mentioned above, we can conclude that the radial distribution of the iron abundance on a logarithmic scale decreases from about +0.4 dex at Galactocentric distances

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Published by Oxford University Press on behalf of Royal Astronomical Society

Table 1. Physical parameters of the investigated Cepheids.

Cepheid	N	P d	JD 245 0000 +	$<H>$ mag	S/N	Phase	$T_{\rm eff}$ K	log g	$V_{\rm t}$ km s^{-1}	[Fe/H] dex
$GCC - a$	13	23.52	6135.817 92	12.02	100	0.22	5116 ± 41	1.0	3.5	0.08
$GCC - b$	12	19.96	6135.880 41	11.96	100	0.23	5276 ± 48	1.0	4.0	0.02
$GCC - c$	11	22.75	6136.838 68	12.39	100	0.69	4814 ± 42	0.8	4.5	0.05
$GCC - d$	10	18.87	6136.949 78	12.14	85	0.18	5693 ± 59	1.0	4.0	0.29

Note. The star's number N and phases are given according to Matsunaga et al. (2015, 2016).

3–4 kpc to about the solar value in the Galactic centre (see fig. 4 in Kovtyukh et al. 2019). Even if the parallaxes for SU Sct and ASAS 181024−2049.6 reported by Bailer-Jones et al. are correct, this fact qualitatively does not change the conclusion about the bend (plateau) in iron abundance distribution at Galactocentric distances of about 2–5 kpc.

This paper reports new abundance results obtained for the above mentioned four stars, whose spectra were obtained by Matsunaga et al. (2015) in H band with the help of IR camera and spectrograph attached to the *Subaru* 8.2-m telescope (Kobayashi et al. 2000).

2 SPECTROSCOPIC ANALYSIS

2.1 Data

Details of the observations of the four program stars can be found in Matsunaga et al. (2015). Some data are also given in Table 1. Here, we can repeat that the resolving power was 20 000, the observed wavelength range was 14 700–17 900 Å, and the spectra with the highest signal-to-noise ratio (S/N) were taken in 2012 July.

2.2 Atmosphere parameter determination

The temperature is a key parameter for the determination of the star's chemical composition. As a rule, the photometric and spectroscopic methods are used for this aim. For variable stars, it is desirable to have simultaneous photometry or a well-populated light curve. For the stars near Galactic centre, which suffer from the significant reddening, the use of photometric method for effective temperature determination is problematic. As for the spectroscopic methods, the most reliable is that, which uses the calibration of the effective temperature on the ratio of the spectral line depths (LDR-method). The lines have different excitation potentials of the lower level, and therefore they behave in a different way depending upon the temperature. In the optical region Kovtyukh (2007) derived 130 spectroscopic criteria, which enables one to determine the effective temperature of the supergiant stars with an accuracy of about 5–25 K.

For the H band, Fukue et al. (2015) derived nine calibrating relations for the giants and supergiants using the lines of the following ions: K I, Ti I, Fe I, and Co I. Those authors employed eight standard stars with well-determined effective temperatures. All of the stars used are quite bright objects with effective temperature in the range of 4000–6000 K.

Jian, Matsunaga & Fukue (2019) discussed 11 calibrating relations in the H band for the stars situated within the temperature range of 3700–5000 K (seven calibrating relations come from Fukue et al. 2015). For this aim 17 459 H-band spectra of the red giant stars from the APOGEE program with well-determined parameters were used. The metallicity effects were taken into account.

In order to derive the elemental abundances in Cepheids from the Galactic nucleus, we decided to significantly increase the number of calibrating relations, and thus to enlarge the range of their use. In fact, the calibrations of Jian et al. (2019) are valid only for the stars with a temperature up to 5000 K, while the most of the Cepheids have temperatures in the range of 6500–6700 K in the maximum light. We used about 50 IR and optical spectra of bright supergiants and classical Cepheids to create temperature calibrations. Spectra in the optical and H band had high resolution ($R = 50\,000$–100 000) and high S/N (S/N > 150–200). For the classical Cepheids, we used the optical spectra obtained in the same phases of the change in brightness as the H spectra. This allowed us to use precise temperature values obtained from the optical spectra to create LDR calibrations. The use of an uniform temperature scale in the optical and IR ranges allowed us to eliminate possible errors in determining the atmospheric parameters and chemical composition. Studied supergiants and Cepheids have temperatures in the range of 4750–6850 K and metallicity from –0.1 to +0.2. At the initial stage, more than 1500 possible LDR calibrations were tested, of which about 100 were selected which showed the highest accuracy. The accuracy of these 100 individual calibrations varies from 60 to 160 K; each calibration has its own temperature range of applicability (Kovtyukh et al., will be published elsewhere). Fig. 1 shows six typical calibrating relations from that number. Part of the calibrating relationships valid up to 6500–6700 K, and thus they are able to cover all the temperature range for classical Cepheids. The stars we used for this program have the solar metallicity; therefore they are applicable for the study of the Galactic central part chemical properties (Kovtyukh et al. 2019 preliminary reported that chemical properties in the Galactic nucleus are similar to those in the solar neighbourhood). The spectra of Cepheids in the centre of the Galaxy have a resolution of 20 000 and fairly large dips between orders. Therefore, only 15–20 calibrations were used to determine the temperatures, the error of the mean is given in Table 1.

Microturbulent velocity $V_{\rm t}$ has been determined for each star using the standard method of avoiding any dependence between iron abundance derived from the studied lines and their equivalent widths (see Fig. 2).

Since no Fe II lines were available at our disposal, the gravity for all program stars were determined using the following procedure. Matsunaga et al. (2015) determined pulsation periods for the four program stars to be about 20 d. Kovtyukh et al. (2005a) investigated the phase-dependent variation of the fundamental parameters of classical Cepheids with period longer than 10 d. Using these data for Cepheids with close periods, as well as the extensive data from Luck (2018) and da Silva et al. (2022), we can conclude that typical gravity for our stars should be close to 0.8–1.0 dex except for the maximum light. We estimate uncertainty in the adopted gravity value to be about 0.3 dex. The atmosphere parameters of our program stars are listed in Table 1.

2.3 LTE abundances

Abundance of some elements were derived in the LTE approximation using atmosphere models calculated with ATLAS9 code (Kurucz

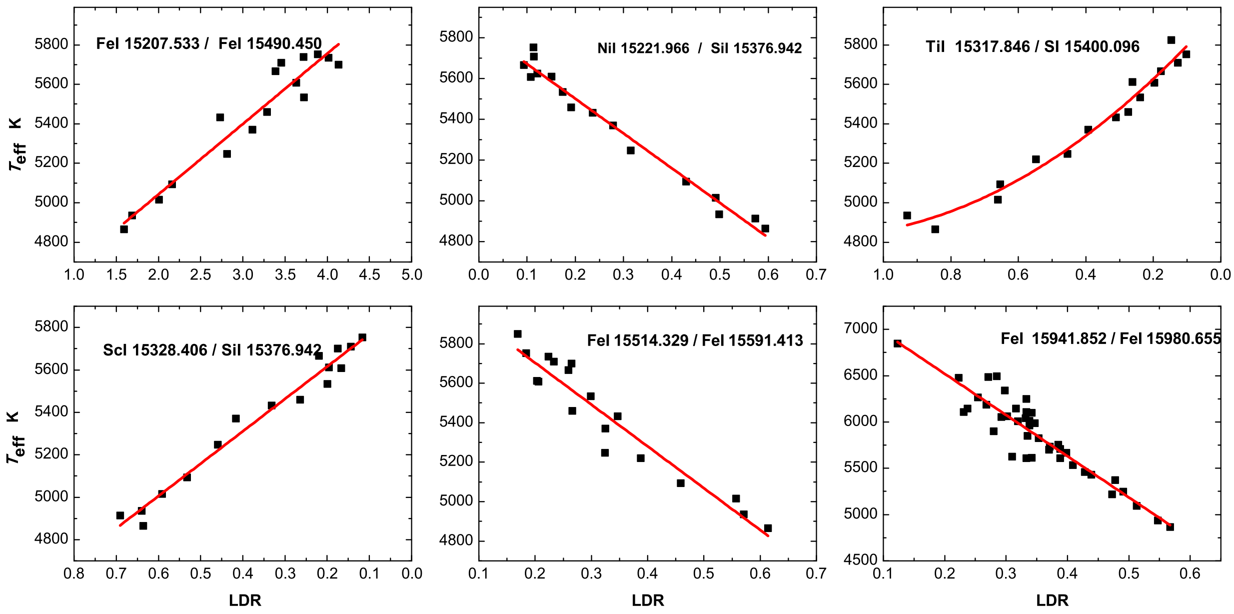

Figure 1. Examples of the new temperature calibrations.

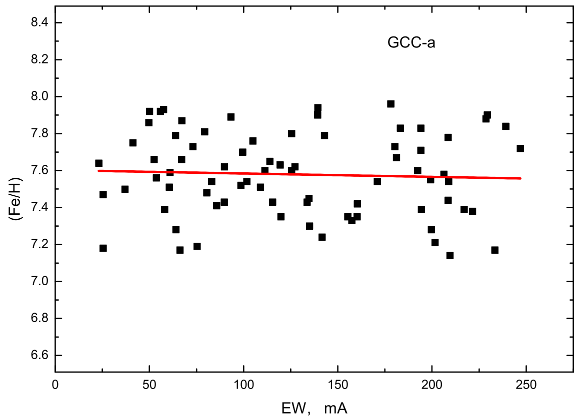

Figure 2. To the determination of microturbulent velocity for *GCC − a*.

1993, 2005). The oscillator strengths were adopted from the Vienna Atomic Line Database (Ryabchikova et al. 2015). The solar reference abundances were taken from Asplund et al. (2009). Results of the LTE abundance determination are given in Table 2.

In Table 3 we give the results of the LTE abundance uncertainties assessment in one program star ‘*d*’ assuming that they can be caused by the uncertainties in the derived atmosphere parameters.

2.4 NLTE analysis and abundances

The abundances of the four elements: magnesium, aluminium, sulphur, and potassium were determined taking into account the departures from LTE. To do this, we used the models of atoms described by us in a series of our previous papers (Korotin 2009; Andrievsky et al. 2010; Černiauskas et al. 2017; Caffau et al. 2019). In the paper of Korotin et al. (2020), we studied the lines of these elements in the IR range in the NLTE approximation. Also in that work, a critical selection of the parameters of these lines was performed, as well as the check for their blending and testing using the spectrum of the Sun. It should be noted that the influence of the NLTE effects for Cepheids is somewhat greater than those described by us in the paper of Korotin et al. (2020), where the spectra of dwarf stars were studied. This is due to a decreased role of the collision rates in the atmospheres of supergiant stars. The NLTE abundances of the above mentioned elements are given in Table 4. To derive the NLTE abundances we used the same atmosphere models as for the LTE analysis. The profile fitting for some lines of the star *GCC-b* is shown in Fig. 3.

The obtained LTE and NLTE abundance results are shown graphically in Fig. 4.

3 DISCUSSION AND CONCLUSION

We have revisited elemental abundance analysis for four classical Cepheids located in the Galactic nucleus (central part of the thin disc). The spectra of these four stars were studied by us earlier using the *Infrared Telescope Facility* (Kovtyukh et al. 2019). *Subaru* telescope spectra analysed here are of the better quality. Moreover, in this paper we presented NLTE abundances of magnesium, aluminium, sulphur, and potassium. The main result is the following. The most reliable LTE iron abundance in four classical Cepheids testifies about the near-to-solar metallicity of the Galaxy central part. The mean (weighted) iron abundance from the four program stars derived in our previous paper (Kovtyukh et al. 2019) was 0.03 dex, while the present value is 0.11 dex.

Table 2 shows that for three program stars the relative-to-solar iron abundance is close to zero within specified errors of determination. Only one star, *GCC − d*, exhibits a slightly higher iron content comparing to other stars (magnesium, calcium, chromium, manganese, and nickel abundances in this star are also increased).

Since all the stars have close pulsation periods, and they located in the same zone of the Galactic nucleus (with their periods they should be the rather young stars with the age of about 30 Myr, see below, and they did not have enough time to migrate in/from this zone), they should have the same origin, i.e. formed from interstellar medium of more or less homogeneous chemical composition. As a by-product, we can propose the following qualitative explanation of the fact of the higher iron (and other elements) abundance. It can

Table 2. LTE abundances in the investigated Cepheids.

		GCC − a			*GCC − b*			*GCC − c*			*GCC − d*	
Ion	[El/H]	σ	NL	[El/H]	σ	NL	[El/H]	σ	NL	[El/H]	σ	NL
6.00	0.17	0.12	8	0.01	0.27	9	− 0.29	0.21	4	− 0.08	0.16	6
14.00	0.30	0.17	5	0.38	0.15	5	0.57	0.00	1	–	–	–
15.00	0.43	–	1	0.53	–	1	− 0.14	–	1	0.47	0.15	2
20.00	0.19	0.26	4	0.27	0.28	4	− 0.23	0.00	1	0.58	–	1
22.00	0.36	0.32	3	0.03	0.38	2	0.51	–	1	–	–	–
22.01	–	–	–	0.00	–	1	–	–	–	–	–	–
24.00	− 0.43	–	1	− 0.25	0.37	3	− 0.17	–	1	0.69	0.10	2
25.00	0.44	–	1	0.12	–	1	− 0.11	–	1	0.50	0.08	2
26.00	0.08	0.22	76	0.02	0.20	80	0.05	0.18	41	0.29	0.15	60
28.00	0.15	0.10	4	0.22	0.35	8	0.23	0.17	4	0.52	0.10	4

Table 3. LTE abundance errors due to uncertainties in atmospheric parameters for *GCC − d*, ($T_{\rm eff}$ = 5693 K, log g = 1.00, $V_{\rm t}$ = 4.00 km s^{-1}, and [Fe/H] = 0.29).

Ion	$\delta T_{\rm eff}+100$	$\delta\log\, g-0.3$	$\delta V_{\rm t}+0.5$
C I	− 0.03	− 0.06	− 0.04
Mg I	0.05	0.04	− 0.01
P I	0.02	− 0.03	− 0.02
S I	0.00	− 0.04	− 0.02
K I	0.05	− 0.02	− 0.05
Ca I	0.07	0.04	0.03
Cr I	0.06	0.03	− 0.03
Mn I	0.08	0.03	0.00
Fe I	0.07	0.03	− 0.02
Co I	0.09	0.03	− 0.01
Ni I	0.06	0.02	− 0.02

be assumed that the star *d* while being at the main-sequence was a planet-hosting star. If it had terrestrial-type exoplanets in orbits close to the star, then with its expansion and subsequent absorption of the rocky planets, the star, apparently should gain an increased abundances of some refractory elements, in particular, iron. If the large-scale mixing in the Cepheid atmosphere has not enough time to mix the gas of the atmosphere with the gas of the stellar interior, and to erase any abundance peculiarities, we will detect such an anomaly. To estimate the total time required for 'digestion' by a star a planet-like body and preservation of its chemical tracers in the supergiant atmosphere is not a simple task. For this purpose, it is necessary to take into account the time required for evaporation of matter from the planet-like body after its absorption by the star's atmosphere, mixing this material by the convection/turbulent diffusion and meridional circulation. The latter is caused by the rotation of the star, and strongly depends on it. We will limit ourselves only to a rough estimate of the characteristic time of the meridional flow. According to Sweet (1950) this time can be expressed by the following equation:

$$t = 8\times 10^{12}\,\frac{M^3}{LR^4}\,\frac{1}{\Omega^2}\ \ \mathrm{yr}.$$

Here all values are in solar units. For our program *d* star with its pulsational period about 19 d, the mass is 10 solar masses (see the corresponding relation in Turner 1996). According to Gieren, Moffet & Barnes (1999), a Cepheid with such a period has a radius of about 100 solar radii. Period–luminosity relation gives the luminosity of this star of about 6600 $\mathrm{L}_{\odot}$. To determine the angular velocity of Cepheid (the radii of Cepheid and the Sun are known), we adopt the typical radius of its progenitor, the main-sequence *B* star, to be about 4 $\mathrm{R}_{\odot}$, and its linear equatorial velocity of about 200 km s^{-1} (according to Brott et al. 2011, typical observed $v\sin i$ value is about 150 km s^{-1} for stars of 10 solar masses, see their fig. 1). Then, after expanding from 4 to 100 $\mathrm{R}_{\odot}$, the rotational velocity of the Cepheid decreases to about 0.3 km s^{-1} (approximately 0.1 of the solar rotational rate). All adopted values give us a characteristic time of meridional circulation of about 10^{10} yr, which is much longer than the lifetime of the studied Cepheid (the lifetime of a star with a mass 10 solar masses on the main sequence is $t_{\rm ms}\approx 10^{10}(\frac{\mathrm{M}_{\odot}}{M})^{2.5}$ yr, i.e. about 30 Myr).

The Cepheid star was a *B*-type star at a previous stage of its life on the main sequence. Until recently, it was believed that exoplanets could only orbit stars with masses up to 3 solar masses. However, Janson et al. (2021) were able to show that more massive stars with masses up to 10 solar masses (B-type stars on the main sequence) can host the planetary systems. Thus, their discovery allows us to assume that the Cepheid atmosphere (if its progenitor B star had a planetary system) could be enriched with some chemical elements due to rocky planet absorption at the giant/supergiant evolutionary stage. At the same time, some planets in a far orbit can survive after the host star expansion, and recent discoveries show that giant stars do indeed have planetary systems (see e.g. Ottoni et al. 2022; Teng et al. 2022).

It is interesting to note that Cepheid *GCC − d* indeed demonstrates a progressive increase in elemental abundances depending on the condensation temperature (Fig. 5). The refractory lithophile (Ca) and refractory siderophile (P, Cr, Fe, and Ni) elements are generally more abundant comparing to the volatiles, like carbon and lithophile species (S and K). The refractory lithophile elements Mg and Al are at the same level of abundance as S and K. The classification of elements is in accordance with Wood, Smithe & Harrison (2019), see their fig. 4.

This scenario is not without some difficulties regarding the conclusion made by Pinilla, Garufi & Garáte (2022), who noted that the intermediate-mass main-sequence stars (*B*1–*B*9 spectral classes) can cause rapid radial diffusion of protoplanetary disc matter, and this process prevents the efficient planetesimals' formation in distant orbits. However, this conclusion only emphasizes that the process of the rocky planet formation around an intermediate-mass main-sequence star is indeed rare, but not excluded. (In connection with this, one can also mention that in the literature there is an information that B stars have planetary systems: *HIP* 78530, main sequence, κ And, subgiant, and several subdwarfs).

If Cepheid engulfed the planet-like body(s) not so long ago (and we see the result in the chemical composition of this star), then the transition to the supergiant stage is a recent event. Consequently, the Cepheid *GCC − d* only managed to enter the instability strip, it is

Table 4. NLTE abundance of the investigated Cepheids.

Star	(Fe/H)	[Fe/H]	[Mg/H]	[Al/H]	[S/H]	[K/H]	[Mg/Fe]	[Al/Fe]	[S/Fe]	[K/Fe]
GCC – a	7.58	0.08	– 0.11	– 0.02	0.64	– 0.03	– 0.19	– 0.10	0.56	– 0.11
GCC – b	7.52	0.02	0.06	– 0.16	0.20	0.00	0.04	– 0.18	0.18	– 0.02
GCC – c	7.55	0.05	– 0.19	– 0.17	0.22	0.28	– 0.24	– 0.22	0.17	0.23
GCC – d	7.79	0.29	0.23	0.10	0.26	0.09	– 0.06	– 0.19	– 0.03	– 0.20

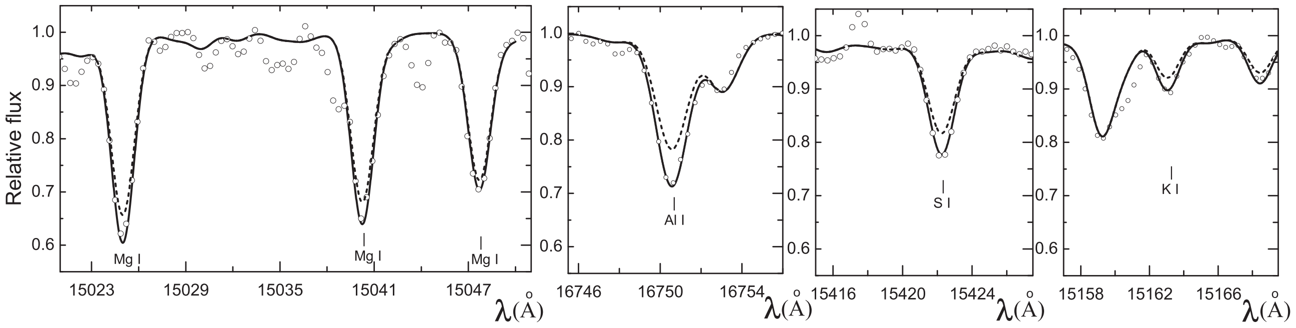

Figure 3. Profile fitting of some lines in the star *b* observed spectrum (open circles). Continuous line – NLTE synthetic spectrum and dashed line – LTE synthetic spectrum calculated with adopted NLTE abundance.

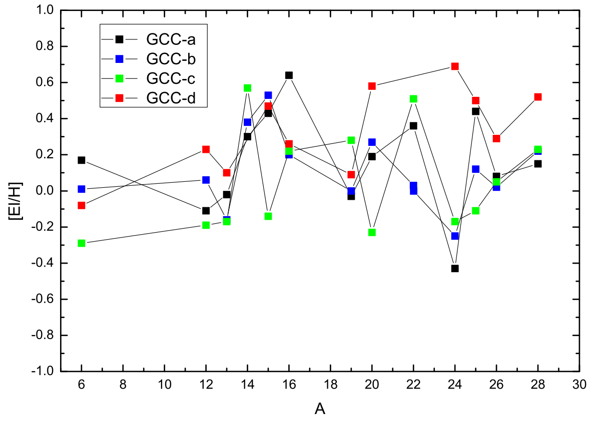

Figure 4. LTE and NLTE abundances in the program Cepheids.

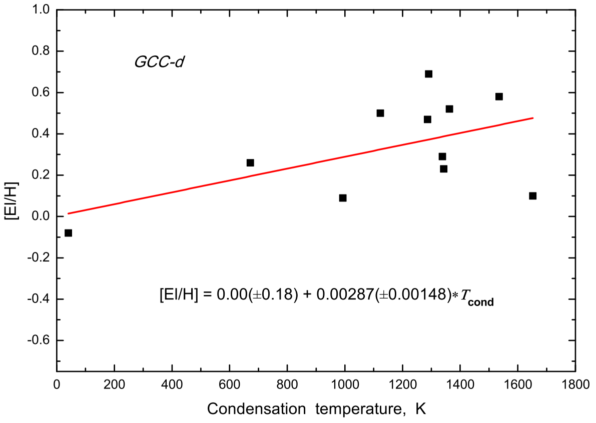

Figure 5. Abundances in Cepheid *d* as a function of condensation temperature.

now at its blue border, and therefore it has a higher temperature (see Table 1).

Cunha et al. (2007) presented data on the elemental abundances in a sample of luminous stars located within several tens of pc from the centre of the Galaxy. The average iron abundance is quite close to the solar value, while abundances of oxygen and calcium are slightly enhanced. This fact is probably related to the formation of numerous massive stars in this region and the overproduction of the α-elements in supernovae Type II explosions.

Davies et al. (2009a) studied two red supergiant stars located in the centre of the Galaxy and found that both stars have iron content close to the solar value, and abundance of α elements relative to the iron abundance is typical for the thin disc stars.

Davies et al. (2009b) also studied two massive clusters containing red supergiant stars. The clusters are located at the end of the Galactic bar (Galactocentric distance is about 4 kpc). The authors determined the iron abundance in the studied program stars as 0.2–0.3 dex subsolar (α elements have the same abundance level), which contradicts the iron abundance in other objects from the Galactic central part. The latter show a moderate supersolar abundances. Taking this into account, authors made a conclusion that there is a strong large-scale abundance variation in the central zone of our Galaxy.

The Quintuplet star cluster was studied by Najarro et al. (2009). This is one of the three recently formed clusters in the inner (50 pc) zone of the Galaxy. Luminous blue variable stars have been the subject of abundance analysis. For iron, the authors found the solar abundance and about 0.3 dex increase in the abundance of the α elements. Note that for the very young stars in the Arches cluster at the Galaxy centre, Najarro et al. (2004) also detected approximately solar metallicity.

Rich et al. (2017) reported abundance results for 17 M giants in vicinity of the Galactic centre. According to these authors, the median metallicity is [Fe/H] $= -0.16$ with a wide range from -0.3 to $+0.3$ dex. They also found that the highest metallicity [Fe/H] $< +0.6$ dex. Most of the program stars are at or below the solar iron abundance.

Schultheis et al. (2020) derived metallicities for 157 M giant stars situated within 150 pc of the Galactic centre. The metallicity distribution is bimodal, with maxima at -0.5 and $+0.3$ dex. The α

elements are enhanced in the metal-poor component, similar to the bulge stars.

Later, Schultheis et al. (2021), investigated the chemical properties of the main stellar components of the Galactic central part, namely, the nuclear stellar disc and nuclear star cluster (the former surrounds the latter). Authors studied K and M giants and found that stars from nuclear stellar disc have higher metallicity than stars from the bulge, but at the same time they have lower metallicity than stars from the nuclear star cluster.

Feldmeier-Krause et al. (2017) analysed the spectra of over 700 late-type stars and concluded that only a very low fraction of metal-poor stars exist in the central part of the Galaxy.

Later, Feldmeier-Krause (2022) derived metallicity in the transition zone between the nuclear star cluster and the nuclear stellar disc. Most of the program objects are the red giant stars. Authors conclude that the metallicity decreases from the nuclear star cluster toward the nuclear stellar disc.

Two subsolar metallicity stars were investigated by Bentley et al. (2022) in the centre of the Galaxy. The resulting metallicity values for these stars (−0.59 and −0.81) are very different from typical metallicity of stars from the Galactic nuclear cluster; however it simply may indicate a different origin of some stars formed in this region. Similar conclusion was made earlier by Do et al. (2015), who found that only approximately 6 per cent of studied stars from the centre of the Galaxy have metallicity less than −0.5.

Thorsbro et al. (2020) analysed 20 M giants from the Galactic centre, and concluded that there are no stars with extremely high metallicity in this zone.

The aforementioned works show that most of the stars in the central part of the Galaxy have a metallicity close to the solar one.

Thus, with this new analysis of four Cepheids in Galactic nucleus, which is based on better quality spectroscopic material than that used by Kovtyukh et al. (2019), we confirmed our previous finding that the chemical properties of the central part of the Galactic nucleus resemble that of the solar vicinity.

ACKNOWLEDGEMENTS

The authors thank the anonymous referee for her/his careful reading of the paper and for the valuable comments, which improved our manuscript.

VVK and SMA are grateful to the Vector Stiftung at Stuttgart, Germany, for support within the program ‘2022–Immediate Help for Ukrainian Refugee Scientists’ under grants P2022-0063 and P2022-0064. Especial thanks to Prof. K. Werner and Dr. V. Suleimanov for their help. SAK thanks the Government of Russian Federation and the Ministry of Science and Higher Education of the Russian Federation for their support (grant N075-15-2020-780).

This research is based on observations obtained with the *Subaru* telescope, programme S12A-053.

4 DATA AVAILABILITY

The data are available at the SMOKA Science Archive https://smoka.nao.ac.jp/.

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