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About the chemical composition of δ Scuti: the prototype of the class of pulsating variables

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Abstract. We derived the chemical abundances in the photosphere of δ Scuti, the prototype of the class of pulsating variables, from the analysis of a spectrum obtained at the Terskol Observatory 2-m telescope with a resolution $R = 52000$ and $S/N = 250$. VLT and IUE spectra were also used. The abundance pattern of δ Sct consists of 49 chemical elements. The abundances of Be, P, Ge, Nb, Mo, Ru, Er, Tb, Dy, Tm, Yb, Lu, Hf, Ta, Os, Pt, and Th were not investigated previously. The lines of third spectra of Pr and Nd also are investigated for the first time. The abundances of heavy elements show overabundances with respect to the Sun up to 1 dex. The abundance pattern of δ Sct is similar to that of the Am-Fm stars.

Keywords. Stars: variables: δ Scuti, stars: abundances, stars: chemically peculiar, stars: individual: (δ Scuti)

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1. Introduction

The δ Scuti pulsating variables are located in the lower part of the instability strip. These stars are the second most numerous group of pulsators in the Galaxy after the pulsating white dwarfs (Solano & Fernley 1997). The recent catalog of Rodriges & Breger (2001) has information available up to January 2000 for about 636 stars of this type. The majority of δ Sct stars belong to Population I.

The chemical composition of δ Sct was investigated by Russell (1995) and by Rachkovskaya (2000). The most detailed abundance pattern was published by Erspamer & North (2003) who found the abundances of 30 elements. The goal of this paper is to derive the abundances of chemical elements in the atmosphere of δ Scuti.

Table 1. Observations

Telescope	Spectral range (Å)	Resolving power	S/N	JD	Exposure (sec)
Terskol 2-m	3610–10270	$R = 52000$	250	2452422.4734	1200
VLT 8-m	3860–4980	$R = 80000$	>300	2452008.4119	40
	6805–8540	$R = 80000$	>300	2452008.4119	40
	8662–9194	$R = 80000$	>300	2452008.4119	40
IUE 0.4-m	1850–3349	0.2 Å	20	2444788.1094	2099
	1850–3349	0.2 Å	20	2448115.1387	720
	1850–3349	0.2 Å	20	2448120.1593	720

2. Observations and data reduction

A high resolution spectrum of δ Sct was obtained using a coude-echelle spectrometer (Musaev *et al.* 1999) mounted on the 2-m "Zeiss" telescope at the Peak Terskol Observatory located near Mt. Elbrus (Northern Caucasus, Russia) 3124 m above sea level.

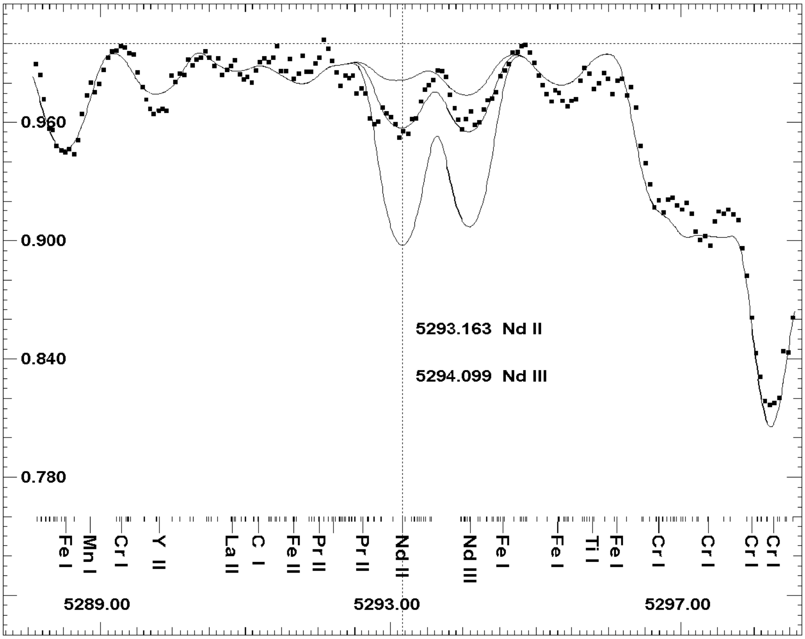

Figure 1. The observed spectrum of δ Sct (squares) and the synthetic spectra (solid lines) calculated with our final abundances. The axes are the wavelength in Å and relative fluxes. The positions of the spectral lines taken into account in the calculations are marked in the bottom part of the figure. For some of the strong lines identifications are given. The position of Nd II λ5293.163 is marked by a vertical dotted line. The different synthetic spectra correspond to Nd abundances lower or higher by 0.5 dex with respect to the optimum value. Nd II λ5293.163 and Nd III λ5294.099 are examples of the lines of the second and the third spectra of neodymium. Both lines can be fit with one value of the abundance.

We used the spectrograph in the resolving power $R = 52000$ mode. The observed wavelength range λ3610-λ10270 was covered by 86 echelle orders. In the observed spectrum, there are gaps between the orders in the wavelength region $\lambda \geqslant 6705$ Å and the width of each gap increases from 0.5 Å to 69 Å as the wavelength increases. The signal-to-noise reaches 250 or more in the red part of the spectrum.

Table 2. Atmospheric parameters of δ Sct

	$T_{\rm eff}$ (K)	log g	$v \sin i$	$v_{\rm micro}$ (km s^{-1})
Philip & Relyea (1979)	7300			
Moon & Dvoretsky (1985)	7200			
Lester *et al.* (1986)	7100			
	7000			
Balona (1994)	7267			
Russell (1995)	7200	3.71	39	2.5
Solano & Fernley (1997)	7000		30.1	
	6900			
Rachkovskaya (2000)	7000	3.1	32	5.4
			30	
Erspamer & North (2003)	6776	3.47	25.51	2.8
Geneva system	6772	3.45		
Iron lines depth ratios	7064			
Adopted values	7000	3.5	25.5	3.8

The first-stage data processing (background subtraction, echelle vector extraction from the echelle-images, and wavelength calibration) was performed using the latest version of the PC-based DECH software (Galazutdinov 1992). For other processes including the continuum placement, we used the URAN software (Yushchenko 1998). The continuum was determined taking into account the calculated spectrum.

The strongest lines of many chemical elements can be observed in the ultraviolet spectral region. To detect these lines we used three IUE spectra of δ Sct from the INES archive, LWR10992HL, LWP18563HL, and LWP18600HL. The wavelength coverage of these spectra is from λ1850 to λ3349 with a spectral resolution is about 0.2 Å. The signal to noise ratio is sufficient for line identification and in some cases for deriving abundances with errors near 0.2-0.3 dex.

Spectra of δ Sct from the VLT archive were also used. The spectral resolving power is 80000, the S/N ratio more than 300, wavelength coverage $\lambda 3860 - \lambda 4980$ and $\lambda 8661 - \lambda 9194$.

Information about all our spectra is in Table 1. For abundance determinations the spectrum of the Terskol Observatory and the IUE spectra were used. The VLT spectrum was used for identification of faint lines.

3. Atmospheric parameters

The information about previous determinations of effective temperature, surface gravity, rotation and microturbulence of δ Sct can be found in Table 2. We tried to find our own values of the atmospheric parameters. Those obtained from Geneva photometry and from the depth ratios of the iron lines, based on the Kovtyukh & Gorlova (2000) method, are listed at the end of this table.

We adopted $T_{\rm eff}$= 7000 K and log $g = 3.5$. These parameters, Erspamer & North (2003) abundances and the values of the microturbulence and rotation velocities were used for the initial calculation of the synthetic spectrum in the entire observed region. It was used for the identification of clean iron lines. For these lines equivalent widths were found and the values of the parameters were tested. It was necessary to change the microturbulence velocity to the value $v_{\rm micro}$= 3.8 km s^{-1}. These parameters and the Erspamer & North (2003) abundances were used to produce a atmosphere model using the Kurucz (1995) ATLAS12 code. The dependancies of iron abundances on the equivalent widths and on

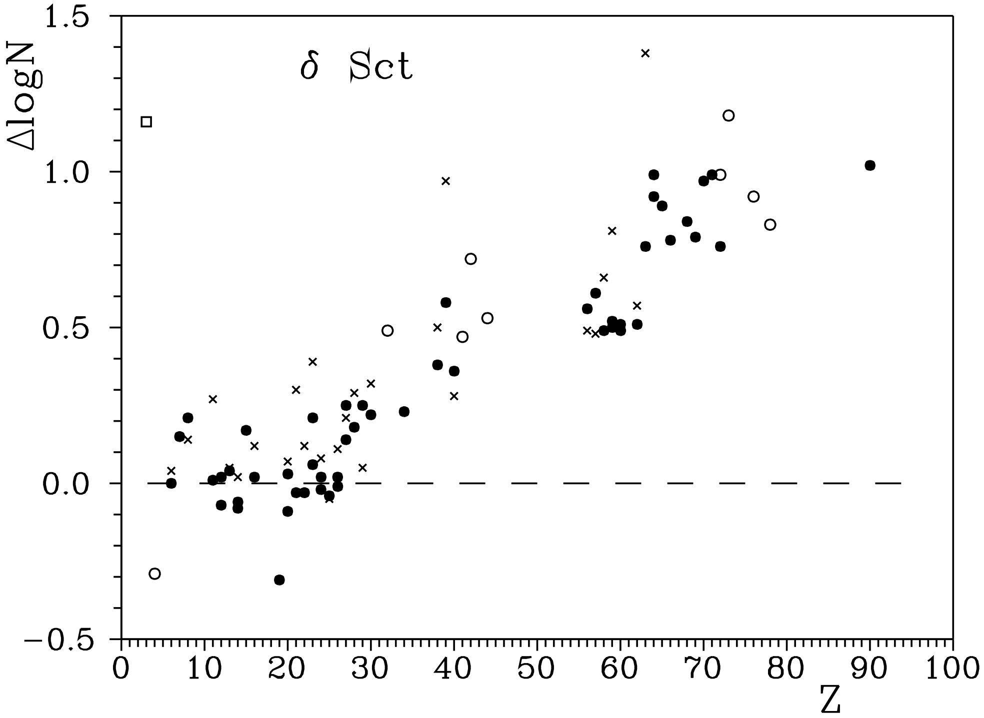

Figure 2. The abundances of chemical elements and ions in the atmosphere of δ Sct with respect to their abundances in the solar atmosphere. Filled circles – Terskol Observatory observations. Open circles – IUE data. Crosses – Erspamer & North (2003). Open square – lithium (Russell 1995)

the excitation levels of individual lines in the spectrum of δ Sct for our model show no correlation. This model was used for our abundance calculations.

4. Methods

The differential spectrum synthesis method is used for all elements, except iron. For each line, we tried to find its counterpart in the solar spectrum atlas of Delbouille *et al.* (1973). The Grevesse & Sauval (1999) solar photosphere model was used. This procedure frees us from uncertainties connected with the oscillator strengths of spectral lines. The URAN code (Yushchenko 1998) and the SYNTHE spectrum synthesis program (Kurucz 1995) are used to approximate the observed spectrum by the synthetic one.

A synthetic spectrum of δ Sct for the whole wavelength range helps us to identify spectral lines. It includes atomic and molecular lines from Kurucz (1995), Morton (2000), Biemont et al. (2002), and the VALD database (Piskunov *et al.* 1995). Hyperfine structure and isotopic splitting are taken into account for Sc, V, Mn, Cu, Ba, and Eu. The splitting data for Ba are taken from Francois (1996) and for the other elements from Kurucz (1995). For all elements except Li, S, K, Ir, Th, and U we found counterparts in the solar spectrum, so that the differential abundances are not strongly influenced by splitting effects. Holweger's partition function for thorium is used (Morell *et al.* 1992).

Table 3. Mean abundance of chemical elements in the atmosphere of δ Sct from IUE observations.

Z	Ident.	n	$*$–GS98	log N
4	Be II	2	-0.29(11)	1.06(11)
32	Ge I	2	0.49(03)	3.90(03)
41	Nb II	2	0.47(00)	1.89(00)
42	Mo II	4	0.72(24)	2.64(24)
44	Ru II	1	0.53	2.37
72	Hf II	2	0.99(01)	1.87(01)
73	Ta II	1	1.18	1.05
76	Os II	2	0.92(03)	2.37(03)
78	Pt I	1	0.83	2.63

5. The abundance pattern of δ Scuti

In Tables 3 and 4 the mean elemental abundances in the atmosphere of δ Sct are given. This tables contains data, obtained from the spectra of the IUE and the Terskol Observatory respectively. Table 3 contains the results from the IUE spectra. Only absolute abundances and relative values with respect to Grevesse & Sauval (1998) are shown in this table. Fig. 2 illustrates the relative abundances in the atmosphere of δ Sct .

The difference in temperature between δ Sct and the Sun is quite large and we were not able to find the counterparts in the solar spectrum for all investigated lines. That is why in Table 4 we give both relative and absolute abundances of the chemical elements in the atmosphere of δ Scuti. The first two columns are the atomic number and identification of investigated species. The next two are the number of lines with counterparts in the solar spectrum and the relative abundance, obtained from these lines, with the last figures of errors in brackets. The fifth column is the total number of lines of given element or ion. Two subsequent triplets of colunms are the mean abundances in the atmosphere of δ Sct for three sets or atmospheric parameters: the best values, and effective temperature and surface gravity shifted by -0.2 dex and +100 K respectively. There are absolute values of abundances in the second triplet and relative, with respect to Grevesse & Sauval (1998), in the first.

The analysis of the tables shows the relative abundances calculated with respect to the absolute solar photosphere abundances are very close to the direct differential abundances.

6. Conclusions

- The abundance pattern of δ Sct consists of 49 chemical elements. The lines of eight of them are found only in the ultraviolet spectrum.
- The abundances of Be, P, Ge, Nb, Mo, Ru, Er, Tb, Dy, Tm, Yb, Lu, Hf, Ta, Os, Pt, and Th were not investigated previously.
- The lines of the third spectra of Pr and Nd are observed. The values of abundances of these elements obtained from the lines of second and third spectra are equal.
- The abundances of heavy elements shows the overabundances with respect to the Sun up to 1 dex.
- The abundance pattern of δ Sct is similar to that of Am-Fm stars.

Table 4. Mean abundance of chemical elements in the atmosphere of δ Sct from Terskol Observatory observations.

		ΔlogN$_{\delta\ Sct-\odot}$		ΔlogN$_{\delta\ Sct-GS98}$				logN$_{\delta\ Sct}$		
Z	Ident.	n	$*-\odot$	n	$*$–GS98	log g-0.2	$T_{\rm eff}$+100	logN	log g-0.2	$T_{\rm eff}$+100
6	C I	7	0.00(06)	14	0.00(12)	-0.02(09)	0.01(09)	8.52(12)	8.50(09)	8.53(09)
7	N I	3	0.04(11)	4	0.15(06)	0.04(11)	0.02(11)	8.07(06)	7.96(11)	7.94(11)
8	O I	4	0.23(18)	5	0.21(17)	0.15(17)	0.17(17)	9.04(17)	8.98(17)	9.00(17)
11	Na I	3	0.07(12)	6	0.01(02)	0.04(07)	0.04(15)	6.34(02)	6.37(07)	6.37(15)
12	Mg I	2	-0.04(15)	8	-0.07(10)	-0.05(12)	-0.03(11)	7.51(10)	7.53(12)	7.55(11)
	Mg II	2	0.03(01)	2	0.02(00)	-0.01(01)	0.00(02)	7.60(00)	7.57(01)	7.58(02)
13	Al I	3	0.14(02)	3	0.04(03)	0.17(01)	0.17(03)	6.51(03)	6.64(01)	6.64(03)
14	Si I	14	0.04(10)	16	-0.08(19)	0.05(09)	0.07(09)	7.47(19)	7.60(09)	7.62(09)
	Si II	2	0.08(06)	3	-0.06(08)	-0.04(09)	-0.01(09)	7.49(08)	7.51(09)	7.54(09)
16	S I	6	0.15(08)	7	0.02(10)	0.15(08)	0.17(07)	7.35(10)	7.48(08)	7.50(07)
19	K I			1	-0.32	-0.30	-0.28	4.80	4.82	4.84
20	Ca I	20	-0.19(12)	22	-0.09(11)	-0.17(11)	-0.14(11)	6.27(11)	6.19(11)	6.22(11)
	Ca II	2	-0.04(07)	3	0.03(00)	0.02(10)	0.01(09)	6.39(00)	6.38(10)	6.37(09)
21	Sc II	10	0.09(07)	10	-0.03(12)	0.03(08)	0.11(08)	3.14(12)	3.20(08)	3.28(08)
22	Ti II	34	0.06(07)	38	-0.03(09)	0.00(09)	0.07(09)	4.99(09)	5.02(09)	5.09(09)
23	V I	3	0.15(03)	3	0.06(02)	0.16(06)	0.15(05)	4.06(02)	4.16(06)	4.15(05)
	V II	5	0.23(12)	5	0.21(14)	0.14(16)	0.26(11)	4.21(14)	4.14(16)	4.26(11)
24	Cr I	22	0.04(06)	22	-0.02(10)	0.04(05)	0.08(06)	5.65(10)	5.71(05)	5.75(06)
	Cr II	23	0.07(09)	26	0.02(10)	0.03(10)	0.08(09)	5.69(10)	5.70(10)	5.75(09)
25	Mn I	13	0.09(06)	14	-0.04(10)	0.09(08)	0.12(05)	5.35(10)	5.48(08)	5.51(05)
26	Fe I			127	0.02(10)	0.03(08)	0.07(05)	7.52(10)	7.53(10)	7.57(10)
	Fe II			31	-0.01(11)	-0.07(11)	-0.01(12)	7.49(11)	7.43(11)	7.49(12)
27	Co I	2	0.27(04)	3	0.14(06)	0.24(08)	0.28(07)	5.06(06)	5.16(08)	5.20(07)
	Co II			1	0.25	0.24	0.24	5.17	5.16	5.16
28	Ni I	51	0.21(08)	51	0.18(09)	0.20(08)	0.25(09)	6.43(09)	6.45(08)	6.50(09)
29	Cu I	2	0.25(02)	2	0.25(07)	0.27(03)	0.32(01)	4.46(07)	4.48(03)	4.53(01)
30	Zn I	4	0.35(13)	4	0.22(15)	0.36(13)	0.36(15)	4.82(15)	4.96(13)	4.96(15)
34	Se I	1	0.35	1	0.23	0.34	0.39	3.64	3.75	3.80
38	Sr II			2	0.38(10)	0.33(10)	0.45(04)	3.35(10)	3.30(10)	3.42(04)
39	Y II	14	0.66(11)	15	0.58(13)	0.61(13)	0.69(14)	2.82(13)	2.85(13)	2.93(14)
40	Zr II	4	0.37(12)	5	0.36(20)	0.33(18)	0.24(15)	2.96(20)	2.93(18)	2.84(15)
56	Ba II	2	0.71(14)	3	0.56(24)	0.53(20)	0.49(08)	2.69(24)	2.66(20)	2.62(08)
57	La II	11	0.67(14)	18	0.61(12)	0.61(10)	0.64(12)	1.78(12)	1.78(10)	1.81(12)
58	Ce II	20	0.52(08)	31	0.49(05)	0.50(10)	0.56(11)	2.07(05)	2.08(10)	2.14(11)
59	Pr II	2	0.61(00)	6	0.52(04)	0.55(05)	0.63(10)	1.23(04)	1.26(05)	1.34(10)
	Pr III			2	0.50(02)	0.50(02)	0.55(07)	1.21(02)	1.21(02)	1.26(07)
60	Nd II	15	0.62(10)	32	0.51(11)	0.53(10)	0.58(13)	2.01(11)	2.03(10)	2.08(13)
	Nd III			3	0.49(02)	0.50(06)	0.49(02)	1.99(02)	2.00(06)	1.99(02)
62	Sm II	1	0.68	8	0.51(04)	0.51(12)	0.55(11)	1.52(04)	1.52(12)	1.56(11)
63	Eu II	2	0.83(00)	4	0.76(11)	0.71(09)	0.81(07)	1.27(11)	1.22(09)	1.32(07)
64	Gd II	1	0.84	8	0.97(05)	0.89(11)	0.93(11)	2.09(05)	2.01(11)	2.05(11)
65	Tb II			1	0.89	0.81	0.89	0.79	0.70	0.79
66	Dy II	2	0.78(05)	7	0.78(18)	0.84(10)	0.87(11)	1.92(18)	1.98(10)	2.01(11)
68	Er II	1	1.03	8	0.84(16)	0.89(18)	0.93(18)	1.77(16)	1.82(18)	1.86(18)
69	Tm II	1	0.89	1	0.79	0.91	0.93	0.79	0.91	0.93
70	Yb II			1	0.97	0.97	0.97	2.05	2.05	2.05
71	Lu II			1	0.99	0.96	1.06	1.05	1.02	1.12
72	Hf II			1	0.76	0.43	0.50	1.64	1.31	1.38
90	Th II			1	1.02	1.02	1.04	1.11	1.11	1.13

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