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Letter to the Editor

The Chemical Composition of Sakurai's Object

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Abstract. The atmospheric parameters and elemental abundances have been derived for Sakurai's object. The atmosphere of the star was found to be H deficient with enhanced carbon and s–process abundances. The effective temperature is $T_{\rm eff}$ = 7250 K, logarithmic gravity, log g = 1.0, and the microturbulent velocity, $\xi_{\rm t}$ = 7 $\pm$ 1 km s^{-1}. These abundances and atmospheric parameters are close to the majority of cool R CrB stars.

The chemical composition, fast brightening from the preoutburst state and the presence of PN indicates that Sakurai's object is a final helium flash object.

Key words: stars: atmospheres–stars: carbon–stars: individual: Sakurai's obj.

1. Introduction

On February,20 1996 Y. Sakurai discovered a possible "slow" nova in Sagittarius (Green 1996). Kushida (1996) reported an accurate astrometry of this object α_{2000} = 17$^{\rm h}$52$^{\rm m}$32$^{\rm s}$.69, δ_{2000} = $-17°41'07''.7$. The first observations after the discovery have been fully described by Duerbeck & Benetti (1996). Those first observations revealed that Sakurai's object could be an object experienced its final helium flash. The star was found to be a nucleus of a PN and along with its fast brightening in visual light by 4.5 magnitudes in less than 2 years it has a pure absorption spectrum with lines of HeI, CI, CII, NI, OI, SiII and faint lines of H (Duerbeck 1996).

We observed the object on July, 03 1996 with the echelle spectrograph of the 6-m telescope. The results of the anaysis of those spectra are reported in this note.

2. Observations and general description of the spectra

The spectra were obtained on July, 03 1996 by one of us (V. Klochkova) with the echelle spectrometer in the prime focus of 6-m telescope (Klochkova 1995). In this spectrometer a 37.5 grooves mm^{-1} and 64.°3 blaze-angle echelle is used together with a 300 grooves mm^{-1} cross disperser. As a detector a 1040 $\times$ 1160 CCD is used with a 1:2 f = 250 mm camera. The pixel size is 16 $\times$ 16 μ. The spectra cover the wavelength region $\lambda\lambda$5000 $\div$ 8000 at a resolution of about 20,000.

Three exposures of 53 minutes were made. This time turned out to be unsufficient for the night with cirruses and so the S/N ratio in the best exposed regions is around 75. The reduction of these spectra was performed with the image reduction system IRAF including the determination of the equivalent widths. Three spectra were coadded after the linearization in the wavelength scale as were all the overlapping regions of the adjacent spectral orders. The resulting coadded spectrum was used for subsequent analysis.

The spectrum appeared to look quite close to early F supergiant spectra except of the faintness of H$_\alpha$ line and the extraordinary strength of CI, CII, OI and SiII lines. We estimated that the spectral type is F2–3II. In appearance the spectrum resembles the spectra of the majority of R CrB stars. The H$_\alpha$ line is, however, stronger than in most R CrB stars indicating of substantial hydrogen abundance. The C_2 $(0,0)$ band at λ5165 is barely visible indicating quite high temperature. The low resolution spectra obtained in April 1997 show already strong absorption in C_2 bands.

The heliocentric radial velocity is 104 $\pm$ 3 km s^{-1} and that of the strong interstellar sodium D lines 0 $\pm$ 3 km s^{-1}. The equivalent widths of the interstellar D$_2$ and D$_1$ lines are 1.25 and 1.16 Å respectively.

3. Abundance analysis

3.1. Atmospheric parameters

Duerbeck & Benetti (1996) found using the $UBVRIJK$ fluxes and E_{B-V} = 0.54 the effective temperature 7250 K from fits with Kurucz's (1979) normal hydrogen abundance models. The reddening was estimated from Balmer decrement of the PN. From the dereddened H$_\beta$ flux of the PN they also estimated the distance d = 5.5 kpc and $M_V = -4.1$. If one assumes the mean mass of R CrB stars of $0.7M_\odot$ this gives the surface gravity of $\log g = 0.88$. Adopting this effective temperature we performed the preliminary abundance analysis using the atmospheric models of hydrogen-deficient stars by Schönberner (1975). The models with effective temperatures of 7000 K and 8000 K, logarithmic gravity 0.5 and 1.0, and C/He abundance ratio 0.03 were used. The models for $T_{\rm eff}$ = 7250 K were constructed by interpolation of indicated models. The adopted $T_{\rm eff}$ was confirmed by excitation equilibria of Si I, Si II, Fe I and Fe II. The surface gravity, $\log g$ = 1.0, was estimated from the ionization equilibria of the same elements. This analysis allowed also to fix the value of microturbulent velocity $\xi = 7\pm1$ km s^{-1} (using mainly FeI lines). With these models we also got the crude estimate of the hydrogen depletion 10^{-3}.

Asplund et al. (1997) observed the object in May and October 1996. They estimated $T_{\rm eff}$ = 7500±300 K, $\log g$ = 0.0±0.3, and $\xi_{\rm t}$ = 8.0 ± 1.0 km s^{-1} for the May spectra, and $T_{\rm eff}$ = 6900 K, $\log g$ = 0.5, $\xi_{\rm t}$ = 6.5 km s^{-1} in October. The present estimate of stellar parameters corresponding to observations in July compares reasonably with those determined by Asplund et al. (1997). The expected uncertainties in these parameters $\Delta T_{\rm eff} = \pm250$ K, $\Delta \log g = \pm0.5$ and $\Delta\xi_{\rm t} = \pm1$ km s^{-1} correspond to abundance errors of 0.2 dex.

3.2. Abundance analysis

For the abundance analysis we used the widely known LTE spectral analysis program WIDTH5 (Kurucz 1970) and for the blended lines the spectrum synthesis code based on the same program. For both codes the calculation of absorption coefficients was modified by extending the C I and C^- absorption to $\lambda \leq 8100$ Å. This was done by using the data by Peach (1970), Travis & Matsushima (1968), and Myerscough & McDowell (1966). The line list compiled by R. Bell (1976) was used in both cases as the source of line data. For some metals the solar oscillator strengths by Thevenin (1989,1990) and for C I lines new $\log gf$ values from Hibbert et al. (1993) and TOPbase (Cunto & Mendoza 1992) were used.

As there are no atmospheric models with the line blanketing for cool hydrogen-deficient stars available, the small grid was produced for this work. The basic code used was MARCS (Gustafsson et al. 1975). To this code the metallic line opacities were added in OS approximation. The OS opacity table for a set of $(T, Pe, \xi_{\rm t})$ was computed by B. Plez (1996). However, this table was computed for the solar mixture. The differences in metal abundances could be well taken into account assuming that all metal abundances change in the same way. More fundamental difficulty is connected with the different $P_{\rm g}/P_{\rm e}$ ratio when the hydrogen is no more the main electron donor. For the models computed, this ratio could be different from the one for the solar mixture up to the magnitude. The errors in the local values of the OS opacities are the same. Nevertheless, the models with such line blanketing included are more realistic than the ones without any lines taken into account. The models were computed with the abundances found by Rao & Lambert (1996)

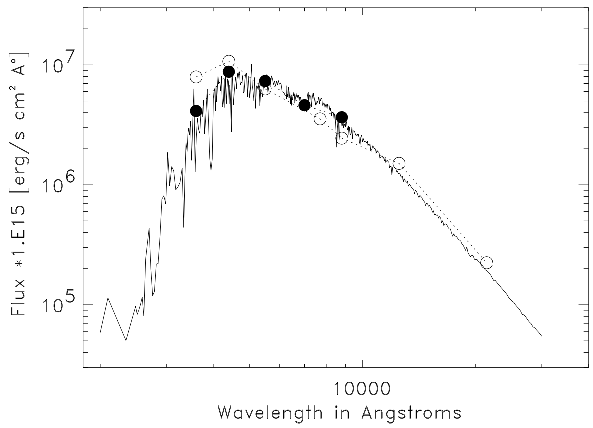

Fig. 1. The synthetic spectrum of the adopted H-deficient model (7250/1.0) and the $UBVRIJK$ broadband fluxes of Sakurai's object. The synthetic spectrum is computed in OS points and then smoothed for plotting.The fluxes from Duerbeck & Benetti (1996) are noted by open symbols and those from Hickel (1996) by filled symbols

for majority of R CrB stars except the abundance of hydrogen which was fixed at the level $\log A$(H) = 8.54 in the scale where $\log A$(He) = 11.54 and A(C)/A(He) = 0.01. The carbon to helium abundance ratio of about 0.01 was confirmed using the only observed in our spectra He I line at 5876 Å. This triplet, however, is not considered to be an accurate indicator of the C/He ratio by Lambert & Rao (1994). Asplund et al. estimated for the May spectra C/He≃10 %. Error in this choice influences the absolute abundances but the abundance ratios are almost not affected. High hydrogen abundance is important as in that case the opacity produced by hydrogen is not negligible as it is usually assumed for hydrogen-deficient stars. The microturbulent velocity of 5 km s^{-1} for OS opacities was adopted as the closest value to the derived velocity. This choice has a minor effect on the resulting temperature structure. The construction of more sophisticated model atmospheres was not attempted as the new models of H-deficient stars by Asplund et al. (1997a) will soon be available.

The synthetic spectrum computed with the adopted model (7250/1.0) is presented in Fig. 1 together with $UBVRIJK$ fluxes from Duerbeck & Benetti (1996) which were observed from February to April, 1996, and $UBVRI$ fluxes observed by G. Hickel (www.kusastro.kyoto-u.ac.jp/vsnet) on August, 25, 1996. This synthetic spectrum was computed with OS opacities and smoothed for plotting by summing 10 consecutive data points. The overall fit is quite good for the later date. The near-UV excess noted by Duerbeck & Benetti has vanished for that time.

The instrumental line width which is needed for synthetic spectrum calculations was estimated from terrestial lines to be 28 km s^{-1}.

The choice of atmospheric parameters was also confirmed with the newly computed models set. The iron abundance derived from Fe II lines turned out to be 0.2 dex larger than from Fe I lines with the error of about 0.3 dex. This could mean that

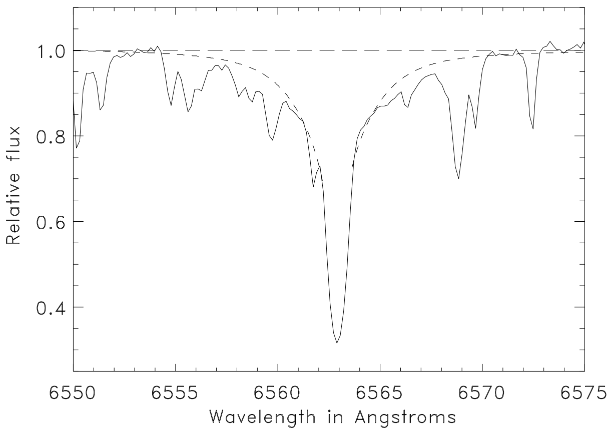

Fig. 2. The observed H_α profile of Sakurai's object and the calculated H_α wings with the model (7250/1.0) and the hydrogen abundance 9.1 (log A(He) = 11.54)

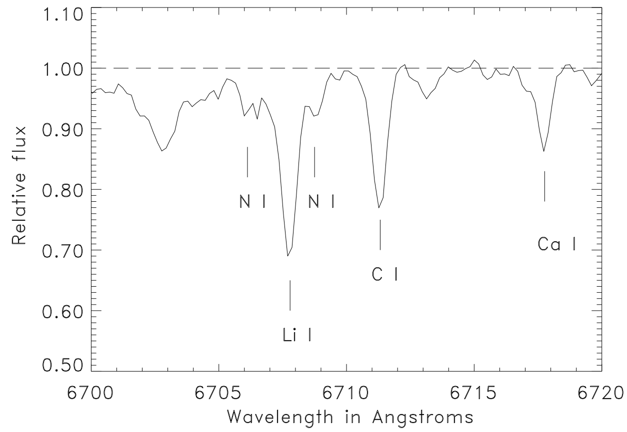

Fig. 3. The observed spectrum of Sakurai's object near the Li I line at λ6707.8

the effective temperature is underestimated by up to 300 K or the logarithmic gravity overestimated by 0.3 dex.

4. Results

Table 1 summarizes the results of abundance determinations together with the mean composition of R CrB stars (Rao & Lambert 1996). The [M/Fe] values found by Asplund et al. (1997) for May and October are also listed. The indicated in this Table errors are the formal errors for abundances derived from different lines. The larger than on the average differences for Na and Ba with Asplund et al. data are caused by differences in used oscillator strengths (Asplund 1997). Next to the errors the source of oscillator strengths is indicated: B – Bell's tape, T – Thevenin (1989,1990), H – Hibbert et al. (1993) and TOPbase.

In the spectrum of Sakurai's object the H_α line has quite pronounced Stark wings showing that the hydrogen abundance is larger than in most R CrB stars. The wings of H_α line could be fitted reasonably well if the hydrogen abundance is 9.1 (log A(He) = 11.54) using the model with $T_{\rm eff}$ = 7250 K and $\log g$ = 1.00. The synthetic H_α profiles were computed with the program BALMER (Kurucz 1993). This fit is presented in Fig. 2. In finding of abundances of other elements we used the H abundance of 9.1. In the case of hydrogen-deficient stars the derived abundances depend strongly on adopted carbon abundance. In this analysis we used log A(C) = 9.44 (normalized to $\log(\sum \mu_i A_i)$).

The iron abundance (metallicity) is below solar by 0.90 dex in mass fraction if the derived carbon abundance, log A(C) = 9.19 $\pm$ 0.45, is used. This is lower than initially adopted C abundance (C/He=0.01) by factor of 2.2. This yet unexplained discrepancy has been found for all R CrB stars (Rao & Lambert 1996) and also for Sakurai's object (Asplund et al. 1997). This discrepancy would be somewhat larger if the carbon continuous opacities from Opacity Project (Seaton et al. 1994) instead of generally larger values of Peach(1970) were used.

Table 1. Chemical composition of Sakurai's object, the R CrB stars and the Sun (normalized to $\log \sum \mu_i A_i$ = 12.15)

El.	Sun	Sakurai's obj.	Ref. gf	[M/Fe]$_{\rm Sak}$ May	July	Oct.	[M/Fe] R CrB
H	12.0	9.1					
Li	3.30	3.5	T	1.5	1.55	1.8	
C	8.55	9.19 ± 0.40	H	2.3	1.99	2.1	1.32
N	7.97	8.50 ± 0.20	B	2.1	1.88	1.8	1.63
O	8.87	8.61 ± 0.25	B	1.8	1.09	1.4	0.29
Na	6.32	5.87 ± 0.25	T	1.6	0.90	1.4	0.76
Mg	7.58	6.22 ± 0.30	T	0.2	-0.01	-0.2	
Al	6.48	5.66 ± 0.20	B	1.3	0.53	0.7	0.49
Si	7.55	6.79 ± 0.36	B	0.8	0.59	0.9	0.56
Ca	6.34	4.95 ± 0.44	T	0.4	-0.04	0.0	-0.01
Sc	3.17	2.98 ± 0.35	T	1.1	1.16	1.6	
Ti	5.02	4.05 ± 0.20	T	0.3	0.38	0.5	
Cr	5.67	4.46 ± 0.30	T	0.0	0.14	0.3	
Fe	7.51	6.16 ± 0.30	T				
Ni	6.25	5.72 ± 0.33	T	1.1	0.82	0.9	0.57
Zn	4.60	4.6	T	1.3	1.4	1.7	0.68
Y	2.24	3.09 ± 0.40	T	2.3	2.20	2.9	0.81
Zr	2.60	2.70 ± 0.35	T	1.6	1.45	1.8	
Ba	2.21	1.94 ± 0.52	B	0.6	1.08	0.7	0.34
La	1.20	1.47 ± 0.45	B	1.6	1.62	1.2	
Ce	1.60	1.34 ± 0.30	B		1.09		
Pr	0.75	≤ 1.2	B		≤ 1.8		

The oxygen abundance was found to be log A(O) = 8.61 $\pm$ 0.25 and the nitrogen abundance log A(N) = 8.50 ± 0.20. These C and O abundances are larger than in majority of R CrB stars (Rao & Lambert 1996) but could be found in some members of R CrB class.

The lithium abundance is very large as in some Li strong R CrB stars (RZ Nor). In Table 1 for the solar Li abundance the meteoritic value is adopted.

Na through Ca abundances behave in the same way as in most R CrB stars.

However based on few lines, we found the enhancement of the elements produced in s–process. The overabundance of light s–process elements is quite large and that of heavy s–process elements moderate. The mean ratio of heavy and light s–process elements defined by Luck & Bond (1985), [hs/ls]≤ -0.6. This ratio could be achieved by mild exposure to neutrons $\tau < 0.3$ mb^{-1} (Vanture 1992; Malaney 1987a,b). The errors in the derived abundances of heavy elements due to the limited number of lines are too large for comparisons of individual abundances with Malaney's predictions.

5. Conclusion

According to high radial velocity, (104 km s^{-1}), the position in the Galaxy, and moderately low metallicity, (-0.9), Sakurai's object could belong to galactic nuclear bulge.

Many characteristics of Sakurai's object show that it could be an final helium flash object and represent the case of a "very late" thermal pulse which occurs when the star is already on the white dwarf cooling track (Blöcker & Schönberner 1996). Indications for this are: the fast rise in brightness, the blue color before the outburst, H-deficiency together with the enrichment of carbon and s–process elements, the object is a central star of an old planetary nebula (Duerbeck 1996). In the case of "very late" thermal pulse hydrogen may be mixed with deep layers of He and C and consumed. Partial burning and mixing of the envelope lead to accelerated brightening. Calculations of Iben & Mc Donald (1995) for a 0.6 $M_{\odot}$ model show $\Delta m_v \approx 5^{\rm m}$ increase in luminosity and cooling from 40000 K to 6300 K during 17 years. The timescale of Sakurai's object is even shorter of that.

The implications of the derived abundances in the context of the last thermal pulse are in details discussed by Asplund et al. (1997) and therefore not repeated here.

The great similarity of the chemical composition, $T_{\rm eff}$ and luminocity of Sakurai's object to that of R CrB stars adds some weight to the final flash conjecture of R CrB stars formation. There have been light variations up to 0.5 mag after reaching some brightness plateau but no deep declines have not yet been observed. Here should be noted that in the case of FG Sge no such characteristic R CrB declines were observed during the first 20 years after it reached its visual maximum.

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