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INVESTIGATION OF ρ Cas (HR 9045, HD 224014) STELLAR ATMOSPHERE

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SUMMARY: The atmosphere of hypergiant ρ Cas is investigated by the method of atmospheric model. Effective temperature and the surface of gravity are determined by comparing the observed and theoretical values of photometrical indices $[c_1], Q$, and equivalent widths of Balmer lines: $T_{\rm eff} = 5450 \pm 200$K, log g=0.1 $\pm$ 0.2. The microturbulence parameter is evaluated as $\xi_t = 10 \pm 1$ km/s, based on studies of FeII lines. The chemical composition of the star is determined. In the atmosphere of ρ Cas the C turned out to be a deficit, N, and Na in excess, other investigated elements practically display solar abundance.

Key words. Stars: fundamental parameters – Stars: abundances – Stars: individual: ρ Cas

1. INTRODUCTION

The chemical composition of A, F, and G class supergiants, giants has attracted particular attention in recent decades. According to the theory of chemical evolution in the stage A, F, G class giants occur deep mixing which leads to the variation of the abundance of the CNO cycle (He, C, N, O) in the giants' atmospheres. A part of carbon nuclei turns into nitrogen nuclei by absorbing protons, as a result, according to the theory of chemical evolution of stars, particular, a deficit of carbon (C) and an abundance of nitrogen (N) should be observed in atmospheres of supergiants of spectral classes A, F, and G.

Boyarchuk and Lyubimkov (1983) have noticed that in addition to the deviations in the C, N, and O abundance in the atmosphere of A, F, and G class supergiants an overabundance of Na is observed. It was hypothesized that an excess abundance of Na can be explained by conversion of some amount of Ne into Na in the cyclic Ne-Na reactions. This Na excess must be released into the atmosphere due to deep mixing. Therefore a study of the chemical composition of A, F, and G supergiants and a comparison of the obtained datum with the predictions of chemical evolution theory remains a topical issue in astrophysics.

In the present work, we determined the chemical composition of the G spectral class ρ Cas (G1 0e) hypergiant star. Hypergiants are interesting, rare objects, only a few stars are known in our Galaxy.

2. OBSERVATIONAL MATERIAL

The spectra of ρ Cas star were obtained on November 06/07, 2019 by using the spectrograph with CCD - matrix of the 2-meter telescope of the Shamakhy Astrophysical Observatory of the Republic of Azerbaijan (R=56000, S/N=150-400). The analysis of spectrograms, were conducted using the DECH package programs, which were specifically developed by Galazutdinov (Galazutdinov 1992). We have assessed the equivalent widths of the spectral lines using two distinct methods: direct integration and Gaussian approximation. The direct integration method involves calculating the equivalent width by numerically integrating the area under the absorption or emission line profile, which provides a precise measurement of the line intensive based on the actual shape of the line. In contrast, the Gaussian approximation method simplifies the line profile by assuming it follows a Gaussian distribution, allowing for an estimation of the equivalent width based on the width and amplitude of a fitted Gaussian curve.

The equivalent width of the H_β line of the Balmer series of hydrogen is W(H_β) =3.63Å, and the equivalent width of the H_γ line is W(H_γ) =2.84Å. The equivalent widths of the used spectral lines are given in Tables 1 and 2.

The measurement error for the equivalent widths (Wλ) has been carefully controlled and does not exceed 5%, ensuring high accuracy and reliability in our data.

Several of the spectral lines under investigation, including Zr II at 4264.92Å and Sm II at 4265.08Å, are positioned close to each other in the spectrum. To accurately distinguish and analyze these closely spaced lines, we employed a combination of high-resolution spectroscopic techniques that provided the necessary spectral resolution. Additionally, advanced line fitting methods were utilized to deconvolve the overlapping lines, ensuring precise measurement of their wavelengths and intensities. This approach allowed us to achieve a higher degree of accuracy in identifying and characterizing each spectral line despite their near coincidence.

3. PARAMETERS OF ATMOSPHERE: EFFECTIVE TEMPERATURE AND SURFACE OF GRAVITY

The atmosphere of the ρ Cas star was studied by the model method. This method has been extensively described (Lyubimkov et al. 2010). We have studied the atmospheres of several A, F, G-spectral class giants and supergiant stars using the model method (for example, Samedov et al. 2023, 2021, Samedov 2019). The model method of determination of atmospheric parameters of stars is based on the comparison of observed and theoretically calculated values of the spectral and photometric quantities. We have determined the effective temperature ($T_{\rm eff}$) and surface of gravity (log g) of the star ρ Cas based on the following criteria:

1. Comparison of observed and theoretically calculated values for equivalent widths of Balmer lines. H_β and H_γ spectral lines of the Balmer series were used.

2. Comparison of observed and theoretically calculated values for index $[c_1]$.

3. Comparison of observed and theoretically calculated values for index Q.

The index $[c_1]$ is defined as $[c_1] = c_1 - 0.2(b - y)$ in the uvby photometric system and the Q index is defined as $Q = (U-B)-0.72(B-V)$ in the UBV system. These indices are released from the absorption effect in interstellar space. The observation values of the quantities $[c_1]$ and Q are determined from the catalog (Hauck and Mermilliod 1998). The theoretical values of these quantities were calculated in (Castelli and Kurucz 2003).The theoretically calculated values of the equivalent widths of the Balmer series are given in (Kurucz 1993).

If there is a significant variation in the observed values of the star's $[c_1]$ and Q photometric indices, this will affect the determination of the star's atmospheric parameters, such as ($T_{\rm eff}$, log g). It should be noted that the range of variation of these indices for the ρ Cas star has not been studied.

Fig. 1 shows the diagram that determines $T_{\rm eff}$ and log g based on the above criteria. Based on Fig. 1 for parameters of the atmosphere of ρ Cas star, the following values are taken: $T_{\rm eff}$ = 5450K ± 200K, log g=0.1 ± 0.2. ρ Cas is a variable star whose effective temperature fluctuates even during quiescent periods. The temperature $T_{\rm eff}$ =5450K is based on the spectrum of the star obtained on November 6/7, 2019. According to Klochkova et al. (2014), the effective temperature of ρ Cas varied between 5777K and 6744K during their observation period, with an average value of about 6200 K. Israelian et al. (1998) also reported that the temperature changes by approximately 750K during the pulsation period. The temperature variation reported by Klochkova et al. (2014) is greater than that found by Israelian et al. (1998). Lobel et al. (1998) reported an effective temperature range of 7250K–6500K based on observations from August 4, 1998, while Israelian et al. (1999) determined $T_{\rm eff}$ =7300K±200K. Kraus et al. (2019) noted an outburst in ρ Cas in 2013, which was accompanied by a temperature drop of approximately 3000K.

4. MICROTURBULENT VELOCITY

Therefore, when determining the microturbulent velocity in the stellar atmosphere we used the FeII lines. When determining ξ_t we use only the FeII lines with the equivalent width $W < 280$ m$\AA$. These lines are formed in the deep layers of the atmosphere which can be considered as plane-parallel layers in the LTE state.

Spectral lines with the equivalent widths $W < 280$ m$\AA$ are widely used in determining the microturbulent velocity (e.g., Lyubimkov et al. 2010).

Based on the found parameters $T_{\rm eff}$ and log g we calculated the corresponding model of the atmosphere; for this Kurucz's ATLAS 9 program was used. The determination of the microturbulent velocity by the model method is based on the study of equivalent widths in a wide range of spectral lines of FeII. Several values are given to the microturbulent velocity,

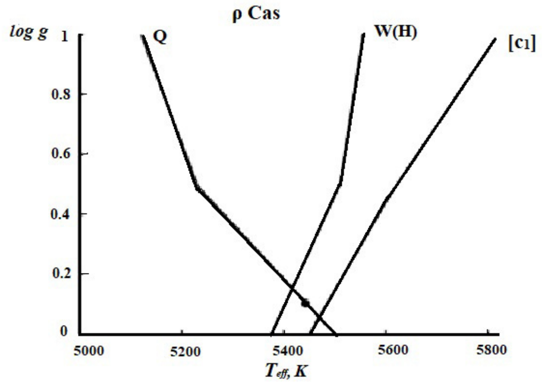

Fig. 1: log g - $T_{\rm eff}$ diagram. The lines are constructed based on a comparison between observed and theoretical values of the equivalent widths of the H_β and H_γ lines, as well as the $[c_1]$ and Q indices. The filled circle represents the accepted values of $T_{\rm eff}$ and log g.

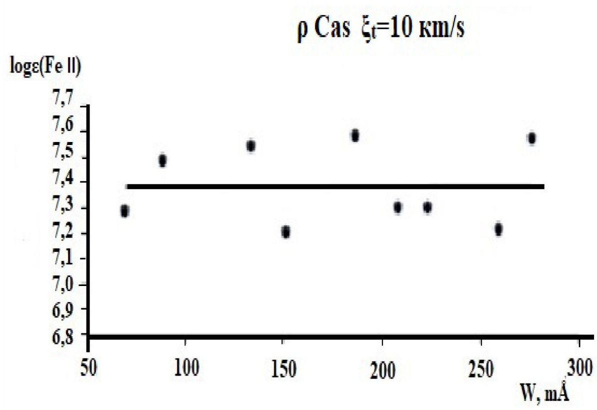

Fig. 2: Determination of the microturbulent velocity. The straight line indicates that when $\xi_t = 10$ km/s, there is no correlation between the iron abundance, log ε(Fe II), and the equivalent widths of the spectral lines (W).

Table 1: List of used FeII lines. For each line, the wavelength, excitation potentials of the lower energy levels, oscillator strengths, measured equivalent widths, and calculated iron abundances are shown.

Line (λ, Å)	$E_{\rm exc}$ (eV)	log gf	W (mÅ)	log ε(Fe)
6482.20	6.19	-1.84	133	7.54
6446.41	6.20	-2.02	88	7.48
6369.46	2.88	-4.29	223	7.30
6179.39	5.54	-2.60	69	7.28
6113.32	3.21	-4.20	208	7.30
6084.10	3.19	-3.85	259	7.21
5627.49	3.37	-4.06	151	7.20
5161.18	2.84	-4.55	276	7.57
5100.85	5.89	-1.92	186	7.58
				log ε(Fe) =7.39 $\pm$ 0.16

and the equivalent widths (W_λ) of the spectral lines of FeII are calculated and compared with the equivalent widths measured from observation (Table 1). We used atomic data for the spectral lines from the VALD-3 database (`http://vald.astro.uu.se`). VALD-3 (Ryabchikova et al. 2015).

Fig. 2 presents the determination of the microturbulence parameter in the atmosphere of the ρ Cas star. As can be seen from Fig. 2 there is no correlation between $\log\varepsilon$(FeII) and W_λ at $\xi_t = 10$ km/s. Thus, we define for the ρ Cas star: $\xi_t = 10 \pm 1$ km/s. de Jager (1998) determined $\xi_t = 11 \pm 2$ km/s for the microturbulent velocity.

5. ABUNDANCE OF THE ELEMENTS

When analyzing microturbulence (ξ_t) the iron abundance is simultaneously found from the FeII lines: $\log\varepsilon$(Fe)=7.39. The abundances of elements are given on logarithmic scale

$$\log\varepsilon(el) = \log\frac{N(el)}{N(H)} + 12$$

For hydrogen, it is assumed that logε(H)=12. Applying our model (basic parameters: $T_{\rm eff} = 5450{\rm K} \pm 200{\rm K}$, log g=$0.1 \pm 0.2$.) we calculated the abundance of the elements at $\xi_t = 10$ km/s. Only the fairly weak lines are used, these lines are formed in deep layers of the atmosphere and the variability in the upper layers of the atmosphere has no effect on the lines we use. The results are presented in Tables 1 and 2.

The difference in abundances of elements $[el/H] = \log\varepsilon_*(el) - \log\varepsilon_\odot(el)$ in the star and Sun is presented in Table 3 and Fig. 3. Solar abundances $\log\varepsilon_\odot$(el) are taken from (Scott et al. 2015, Grevesse et al. 2015).

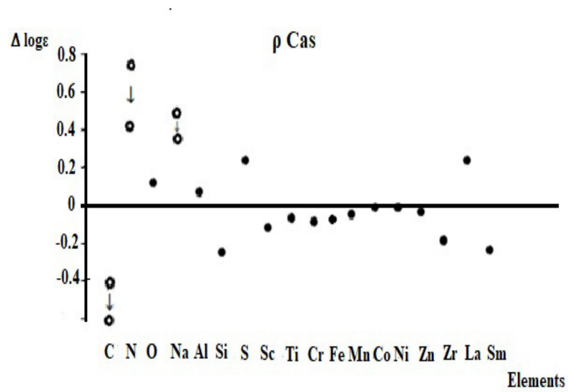

Fig. 3: The difference in abundances of elements between ρ Cas and the Sun. The horizontal line at zero represents the solar abundances. Elements corrected for the non-LTE effects are depicted with open circles, and the direction of the corrections (decreasing) is indicated by an arrow.

Table 2: List of used lines. The table presents the wavelengths of spectral lines for the specified elements, the excitation potentials of the lower energy levels, oscillator strengths, measured equivalent widths, and the calculated abundances of the elements.

Line (λ, **Å**)	$E_{\rm excit}$ **(eV)**	log **gf**	**W, m**$\AA$	$\log\varepsilon$
CI				
4775.89	7.46	-2.30	51	8.05
5800.60	7.95	-2.34	15	7.95
6010.68	8.64	-1.94	6	7.82
6413.55	8.77	-2.00	10	8.17
6587.61	8.54	-1.00	105	8.15
6671.85	8.85	-1.65	11	7.94
7087.83	8.65	-1.44	23	7.90
7108.93	8.64	-1.59	32	8.19
7111.47	8.64	-1.08	54	7.96
7115.17	8.64	-0.93	75	8.00
7476.18	8.77	-1.57	24	8.16
				$\log\varepsilon$**(C)** $=8.03\pm0.13$
NI				
7442.30	10.33	-0.38	80	8.58
7468.31	10.33	-0.19	100	8.55
				$\log\varepsilon$**(NI)** $=8.57\pm0.02$
OI				
6155.97	10.74	-1.01	16	8.88
6156.78	10.74	-0.69	24	8.74
				$\log\varepsilon$**(O)** $=8.81\pm0.1$
NaI				
5682.63	2.09	-0.70	281	6.54
6160.75	2.10	-1.26	280	6.83
				$\log\varepsilon$**(Na)** $=6.69\pm0.21$
SiI				
5754.22	4.93	-1.84	44	7.13
5772.15	5.06	-1.36	94	714
6527.29	5.85	-1.07	120	7.74
6848.58	5.84	-1.53	8	7.24
7034.90	5.85	-0.62	90	7.11
7405.77	5.59	-0.31	217	7.35
7424.61	5.59	-1.61	19	7.11
				$\log\varepsilon$**(Si)** $=7.26\pm0.23$
ScII				
5318.35	1.35	-1.87	290	3.11
5357.20	1.50	-2.11	214	3.26
5552.22	1.45	-2.09	110	2.75
				$\log\varepsilon$**(ScII)** $=3.04\pm0.26$
TiI				
4299.63	0.82	-0.43	269	5.13
4639.36	1.73	0.03	85	4.96
4639.94	1.73	-0.08	62	4.73
4650.01	1.73	-0.56	17	4.62
5035.90	1.45	0.41	75	4.75
5219.70	0.02	-2.11	28	4.59
5460.50	0.05	-2.68	22	5.10
5739.48	2.24	-0.47	24	5.11
5739.98	2.23	-0.69	10	4.92
6258.10	1.44	-0.39	51	4.69
				$\log\varepsilon$**(Ti)** $=4.86\pm0.21$

Table 2. continued.

Line (λ, **Å**)	$E_{\rm excit}$ **(eV)**	log **gf**	**W, m**$\AA$	$\log\varepsilon$
CrI				
4042.24	2.53	-1.21	66	5.93
4257.35	3.00	-1.26	22	5.91
4261.34	2.90	-0.53	39	5.33
4381.11	2.70	-1.50	8	5.39
4410.30	3.00	-1.22	31	5.98
4458.54	3.00	-0.41	39	5.29
4569.52	3.11	-0.74	10	5.13
4646.21	1.03	-1.63	129	5.13
4633.26	3.11	-1.18	30	6.01
4637.76	2.53	-0.72	77	5.43
4697.84	3.35	-0.64	16	5.43
4767.86	3.54	-1.03	6	5.59
4775.13	3.54	-1.12	4	5.52
5177.40	3.41	-0.62	10	5.33
5287.18	3.42	-0.93	14	5.68
5390.38	3.35	-0.99	17	5.76
5648.26	3.81	-0.77	3	5.38
5694.74	3.84	-0.26	14	5.39
5719.82	3.00	-1.51	5	5.41
				$\log\varepsilon$**(Cr)** $=5.53\pm0.28$
AII				
5557.06	3.13	-2.11	12	6.38
7836	4.00	-0.49	107	6.62
				$\log\varepsilon$**(AI)** $=6.50\pm0.17$
SI				
4694.11	6.50	-1.77	140	7.39
4695.44	6.50	-1.92	39	7.33
6052.66	7.84	-0.83	84	7.38
6757.15	7.84	-0.45	152	7.39
				$\log\varepsilon$**(S)** $=7.37\pm0.03$
ScI				
5671.82	1.44	0.54	23	3.17
				$\log\varepsilon$**(ScI)** $=3.17$
MnI				
4070.27	2.18	-1.09	109	5.1
4452.99	2.93	-0.64	179	5.64
4671.68	2.88	-1.68	20	5.48
4727.48	2.91	-0.47	92	5.52
5388.50	3.36	-1.37	10	5.28
5457.46	2.15	-2.89	8	5.52
6013.49	3.06	-0.48	23	5.05
				$\log\varepsilon$**(Mn)** $=5.37\pm0.23$
CoI				
4068.54	1.95	-1.11	99	4.99
4110.53	1.04	-1.82	186	5.13
4570.02	3.62	-0.40	8	4.71
4727.94	0.43	-3.33	34	5.02
5094.95	2.03	-2.12	7	4.71
5287.79	4.03	-0.33	5	4.83
7417.38	2.03	-1.98	28	5.05
				$\log\varepsilon$**(Co)** $=4.92\pm0.17$

Table 2. continued.

Line (λ, **Å**)	$E_{\rm excit}$ **(eV)**	log **gf**	**W, m**$\AA$	$\log\varepsilon$
NiI				
4009.98	3.62	-1.17	94	6.48
4017.57	3.69	-0.53	113	5.99
4023.99	3.69	-0.81	118	6.23
4551.22	4.15	-0.86	20	5.89
4600.36	3.58	-0.40	220	6.14
4715.76	3.53	-0.30	226	6.00
4752.42	3.64	-0.60	90	5.83
4814.60	3.58	-1.62	26	6.17
4832.69	3.78	-0.95	95	6.33
4841.97	4.15	-1.20	10	5.91
4918.36	3.82	-0.08	294	6.32
4930.80	3.83	-1.56	26	6.36
4952.28	3.59	-1.69	38	6.43
4980.17	3.59	-0.36	197	5.98
5606.80	3.88	-1.70	16	6.28
6025.75	4.22	-1.53	24	6.59
6116.18	4.07	-1.08	41	6.24
6327.60	1.67	-3.21	41	5.92
6370.35	3.53	-1.80	50	6.50
				$\log\varepsilon$**(Ni) =6.19±0.23**
ZnI				
6362.34	5.77	0.15	75	4.52
				log ε**(Zn) =4.52**
ZrI				
4241.69	0.65	0.14	7	2.38
4027.20	0.62	-0.23	9	2.87
				$\log\varepsilon$**(ZrI) =2.63±0.35**
ZrII				
4071.09	0.99	-1.66	162	2.53
4110.06	0.75	-1.40	230	2.28
4264.92	1.66	-1.41	62	2.40
				log ε**(ZrII) =2.40±0.13**
LaI				
5377.05	2.29	-0.43	23	1.35
				$\log\varepsilon$**(La) =1.35**
SmII				
4123.95	0.48	-0.69	80	0.75
4256.39	0.38	-0.15	232	0.73
4265.08	0.18	-1.04	64	0.66
				$\log\varepsilon$**(Sm) =0.71±0.05**

Open circles indicate the differences in the C, N, and Na elements in the star and Sun according to the literature data require non-LTE corrections. It is necessary to insert corrections – (0.3-0.4)dex. into the value of $\log\varepsilon$(N)–(0.2-0.3) dex. into the value of $\log\varepsilon$(C) (Lyubimkov et al. 2011, 2015)–(0.1- 0.2)dex. into the value of $\log\varepsilon$(Na) Andrievsky et al. (2002).

As can be seen in the atmosphere of the star, C turned out to be in deficit, N and Na in excess, the other investigated elements practically display the solar abundance. This means that the star ρ Cas was formed from matter with the same chemical composition as the Sun. This conclusion is interesting from the point of view of models of the Galactic chemical evolution. According to the calculations of these models (for example, Spitoni et al. 2009) the enrichment of the Galactic disk with heavy matter is very small during the age of the Sun (within 4.5 billion years). The oxygen abundance and metallicity have retained their original abundance, but evolutionary changes were observed in the composition of the C, N, and Na elements. Thus, the predictions of the theory of evolution are confirmed by observations. The abundances of elements in the atmosphere of the star ρ Cas have been determined (Boyarchuk and Lyubimkov 1983). In (Boyarchuk and Lyubimkov 1983), and it was concluded that C is deficient, N, and Na are in excess, and the amount of other studied elements is the same as in the Sun. Israelian et al. (1998) demonstrated that the atmosphere of the ρ Cas star contains excess of N [Na/H] = 0.65 ± 0.15. Additionally, the abundances of Si, Mg, and Ca are slightly enhanced, with the mean increase of 0.3 ± 0.1 dex.

Table 3: The difference in abundances between ρ Cas and the Sun.

Element	$\log\varepsilon_*$	$\log\varepsilon_\odot$	$\Delta\log\varepsilon = \log\varepsilon_* - \log\varepsilon_\odot$
C	8.03	8.43	-0.4
N	8.57	7.83	0.74
O	8.81	8.69	0.12
Na	6.69	6.21	0.48
Al	6.50	6.43	0.07
Si	7.26	7.51	-0.25
S	7.37	7.13	0.24
Sc	3.04	3.16	-0.12
Ti	4.86	4.93	-0.07
Cr	5.53	5.62	-0.09
Fe	7.39	7.47	-0.08
Mn	5.37	5.42	-0.05
Co	4.92	4.93	-0.01
Ni	6.19	6.20	-0.01
Zn	4.52	4.56	-0.04
Zr	2.40	2.59	-0.19
La	1.35	1.11	0.24
Sm	0.71	0.95	-0.24

The abundance of elements in the atmospheres of giants and supergiants have been determined by numerous authors (for example, Lyubimkov et al. 2010, 2011, 2015, 2019, Luck et al. 2006) and it has been shown that the O abundance and metallicity of these stars are close to those of the Sun, C is in deficit, while N, and Na are in excess.

6. CONCLUSION

1. The effective temperature and surface of gravity of the ρ Cas star are determined by the method of atmospheric model. The following values of the effective temperature and surface of gravity were found: $T_{\rm eff}$ = 5450±200 K, log g=0.1±0.2.

2. The microturbulence parameter was found as $\xi_t = 10 \pm 1$ km/s on the basis of studies of FeII lines.

3. The abundance of elements in the atmosphere of ρ Cas star was determined and compared with their abundances of the Sun. A deficiency of C and excess of N and Na were found. The abundance of other studied elements is close to the solar. This means that the star ρ Cas was formed from matter with the same chemical composition as the Sun.

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ИСТРАЖИВАЊЕ АТМОСФЕРЕ ЗВЕЗДЕ ρ Cas (HR 9045, HD 224014)

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Оригинални научни рад

Атмосфера хиперџина ρ Cas истражена је кроз моделовање атмосфере. Поређењем посматраних и теоријских вредности фотометријских индекса $[c_1], Q$, и еквивалентних ширина Балмерових линија одређене су вредности $T_{\rm eff} = 5450 \pm 200$K, $\log g = 0.1 \pm 0.2$ за ефективну температуру и површинску гравитацију. Параметар микротурбуленције процењен је на $\xi_t = 10 \pm 1\,{\rm km\,s^{-1}}$ на основу проучавања Fe II линија. Одређен је хемијски састав звезде. У атмосфери ρ Cas, C је у дефициту, N и Na присутни су у већој мери у односу на Сунце, док остали проучавани елементи показују хемијску заступљеност блиску Сунчевој.