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The continuing saga of Sakurai's object (V4334 Sgr): dust production and helium line emission

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ABSTRACT

We report further UKIRT spectroscopic observations of Sakurai's object (V4334 Sgr) made in 1999 April/May in the 1–4.75 μm range, and find that the emission is dominated by amorphous carbon at $T_\mathrm{d} \sim 600\,\mathrm{K}$. The estimated maximum grain size is 0.6 μm, and the mass lower limit is $1.7 \pm 0.2 \times 10^{-8}\,\mathrm{M}_\odot$ to $8.9 \pm 0.6 \times 10^{-7}\,\mathrm{M}_\odot$ for distances of 1.1–8 kpc. For 3.8 kpc the mass is $2.0 \pm 0.1 \times 10^{-7}\,\mathrm{M}_\odot$.

We also report strong He I emission at 1.083 μm, in contrast to the strong absorption in this line in 1998. We conclude that the excitation is collisional, and is probably caused by a wind, consistent with the P Cygni profile observed by Eyres et al. in 1998.

Key words: stars: AGB and post-AGB – circumstellar matter – stars: individual: Sakurai's object – stars: individual: V4334 Sgr – infrared: stars.

1 INTRODUCTION

Sakurai's object (V4334 Sgr) has been identified as a born-again giant undergoing its final helium shell flash (Benetti et al. 1996), and is the first star seen in this stage of evolution since V605 Aql in 1919. Furthermore, this is the first time that a final helium flash object has been observed using non-optical techniques, and Sakurai's object gives us a rare glimpse into a rapid phase of the post-AGB evolution of a low- to intermediate-mass star.

A post-AGB star is a cool red giant that has ejected its envelope following the development of a superwind, exposing the hot core. The core of Sakurai's object has undergone H and He burning, producing a carbon- and helium-rich object, which is also hydrogen-poor (Asplund et al. 1997, 1999). This combination is similar to the R Coronae Borealis (RCB) stars, which undergo periods of fading as a result of the occasional production of carbon dust that temporarily obscures the star (Clayton 1996). The similar optical fading of Sakurai's object can be seen in Fig. 1. Our previous infrared observations (Eyres et al. 1998b) detected the presence of graphitic carbon dust, photospheric CN, C_2 and CO, whilst later observations showed a strong He I 1.083 μm P Cygni profile (Eyres et al. 1999), suggesting that Sakurai's object is in an RCB-like phase. Here we report United Kingdom Infrared Telescope (UKIRT) observations during the deep optical minimum that began in early 1999.

2 OBSERVATIONS

Spectra of Sakurai's object in the 1–5 μm region were obtained at UKIRT on 1999 April 22 and May 4. The spectra were obtained with the facility instrument CGS4, using standard observing procedures. Details of the observations are provided in Table 1, in which R is the resolving power. The calibration stars, all F dwarfs located reasonably close in the sky to Sakurai's object ($\alpha = 17^\mathrm{h}52^\mathrm{m}32^\mathrm{s}$, $\delta = -17°41'07''$, J2000), were observed either before or after it in order to provide a close match in airmass. The assumed magnitudes of the calibration stars were determined from the known visual magnitudes (Simbad data base) and standard colour relations (Tokanaga 1999). Absorption lines of hydrogen were removed from the spectra of the calibration stars prior to ratioing; a few could not be removed because of coincidences with strong telluric absorption lines; in such cases we interpolated across the induced emission feature in the final flux-calibrated spectrum. Similarly, we interpolated across residual absorptions or emissions in the vicinity of a few of the strongest telluric absorption features in cases where the features did not divide out.

The high-resolution 1.06–1.12 μm spectrum, obtained on 1999 May 4 with a 150 line mm^{-1} grating in third order, is contaminated by longer-wavelength radiation in second order. It was obtained solely to measure the He I 1.083-μm line profile, which is not affected by the contamination. Flux calibrations of the other spectra are uncertain by ±30 per cent.

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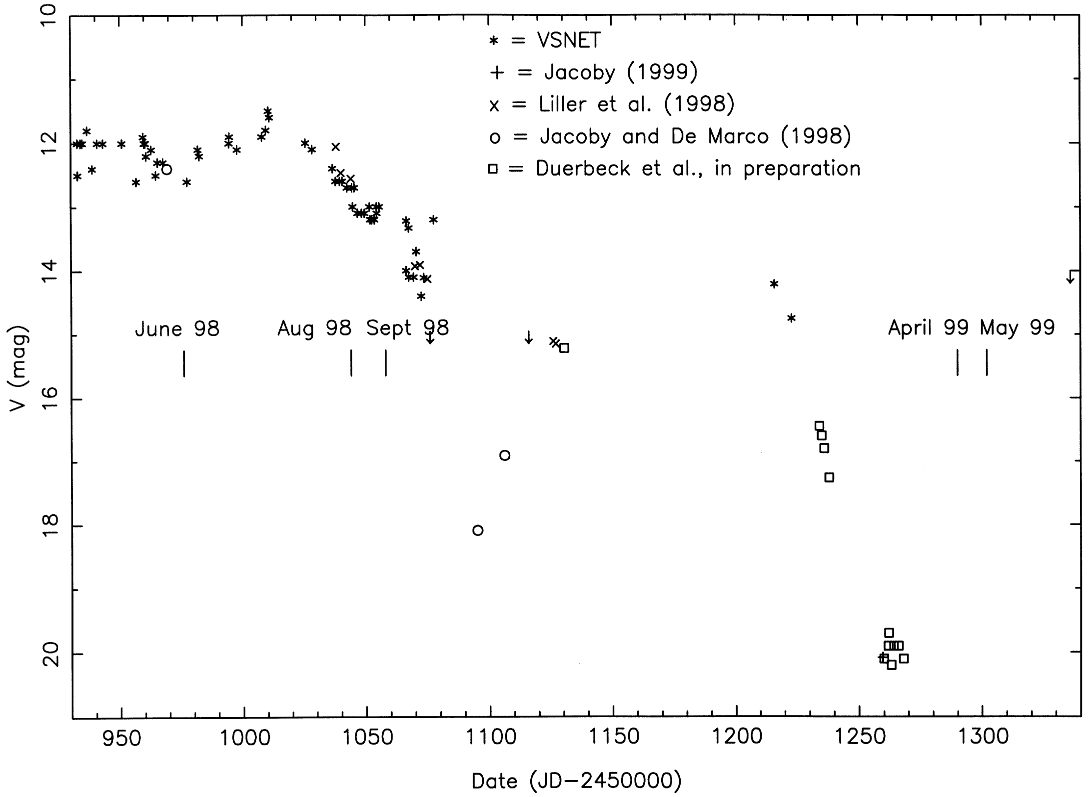

Figure 1. *V*-magnitude light curve covering the period of our 1998 and 1999 observations extended to show the development of the fading period. Dates of our observations are marked with vertical lines. Downward arrows indicate limits from Liller et al. (1998); the sources of the other points are as indicated. The June, August and September dates are of our earlier infrared observations (Eyres et al. 1999).

Table 1. Log of UKIRT observations.

Date	λ range (μm)	R	Slit (arcsec)	Exposure (s)	Calibrator star			Calibrator magnitude
					ID	α, δ (J2000)		
1999 April 22	1.03–1.35	950	0.6	720	HD 153363	17 00 09	−24 59 20	$J = 4.96$
	1.41–2.05	690	0.6	192	HD 153363			$H = 4.75$
	1.88–2.52	880	0.6	144	HD 153363			$K = 4.71$
1999 May 04	1.06–1.12	4800	0.6	1440	HD 157968	17 27 02	−12 30 45	$J = 5.23$
	2.98–3.62	1300	0.6	240	HD 159876	17 37 35	−15 23 54	$L = 2.77$
	4.59–4.75	7400	0.6	216	HD 159876			$M = 2.77$

3 RESULTS AND DISCUSSION

The *JHKLM* spectrum is shown in Fig. 2. In the *L* and *M* bands emission features due to absorption lines in the calibration star are superimposed on the dust continuum (see Section 2); these were removed before further analysis. All data were dereddened taking $E(B-V) = 1.15$ (Eyres et al. 1998a).

3.1 The dust

The emission in the *K*, *L* and *M* bands is clearly dominated by dust. As the star may still contribute at *K*, the *L*- and *M*-band data obtained on the same date only were fitted with a function of the form $(c/\lambda)^{\beta} B_{\lambda}(T_{\rm d})$, where $T_{\rm d}$ is the dust temperature and β is the β index of the dust defined in terms of dust emissivity $\epsilon \propto \lambda^{-\beta}$ in the normal way. The best fit was obtained with $\beta = 1.0 \pm 0.3$, at a temperature of 600 ± 30 K. Since the emission peaks at $\lambda_{\max} \sim 4\,\mu$m and $\beta \approx 1$, we can use the relationship $(2\pi a/\lambda_{\max}) < 1$, where a is the grain radius, to estimate a maximum grain radius of $0.6\,\mu$m. Assuming that (i) the dust shell is optically thin for $\lambda \lesssim 5\,\mu$m, (ii) the dust is amorphous carbon, consistent with $\beta \approx 1$, and (iii) the carbon emissivity as in Evans et al. (1998), the mass of the dust, for $E(B-V) = 1.15$ and distance D kpc, was found to be $1.4 \pm 0.1 \times 10^{-8} D^2\,{\rm M}_{\odot}$. The dip in the visual band and lack of stellar component in the near-infrared indicate that the dust is optically thick, so that the mass obtained is therefore a lower limit. The distance to Sakurai's object is not well determined, but a lower distance estimate of 1.1 kpc (Kimeswenger & Kerber 1998) and an upper of 8 kpc (Duerbeck et al. 1997) give a range for the dust mass from $1.7 \pm 0.2 \times 10^{-8}\,{\rm M}_{\odot}$ to $8.9 \pm 0.6 \times 10^{-7}\,{\rm M}_{\odot}$. If we take $D = 3.8$ kpc, as in our previous papers, then $M_{\rm dust} = 2.0 \pm 0.1 \times 10^{-7}\,{\rm M}_{\odot}$.

If the spectra are dereddened by $E(B-V) = 0.71$ (Pollacco 1999), the best fit is obtained at a temperature of 590 ± 30 K, again with $\beta \approx 1.0 \pm 0.3$. Using the same assumptions as above, the mass of the dust at a distance of D kpc was found to be $1.1 \pm 0.2 \times 10^{-8} D^2\,{\rm M}_{\odot}$. Hence the value of $E(B-V)$ used has only a small effect on the M/D^2 ratio.

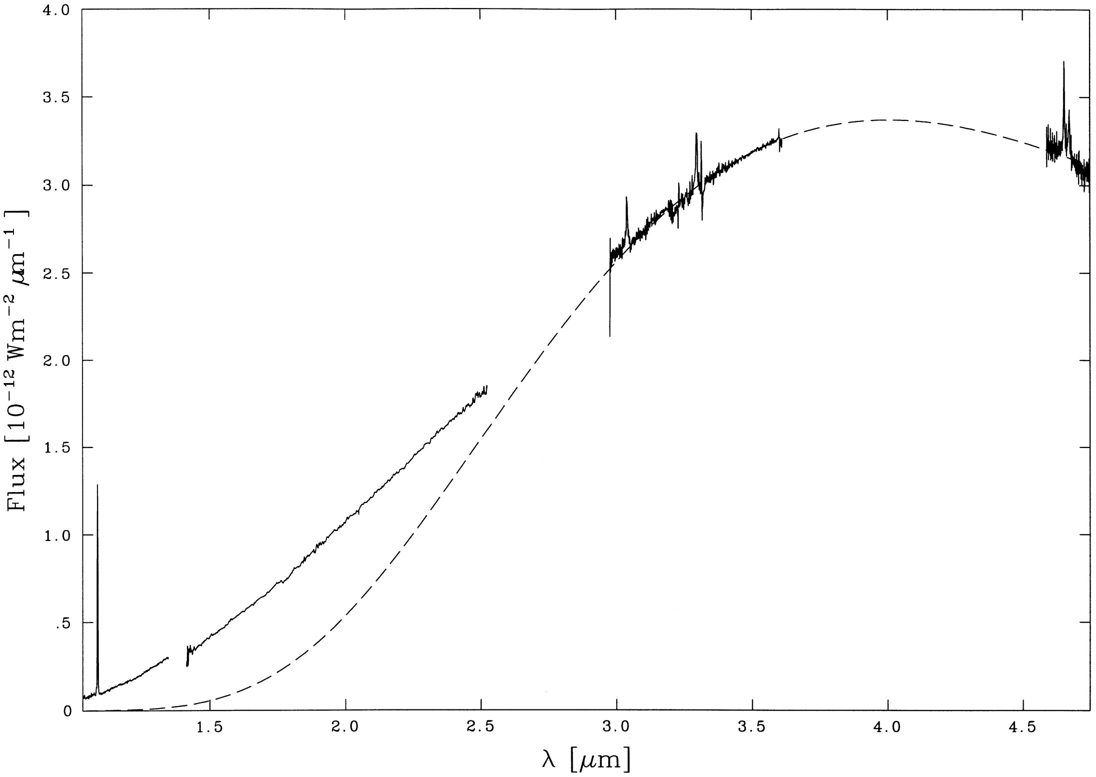

Figure 2. *JHKLM* composite dereddened spectrum from UKIRT. The *JHK*-band data are from 1999 April 22 and the *LM*-band data from 1999 May 04. The apparent emission features between 3.0 and 4.7 μm superimposed on the dust continuum arise in the calibration star. The (dotted line) fit to the dust continuum is for carbon at ~580 K (see text). Note the strong helium emission at 1.083 μm.

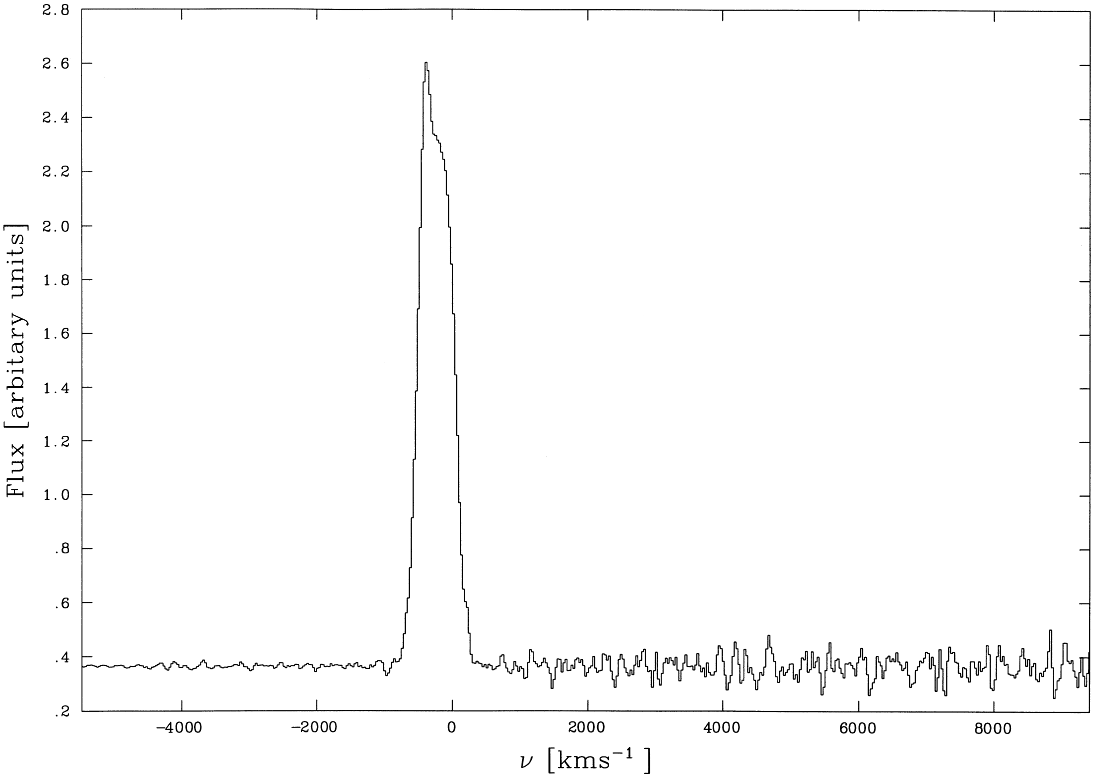

Figure 3. The continuum-subtracted He I line at 1.083 μm, which is seen for the first time without the P Cygni absorption profile reported by Eyres et al. (1999). The velocity frame is in the rest frame of the He I line.

Fading is observed in the optical light curve of Sakurai's object, presumably because of obscuration by dust formation (Fig. 1). In the observation of 1997 July 7 (Eyres et al. 1998b), the continuum level decreases with increasing wavelength because emission from the central star is the major contributor to the continuum flux. In the present data this decrease is absent, suggesting that the stellar contribution to the flux shortward of ~2.4 μm is swamped by the contribution from the dust (Eyres et al. 1998b). However, the simple dust model underestimates the *JHK* bands, indicating that a more sophisticated analysis of the dust emission is needed for this part of the spectrum. This is beyond the scope of this paper, and we will present a more detailed analysis elsewhere.

The dust emission described here is compared with the *ISO* data (Eyres et al. 1998b), obtained on 1998 April 14, which suggested graphitic dust at a temperature of ~680 K. The peak infrared flux has increased by a factor of 10 from that observed by Eyres et al. (1998b). This implies that we are seeing the formation of significantly more dust than previously existed. The visual magnitude of the star has remained exceptionally faint for ~200 d, suggesting that the dust is obscuring the star completely. At present it is not clear if the 1997 and 1999 emissions are from the same dust. However, it is difficult to see how graphitic ($\beta \approx 2, \mathrm{sp}^2$) dust can be converted to amorphous ($\beta \approx 1, \mathrm{sp}^3$) in a hydrogen-poor environment (Duley & Williams 1990). While, as noted above, a more rigorous analysis of the dust emission is necessary, the likelihood is therefore that the 1997 and 1999 dusts are different.

Kerber et al. (1999) observed a dust continuum on 1997 February 25 using ISOCAM photometry. Their results indicate that the peak infrared flux increased by a factor of 10 from that observed by Eyres et al. (1998b), in agreement with UKIRT observation. They found $T_\mathrm{d} \sim 1500\,\mathrm{K}$, significantly hotter than our value. From the data presented here we cannot say whether the dust is in the form of blobs that are eclipsing the star or is in the form of complete shells surrounding the star.

3.2 The He line

In the most recent spectra, the deep He I 1.083 μm absorption feature observed by Eyres et al. (1999) has disappeared, leaving only a strong He I emission (see Fig. 3). Comparison of the emission-line flux with those in earlier spectra (see Table 2) shows that it has not changed since early 1998. It has been unaffected by fading of the visual flux (Fig. 4), suggesting that it is not caused by irradiation. Furthermore the absence of He II emission lines (e.g. $\lambda = 1.256\,\mu\mathrm{m}$) in the spectrum indicates that the He I emission is not due to recombination. The He I emission arises from the transition from the $2\mathrm{p}^3\mathrm{P}$ state to the metastable $2\mathrm{s}^3\mathrm{S}$ state (Osterbrock 1964). All this indicates that excitation is collisional. The probable mechanism for the collisions is a wind, consistent with the P Cygni profile previously observed by Eyres et al. (1999).

For such a wind, the full width at half-maximum of the line

Table 2. Helium line flux.

Date	Flux ($10^{-16}\,\mathrm{W\,m^{-2}}$)
1998 March 17	10.0 ± 0.3
1998 April 21	9.4 ± 0.3
1998 June 11	10.0 ± 0.3
1998 August 18	9.5 ± 0.2
1999 April 21	10.3 ± 0.3
1999 April 22	11.6 ± 0.3

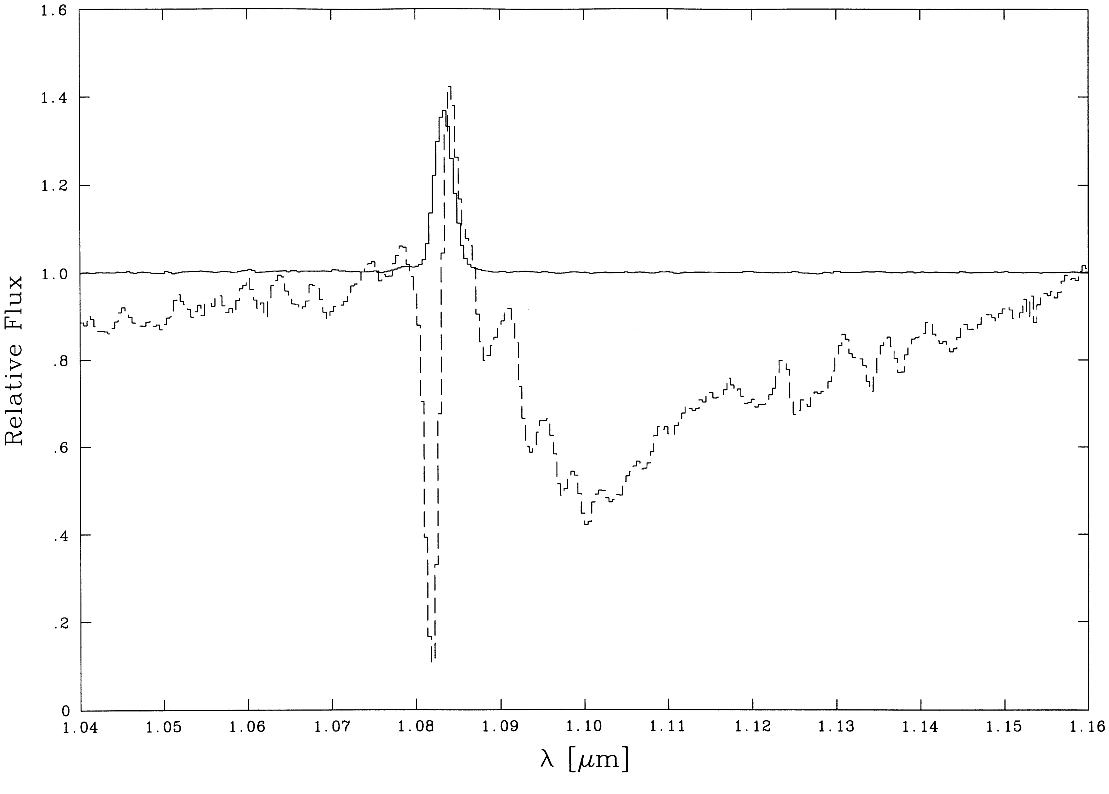

Figure 4. The 1999 April 21 He I emission line (solid line) overlaid with the He I line with P Cygni profile from 1998 August 18 (dotted line), indicating that the line emission flux is unchanged.

suggests a velocity of $\sim 600 \pm 30\,\mathrm{km\,s^{-1}}$, which is consistent within the uncertainties with the $\sim 670 \pm 50\,\mathrm{km\,s^{-1}}$ obtained by Eyres et al. (1999). This suggests that the line emissions seen in 1998 and 1999 are produced by the same wind. However, the present observations indicate that the star is now completely obscured. The peak of the He I emission line shows some non-uniformity (Fig. 3), suggesting that there is structure in both the wind and the dust shell. By comparing the He I line from 1999 April 21 with that from 1998 August 18, it can be seen that, in 1999, the line has reduced flux on the redward side and increased on the blue (Fig. 4). This is consistent with a dust shell obscuring not only the star but also the receding wind beyond the star. This interpretation requires a more detailed analysis, in particular taking into account multiscattering. This is beyond the scope of this paper and will be addressed in future work.

4 CONCLUSIONS

Sakurai's object is in an RCB-like phase, and is undergoing a period of high mass loss and dust production. Comparison of the amorphous carbon dust consistent with UKIRT observations and the graphitic dust observed with ISO suggests that two distinct types of dust have been produced. The dust seen in 1999 is responsible for the obscuration of the central star.

The He emission at 1.083 μm seen in the present observations and the broad P Cygni profile absorption feature (Eyres et al. 1999), which is now obscured by the strong dust emission, can be attributed to an ejected shell containing helium, which is stimulated to emission by collisions within a wind.

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