A&A 367, 933–938 (2001)
DOI: 10.1051/0004-6361:20010067

Astronomy & Astrophysics

Research Note

The spectrum of V4334 Sgr (Sakurai's object) in August, 1998*

Ya. V. Pavlenko[1,2] and H. W. Duerbeck[3]

[1] Main Astronomical Observatory of Academy of Sciences of Ukraine, Golosiiv woods, Kyiv-127, 03680, Ukraine
[2] Isaac Newton Institute of Chile, Kiev Branch, Chile
[3] WE/OBSS, Free University Brussels (VUB), Pleinlaan 2, 1050 Brussels, Belgium
e-mail: hduerbec@vub.ac.be

Received 23 October 2000 / Accepted 10 January 2001

Abstract. Theoretical spectral energy distributions are computed for a grid of hydrogen-deficient and carbon-rich model atmospheres with a range in $T_{\rm eff}$ of 4000−5500 K and $\log g$ of 1.0−0.0, using the technique of opacity sampling, and taking into account continuous, atomic line and molecular band absorption. The energy distributions are compared with the spectrum of V4334 Sgr (Sakurai's object) of August 12, 1998 in the wavelength interval 300−1000 nm. This comparison yields an effective temperature of V4334 Sgr of $T_{\rm eff} = 5250 \pm 200$ K, and a value for the interstellar plus circumstellar reddening of $E_{B-V} = 1.3 \pm 0.1$.

Key words. stars: individual: V4334 Sgr – stars: AGB and post-AGB – stars: fundamental parameters

1. Introduction

V4334 Sgr, the "novalike object in Sagittarius", was discovered by Y. Sakurai on February 20, 1996 (Nakano et al. 1996). Soon after discovery, it was found to be a final He flash object, a star on the rare evolutionary track that leads from the central stars of planetary nebulae back to the red giant region, also called a "born-again giant". Its progenitor was a faint blue star ($\sim 21^{\rm m}$) in the centre of a low surface brightness planetary nebula (Duerbeck & Benetti 1996). Early spectroscopic studies of the object found an increasing hydrogen deficit in the atmosphere, and a C/O ratio >1 (Asplund et al. 1997; Kipper & Klochkova 1997).

Unlike the slowly evolving born-again giant FG Sge, which rose in brightness during the first half of the 20th century, V4334 Sgr is a very quickly evolving object (Fig. 1). It shows striking similarities with the unfortunately poorly documented final He flash object V605 Aql that erupted in 1918–1923 (see Clayton & de Marco 1997; for an overview). Between March 1996 and April 1997, V4334 Sgr evolved from early F to late red giant stages. Infrared observations by Kimeswenger et al. (1997) and by Kamath & Ashok (1999) show a noticeable excess in the infrared K band starting March 1997, indicative of dust formation. However, only in early 1998 a $\sim 1^{\rm m}$ depression appeared in the optical light curve (Liller et al. 1998; Duerbeck et al. 1999, 2000). This moderate depression persisted for a few months, and was followed by a $\sim 6^{\rm m}$ decline which started in August 1998. After a partial recovery in late 1998 – early 1999, the dust obscuration continued with increasing strength, and it may be assumed that in the year 2000, only the short-wavelength tail of the cool dust envelope can be observed in the optical spectrum, while the stellar photosphere is engulfed in the opaque dust shell. Unfortunately, not much is know about these late phases, since the spectroscopic coverage is poor due to the extreme faintness of the object in the visible region.

A spectrum of V4334 Sgr was obtained on April 29, 1997, before any dust obscuration in the optical region became evident, but after the strong IR excess had evolved. This spectrum was compared with theoretical spectral energy distributions (Pavlenko et al. 2000). The authors derived a temperature of $T_{\rm eff} = 5500$ K, and an interstellar reddening of $E_{B-V} = 0.7$. In this paper, we apply the same methods to a spectrum which was taken 15 months later.

2. Observations

On August 12, 1998, a spectrum (range 355−1000 nm, resolving power ∼2000) was taken by A. Piemonte with

Send offprint requests to: Ya.V. Pavlenko,
e-mail: yp@mao.kiev.ua

* Based on observations collected at the European Southern Observatory, La Silla, Chile.

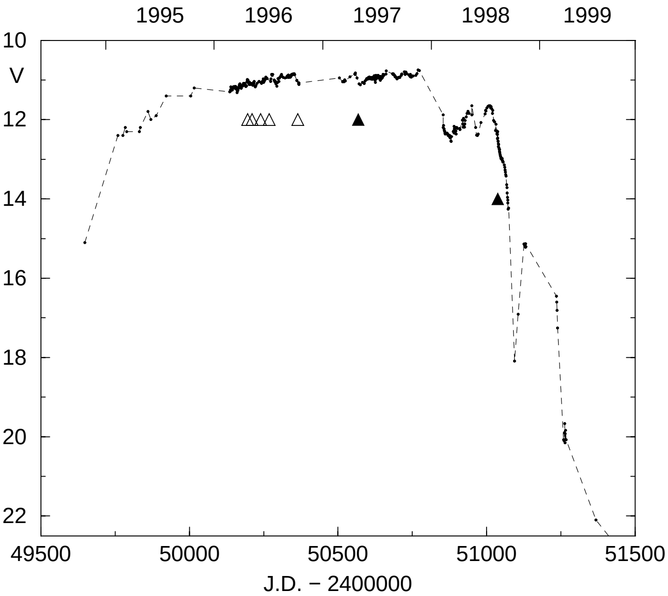

Fig. 1. The visual light curve of V4334 Sgr, according to Duerbeck et al. (2000). The times of five spectroscopic observations, analyzed by Asplund et al. (1997, 1999) and Kipper & Klochkova (1997), are indicated by open triangles. The times of our two spectroscopic observations of April, 1997 and August, 1998 are marked by filled triangles. The second observation took place at the beginning of a deep brightness decline

the B&C Cassegrain spectrograph attached to the ESO 1.52 m telescope, and kindly put at the authors' disposal. It was taken around the time of the onset of the $\sim 6^{\rm m}$ decline, at a time when V4334 Sgr was obviously already suffering $\sim 1^{\rm m}$ of visual dust obscuration (Fig. 1).

The spectrum was reduced using standard IRAF routines, and the spectral energy distribution (SED) was derived using spectrophotometric standard stars. The observed SED is influenced by interstellar reddening as well as by additional circumstellar reddening. The value of the interstellar reddening is still not accurately known; we will assume $E_{B-V} = 0.7$ in the following, as was derived in the analysis of the "dustless" spectrum of April 29, 1997, by Pavlenko et al. (2000); note, however, that Duerbeck et al. (2000) prefer $E_{B-V} = 0.8$, a value which is also consistent with the observed versus theoretical Balmer decrement of the planetary nebula surrounding V4334 Sgr (Kerber et al. 2000).

We will assume that the dusty envelope acts like an additional amount of interstellar reddening. Dereddened spectral energy distributions of the August 12, 1998 spectrum were calculated for assumed values $0.7 \leq E_{B-V} \leq 1.3$, and compared with model atmospheres.

3. Procedure and results

Our computations of model atmospheres and synthetic spectra are carried out in a classical approach: a plane-parallel model atmosphere in LTE, with no energy divergence. We assumed chemical compositions of V4334 Sgr as determined by Asplund et al. (1997) and Kipper & Klochkova (1997). Their results differ in some details, not least because there are differences in the physical input parameters and in the details of the procedure.

Table 1. Abundances of H, He, C, N, O (scaled to $\sum N_i = 1$) used in this paper

Element	Asplund et al. (1997)	Asplund et al. (1999)	Kipper & Klochkova (1997)	[C] = +0.6
H	−1.730	−2.42	−2.10	−2.45
He	−0.027	−0.020	−0.01	−0.05
C	−1.73	−1.62	−2.01	−1.05
N	−2.53	−2.52	−2.70	−2.55
O	−1.93	−2.02	−2.59	−2.05

The abundances of *some* elements obtained by Asplund et al. (1997) for May 1996 are given in the second column of Table 1. Asplund et al. (1999) obtained another set of abundances for October 1996. For comparison, we show the abundances of Kipper & Klochkova (1997), obtained independently for a spectrum of July 1996. In general, their results differ more from Asplund et al. (1997) than the results of Asplund et al. (1997) and (1999). Therefore, they provide a more interesting baseline for numerical experiments carried out to clarify the dependence of our results on input abundances.

From the common point of view, hydrogen is an important element, and its abundance in the atmosphere of V4334 Sgr is steadily declining (Asplund et al. 1997). However, Pavlenko et al. (2000) showed that the dependence of our results on $\log N(\rm H)$ is much weaker than that found by Asplund et al. (1997) for the early stages of its evoluton. Indeed, in the case of lower $T_{\rm eff}$ (< 6500 K) the contribution of H and $\rm H^-$ to the total opacity in the line forming region is reduced in comparison with "hot models", because molecular absorption which does not include hydrogen compounds dominates there.

Furthermore, and more importantly, the input carbon abundance of Asplund et al. (1997) is larger by up to 0.6 dex than that which was obtained by them from the fine analysis of high resolution spectra. That is the well known "carbon abundance problem" (Asplund et al. 2000), which has, unfortunately, not yet been resolved.

One may think that, in the meantime, the model atmospheres should *not* be computed with the derived C abundances by Asplund et al. (1999) but rather with the higher input values. The use of the derived lower C abundance would result in a new "carbon problem" and thus even lower C abundances would be derived. To clarify the case, we studied the impact of higher carbon abundances on the model atmospheres and SEDs of V4334 Sgr. We used 4 abundance sets (i.e. Asplund et al. 1997, for May 1996; Kipper & Klochkova 1997, for July 1996; Asplund et al. 1999, for October 1996, and the "carbon rich case" with

[C] = + 0.6 with respect to the Asplund et al. 1999, abundance) in order

- to model the impact of abundance changes on our results;
- to avoid possible uncertainties related with the "carbon problem".

Opacity sampling of model atmospheres and synthetic spectra of V4334 Sgr were computed by the SAM941 (Pavlenko 1999) and WITA6 programmes, respectively. The model atmosphere computation procedure is described in Pavlenko et al. (2000) and Pavlenko (2000). To clarify the topic, some details of the computation procedure are given here:

- Convection was treated in the frame of the mixing-length theory with $l/H = 1.6$. Overshooting was not considered in the computations;
- the list of atomic lines was taken from VALD (Piskunov et al. 1995);
- molecular opacities were computed in the frame of the JOLA approach. We take into account the absorption in the 20 band system of diatomic molecules (see Table 2 in Pavlenko et al. 2000);
- bound-free absorption of C I, N I and O I atoms were computed using the cross-sections of Hoffsaess (1979);
- SAM941 and WITA6 use the same opacity lists.

Model atmospheres, synthetic spectra and SEDs were computed for a microturbulent velocity of 5 $\mathrm{km\,s^{-1}}$, which is a typical value for atmospheres of post-AGB stars. The resulting theoretical spectra were convolved by a Gaussian with a half-width of 0.5 nm.

Basically, the atmospheric structure of chemically peculiar stars should respond to abundance changes (Pavlenko & Yakovina 1994, 2000). To study the impact of the set of input abundances on our results, we carried out a few numerical experiments with model atmospheres computed with abundances of Asplund et al. (1999) and Kipper & Klochkova (1997).

The comparison of the temperature structure of a model atmosphere $T_{\rm eff}/\log g = 5200/0.0$ computed for the four abundance grids is shown in Fig. 2. We prefer to use pressure as a depth parameter, because temperature structures in the coordinates $(\tau_{\rm ross}, T)$ look very similar (see Fig. 2b in Pavlenko et al. 2000). In general, the photospheres are shifted outwards for higher carbon abundances due to the opacity increase. Let us note a few items:

- The structure of model atmospheres of V4334 Sgr, computed for abundances by Asplund et al. (1999), Kipper & Klochkova (1997), and the "carbon-rich case" differ substantially, especially in the deep layers. Differences of model atmospheres computed for Asplund et al.'s (1999) abundances obtained for May and October of 1996 are rather marginal;
- the structure of the outermost layers of model atmospheres computed for the Asplund et al. (1997) and Kipper & Klochkova abundances is similar. Moreover, the differences of the computed SEDs are rather weak (Fig. 3). More pronounced differences are found for the "carbon-rich" case;
- in the blue region, the "flux peaks" which correspond to the minima of molecular absorption, are less pronounced for the model based on Kipper & Klochkova's (1997) abundances, but even more so in the observed spectrum (Fig. 3);
- We have to admit that there is an obvious lack of computed opacity in the blue region, and the model is only correct in a qualitative sense (Pavlenko & Yakovina 2000).

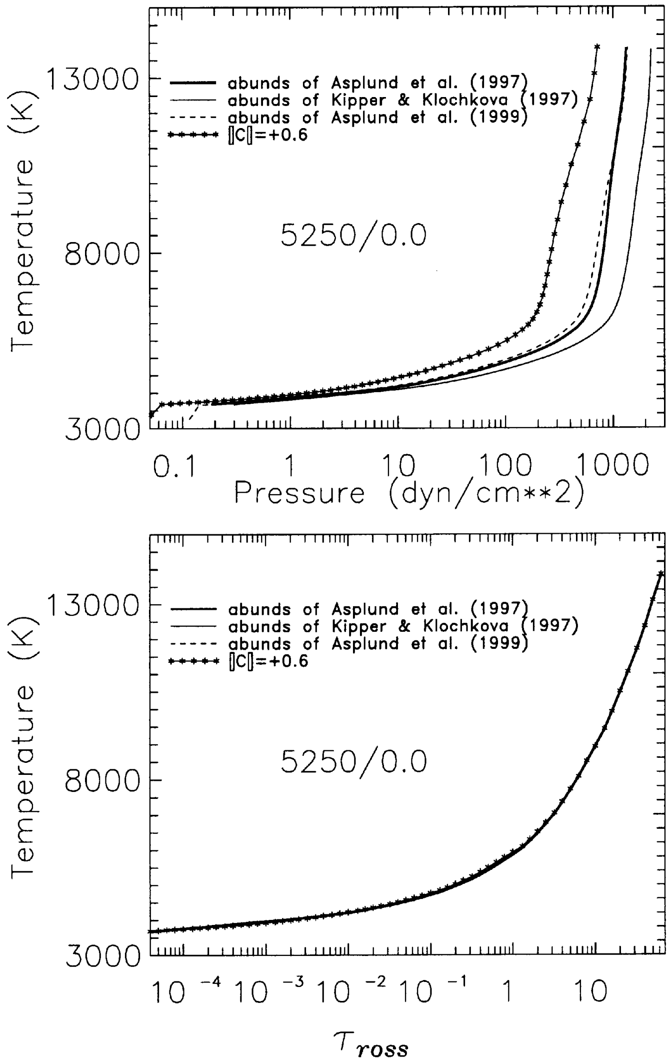

Fig. 2. The $T = f(P_{\rm g})$ structure of model atmospheres computed for Asplund et al. (1997), Kipper & Klochkova (1997), Asplund et al. (1999), and [C] = + 0.6 abundances. A second diagram shows their $T = f(\tau)$ structure

The overall shape of the spectrum of V4334 Sgr is governed by the bands of the C_2 Swan system and by the violet and red systems of CN (Pavlenko et al. 2000). In the near UV ($\lambda < 400$ nm), atomic absorption becomes important (see Pavlenko & Yakovina 2000).

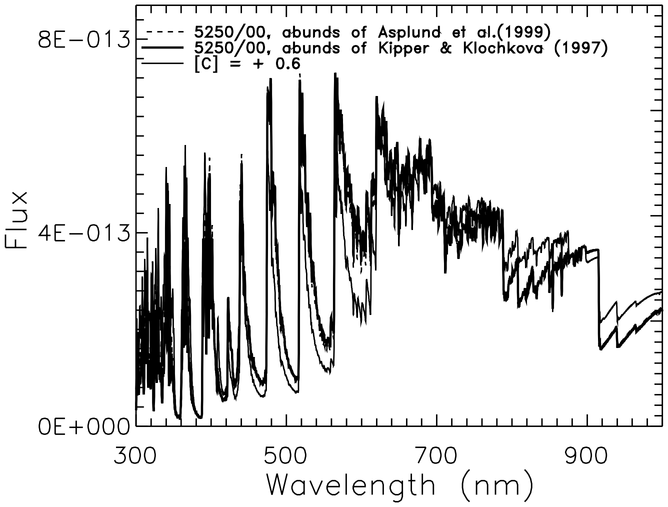

Fig. 3. SEDs computed for model atmospheres 5200/0.0 with abundances taken from Asplund et al. (1999), Kipper & Klochkova (1997) and the "carbon-rich" case. The first two SEDs nearly coincide

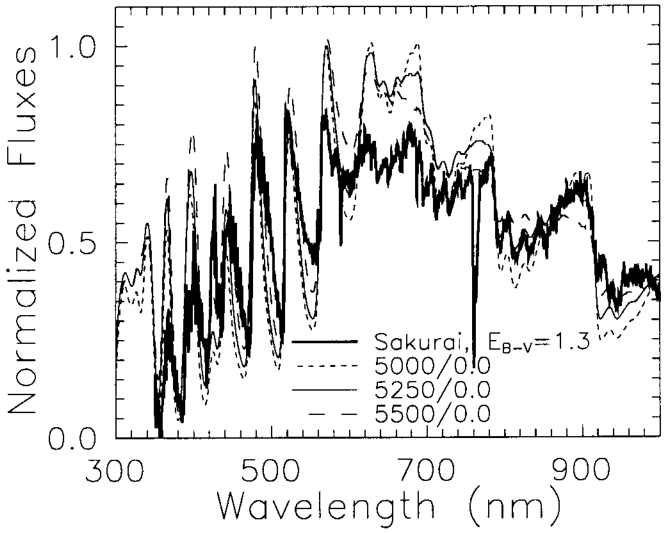

Fig. 4. Synthetical spectra for different effective temperatures and $\log g = 0$ are superimposed on the spectrum of V4334 Sgr (thick line) observed in August, 1998

Computed and observed spectra were normalized to equal flux at $\lambda \sim 740$ nm. In general, our main conclusions show a rather weak dependence on the choice of λ normalization (see Pavlenko et al. 2000).

Nevertheless, the SED of V4334 Sgr depends critically on $T_{\rm eff}$ (Pavlenko & Yakovina 2000). For the spectrum of August 12, 1998, a best fit was obtained for $T_{\rm eff} \sim 5250$ K and $E_{B-V} = 1.3$ (Fig. 4). The fit is based on the Asplund et al. (1999) abundances for October 1996. The corresponding values derived for our spectrum of April 29, 1997, are $T_{\rm eff} = 5500$ K and $E_{B-V} = 0.7$ (Pavlenko et al. 2000). In contrast to the rapid cooling of V4334 Sgr in 1996, $T_{\rm eff}$ has apparently declined by only ~250 K in the course of the $15\frac{1}{2}$ months between early 1997 and mid-1998.

4. Discussion

Our SEDs were computed in the plane-parallel approach. This may be used for $T_{\rm eff} = 5500$ K (see discussions in Asplund et al. 1998; Pavlenko et al. 2000), but model atmospheres for $T_{\rm eff} = 5250$ K are more likely affected by sphericity effects. Fits of model atmospheres with $\log g = 0$ and $\log g = 1$ to the observed spectrum have similar quality. This, however, only indicates that the dependence of the model on gravity is rather weak.

It is noteworthy that our theoretical fluxes are much too high, between 600 and 700 nm, which suggests that an important molecular line opacity is missing. A similar effect was noted by Asplund et al. (1997) in R CrB for λ 500 nm. It is doubtful that the assumption of geometry and homogeneity is able to produce a shortage of flux at such a very specific wavelength interval. In V4334 Sgr, the effect is probably caused by the absorption of one or more molecules which are not yet identified.

The observed and computed spectra for August, 1998 are more discrepant in the blue region, while the fit in the red looks acceptable. A similar phenomenon was found in the investigation of the April 1997 spectrum. By August 1998 the dust envelope had become thick, while it was absent or marginal in April 1997. Thus we conclude that the discrepancies are likely not caused by dust, but by one of the other effects outlined above. In the frame of our simple model, which assumes that the circumstellar and the interstellar dust have similar properties in the visible part of the spectrum, E_{B-V} increased from 0.7 to 1.3, according to our spectroscopic analysis. Apparently, in 1997 there was no "active" optical circumstellar reddening in the line of sight, which is proven by the similar effective temperatures derived from spectroscopy and photometry (Fig. 2 of Asplund et al. 1997), while at that time some dust clouds may have already formed outside the line of sight, in order to account for the IR excess as observed by Kimeswenger et al. (1997) and Kamath & Ashok (1999). The increase in E_{B-V} between April 1997 and August 1998, $\Delta E_{B-V} = 0.6$, is thus caused by circumstellar reddening of newly formed dust. If the optical properties of this material are similar to those of interstellar material, it should cause a drop in V by $0.6 \times 3.1 \sim 1.85$ mag (with an uncertainty of ± 0.1) with respect to a "dust-free" lightcurve.

In order to estimate the magnitude of V4334 Sgr in such a "dustfree" lightcurve, the trend in the 1996–97 V light curve (as taken from Duerbeck et al. 2000) was linearly extrapolated to August, 1998, and an "expected" magnitude of $V = 10.75$ was derived; if the 1997 data alone are used for an extrapolation, the result is $V = 10.65$. In fact, the object is observed at $V = 12.55$. If we trust in the validity of the linear extrapolation, the circumstellar A_V, which is necessary to arrive at the observed brightness, is 1.85 ± 0.05, in good agreement with the value expected from the result of the spectroscopic study.

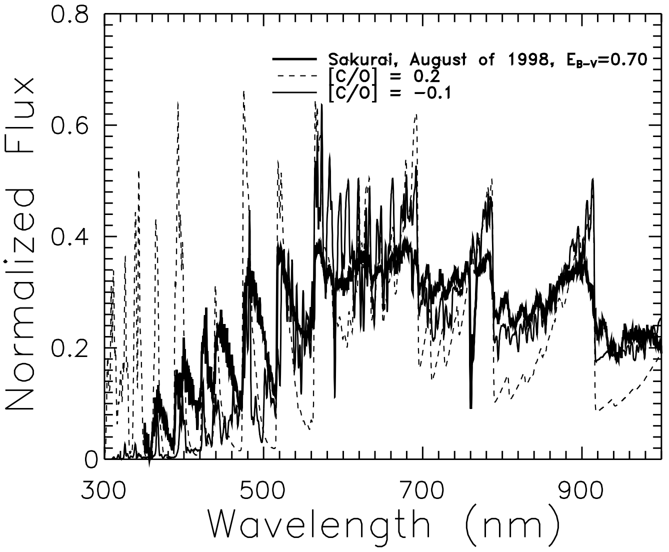

Fig. 5. Fits to SEDs with model 4000/0.0 of different abundances. The expected very strong carbon bands can be decreased in strength by reducing the C/O ratio, but the overall fit would still be poor

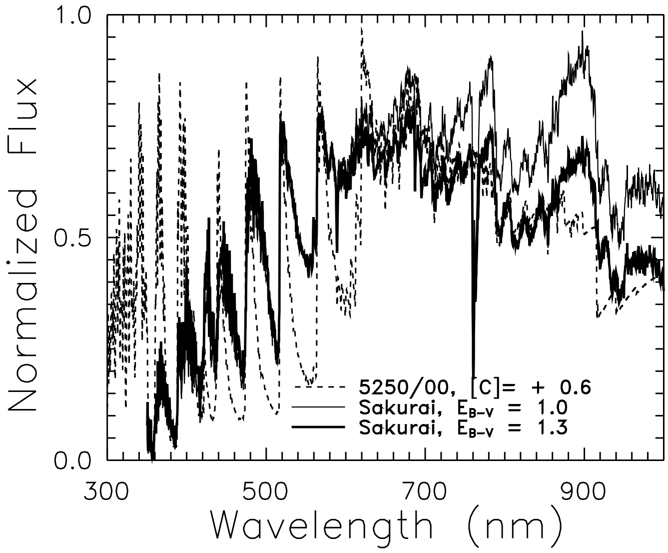

Fig. 6. Fits to SEDs of August 12, 1998 dereddened for $E_{B-V} = 1.0$ and 1.3 with model 5250/0.0 of the "carbon-rich" case. There are some obvious problems of the fittings in the red and in the blue

Is there another way to explain the observed spectrum of August, 1998, e.g. by keeping the reddening at its original value of $E_{B-V} = 0.7$, and decreasing the surface temperature? If $T_{\rm eff}$ is assumed to be as low as 4000 K, a general agreement with the overall SED may be achieved, but the fit to the molecular bands is extremely poor. The fit cannot be improved, even if the abundances of C, N, O are permitted to vary (Fig. 5). Here we show computations for different C/O ratios (given in logarithmic scales). If O is more abundant than C, a completely different molecular chemistry takes place, and bands of oxygen compounds would appear in V4334 Sgr. Figure 5 illustrates that any changes of carbon abundances do not result in a better fit of the observed spectrum.

The estimate of $T_{\rm eff}$ depends on the assumed E_{B-V}. Figure 6 shows some fits of computed spectra to the observed spectrum of V4334 Sgr, dereddened for $E_{B-V} = 1.0$. There we also plot the SED of V4334 Sgr, computed for the "carbon-rich" case. This permits us to better assess the uncertainties in these estimates. As we see in Fig. 6, our fit with $E_{B-V} = 1.0$ looks less perfect both in the red and in the blue both for the Asplund et al. (1999) abundances for May 1996 and even for the "carbon-rich" case. Neither variations of $\log N(\rm C)$ nor of E_{B-V} allow us to obtain a better fit to the SED observed in August, 1998.

Thus we conclude that $T_{\rm eff}$ of V4334 Sgr was near 5250 K in August, 1998, and that the overall modification of the SED is caused by circumstellar dust.

The temporal changes of $T_{\rm eff}$ during 1996–1998 are shown in Fig. 7. Following the assumption of Duerbeck et al. (1998), that changes of $T_{\rm eff}$ were caused by the growth of the pseudophotosphere surrounding a mass-losing object that radiates at approximately constant luminosity, we conclude that its expansion had noticeably slowed down or had even almost come to a halt during 1997–1998, and its temperature had almost stabilized. This stage was accompanied by dust formation processes in the envelope above the stellar photosphere, whose strength increased with time. The object recovered only partly from these events, so that by the second half of 1999 the photosphere of V4334 Sgr had become basically invisible in the optical region.

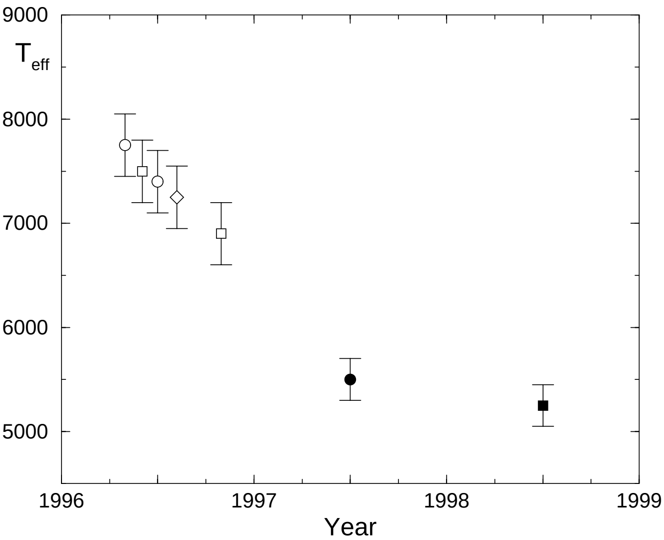

Fig. 7. Temporal changes of $T_{\rm eff}$ in V4334 Sgr. Open circles: Asplund et al. (1997), open squares: Asplund et al. (1999), open diamond: Kipper & Klochkova (1997), filled circle: Pavlenko et al. (2000), filled square: this paper

5. Conclusions

A comparison of the observed spectra of V4334 Sgr in April, 1997 and August, 1998 with computed SEDs shows that the temperature of the radiating atmosphere had only decreased in $T_{\rm eff}$ by 250 K, while the E_{B-V} had increased by 0.6. This appears to be in perfect agreement with the observed depression in the visual light curve, if a standard interstellar extinction law $A_V = 3.1 \times E_{B-V}$ is assumed for newly formed circumstellar dust. Thus there is not only photometric, but also spectroscopic evidence that (a) the light curve depressions are caused by dust, and that (b) the luminosity and mass loss changed in such a way that the pseudophotosphere was kept at an almost constant effective temperature in 1997–1998.

Acknowledgements. We cordially thank Dr. A. Piemonte for taking the spectrum, Prof. T. Kipper and Dr. M. Asplund for useful discussions, and the VALD database team for helpful service. Partial financial support of the investigations of Ya. Pavlenko was provided by a Small Research Grant of the American Astronomical Society.

References

Asplund, M., Gustafsson, B., Lambert, D. L., & Rao, N. K. 1997, A&A, 321, L17
Asplund, M., Gustafsson, B., Kameswara Rao, N., & Lambert, D. L. 1998, A&A, 332, 651
Asplund, M., Lambert, D. L., Kipper, T., Pollacco, D., & Shetrone, M. D. 1999, A&A, 343, 507
Asplund, M., Gustafsson, B., Lambert, D. L., & Rao, N. K. 2000, A&A, 353, 287
Clayton, G. C., & de Marco, O. 1997, AJ, 114, 2679
Duerbeck, H. W., & Benetti, S. 1996, ApJ, 468, L111
Duerbeck, H. W., van Genderen, A., Jones, A., & Liller, W. 1999, South. Stars, 38, 80
Duerbeck, H. W., Liller, W., Sterken, C., et al. 2000, AJ, 119, 2360
Hofsaess, D. 1979, Atom. data Nucl. data Tab., 24, 285
Kamath, U. S., & Ashok, N. M. 1999, MNRAS, 302, 512
Kerber, F., Palsa, R., Köppen, J., Blöcker, T., & Rosa, M. R. 2000, ESO Messenger, No. 101, 27
Kimeswenger, S., Gratl, H., Kerber, F., et al. 1997, IAU Circ., 6608
Kipper, T., & Klochkova, V. 1997, A&A, 324, L65
Liller, W., Janson, M., Duerbeck, H. W., & van Genderen, A. M. 1998, IAU Circ., 6825
Nakano, S., Sakurai, Y., & Benetti, S., et al. 1996, IAU Circ., 6322
Pavlenko, Y. V., & Yakovina, L. A. 1994, Astrophys. Rep., 38, 768
Pavlenko, Ya. V. 1997, Ap&SS, 253, 43
Pavlenko, Ya. V. 1999, Astron. Rep., 43, 94
Pavlenko, Ya. V., & Yakovina, L. A. 2000, Astron. Rep., 44, 209.
Pavlenko, Ya. V., Yakovina, L. A., & Duerbeck, H. W. 2000, A&A, 354, 229
Pavlenko, Ya. V. 2000, Ap&SS, submitted
Piskunov, N. E., Kupka, F., Ryabchikova, T. A., Weiss, V. V., & Jeffery, C. S. 1995, Ap&SS, 112, 525
Pollacco, D. 1999, MNRAS, 304, 127