FUNDAMENTAL PARAMETERS AND CHEMICAL COMPOSITION OF CEPHEID X SGR.

I.A. Usenko[1], A.Yu. Knyazev[2], L.N. Berdnikov[3], V.V. Kravtsov[3,4]

[1] Department of Astronomy of I.I. Mechnikov Odessa National University T.G.Shevchenko Park, Odessa 65014 Ukraine, *igus99@ukr.net*

[2] South African Large Telescope, P.O. Box 9, Observatory, Cape Town, 7935 South Africa, *aknyazev@saao.ac.za*

[3] Sternberg Astronomical Institute, Moscow University, Moscow, 119899 Russia *lberdnikov@yandex.ru*

[4] Universidad Católica del Norte, Avenida Angamos 0610, Autofagasta, Chile *vkravtsov@ucn.cl*

ABSTRACT. Five high-resolutioned spectra of unusual Cepheid X Sgr have been obtained during its pulsational period. For the first time we obtain accurate fundamental parameters and abundances of chemical elements, in particular of sodium, magnesium and aluminium. We estimate the mean $T_{\rm eff} = 6143 \pm 30$ K; $\log g = 2.00$; $V_t = 4.35$ km s^{-1} . The estimated effective temperature and surface gravity are relatively high compared to the typical values characteristic of Cepheids with pulsational period around 7 days. A deficit of carbon ([C/H] = -0.26±0.04 dex), overabundances of sodium ([Na/H] =+0.31±0.04 dex) and aluminium ([Al/H] = +0.21±0.08 dex) are typical for Cepheids passing through the first dredge-up phase. However, an obvious overabundance of magnesium ([Mg/H] = +0.19±0.04 dex) is unusual. The abundance of iron ([Fe/H] = -0.02±0.01 dex) is very close to the solar one. Abundances of α - elements, (those of Fe-group, as well as "light " and "heavy", s- and r-process elements) are comparable to the solar values, except for several elements showing slight over- or underabundances.

1. Introduction

X Sgr is one of the most famous objects among Cepheid variables. Being 7-days pulsational period's variable, the longest for so called "bump" Cepheids, it demonstrates an unusual character of its absorptional lines: they have splitting character, showing additional blue- or red- shifted absorption features in the line profiles (Sasselov & Lester, 1990). Moreover, these ones show remarkable changes during the pulsational period (see, for example, Figure 1 from Mathias et al., 2006). At that this fact concern only strong low-excitational lines, but the absence of phase lag between weak metal lines forming low in the atmosphere and H_α (which is formed higher) is obvious (Mathias et al., 2006). Kovtyukh et al. (2003) and Mathias et al. (2006) attempted to explain the strange behaviour of X Sgr line profiles. The former group of authors interprets this fact as the combined effect of strong line broadening (rotation and macro-turbulence) and non-radial oscillation, excited through resonances. Mathias et al. (2006) in turn suggest either the shock waves propagation per pulsation period as a result of κ - mechanism acting in the star or a binary nature of the star as a possible cause of unusual behaviour of spectral lines. Nevertheless, the evolutionary status of X Sgr still remain uncertain. Despite the fact that the star is quite bright ($< V > = 4.^m6$), its fundamental parameters and chemical composition are poorly studied. Indeed, two CCD spectra in red region 5380 - 8710 Åand two photographic plate spectra in blue region 4300 - 4600 Åwere obtained and analyzed by Luck & Lambert (1981) and Giridhar (1983), respectively. Luck & Lambert (1981) obtained their spectra near the minimum ($\phi = 0.47$) and maximum ($\phi = 0.06$) of light, whereas the spectra gathered by Giridhar (1983) correspond to the descending branch ($\phi = 0.258$ and 0.394, respectively). In addition, the number of elements with determined abundances did not exceed thirteen items. The ultimate goal of this study is to determine precise fundamental parameters and chemical composition using of X Sgr using five newly-obtained, high-resolution spectra, gathered at different phases of its pulsational cycle.

2. Observations and data reduction

The observations have been carried out in August 2011 with GIRAFFE (Grating Instrument for Radiation Analysis with a Fibre Fed Echelle) spectrograph mounted at the Coudé focus of the 1.9m telescope at the South African Astronomical Observatory (SAAO), South Africa. Five spectra of this Cepheid have been obtained during weekly observational set. Information about X Sgr spectroscopic observations and heliocentric radial velocity measurements is given in Table 1. Phases were calculated according to the ephemeris published by Berdnikov & Caldwell (2001):

$$HJD_{max} = 2451653.5600 + 7.01281E \qquad (1)$$

Table 1: Observations of X Sgr and radial velocities measurements.

Spectrum	HJD 2450000+	Phase	Exp. (min.)	RV ($\mathrm{km\,s^{-1}}$)	σ ($\mathrm{km\,s^{-1}}$)
1080044	5784.4374	0.047	40	−26.12	0.22
1080107	5785.3798	0.182	40	−19.42	0.20
1080198	5788.4230	0.616	20	−3.45	0.18
1080243	5789.4562	0.763	19	+1.26	0.21
1080284	5790.4428	0.904	44	−21.60	0.29

GIRAFFE allows to obtain high-resolution CCD echelle spectra (R = 39 000) due to two dispersional prisms optimized for the blue (3770-5560 Å) and red (5200-10400 Å) spectral ranges. For our observations we used the red prism and a fiber with a projection diameter of 2". The detector was a 1024 × 1024 pixel TEK6 CCD camera. The total recorded spectral range (4300-6750 Å) containes 48 spectral orders.

At the beginning of each night and before each exposure, we observed the spectra of a hollow-cathode (Th+Ar) lamp, which allowed us to take into account all temperature trends by cross-correlating the 2D images of comparison spectra during the reduction. On each night, we also observed CAMERA FLATS to correct the pixel sensitivity and FIBER FLATS to find the position of spectral orders and to applay a correction for the spectral sensitivity effect along each order (blaze correction).

The data have been reduced using the stsndard XSPEC2 software (Balona, 1999). The procedure included: (1) background substraction; (2) search for and extraction of the 1D fragments corresponding to individual orders from the 2D images; (3) blaze correction; (4) construction of the dispersion curves from hollow-cathode lamp spectra; (5) wavelength calibration; (6) applying the heliocentric correction; (7) determination of the radial velocity by means of the cross-correlation technique.

Phase-folded radial velocity (RV) curve approximated by the cubic spline is represented in Figure 1.

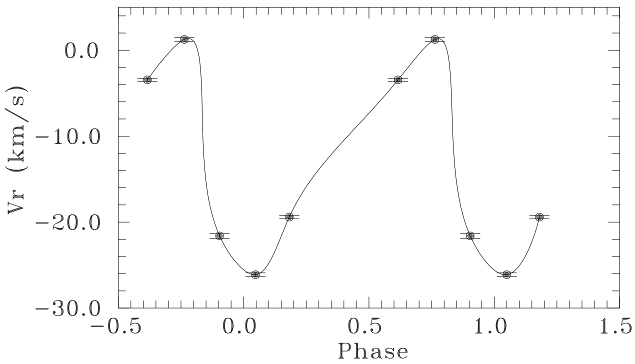

Figure 1: Radial velocity curve of X Sgr folded with the dominant pulsational period of 7.01281 days, approximated by the cubic spline.

We used the DECH 20 software package (Galazutdinov, 1992) to normalise the individual spectra to the local continuum, to identify the lines of different chemical elements and to measure the equivalent widths (EWs) of the individual spectral lines.

2. Fundamental parameters and chemical composition

For each spectrum we have obtained a set of fundamental parametrs and individual elemental abundances. Effective temperatures has been evaluated using spectroscopic criteria based on the deph ratios for selected pair of spectral lines most sensitive to the temperature changes (Kovtyukh & Gorlova, 2000). This method provides an internal accuracy in determining $T_{\rm eff}$ of ∼ 10-30 K. Surface gravity has been derived using the ionization equilibrium condition for Fe I and Fe II atoms with an accuracy of ∼ 0.15 dex. Microturbulent velocity V_t , has been deduced (with an accuracy of 0.25 $\mathrm{km\,s^{-1}}$) following the standard procedure assuming that the abundance of ionized iron Fe II determined from a set of lines should be independent of their equivalent widths (Kovtyukh & Andrievsky, 1999).

The results are summarised in Table 2.

Table 2: Atmosphere parameters of X Sgr

Spectrum	Phase	$T_{\rm eff}$ (K)	log g	V_t ($\mathrm{km\,s^{-1}}$)
1080044	0.047	6367±10	2.10	4.30
1080107	0.182	6223±28	2.00	4.50
1080198	0.616	5791±25	1.90	4.30
1080243	0.763	5900±50	2.00	4.40
1080284	0.904	6435±38	2.10	4.30
Mean		6143±30	2.00	4.35

Figure 2 shows the variations of the effective temperature in dependence of the pulsational phase.

Table 3: Elemental abundance for X Sgr spectra

Element	1080044			1080107			1080198			1080243			1080284		
	[El/H]	σ	NL	[El/H]	σ	NL	[El/H]	σ	NL	[El/H]	σ	NL	[El/H]	σ	NL
C I	-0.29	0.21	6	-0.10	0.13	8	-0.41	0.23	8	-0.29	0.33	6	-0.29	0.21	9
O I	+0.35	0.00	1	+0.04	0.36	3	+0.11	0.17	2	+0.16	0.04	2	+0.23	0.06	2
Na I	+0.22	0.22	2	+0.34	0.19	6	+0.22	0.12	5	+0.42	0.32	6	+0.38	0.13	5
Mg I	+0.24	0.04	3	+0.07	0.19	5	+0.09	0.35	3	+0.25	0.20	4	+0.18	0.14	3
Al I	-0.16	0.04	2	+0.29	0.19	2	+0.20	0.14	2	+0.45	0.15	2	+0.27	0.07	2
Si I	+0.06	0.19	15	+0.21	0.14	11	+0.04	0.11	11	+0.02	0.14	12	-0.05	0.17	8
Si II	-	-	-	+0.43	0.00	1	+0.20	0.00	1	-0.43	0.00	1	-0.34	0.00	1
S I	-0.09	0.11	2	+0.28	0.32	3	+0.17	0.25	3	+0.03	0.22	4	+0.10	0.34	4
Ca I	-0.18	0.20	11	-0.15	0.09	10	+0.02	0.22	19	-0.01	0.08	7	-0.01	0.21	15
Sc II	-0.07	0.26	5	-0.18	0.12	5	-0.17	0.26	4	-0.06	0.26	3	-0.05	0.17	10
Ti I	+0.01	0.22	32	+0.03	0.27	28	+0.13	0.24	31	+0.05	0.26	23	+0.18	0.25	16
Ti II	-0.15	0.13	9	+0.16	0.19	7	-0.01	0.13	5	+0.01	0.07	4	-0.10	0.14	7
V I	+0.33	0.26	10	+0.30	0.24	9	+0.09	0.22	8	+0.26	0.14	6	+0.25	0.22	8
V II	-0.20	0.28	4	-0.11	0.00	1	+0.05	0.42	3	+0.01	0.23	3	-0.04	0.17	4
Cr I	-0.11	0.30	25	+0.20	0.23	33	+0.03	0.25	25	+0.06	0.24	25	+0.16	0.20	16
Cr II	+0.07	0.22	8	-0.10	0.19	8	-0.13	0.19	7	-0.07	0.22	7	-0.07	0.23	6
Mn I	-0.13	0.17	9	+0.04	0.21	9	-0.12	0.21	11	+0.00	0.31	7	-0.08	0.21	7
Fe I	-0.03	0.17	111	-0.03	0.18	94	-0.02	0.16	94	-0.01	0.17	82	+0.00	0.16	70
Fe II	-0.03	0.15	26	-0.03	0.19	26	-0.02	0.18	28	-0.02	0.13	29	+0.00	0.14	21
Co I	-0.00	0.23	16	+0.10	0.19	15	-0.15	0.23	12	+0.13	0.57	12	+0.23	0.23	7
Ni I	-0.23	0.20	53	-0.03	0.21	46	-0.10	0.21	38	+0.00	0.20	36	+0.03	0.21	29
Cu I	+0.16	0.23	2	+0.11	0.40	3	+0.03	0.00	1	+0.43	0.00	2	+0.32	0.23	3
Zn I	-0.24	0.43	3	-0.39	0.19	2	-0.40	0.12	2	-0.06	0.50	2	-0.36	0.08	3
Sr I	-	-	-	-	-	-	-0.08	0.00	1	-	-	-	-	-	-
Y II	+0.04	0.23	6	+0.07	0.27	7	-0.08	0.14	4	+0.09	0.40	6	-0.04	0.32	5
Zr II	+0.15	0.54	3	-0.03	0.31	6	-0.03	0.36	4	-0.17	0.26	4	+0.23	0.23	6
Ru I	+0.04	0.00	1	+0.11	0.00	1	-	-		-	-	-	-	-	-
La II	+0.15	0.21	3	+0.17	0.34	3	+0.22	0.23	3	+0.15	0.19	5	+0.30	0.27	7
Ce II	+0.00	0.23	9	-0.05	0.16	5	-	-	-	-0.11	0.26	7	-0.01	0.09	6
Pr II	-0.35	0.03	3	-0.05	0.24	2	+0.01	0.04	2	+0.06	0.44	2	+0.24	0.09	2
Nd II	-0.16	0.18	10	-0.26	0.31	7	-0.08	0.26	10	+0.05	0.25	8	-0.00	0.30	8
Sm II	-0.05	0.23	2	-0.03	0.00	1	+0.09	0.12	3	-0.10	0.39	2	-0.06	0.28	3
Eu II	+0.10	0.33	2	+0.11	0.17	2	+0.26	0.07	2	-0.05	0.00	1	+0.11	0.05	2
Gd II	-0.53	0.00	1	+0.24	0.00	1	+0.05	0.00	1	-0.34	0.00	1	-0.23	0.00	1

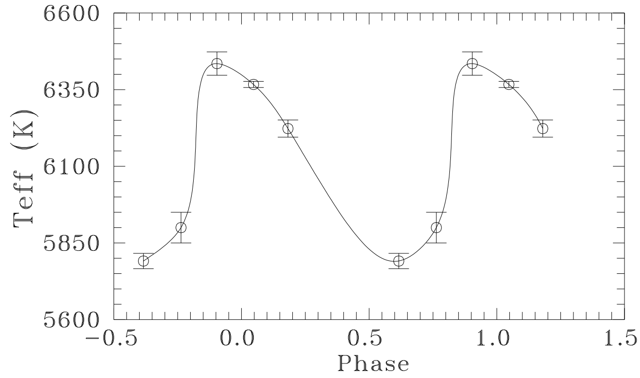

Figure 2: The effective temperature variations of X Sgr during its pulsational period, approximated by the cubic spline.

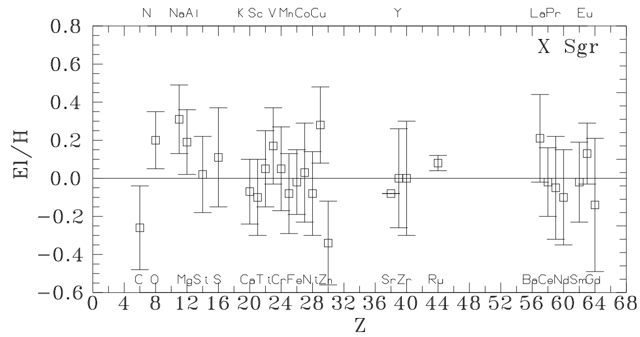

Figure 3: Average elemental abundances obtained for X Sgr using our observations.

Because of the pronounced splitting and variation of the absorption lines of X Sgr, we cannot use the Gaussian approximation to measure the equivalent widths of the lines assigned for the analysis. Therefore we used the equivalent widths obtained by forth integration only, except for the individual lines of "key elements" of yellow supergiant evolution (C, O, Na, Mg, Al), - in this case the relation between the line depths and equivalent widths have been applied.

All the atmosphere models and chemical composition for each spectrum were calculated using the version of the WIDTH9 code on the basis of the interpolation of Kurucz (1992) models grid with the "solar" log gf values, adopted from Kovtyukh & Andrievsky (1999). The data on the elemental abundances derived from individual spectra of X Sgr are given in Table 3 whereas Table 4 lists the average ones in comparison with the Luck & Lambert (1981) and Giridhar (1983) data. The least reliable estimates of the elemental abundances resulting from the analysis of a single spectral line are given in the parentheses in Table 3. Figure 3 gives a graphical representation of the data listed in Table 4.

Table 4: Average elemental abundances for X Sgr

Element	This work			Other authors	
	[El/H]	σ	NL	L&L[1]	SG[2]
C I	-0.26	0.22	37	-0.15	-
O I	+0.20	0.15	10	+0.07	-
Na I	+0.31	0.18	24	-	-
Mg I	+0.19	0.17	18	-	-
Al I	+0.21	0.23	10	-	-
Si I	+0.06	0.16	57	+0.07	-
Si II	-0.04	0.42	4	-	-
S I	+0.11	0.26	16	-	-
Ca I	-0.07	0.17	62	+0.24	-0.20
Sc II	-0.10	0.20	27	-0.13	-
Ti I	+0.08	0.24	130	-0.03	+0.13
Ti II	-0.05	0.15	32	-	+0.13
V I	+0.26	0.22	41	+0.37	-
V II	-0.06	0.26	15	-	-
Cr I	+0.09	0.25	124	+0.33	+0.20
Cr II	-0.07	0.19	36	-	+0.20
Mn I	-0.08	0.21	36	-	-
Fe I	-0.02	0.17	451	+0.02	+0.07
Fe II	-0.02	0.16	130	+0.01	+0.07
Co I	+0.03	0.26	61	+0.09	-
Ni I	-0.08	0.22	202	+0.09	-
Cu I	+0.28	0.20	11	-	-
Zn I	-0.34	0.22	12	-	-
Sr I	-0.08	-	1	-	-
Y II	+0.00	0.26	28	-	-
Zr II	+0.00	0.30	23	-	-
Ru I	+0.08	0.04	2	-	-
La II	+0.21	0.23	21	+0.32	-
Ce II	-0.02	0.18	27	-	-0.20
Pr II	-0.05	0.27	11	-	-
Nd II	-0.10	0.25	43	-	-
Sm II	-0.02	0.21	11	-	-0.20
Eu II	+0.13	0.16	9	-	-
Gd II	-0.14	0.35	4	-	-

NL - number of lines

[1] - Luck & Lambert (1981)

[2] - Giridhar (1983)

4. Conclusions

As seen from Table 2, the mean value of the effective temperature 6143±30 K, is in good agreement with 6125 K and close to 6100 K deduced by Luck & Lumbert (1981) and Giridhar (1983), respectively. Our surface gravity value of 2.00 formally coincides with Giridhar's estimates (2.00) and is in agreement within the error bars with the value (1.90) reported by Luck & Lambert (1981). ones, but the Microturbulent velocity of 4.35 $\mathrm{km\,s^{-1}}$ agrees within the error of measurement with the value of 4.25 $\mathrm{km\,s^{-1}}$ given by Giridhar (1983) and is considerably higher than the value of 3.00 $\mathrm{km\,s^{-1}}$ obtained by Luck & Lambert (1981). Kovtyukh et al. (2003) have noted the fact that X Sgr like another three Cepheids, suspected to have non-radial pulsations (V1334 Cyg, EV Sct and BG Cru), has rather high $T_{\rm eff}$, - above 6000 K. In turn we would note the relatively high value of surface gravity for a classical Cepheid with pulsational period near 7 days.

With respect to the elemental abundances obtained in the present study, we would like to summarize the following points:

1. The iron abundance is very close to solar one, and is in good agreement with the results published by Luck & Lambert (1981). Giridhar (1983) has obtained higher value of +0.07 dex.

2. Carbon is found to be underabundant in agreement with the findings by Luck & Lambert (1981). The obtained oxygen abundance is unfortunately unreliable due to the line blending.

3. We estimated for the first time the abundances of the "key elements" of yellow supergiants evolution. All three elements Na, Mg and Al are found to be enhanced in the atmosphere of the star. The overabundance of magnesium is very unusual, taking into account that the most Cepheids and nonvariable supergiants demonstrate its deficit as a result of MgAl process after first dredge-up.

4. α - elements abundances are close to the solar ones.

5. The same can be noted for the elements of Fe-group, as well as for "light " and "heavy" - s-process and r-process elements: their abundances demonstrate either slight enrichment or deficit with respect to the solar values. The abundances of the majority of these elements were obtained for the first time for this star.

The obtained in this study results suggest that X Sgr is probably a Cepheid after first dredge-up phase. Indeed it shows deficit of carbon, overabundance of nitrogen ([N/H] = +0.6 dex according Luck & Lambert (1981)), sodium and aluminium. At the same time the unusual overabundance of magnesium is in disagreement, however.

References

Balona L.A.: 1999, *Internal SAAO Report* SAAO, CapeTown, **1**.

Berdnikov L.N., & Caldwell, J.A.R., 2001, *J. Astron. Data*, **7**.

Galazutdinov G.A.: 1992, *Preprint SAO RAS*, **92**.

Giridhar S.: 1983, *J. Astroph.*, **4**, 107.

Kovtyukh V.V., Andrievsky, S.M.: 1999, *A&A*, **351**, 597.

Kovtyukh V.V., Gorlova N.I.: 2000, *A&A* **358**, 587.

Kovtyukh V.V., Andrievsky S.M., Luck R.E., Gorlova N.I.: 2003, *A&A*, **401**, 661.

Kurucz R.: 1992, *In: The Stellar Populations of Galaxies, (eds) B.Barbuy and A.Renzini, IAU Symp.*, **149**, 225.

Luck R.E., Lambert D.L.: 1981, *ApJ*, **245**, 1018.

Mathias P., Gillet D., Fokin A.B., Nardetto N., Kervella P., Mourad D.: 2006, *A&A*, **457**, 575.

Sasselov D.D., Lester J.B.: 1990, *ApJ*, **362**, 333.