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ON THE OPTICAL SPECTRUM OF 89 Her

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Abstract. The high resolution spectra of a post-AGB candidate, binary system 89 Her, were analysed for the chemical composition. The star was found to be metal deficient with [Fe/H] = -0.50 ± 0.20. No enhancement of s-process elements was found. The refractory elements are depleted but this is not the reason of metal deficiency. More than 320 narrow and weak emission lines from low levels of neutral metals were identified. Radial velocities of these lines coincide with the systemic velocity. We propose that the circum-binary dusty disk is observed face-on.

Key words: stars: AGB and post-AGB – stars: atmospheres, abundances – stars: individual (89 Her)

1. INTRODUCTION

The bright star 89 Her seems to be in a post-AGB evolutionary phase. It is an F2 Ibe supergiant with a dust shell with a color temperature of about 800 K, at Galactic latitude +23° (Waters et al. 1993). Luck et al. (1990) analyzed its chemical composition among other 3 high Galactic latitude supergiants and found that the star is slightly metal-poor ([Fe/H]≈ -0.4) indicating its origin in the Galaxy thick disk. Carbon and nitrogen were found to be overabundant. The enhancements of heavy s-process elements were not found, and this disagree with a post-AGB star status which was suggested from the presence of dust shell. Luck et al. (1990) for 89 Her found $T_{\rm eff}$ = 6500–6600 K, $\log g$ = 0.3–0.8 and $v_{\rm t}$ = 4.3 km s^{-1}.

Arellano Ferro (1984) found that the star is a binary system, this was confirmed by Waters et al. (1993) who determined a period of 288.4 days. They also constructed a qualitative model of the system.

Some years ago Takeda et al. (2007) analyzed 89 Her among other post-AGB candidates trying to find the abundances of the volatile elements C, N, O, S, and Zn. The following values of atmospheric parameters were found: $T_{\rm eff}$ = 7177 K, $\log g$ = 1.66 and $v_{\rm t}$ = 8.0 km s^{-1}. While these parameters differ considerably from those found by Luck et al. (1990), the derived abundances are quite close, except for N, for which the value of Luck et al. (1990) is larger by 0.5 dex. This is the reason why we decided to reexamine this well studied star with the new observational data of high quality.

The spectra were obtained on the Canada-France-Hawaii Telescope (CFHT) with the echelle spectropolarimeter ESPaDOnS by the Queued Service observing team. The observing dates were 2009-09-07, 2009-09-28, 2009-10-05 and 2010-02-

01. Alltogether 33 spectra were used. The spectra cover 370–1000 nm region with $R \approx 65\,000$.

2. ANALYSIS

2.1. Measurement of the spectra

The spectra of every observing date were preliminary coadded, and therefore four averaged spectra were obtained. The line identification and subsequent full analysis was performed for the spectrum obtained on the latest date (2010 Feb. 1). The wavelengths, equivalent widths and half-widths (FWHW) of lines were measured with the IRAF task 'splot'. Due to heavy blending of most lines that measurement included the Gaussian decomposition of blends. This was reasonably possible down to the wavelength of about 400 nm. However, most of the measured lines were still seriously affected by blending and therefore during the subsequent analysis were rejected.

Table 1. Basic parameters of 89 Her (SIMBAD database).

HD 163506 = 89 Her		
Coordinates (J2000)	α	17 55 25.19
	δ	+26 02 59.97
Galactic coordinates	ℓ	51.43
	b	+23.19
Mean magnitude	B	5.80
	V	5.47
	J	5.50
	K	3.63
Spectral type		F2 Ibe
IRAS fluxes (Jy)	f_{12}	97.52
	f_{25}	54.49
	f_{60}	13.42
	f_{100}	6.04
Radial velocity		–28.5 km s^{-1}

For the identification of lines the Rowland tables (Moore et al. 1966) were used. The heliocentric radial velocity of the star, -30.08 ± 0.29 km s^{-1} was found from the 2010 Feb. 1 spectra.

2.2. Chemical composition

The measured equivalent widths were analyzed with the Kurucz (1979) program WIDTH5. The solar oscillator strengths by Thevenin (1989, 1990) were used for most of the lines. For C, N and O the oscillator strengths were taken from Wiese et al. (1996). For the lines of S I we used the data from Bell's tape (Bell 1976), and for some lines of Ca II the oscillator strengths are from University of Kentucky database (van Hoof 1999).

2.2.1. Atmospheric parameters and model atmospheres

The atmospheric parameters were found iteratively. We started with the parameters found by Luck et al. (1990): $T_{\rm eff}$ = 6500–6600 K, $\log g$ = 0.3–0.8 and $v_{\rm t}$ = 4.3 km s^{-1}. The model atmospheres were chosen from Kurucz (1979).

The effective temperature was found using the requirement that the derived abundance should not depend on the excitation potential of the lines (excitation equilibrium). The surface gravity was estimated from the ionization equilibrium of the Fe I and Fe II lines. At the same time the microturbulent velocity was found from the requirement that the derived abundance should not depend on the reduced equivalent width of the lines, using the so-called Blackwell diagrams (Saffe & Levato 2004). Such trials were performed for $T_{\rm eff}$ = 6500–7000 K and $\log g$ = 0.5–1.5. When plotting the Blackwell diagrams for Fe II, we found some bending up at $\log EW/\lambda > -1.3$. This corresponds to $EW > 200$ mÅ. In the following these strong lines were excluded.

In this way we found $T_{\rm eff} = 6600 \pm 50$ K and $\log g = 0.8 \pm 0.1$. It is interesting, that Waters et al. (1993) found the best fit of the spectral energy distribution of this star in the UV and optical regions with the synthetic distribution calculated with the Kurucz model (6500/1.0).

When analyzing the iron lines different microturbulent velocities for Fe I $v_{\rm t} = 3.0$ km s^{-1} and for Fe II $v_{\rm t} = 6.4$ km s^{-1} were found. In this case [Fe/H]=-0.50 ± 0.20 if the solar iron abundance is $\log A(\rm Fe) = 7.50$. The effect of non-LTE effect on Fe I and Fe II lines in supergiants has been discussed by Boyarchuk et al. (1985) with the conclusion that Fe II is not significantly affected and for Fe I the effect is small for lines with $EW < 200$ mÅ, and therefore non-LTE effects were not taken into account for iron.

The reason why the ionic lines show much larger velocities could be explained taking into account that these lines in general are stronger and are formed in much shallower region of the atmosphere, where the microturbulent velocity is expected to be larger.

We tried to model very schematically the variable microturbulent velocity profile in the atmospere and to look whether our Blackwell diagrams could be explained. According to one of such models in the uppermost atmospheric layer ($\rho_x = 0.015$) the microturbulent velocity is $v_{\rm t} = 20$ km s^{-1} and then falls linearly with ρ_x until at $\rho_x = 9.7$ it becomes 2 km s^{-1} and after that remains constant. This velocity run was applied both to Fe I and Fe II lines. The dependences of derived abundances on reduced equivalent widths are the same as they were with different but constant microturbulent velocities for Fe I and Fe II. Here we used the mass depth parameter ($\rho_{\rm x} = P_{\rm tot}/g$) which is a customary in the Kurucz models.

The result, that ionized atoms give higher microturbulent velocities than neutral atoms in F-type supergiants, has been known quite a long time. So, Wright (1946) using the curve-of-growth technique for α Per (F5 Ib) has found microturbulent velocities 5.0 and 7.5 km s^{-1} for Fe I and Fe II, respectively. Strange enough, Takeda et al. (2007) for 89 Her found no differences in mircoturbulent velocities for Fe I and Fe II.

For other elements the microturbulent velocity was determined independently. When this was not possible due to a small number of lines with different equivalent widths, the values found for iron were used.

For the following analysis a new metal-defficient, [Fe/H] = –0.5, model (6600/0.8) was constructed by interpolation between the Kurucz models with $T_{\rm eff} = 6500$–7000 K and $\log g = 0.5$–1.5. The observed wings of the Hα line fit quite well with the synthetic profile calculated using the adopted model (see section 2.4). A good fit of the spectral energy distribution with a similar model given by Waters et al. (1993) was already mentioned.

2.3. The abundances

The results of abundance determinations are presented in Table 2. The errors given in the Table are random errors due to the differences of abundances determined from different lines. The systematic errors due to inaccuracy of the effective temperature $\Delta T_{\rm eff} = \pm 50$ K and surface gravity $\Delta \log g = \pm 0.1$ are much smaller, both about ± 0.05 dex. In Table 2 the microturbulent velocities determined for various elements are also given. If that determination was not possible, then $v_{\rm t} = 6.4$ km s^{-1} was used for ionic lines, and 3.0 km s^{-1} for the lines of

Table 2. Chemical composition of 89 Her. The derived microturbulent velocities and the number of used lines are indicated.

El.	Sun[1] $\log\varepsilon$	Ion	89 Her $\log\varepsilon$	89 Her [El/H]	$v_{\rm tur}$ [km/s]	Number of lines
C	8.55	C I	8.34 ± 0.16	–0.3	4.5	32
N	7.97	N I	8.09 ± 0.18	–0.3	5.0	14
O	8.87	O I	8.65 ± 0.20	–0.3	7.0	10
Na	6.33	Na I	6.02 ± 0.26	–0.31	4.0	7
Mg	7.58	Mg II	7.57 ± 0.32	–0.01		3
		Mg I	7.34 ± 0.28	–0.34	4.0	69
Al	6.47	Al I	5.96 ± 0.33	–0.51		4
Si	7.55	Si I	7.30 ± 0.21	–0.25	4.0	44
		Si II	7.25 ± 0.16	–0.30	7.0	4
S	7.33	S I	7.05 ± 0.22	–0.28	4.0	19
Ca	6.36	Ca I	5.74 ± 0.19	–0.62	4.0	31
		Ca II	5.77 ± 0.11	–0.59		7
Sc	3.17	Sc II	1.91 ± 0.20	–1.26		15
Ti	5.02	Ti II	4.02 ± 0.13	–1.00	7.0	47
V	4.00	V II	3.31 ± 0.17	–0.69	7.0	7
Cr	5.67	Cr I	5.14 ± 0.37	–0.53	5.5	26
		Cr II	5.21 ± 0.15	–0.46	6.6	38
Mn	5.39	Mn I	4.72 ± 0.34	–0.67		14
Fe	7.50	Fe I	6.94 ± 0.20	–0.56	3.0	247
		Fe II	7.07 ± 0.21	–0.43	6.4	62
Co	4.92	Co I	4.05 ± 0.34	–0.87	3.0	3
Ni	6.25	Ni I	5.73 ± 0.26	–0.52	3.0	52
		Ni II	5.76 ± 0.26	–0.49		2
Cu	4.21	Cu I	3.81 ± 0.18	–0.40		2 (blends)
Zn	4.60	Zn I	4.19 ± 0.06	–0.41		3
Y	2.24	Y II	1.70 ± 0.18	–0.54		12
Zr	2.60	Zr II	1.87 ± 0.13	–0.73		19
Ba	2.15	Ba II	1.38 ± 0.32	–0.77		4
Ce	1.58	Ce II	0.56 ± 0.19	–1.02		11 (blends)
Nd	1.50	Nd II	0.96	–0.54		1
Sm	1.01	Sm II	0.49 ± 0.23	–0.52		9
Eu	0.51	Eu II	0.08	–0.43		1

[1] Grevesse et al. (1996), relative to $\log\varepsilon$(H).

neutral elements. The mean microturbulent velocity weighted with the number of used lines is $v_{\rm t} = 6.7 \pm 0.3$ km s^{-1} for ionic lines and 3.7 ± 0.9 km s^{-1} for atomic lines. Earlier Luck et al. (1990) found $v_{\rm t} = 4.3$ km s^{-1} and Takeda et al. (2007) 8.0 ± 0.5 km s^{-1} without any difference between atomic and ionic lines.

From Table 2 one could see that 89 Her is a metal deficient star with [Fe/H] = -0.50 ± 0.20. Similar metal deficiency has been found by Luck et al. (1990) and Takeda et al. 2007).

We do not find the Li I line at 6707.8 Å which earlier was found by Giridhar et al. (1988) to be quite strong. In spite of small number of the used lines, the abundances of s-process elements can be considered as not enhanced (see the conclusion concerning a possible depletion of refractive elements).

The abundance of carbon is found to be slightly subsolar. Takeda et al. (2007)

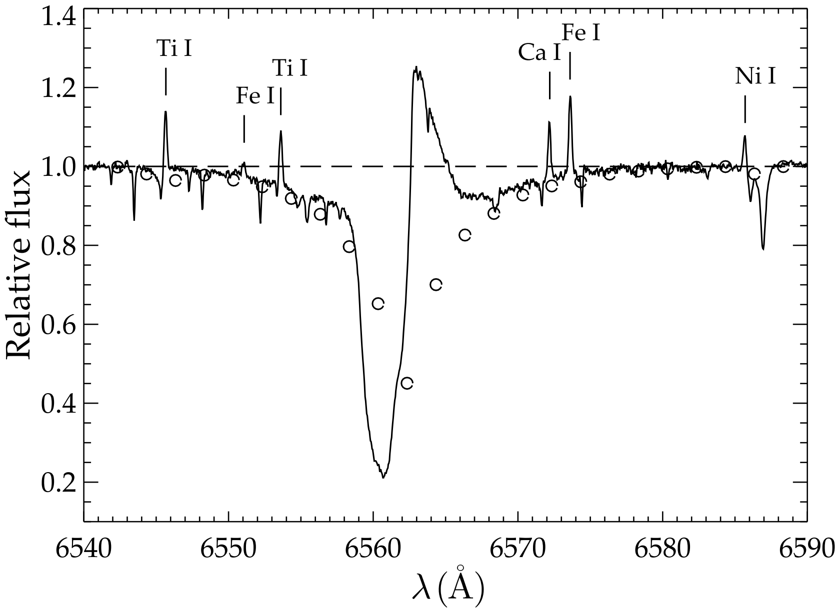

Fig. 1. The Hα line observed on 2009-09-28. The circles denote the synthetic profile calculated with the adopted metal-deficient model (6600/0.8). The calculated profile is shifted according to radial velocity of the star. Some weak emission lines of neutral metals are also indicated.

found very close carbon abundance taking into account the non-LTE corrections of about −0.1 dex. We included the correction of the same size in the fifth column ([Fe/H]) of Table 2. (In the case of using non-LTE corrections, only one decimal place is given in the 5th column of Table 2).

For the used six N I lines Takeda et al. (2007) found the non-LTE correction of about –0.34. At the same time their oscillator strengths were about 0.1 dex larger than those used in this work. Again, the non-LTE correction of the same size is included into [N/H].

The stronger O I lines are significantly affected by non-LTE effects. Takeda et al. (2007) found that for the O I triplet at 7774 Å the correction is as large as –1.20 dex. However, for the weaker lines, with $\log EW/\lambda < -2.0$, the corrections are smaller than –0.1 dex (Mishenina et al. 2000). These corrections were also included into [O/H] given in Table 2.

For S I lines we used the oscillator strengths from the Bell tape (Bell 1976). A non-LTE correction of –0.1 dex was included into [S/H].

According to Takeda et al. (2005), non-LTE effects in the determination of the abundance of Zn I are insignificant (< 0.1 dex) even in low-gravity F supergiants. However, in the later work (Takeda et al. 2007) for Zn I found about +0.2 dex non-LTE correction for the model (7177/1.66). The difference between our and last Takeda et al. results of Zn abundance is caused by two factors: first, they have used the oscillator strengths for Zn I by Biemont & Godefroid (1980) which are about 0.21 dex smaller than our values, second, we did not add any non-LTE correction to our result.

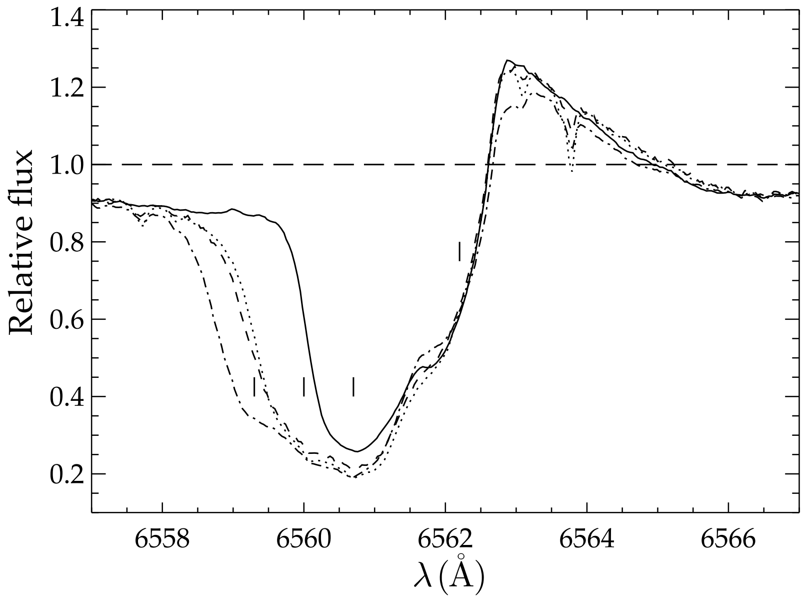

Fig. 2. Changes in the Hα line observed on 2010-02-01 – full line, on 2009-10-05 – dotted line, on 2009-09-28 – dashed line and on 2009-09-07 – dash-dotted line. The positions of components derived by Gaussian decomposition are indicated with vertical ticks and listed in Table 3. The position of the emission peak corresponds to the radial velocity of about –30 km s^{-1}.

Table 3. Results of the Gaussian decomposition of the Hα line in the spectra of 89 Her. The numbers correspond to the components in Figure 2 counting from blue to red. The velocities of the components are heliocentric.

No.	λ [Å]	$v_{\odot}$ [km/s]	EW [Å]	Spectrum & date
1	6559.3	–160	0.77	s4(Sept. 7 2009)
2	6560.1	–124	0.17	s4
	6560.2	–119	0.42	s3(Sept. 28 2009)
	6559.9	–133	0.93	s2(0ct. 5 2009)
3	6560.9	–87	1.11	s4
	6561.0	–83	0.80	s3
	6561.1	–78	0.92	s2
	6560.7	–97	0.84	s1(Feb. 1 2010)
4	6562.3	–25	0.47	s4
	6562.3	–26	0.52	s3
	6562.1	–29	0.94	s2
	6561.9	–40	0.55	s1

2.4. Emission lines

The spectrum of 89 Her shows emission in the Hα line, in the Na ID doublet and in numerous weak lines belonging to neutral metals.

In Figure 1 the Hα line is shown together with some of the weak emission lines. The Hα profile, calculated for the metal deficient model (6600/0.8), is also plotted. The wings of this synthetic profile fit well with the observed wings. The evolution

Table 4. Results of the Gaussian decomposition of the Na ID lines in the spectrum of 89 Her. The radial velocity is heliocentric.

No.	λD_2 [Å]	EW [Å]	$v_\odot$ [km/s]	λD_1 [Å]	EW [Å]	$v_\odot$ [km/s]	Spec.
1	5886.91	0.149	−156.0	5893.06	0.192	−146.5	s4
2	5887.43	0.301	−129.5	5893.54	0.217	−122.1	s4
	5887.43	0.406	−129.5	5893.60	0.387	−119.0	s3
	5887.58	0.508	−121.9	5893.56	0.368	−121.1	s2
3	5887.89	0.431	−106.1	5893.87	0.292	−105.3	s4
	5887.92	0.499	−104.5	5893.77	0.365	−110.4	s3
	5887.99	0.466	−101.0	5893.96	0.367	−100.7	s2
	5888.01	0.618	−100.0	5893.97	0.442	−100.2	s1
4	5889.25	0.317	−36.8	5895.22	0.207	−36.6	s4
	5889.25	0.336	−36.8	5895.22	0.270	−36.6	s3
	5889.27	0.271	−35.8	5895.28	0.262	−33.6	s2
	5889.21	0.360	−38.8	5895.19	0.296	−38.1	s1
5	5889.82	0.533	−7.8	5895.71	0.274	−11.7	s4
	5889.84	0.643	−6.8	5895.72	0.273	−11.2	s3
	5889.82	0.528	−7.6	5895.72	0.262	−6.4	s2
	5889.85	0.463	−6.3	5895.74	0.410	−10.1	s1

of the Hα profile in time is presented in Figure 2. The emission component and the reddest absorption components are quite stable, but the blue wing changes fast with time scale less than a month. Earlier Arellano-Ferro (1985) has not found so fast changes. In Table 3 the results of the Gaussian decomposition of the Hα line and the time evolution of the components are shown. The table also lists the heliocentric radial velocities of the components. As the mean stellar velocity is about –30 km s^{-1}, the outflow velocity could be as large as 130 km^{-1}. The Hα emission component is at the velocity of the star, –30 km s^{-1}.

The changes in the Na ID lines are shown in Figure 3. The Gaussian decomposition allows to separate five absorption components listed in Table 4. Three or four the bluest components could be formed in the same moving layers as the blue Hα components. No counterparts are present for component 5. This component shows no changes in intensity and radial velocity. Similar velocity for this component was reported by Kiss et al. (2003). Most probably this is an interstellar line. Its equivalent width is, however, about twice larger what is expected from a small reddening of 89 Her, $E_{B-V} = 0.1$, and the Munari & Zwitter (1996) calibration of the Na I interstellar line equivalent widths versus reddening. There is also a local emission component marked by black dot in Figure 3. The radial velocity of this component is -28.8 ± 0.3 km s^{-1} and not variable. This could be what is left from the P Cygni emission component masked by the interstellar line.

Numerous weak emission lines (more than 330) were identified. Some of them (24) were first noted by Sargent & Osmer (1969) and 10 additional lines were found by Climenhaga et al. (1987). We found, that all these lines arise from low excitation ($\varepsilon < 6$ eV) levels of neutral metals. The presence of ionic lines claimed by Climenhaga et al. (1987) was not confirmed. The heliocentric radial velocity from these lines for all four spectra is -28.37 ± 0.25 km s^{-1}, which is similar to the value found by Climenhaga et al. (1987), -27.94 ± 2.28 km s^{-1}, and is close to the mean velocity of the system, -28.71 ± 0.16 km s^{-1} (Waters et al. 1993). Part of the feature noted by black dot and explained above as a remnant of Na ID

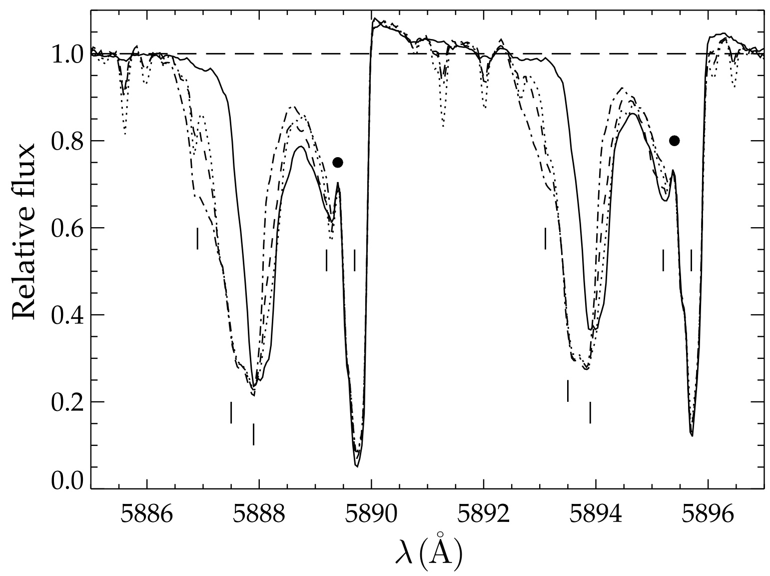

Fig. 3. The changes in the Na ID doublet. The positions of the components, derived by the Gaussian decomposition, are indicated by vertical ticks and listed in Table 4. Dots indicate the local emission peaks with constant wavelength and intensity.

photospheric emission could also be an emission originated in the same region as weak emission lines as their radial velocities nearly coincide.

As the used spectra were not flux calibrated, a crude calibration was performed using the Kurucz (1991) synthetic fluxes for metal-deficient models (6500/1.0) and (6750/1.0). Resulting emission line fluxes allowed us to find the excitation temperature $T_{\rm exc} = 4300 \pm 1000$ K from Ti I, V I, Fe I and Co I lines with the upper level excitation potential between $\varepsilon = 2.2 - -6.0$ eV. The error is large mainly due to difficulty in placing the continuum.

2.5. Luminosity

An important parameter for understanding the evolutionary status of a star is its luminosity. The early determinations M_V values for 89 Her are quite consistent. Searle et al. (1963) derived $M_V = -7.1 \pm 0.5$ from their spectroscopic analysis. This was confirmed by Osmer (1972) with $M_V = -6.6$ who used photoelectric equivalent widths of O I 777 nm triplet.

89 Her has been observed by *Hipparcos*. According to the new reduction of the observations (van Leeuwen 2007) its parallax is $\pi = 0.76 \pm 0.23$ mas. With its observed visual magnitude $V = 5.47$ and $E_{B-V} \approx 0.1$, the absolute magnitude is $M_V = -5.43$. Taking into account a possible error, this could be as large as –6.34.

Arellano Ferro et al. (2003), using a new calibration of $EW(\mathrm{OI}_{7774})$ in absolute magnitudes, for 89 Her have found $M_V = -7.375 \pm 0.38$. We measured the equivalent widths of O I triplet at 777 nm for all our spectra. The full integration including nonidentified minor blends gave $EW = 0.53$ Å for the 7772 Å line and $EW = 1.47$ Å for the full triplet. This correponds to $M_V = -6.41$ and $M_V = -6.78$, respectively, using the calibration of Arellano Ferro et al. (2003).

If the minor blends are excluded by Gaussian decomposition, the resulting luminosity becomes even lower, –5.5 and –6.0 respectively. Since we have used the spectra with the much higher resolution ($R = 65\,000$) than Arellano Ferro et al. (2003) ($R = 18\,000$), our case of full integration should correspond better to their calibration. In that case the absolute magnitude derived from the *Hipparcos* data, $M_V \approx -6.3$, and from the equivalent widths of O I 777 nm triplet, $M_V \approx -6.6$, are quite close. The bolometric correction corresponding to the temperature of 89 Her is $BC = -0.10$.

3. CONCLUSIONS

For 89 Her we do not confirm the very high luminosity, $M_V = -7.375 \pm 0.38$, found by Arellano Ferro et al. (2003). Their value is close to the maximum luminosity of AGB stars, $M_{\rm bol} = -7.1$. That limit is based on the maximum possible core mass of $1.4\,M_{\odot}$ before the core He ignition and the core mass versus luminosity relation of Paczyński (1970). Instead, we estimate $M_V \approx -6.5$ based on the *Hipparcos* parallax and the equivalent widths of O I 777 nm triplet. In the last case we used the calibration derived by Arellano Ferro et al. (2003).

We confirmed the earlier findings that in the atmospheres of F supergiants the microturbulent velocity increases with the height. This situation reveals itself by different values of microturbulent velocities found from the lines of neutral atoms and ions. Oddly enough, this was not found for 89 Her in the previous studies.

A scenario for the selective depletion of refractory elements in stellar atmospheres was proposed by Waters et al. (1992). The suggestion of dust-gas separation in circum-binary disk is now gaining more support with the increase of detected binaries among post-ABG stars (Giridhar & Arellano Ferro 2005). The essence of this idea is that a low mass accretion rate of gas and dust from a circum-system disk can lead to the selective accretion of only gas due to differential forces that act on the gas and the dust.

The rate of such depletion could be studied from the plots of elemental abundances versus their condensation temperature. In Figure 4 we plot the element abundances found for 89 Her versus their condensation temperatures taken from Lodders (2003). The size of the symbols is proportional to the logarithm of the number of the used spectral lines. One can see that iron indeed could be depleted but not very much (< 0.2 dex). Zincum is considered to be a volotile element due to its low condensation temperature. Even taking into account possible non-LTE effects zinc is slightly deficient, –0.3 dex. The deficiency of iron is only slightly larger indicating that 89 Her was metal-deficient already before any depletion by dust grains was acting. The s-process elements are clearly underabundant. If we compare the s-process abundances with the abundances of the elements with the same condensation temperature (Al, Ca, V), we see that the depletion of s-process elements is of the same order. This means that we find no evidence of the AGB nucleosynthesis and the third dredge-up in 89 Her.

The radial velocity of weak emission lines was found to be very close to the systemic velocity. There are no ionic and forbidden lines among the emission lines. Also, the excitation temperature of upper levels is rather low. This indicates that the medium, where these lines are forming, is rather dense and cool, and it moves toward the observer with the systemic velocity. All this we interpret as an indication that these lines are formed in the circum-binary disk which is an important constituent of the model proposed by Waters et al. (1993). As

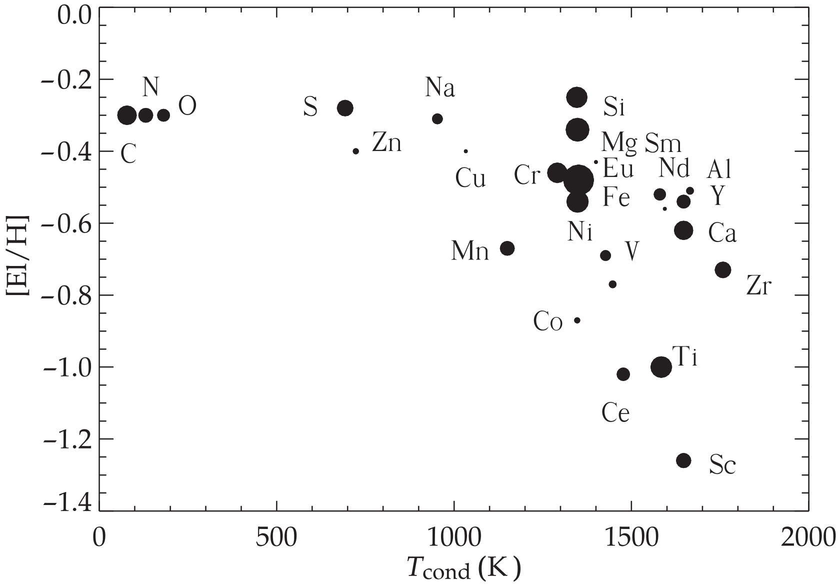

Fig. 4. The abundances of elements in 89 Her versus their condensation temperature. The symbol diameters are proportional to the logarithm of the number of spectral lines used ($\ln N_{\rm lines}$). Two elements, Nd and Eu are represented only by one line.

these weak emission lines are sharp and are not split, this indicates almost face-on orientation of the disk.

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