MODELS OF ENERGY DISTRIBUTION IN SPECTRUM OF SAKURAI'S OBJECT

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ABSTRACT. Theoretical energy distributions in a spectrum of Sakurai's object (SO) are calculated for a grid of hydrogen-deficient and carbon-rich model atmospheres of T_{eff} = 5000-6200 K and log g= 0.0-1.0. Model atmospheres of SO are computed by the technique of opacity sampling with account of atomic and molecular absorption. Theoretical energy distributions are compared with the spectrum of SO in April 1997 at $\lambda\lambda$ 300 − 1000 nm. We show, that (1) theoretical energy distributions agree well at least qualitavely with the observed ones and depend strongly on T_{eff} ; (2) an absorption by the C_3 and CN bands is dominated in visible and near IR region of the SO spectrum, an atomic absorption becomes important in UV and blue region. We estimate for SO $T_{eff} \approx 5500$K and its interstellar reddening $E_{B-V} = 0.70$ for April, 1997.

Key words: Sakurai's object, AGB and post-AGB evolution, model atmospheres, synthetic spectra.

1. Introduction

Sakurai's object (SO, V4334 Sagittarii) was discovered on February 20, 1996 (Nakano et al., 1996) as "novalike object in Sagittarius" at $\sim 11^m$, but no emission lines were found in its spectrum. Its progenitor was a faint blue star ($\sim 21^m$) in the centre of a low surface brightness planetary nebula.

It is supposed that the beginning of the flash was in the end of 1994. Then the effective temperature of SO decreased, but its optical luminosity increased in 1995-1997. In early and in late 1998 abrupt declines of brightness at all colours occurred. This is interpreted as onsets of dust formation, very similar to those observed in R CrB variables (see Duerbeck et al. 1999). The nature of observed processes testifies that SO is an AGB star at a final stage of helium source flare (Duerbeck & Benetti 1996), that was predicted by theory (Iben 1984). The exact spectral classification of SO is essentially hindered due to the unusual abundances: there is a hydrogen deficit in the atmosphere, and C/O > 1 (Asplund et al. 1997, Kipper & Klochkova, 1997). From the spring of 1997 SO is classificated as C-star (Arhipova et al. 1998).

We compute and compare with observations theoretical energy distributions in the SO spectrum and determined the effective temperature of SO in April 1997. This requires calculations of model atmospheres with peculiar chemical abundances and synthetic spectra taking into account the numerous atomic lines and molecular bands in the wide spectral region.

2. Observations

In our work we use an observed spectrum of SO in the range of $\lambda\lambda$ 300-1000 nm, taken April 29, 1997 (see Duerbeck et al. 1999 for more details). No obvious dust obscuration is seen in the light curve of SO at this data. However, Kamath & Ashok (1999) claim that some dust had formed in April-May 1997.

The extinction is still an unclear point. We use the correction for the interstellar reddening E_{B-V}=0.54 as well 0.70 (see Pavlenko et al. 2000).

3. Procedure.

Our computations of model atmospheres and synthetic spectra are carried out for classical approaches: LTE, plane-parallel model atmosphere, no energy divergence. The chemical composition of SO of Asplund et al. (1997) is used (see Table 1). It agrees well enough with the data of Kipper & Klochkova (1997). Ionization-dissociation equilibrium is calculated for a set of 70 atoms, ions and molecules. For computing of absorption by atoms and ions we use VALD line lists (Piskunov et al. 1995). Molecular absorption in frequencies of 20 band systems of diatomic molecules (see Table 2) is calculated in the "just overlapping approximation" (JOLA) approach. The input information for

Table 1: Abundances of chemical elements in the atmosphere of SO (Asplund et al. 1997), $\sum N_i = 1$

Z	Element	log N (SO)	log N (Sun)
1	H	-1.73	-0.04
2	He	-0.03	-1.05
3	Li	-7.83	-10.88
6	C	-1.73	-3.48
7	N	-2.53	-3.99
8	O	-1.93	-3.11
10	Ne	-2.13	-3.95
11	Na	-4.73	-5.71
12	Mg	-4.83	-4.46
13	Al	-4.83	-5.57
14	Si	-4.33	-4.49
16	S	-4.83	-4.83
19	K	-6.63	-6.92
20	Ca	-5.83	-5.68
21	Sc	-8.33	-8.94
22	Ti	-7.33	-7.05
24	Cr	-6.93	-6.37
26	Fe	-5.13	-4.37
28	Ni	-5.33	-5.79
29	Cu	-6.53	-7.83
30	Zn	-6.73	-7.44
37	Rb	-7.73	-9.44
38	Sr	-6.53	-9.14
39	Y	-8.13	-9.80
40	Zr	-8.43	-9.44
56	Ba	-9.93	-9.91
57	La	-9.83	-10.82

Table 2: Band systems of diatomic molecules that were taken into account in this paper

Molecule	System	
C_2	$e^3\Pi_g$-$a^3\Pi_u$	Fox-Herzberg
C_2	$d^3\Pi_g$-$a^3\Pi_u$	Swan
C_2	$A^1\Pi_u$-$X^1\Sigma_g^+$	Phillips
C_2	$b^3\Sigma_g^-$-$a^3\Pi_u$	Ballik-Ramsay
CN	$B^2\Sigma^+$-$X^2\Sigma^+$	violet
CN	$A^2\Pi$-$X^2\Sigma^+$	red
CS	$A^1\Pi$-$X^1\Sigma^+$	
CO	$A^1\Pi$-$X^1\Sigma^+$	
CO	$C^1\Sigma^+$-$A^1\Pi$	Herzberg
CO	$B^1\Sigma^+$-$A^1\Pi$	Angström
NO	$A^2\Sigma^+$-$X^2\Pi_r$	γ
NO	$B^2\Pi_r$-$X^2\Pi_r$	
NO	$C^2\Pi_r$-$X^2\Pi_r$	δ
MgO	$B^1\Sigma^+$-$X^1\Sigma^+$	
AlO	$C^2\Pi_r$ -$X^2\Sigma^+$	
AlO	$B^2\Sigma^+$-$X^2\Sigma^+$	
SiO	$E^1\Sigma^+$-$X^1\Sigma^+$	
SiO	$A^1\Pi$-$X^1\Sigma^+$	
SO	$A^3\Pi$-$X^3\Sigma^-$	
CaO	$C^1\Sigma$-$X^1\Sigma$	

this calculations is described in Pavlenko & Yakovina (1999). Note, that we suppose that all carbon exists in the form of ^{12}C.

Opacity sampling model atmospheres of SO and its synthetical spectra are computed by SAM941 (Pavlenko 1999) and WITA6 programs, respectively. The last is the version of the program WITA31 (Pavlenko 1997). In WITA6 some additional opacity sources, i.e. bound-free absorption of C I, O I, C^- are included (see Pavlenko et al. 2000 for more details).

We put microturbulent velocity in SO atmosphere 5 km/s, as a typical value for atmospheres of post AGB stars. Theoretical spectra are convolved by a gaussian with half-width 0.5nm.

4. Results

In Fig. 1 we show an identification of the main features in the SO spectrum of April 1997. Its overall shape is governed by the bands of C_2 Swan system and by violet and red systems of CN. In the near UV ($\lambda < 400$ nm) the atomic absorption becomes important. In our low-resolution spectrum only the strongest atomic lines can be identified: Ca^+ H and K (λ 393.48, λ 396.96 nm), Na D (λ 589.16, λ 689.75 nm), IR triplet of Ca^+ (λ 850.03, λ 854.44, λ 866.45 nm).

A comparison of observed and computed energy distributions shows their reasonably good *qualitative* agreement. Thus, the main opacity sources in the atmosphere of SO can be considered as well defined. At the same time, the comparison of observed and computed flux intensities of C_2 and CN bands in the near UV part of the spectrum of SO shows that the theo-

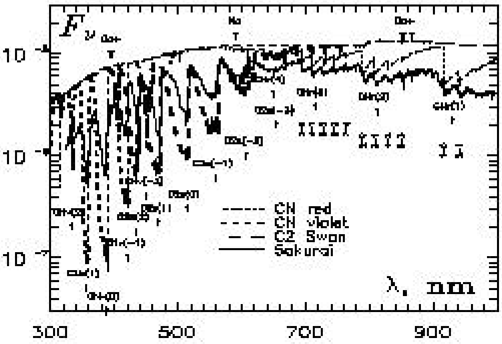

Figure 1: Identification of the strongest features in the SO spectrum of April 1997.

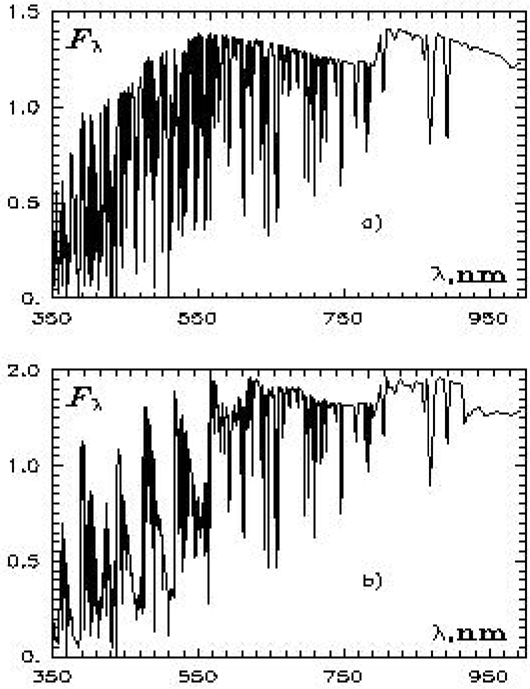

Figure 2: Theoretical energy distributions computed for SO model atmosphere 6250/1.0 without (a) and with (b) molecular (JOLA) absorption.

retical bands appear essentially deeper.

Our calculations show, that strong enough molecular bands appeares in the spectum computed for $T_{eff} \sim 6000$ K (Fig. 2). They become stronger, when T_{eff} drops, because molecular densities of C_3 and CN should increase with the lowering of effective temperature. Comparison of observed and computed fluxes F_λ for model atmospheres with $T_{eff} = 5000$ and 6000 K is shown in Fig. 3. This picture shows that the energy distribution in the spectrum of SO depends critically on T_{eff}. The best fit we obtained for an intermediate $T_{eff} \sim 5500$ K. It can be seen on Fig. 4.

To study an inpact of log g on the SO spectrum we computed two model atmospheres 5500/1.0 and 5500/0.0 and theoretical energy distributions for these models. We conclude that the dependence of the SO spectrum on log g is of "second order importance" and it also can be affected by the sphericity effects in the SO atmosphere.

In Fig. 4 we show the fits to the observed SO spectrum, corrected for $E_{B-V} = 0.70$ and 0.54. The fit with $E_{B-V} = 0.70$ looks better, especially in the red part of the spectrum.

There are several hints that the chemical abundances in the SO atmosphere are changed in short time scales (1995-1997, see Asplund et al. 1997 for details). Therefore, a study of a dependence of the output fluxes on the H, C, N, O abundances is of interest. First of all, the abundance changes affect the chemical balance, and, hence, the emitted spectra of SO. Furthe-

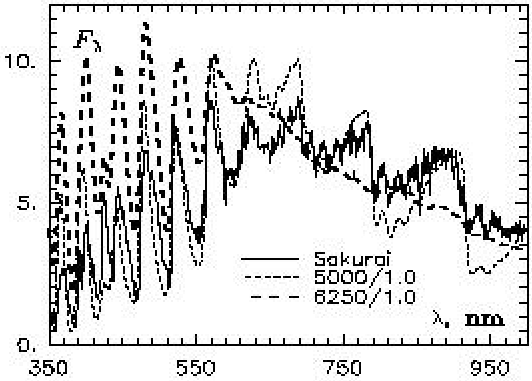

Figure 3: Comparison of the observed and computed radiative fluxes for model atmospheres with T_{eff} = 5000 and 6000 K

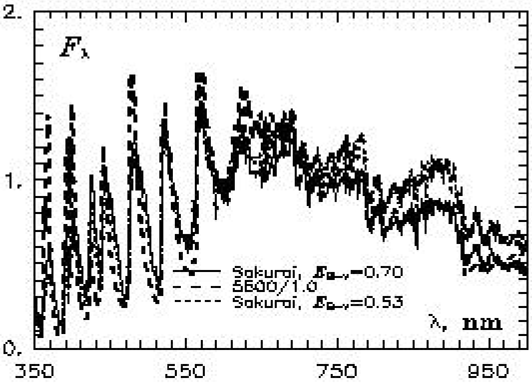

Figure 4: Comparison of computed radiative fluxes for atmosphere models with T_{eff} = 5500 and observed SO spectrum corrected for E_{B-V} = 0.54 and 0.70.

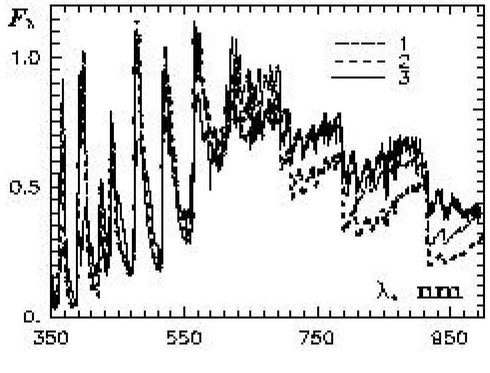

Figure 5: Comparison of the observed spectrum of SO and theoretical ones on different input hydrogen abundances

more, a structure of model atmospheres is changed also. As a result, we have a complicate dependence of the SO spectra on abundances. We computed several model atmospheres for different abundances and found that variations of the hydrogen abundance, for example from the $logN(H) = -4.0$ (hydrogen abundance in R CrB atmosphere, see Asplund at al. 1997) up to $\log N(H) = -1.73$ (a case of SO, see Table 1), show a rather weak impact on the model atmospheres or output spectra of SO (fig. 5). In general, a dependence of the theoretical spectra of SO from the H, C, N, O abundances is rather complicate.

5. Discussion

There are several essensial subjects for discussion in this work: adopted approaches for computations, the enormous intensities of the theoretical spectra of carbon-containing molecules in blue and UV region, the estimations of T_{eff} for SO in April, 1997 and interstellar reddening E_{B-V}.

Our computations were carried out in the framework of plane-parallel approach. We simplify the real situation (see Asplund et al. 1997) by ingoring of the sphericity effects. Note, however, that there are a few other problems to be studied even in the framework of this simple approach. Furthemore, shpericity effects should affect mainly the outermost layers, whose structure depends also on many processes: dust particles formation, depletion of molecular species, chromospheric-like effects, interaction with the dusty envelope, nonhomogenuity, etc. Unfortunately, for the time being, physics of the processes is poorly known yet.

Also the accuracy of JOLA approach can be unsufficient for faint molecular bands. But we note, that only due to using JOLA we could to make such a wide work, while the contribution of faint bands in total molecular absorption is usually small.

We note some enhancening of the theoretical C_2 and CN bands in blue and UV region. One may interpret these results within the frame of the phenomenon of "too strong carbon lines" (see Asplund et al. 1997) for type R CrB stars or as an impact of the dust (Duerbeck et al. 1999). It can be also a consequence of the lack of the continuum or line opacities in the blue part of the spectrum (Pavlenko & Yakovina 1999). The last is caused by incompletness of lists of the used atomic lines and molecular bands.

Obtained in this work T_{eff} SO in April 1997 $T_{eff} \sim 5500$ K is lower than the value of Kipper and Klochkova (1997) $T_{eff} = 7250$ K for July, 1996. In general, effective temperatures of SO were reduced by time in 1995 - 1997. Arhipova et al. (1998), using the photometric calibration of "normal" C-giants, determined for SO T_{eff} =5100 K in March, 1997 and 4600 K in June, 1997. Their T_{eff} are lower than our estimation for April, 1997, but one should remember about uncertainties of spectral classification of SO due to its unusual evolutionary status.

We found that the observed spectrum of Sakurai's object in April, 1997 corrected by interstellar reddening E_{B-V}= 0.70 is well fitted by theoretical spectra computed for model atmosphere 5500/1.0. In that way, in the frame of our self-consistent approach, we *independently* obtained also the interstellar reddening parameter which was poorly known for SO (see discussion in Pavlenko et al. 2000).

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