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THREE GIANTS – MEMBERS OF THE OPEN CLUSTER M 67

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ABSTRACT. We determined the atmospheric parameters and chemical composition of the three giants, which are members of the open cluster M 67. The high resolution spectra (R = 60 000) were obtained with the echelle spectrograph NES mounted on the 6-meter telescope of the SAO RAS Obtained variations in Na and Zr abundances are within the determination errors. The Li abundance suggest a depletion of Li in the course of stellar evolution. For studied giants, the iron abundances derived from the neutral and ionized iron lines have not shown any significant discrepancies. The [Ba/Fe] values are close to the solar ones.

Keywords: stars: abundances – stars: atmospheres – Galaxy: open clusters and associations: individual: M 67

1. Introduction

The open cluster M 67 (NGC 2682) was discovered by Johann Gottfried Koehler in 1779 and is one of the best studied open clusters (OCs). It is also one of the oldest known Galactic clusters with an estimated age of about 4.3 Gyr (Pietrukowicz, 2006), it lies at a distance between 800 and 900 pc away (e.g. Sarajendini *et al.*, 2009), and has the reddening value E(B–V) = 0.041±0.004 (Taylor, 2007). M 67 contains a high percentage of blue stragglers, stars which are bluer and more luminous than the main-sequence turn-off point of the cluster (Pribulla et al 2008); for this cluster, the turn-off occurs near B−V = 0.55, and V = 13.0.

Our target stars, namely 84, 141, 151 (Fagerholm, 1906) show enhancement in CN band strengths and are ‘clump’ giants (Pagel, 1974). Carraro *et al.* (1996) evaluated the mass loss in M 67 based on the determinations of masses of the clump stars and RGB giants. Due to a small offset as d[B–V] = 0.01 mag, it was unfeasible to use the clump stars to infer the efficiency of mass loss along the RGB phase. They also reported that there was no evidence for a dependence of the mass-loss rate from RGB stars on metallicity.

Tautvaišienė *et al.* (2000) analyzed spectra of six core helium-burning ‘clump’ stars and three giants in M 67 to detect any signs of extra mixing associated with the He-core flash. They claim that the metallicity of M67 is close to solar ([Fe/H] = −0.03±0.03, the carbon is depleted by about 0.2 dex, nitrogen is enhanced by about 0.2 dex and oxygen is unaltered. The mean C/N and $^{12}C/^{13}C$ ratios are lowered to the values of 1.7±0.2 and 24±4 in the giants and to the values of 1.4±0.2 and 16±4 in the clump stars. The results obtained enabled to suggest that extra mixing of CN-cycled material to the stellar surface takes place after the He-core flash. Abundances of other elements in investigated stars were found to be close to the solar ones.

Our goal is to re-determine the parameters and chemical composition of the three clump stars of the M 67 cluster. The stars in question are shown on the Hertzsprung-Russell diagram for M 67 presented in Fig. 1; the V and B–V values have been adopted from Geller *et al.* (2015).

2. Observations and radial velocities

The main characteristics of the M 67 cluster stars, as well as the observational data, are given in the Tables 1, 2, respectively.

The spectral data have been obtained with the echelle spectrograph NES (Panchuk *et al.*, 2006, 2017) mounted on one of the Nasmyth focus platforms of the 6-meter telescope of the SAO RAS. NES provides a resolving power of R≥60000 within the wavelength region 3200-10000 ÅÅ. The reduction of stellar spectra, as well as the measurement of radial velocities VR, has been performed using the DECH20 software package (Galazutdinov, 1992).

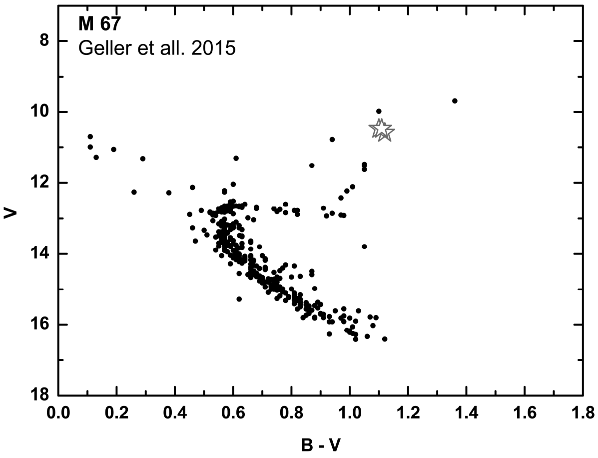

Figure 1: The H-R diagram for M 67; the V and B–V data have been taken from Geller *et al.* (2015). Clump giants marked as asterisks.

Mathieu *et al.* (1986) have reported that the M 67 mean radial velocity VR = 33.5±2.8 km/s (for 65 cluster member stars). It can be seen that there is good agreement between our VR values and those obtained by other authors (Table 2).

3. Parameter determination

The effective temperatures T_{eff} were estimated by calibration of line-intensity ratios – T_{eff} (Kovtyukh *et al.*, 2006); the results are presented in Table 3.

To determine the gravity log g we used two methods: iron ionisation equilibrium (IE) and parallaxes (Pi). The obtained log g values are given in Table 4.

For two stars (namely, 84 and 141), we have obtained a noticeable difference in the value of gravity values, which is associated with use of two different methods. Further computations of elemental abundances have been performed using log g derived under conditions of ionization equilibrium for iron.

It should be noted that when using the parallax, we encountered a certain problem with parallax measurements can result in different distances to objects, which in turn leads to different values of gravity. For example, the parallax for the star 84 is 0.00097 and corresponds to the distance to the object 1030 pc. For the star 141, the parallax is 0.00088 and the relevant distance is 1136 pc. For the star 151 the parallax was markedly different from those for the two other target stars: the parallax for 151 is 0.00240; that means the determined distance, which is 417 pc. The latter distance value differs significantly from the distances to this cluster estimated earlier (e.g. Sarajendini *et al.*, 2009), as well as from the data obtained recently by Viani & Basu (2017), who have reported that from the resulting isochrones that fit the M 67 cluster, the age range is between 3.6 and 4.8 Gyr while the distance is between 755 and 868 pc.

Microturbulent velocity V_t was determined from independence of an abundance log A(Fe) from equivalent width EW for Fe I lines. The metallicity [Fe/H] was adopted as the iron abundance determined from Fe I lines.

All the parameters, which we have obtained, are presented in Table 5.

4. Chemical abundance determination

The elemental abundances were determined using Castelli & Kurucz's (LTE) models; the Kurucz WIDTH9 code was used for the LTE determination of Si, Ca, Ni, Fe, Zn, Y, Zr, La, Ce, Pr, Nd and Sm abundances; the modified latest version of STARSP (Tsymbal, 1996) was employed for the LTE determination of Li and Eu abundances; and the modified MULTI code (Carlsson, 1986; Korotin *et al.*, 1999) was used for the NLTE determination of O, Na, Al, Mg, Ca and Ba abundances. The spectrum synthesis fitting of the Mg and Na lines to the observed profiles for 141 star is shown in Figs. 2, 3.

The elemental abundances [El/Fe] as function of metallicity [Fe/H] for the investigated stars are depicted in Fig. 4.

Table 1. The main characteristics of the target M67 giants

Star	star(2)	star(3)	alpha	Delta	V	B-V	Sp
84	6492	1074	8:48:28.54	12:03:58.7	10.59	1.12	G8III
141	6485	1010	8:48:38.72	11:59:18.6	10.48	1.11	K2 III
151	6494	1084	8:48:42.03	12:05:09.0	10.48	1.10	G8III

the name of stars have been taken from: (1) – Fagerholm (1906), (2) – Montgomery *et al.* (1993), (3) – Sanders (1977); the V, B–V and Sp Type data have been adopted from Geller *et al.* (2015) and Pribulla *et al.* (2008), respectively.

Table 2. Observations and radial velocities VR (km/s)

Star	Spec	λ (Å)	date	VR_{our}	VR_1	VR_2	VR_3
84	S34902	4500-6000	24.04. 2002	34.4	34.1	33.8	-
141	S39508	5275-6765	15.04. 2003	33.9	32.7	-	33.0
151	S39602	5275-6765	16.04. 2003	33.9	33.7	-	-

VR_1 have been taken from Geller *et al.* (2015); VR_2 – from Jacobson *et al.* (2011); VR_3 – from Yong *et al.* (2005).

Table 3. T_{eff} estimates

Star	T_{eff}	σ_1 ±	σ_2 ±	n
84	4755	28.7	64	5
141	4755	13.0	71	26
151	4745	17.6	75	18

where σ_1 is SEM, σ_2 is the individual error, n is the number of relevant calibrations.

Table 4. Surface gravity determinations

Star	T_{eff}	Pi	V	BC	log g(Pi)	log g (IE)
84	4755	0.00097	10.59	-0.433	2.25	2.7
141	4755	0.00088	10.48	-0.433	2.12	2.7
151	4745	0.00240	10.48	-0.439	2.98	2.8

where Pi have been adopted from SIMBAD, GAIA collaboration (2016); the Bolometric correction (BC) from Flower (1996).

Table 5. The parameters obtained for the target stars

Star	Spec	T_{eff}	log g	Vt	[Fe/H]
84	34902	4755	2.7	1.4	0.01
141	39508	4755	2.7	1.4	0.01
151	39602	4745	2.8	1.3	0.04

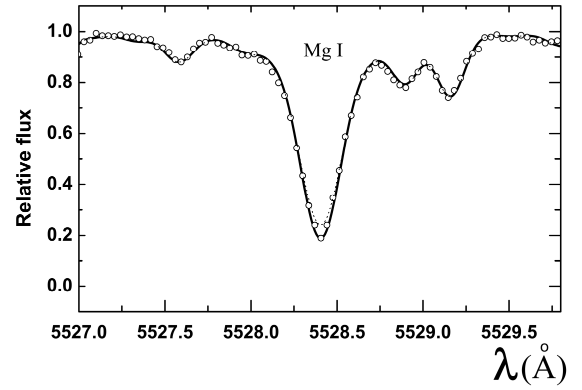

Figure 2: Observed (circles) and calculated (NLTE, solid, and LTE, dashed lines) spectra in the region of Mg I line for 141 star.

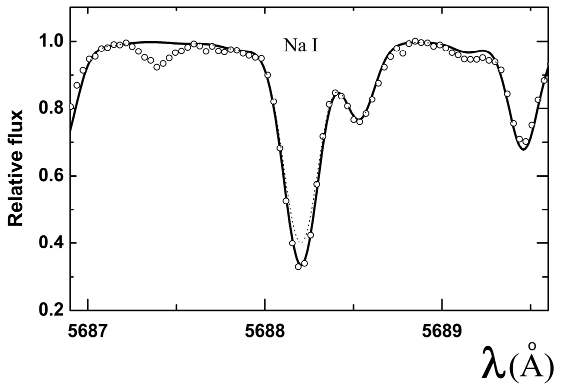

Figure 3: Observed (circles) and calculated (NLTE, solid, and LTE, dashed lines) spectra in the region of Na I line for 141 star.

To determine the systematic errors in the elemental abundance resulting from uncertainties in the atmospheric parameter determinations, we derived the elemental abundance of star 141 (T_{eff}/4755, log g/2.7, V_t/1.4, [Fe/H]/0.01) for several models with modified parameters ($\delta T_{eff}=\pm 50$ K, δ log g= ± 0.2, $\delta V_t=\pm 0.1$).

The total uncertainty due to parameter and EW errors for Fe I, Fe II are 0.06, 0.08, respectively. The determination accuracy varies from 0.06 to 0.15 dex.

A comparison of our data with the results of other authors is given in Table 6.

In general, there is good agreement between our determinations and those of other authors for all parameters, except for the gravity.

5. Results and discussions

We have compared our determinations with those of other authors; as an example, Fig. 5 illustrates the results of the comparison of our data for the star 84 with the data obtained by Tautvaišienė *et al.*, (2000).

The authors have found that the stars 84, 141 and 151 show a slight overabundance of Na (+0.17, +0.24 and +0.22, respectively) and underabundance of Zr (–0.18, –0.19, –18, respectively).

Sodium. The target three stars have been also studied by Jacobson *et al.* (2011). For the M 67 stars 84, 141 and 151 the authors have reported slightly different individual values of [Na/Fe], such as -0.06, 0.15, and 0.10, respectively. According to our LTE determinations, the Na abundances are 0.03, 0.11, and 0.08, respectively, these values are fairly similar to the determinations by Jacobson *et al.* (2011). Yong *et al.* (2005) have reported an overabundance of Na ~ +0.30 for the cluster M67. In all the afore-mentioned studies, the Na I lines λ 5682.64, 6154.23 and 6160.75 Å were used for the Na abundance determinations.

In so doing, despite the difference (about 0.2 dex) in the sodium abundance obtained by Tautvaišiene *et al.* (2000) and Jacobson *et al.* (2011), the equivalent widths EW of the lines 6154.23 and 6160.75 Å, e.g., for the star 84, given in both these paper are similar, the EWs are 84 and 110 mÅ, and 82 and 106 mÅ, respectively.

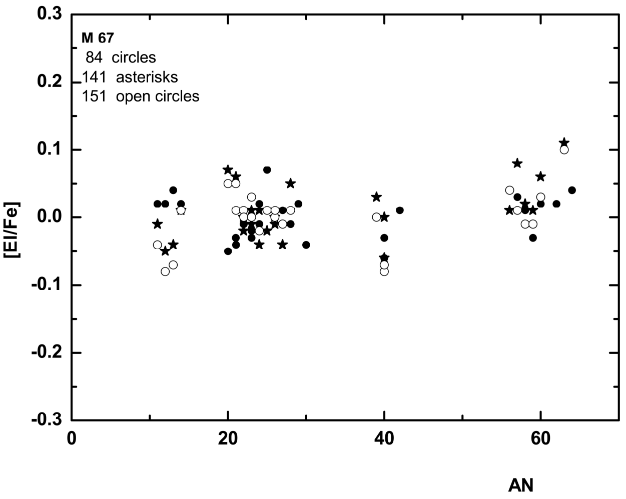

Figure 4: [El/Fe] vs. [Fe/H] for the target stars

Table 6. A comparison of our findings with the results of other authors

#	Star	T_{eff}	log g	[Fe/H]	reference
1	84	4755	2.7	0.01	This work
		4702	2.40	-	Kordoratis *et al.*, 2013
		-	2.56	-	Pace *et al.*, 2012
		4650	2.5	0.00	Jacobson *et al.*, 2011
		4750	2.4	-0.02	Tautvaisiene *et al.*, 2000
2	141	4755	2.7	0.01	This work
		4700	2.4	0.09	Jacobson&Friel, 2013
		-	2.56	-	Pace *et al.*, 2012
		4700	2.4	0.08	Jacobson *et al.*, 2011
		4730	2.4	-0.01	Tautvaisiene *et al.*, 2000
3	151	4745	2.8	0.04	This work
		4740	2.62	-	Meszaros *et al.*, 2013
		4700	2.4	-0.02	Jacobson *et al.*, 2011
		4760	2.4	-0.03	Tautvaisiene *et al.*, 2000

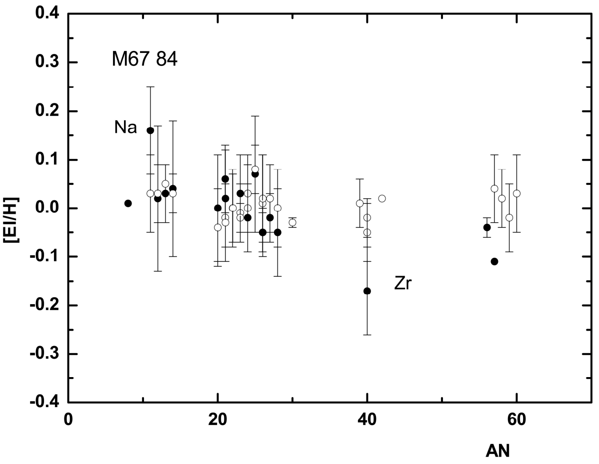

Figure 5: A comparison of our data for the M 67 cluster star F84 (open circles) with those obtained by Tautvaišienė *et al.* (2000) (full circles).

Zirconium. For the target stars, Jacobson *et al.* (2011) found underabundance of Zr equal to –0.18, –0.16 and –0.10, respectively. Later, Jacobson *et al.* (2013) have redetermined the zirconium abundances and obtained an average value <[Zr/Fe]> of –0.01 ± 0.07 for the M67 cluster. Yong *et al.* (2005) have found [Zr/Fe] = −0.28 ± 0.03 for M67; however, Maiorca *et al.* (2011) have obtained [Zr/Fe] = +0.04 ± 0.05. While in the studies by Tautvaišienė *et al.* (2000), Jacobson *et al.* (2011, 2013), Yong *et al.* (2005), as well as in our study, the same Zr I lines, namely 6134.57, 6140.46, 6243.18, 6313.03 Å were used, Maiorca *et al.* (2011) used the UV Zr II lines, namely 4050.32, 4208.98, 4379.74 Å.

According to our Zr abundance determinations, there is a slight deficit of Zr for the three target stars: the mean underabundance from Zr I lines is –0.05 ± 0.01 and from Zr II lines <[Zr/Fe]> is – 0.02 ± 0.01.

Thus, in the studied stars in M67, the differences observed in elemental abundance, in particular of sodium and zirconium, depend on the individual approach of different authors and are within the errors of determination.

Now, let us consider the behavior of several elements (Li, Fe, Ba), which are especially manifested in OC's stars.

Lithium. Clump giants have shown Li abundances slightly lower than the upper limit of the first dredge up (Fig.6). We have only determined the upper limit of the Li abundance, which is about 0.0 in our stars (141 and 151). These values corroborate the Li abundance of star 141 (0.0) obtained by Pace *et al.* (2012). This value corresponds to a greater depletion of Li during the evolution of stars due to the presence of additional mechanisms that change the lithium abundance and operate inside stars (for example, meridional circulation or diffusion) or are the result of deeper mixing.

The iron problem. Yong *et al.* (2004) and Shuler *et al.* (2004) have found remarkable discrepancies between the iron abundances determined with Fe I and Fe II lines in the dwarf stars in the young clusters Hyades, Pleiades and M34. Till now the cause of that is unknown: NLTE effects (Yong *et al.*, 2004) for lines Fe II are negligible; blended lines are not used. We applied the same lines of Fe I and Fe II as in above mention papers and obtained the same iron abundances from lines of both species (within the given accuracy of determinations).

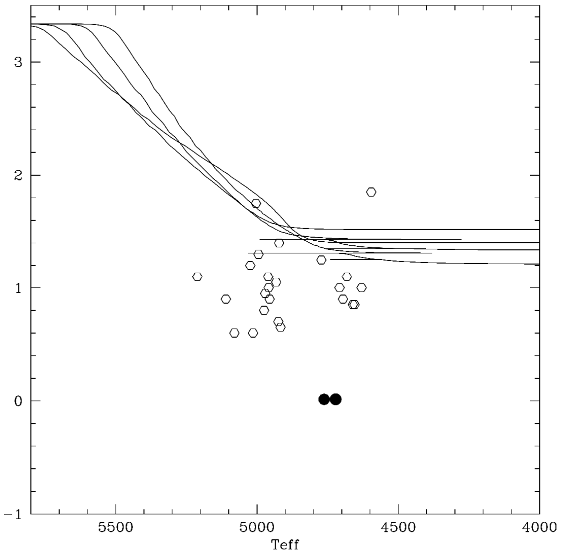

Figure 6: Li abundance vs. T_{eff}; our data are marked with full circles; trend lines illustrate the calculations performed by C. Charbonnel for the Li abundance after the first dredge-up; and the data obtained by Mishenina *et al.* (2006) for the clump giants are marked with open circles.

The Ba puzzle. The observed Ba overabundance in young OC's may be due to different causes: 1) additional enrichment with s-process elements from low mass AGB stars (d'Orazi *et al.*, 2009) or with i-process elements (Mishenina *et al.*, 2015); 2) NLTE corrections (Reddy & Lambert, 2015), but LTE correction is small, < 0.05 dex; 3) chromospheric activity or microturbulent velocity Vt (Reddy & Lambert, 2017). And if the study of influence of chromospheric activity on Ba line intensity can be reasonable, then the variation of the turbulent velocity by 3 times for one line, moreover having a depth of line formation of about log τ = –2 in solar atmosphere, has no substantial grounds. So, there is no definitive answer about the origin of Ba overabundance for today. Our [Ba/Fe] values are from 0.01 to 0.04 dex, it is near solar value. M 67 is old cluster and this is the expected result.

6. Conclusion

- The results which we have obtained show good agreement with the data reported by other authors.
- Variations in sodium and zirconium abundances are within the given accuracy of determinations.
- The Li abundance determinations suggest a greater depletion of lithium in the course of stellar evolution.
- For M 67 giants, the iron abundances derived from the neutral and ionized iron lines have not shown any significant discrepancies.
- M 67 is found to be an old open cluster with the [Ba/Fe] values close to the solar ones.

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