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The rapid evolution of the born-again giant Sakurai's object

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Abstract. The extraordinarily rapid evolution of the born-again giant Sakurai's object following discovery in 1996 has been investigated. The evolution can be traced both in a continued cooling of the stellar surface and dramatic changes in chemical composition on a timescale of a mere few months. The abundance alterations are the results of the mixing and nuclear reactions which have ensued due to the final He-shell flash which occurred during the descent along the white dwarf cooling track. The observed changes in the H and Li abundances can be explained by ingestion and burning of the H-rich envelope and Li-production through the Cameron-Fowler mechanism. The rapidly increasing abundances of the light s-elements (including Sc) are consistent with current s-processing by neutrons released from the concomitantly produced ^{13}C. However, the possibility that the s-elements have previously been synthesized during the AGB-phase and only mixed to the surface in connection with the final He-shell flash in the pre-white dwarf cannot be convincingly ruled out either. Since Sakurai's object shows substantial abundance similarities with the R CrB stars and has recently undergone R CrB-like visual fading events, the "birth" of an R CrB star may have been witnessed for the first time ever. Sakurai's object thus lends strong support for the suggestion that at least some of the R CrB stars have been formed through a final He-shell flash in a post-AGB star.

Key words: stars: variables: general – stars: individual: Sakurai's object – stars: AGB and post-AGB – stars: evolution – stars: abundances

1. Introduction

Normally stellar evolution proceeds on time scales of millions or billions of years. Notable exceptions are e.g. supernovae, though such cataclysmic events only mark the end point of the evolution as normal stars. Witnessing stellar evolution in real time without a simultaneous complete destruction of the star is thus very rare. "Born-again" giants do, however, offer such a remarkable opportunity, which offers important windows through which stellar nucleosynthesis and evolution can be glimpsed.

On its initial descent of the white dwarf cooling track, a star may be ballooned back to supergiant dimensions by a final He-shell flash which is triggered by the compressional heating of the stellar interior. Rather than fading steadily to oblivion as a white dwarf the star makes a second appearance as a luminous giant, a "born-again" giant. Theoretical estimates suggest that about 10% of all low- and intermediate mass stars going through a planetary nebula phase will experience such a final He-shell flash (Renzini 1990; Iben et al. 1996). The observational rarity of such events is the result of the very short life-time as a born-again giant – typically 100–1000 years, depending mainly on the stellar envelope mass – before it completes its loop in the Hertzsprung-Russell diagram and once again starts contracting to become a white dwarf, this time for good.

To date, only three stars are believed to have been observed going through a born-again phase: V605 Aql (Nova Aql 1919), FG Sge and the recently discovered Sakurai's object (V4334 Sgr) (Nakano et al. 1996). A further handful of stars (e.g. Abell 30 and Abell 78) presently in a seemingly second stage as planetary nebulae may be identified as having recently been born-again giants. Furthermore, the R CrB variables could also possibly be born-again giants (Asplund et al. 1997b; Asplund et al. 1998; Lambert et al. 1998); their H-deficiency can be explained if the final He-shell flash occurs after the outer H-burning shell has been extinguished, in which case the convection zone due to the He-flash may ingest and burn the H-rich envelope.

Both V605 Aql, FG Sge and Sakurai's object have shown a remarkably fast stellar evolution. From having been an O star at the end of last century (van Genderen & Gautschy 1995), FG Sge has continued to brighten in the visual while cooling, presumably the result of the expansion following the final He-shell flash (see Kipper 1996 for a recent review). Furthermore, an enrichment of s-process elements which took place within seven years has been reported (Langer et al. 1974). Lately, FG Sge has also started to show R CrB-like variability (Papousek 1992), which may classify the star as a "new-born" R CrB star, in particular since there are hints that the star may be H-deficient (Gonza-

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lez et al. 1998). After discovery in 1996, Sakurai's object has shown an exceedingly rapid evolution, even out-pacing FG Sge; whether or not it is evolving faster than V605 Aql is difficult to judge considering the scarceness of data from the outburst in 1919 but the evolutionary speed for V605 Aql may have been comparable (Clayton & de Marco 1997). Like FG Sge Sakurai's object has cooled significantly (Asplund et al. 1997b; Duerbeck et al. 1997). More impressively though, its chemical composition seems to have been altering drastically on a time scale of a mere few months (Asplund et al. 1997b). FG Sge's title as the "fastest evolving star ever identified" (van Genderen & Gautschy 1995) is certainly called in doubt by Sakurai's object.

Sakurai's object offers a unique opportunity to study stellar evolution and attendant nucleosynthesis in real time. Several papers has been devoted to the star and its remarkable evolution (e.g. Asplund et al. 1997b; Duerbeck & Benetti 1996; Duerbeck et al. 1997; Eyres et al. 1998; Jacoby et al. 1998; Kimeswenger & Kerber 1998; Kipper & Klochkova 1997; Shetrone & Keane 1998). However, the published abundance analyses of the star have relied on very different model atmospheres and spectral features, making a direct comparison of the results difficult. Therefore we have re-analysed the available spectra, both published (Asplund et al. 1997b; Kipper & Klochkova 1997; Shetrone & Keane 1998) and unpublished (D. Pollacco and G. Wallerstein, unpublished research), in a homogeneous way, using the same model atmospheres and whenever possible the same spectral lines to avoid as far as possible systematic differences. The resultant map of the evolution of its composition offers important clues to the star's immediate past history.

2. Observations

Some of the observations on which the present study is based have previously been used by Asplund et al. (1997b), Kipper & Klochkova (1997) and Shetrone & Keane (1998) for abundance analyses. For completeness we repeat the observational details here, together with the relevant information on the previously unpublished spectra.

The spectra of Asplund et al. (1997b) cover 3 700–10 150 Å at a resolving power of about 30 000 and were obtained with the 2.7 m telescope at McDonald Observatory on May 5 and 6 and on October 7, 1996. Another spectrum was acquired with the McDonald 2.1 m telescope on May 9, 1996, which covers the region 5 720 Å to 7 200 Å at a resolving power of about 60 000; the three May spectra have been combined to a single line list. Shetrone & Keane (1998) observed Sakurai's object on April 20, 1996, with CTIO 4 m telescope with a resolving power of about 14 000. The spectrum covers the region 3 800–7 500 Å with S/N ranging from 100 to 200, depending on the wavelength region. In addition G. Wallerstein (unpublished research) obtained a spectrum of the star with the CTIO 4 m telescope at a resolving power of about 12 500 on April 25. The two April spectra have here been combined to one line list though greater weight has been given to the April 20 spectrum due to its higher quality. A spectrum obtained with the William Herschel 4.2 m telescope (Pollacco, unpublished research) was acquired on June 4, 1996, at a resolving power of 45 000 and S/N of about 70. The spectrum covers the wavelength region 3 800–8 000 Å. Finally, Kipper & Klochkova (1997) obtained spectra of the star on July 3, 1996, with the echelle spectrometer on the Russian 6 m telescope, providing a spectral resolving power of about 20 000 and S/N of around 75. The wavelength coverage was 5 000–8 000 Å. In addition, other spectra obtained by us or kindly provided by various colleagues have been attempted for abundance analyses, but in all cases the resolution proved insufficient for reliable results, and they are therefore not included in the present study.

With the exception of a few spectral regions for which spectral synthesis was carried out (see below), the abundance analysis is based on lines for which equivalent widths could be measured readily. The line lists for the April, June and July spectra were modelled with the aid of the line list used by Asplund et al. (1997b) for the May and October observations whenever the spectral coverage allowed. The lines are thus in general not the same in the present study as in the original works by Shetrone & Keane (1998) and Kipper & Klochkova (1997). Spectral synthesis was applied to a few wavelength regions of particular interest: Hα, Hβ, the C_2 Swan 0–1 and 1–0 band-heads, the Li D doublet at 6 707 Å, the blended C II lines at 6 578.05 Å and 6 582.88 Å and the He I D_3 line at 5 876 Å, which is blended by two C I lines. The adopted atomic data were the same as in Lambert et al. (1998). The gf-values for the C I lines present in the above synthesized regions were decreased according to the magnitude of the "carbon problem" (typically 0.7 dex) of the individual spectra, see Sect. 3.

3. Derivation of the stellar parameters

In order to derive accurate stellar parameters a range of different $T_{\rm eff}$ and $\log g$ criteria was utilized: ionization balance (mainly N I/N II, Si I/Si II, Cr I/Cr II, and Fe I/Fe II), excitation balance (O I, Fe I and Fe II), and line strengths of sensitive spectral features (C_2, C II and He I lines). The extended line wings of Hα and Hβ allowed a determination of the stellar H abundance, but the profiles also provided additional information on the adopted $T_{\rm eff}$ and $\log g$ (Fig. 1). The microturbulence parameter $\xi_{\rm t}$ was estimated mainly from C I, Ti II, Fe I, Fe II and Y II lines of different strengths; to within the uncertainties all species indicated the same $\xi_{\rm t}$. The derived temperatures from $B-V$ colours (Duerbeck et al. 1997) assuming a reddening of $E(B-V)=0.70$ (N.K. Rao, private communication) provided another temperature estimate which was in very good agreement with the other criteria (Fig. 2). Line-blanketed, hydrogen-deficient model atmospheres similar to those described by Asplund et al. (1997a) but with a range of hydrogen abundances especially constructed for the present analysis formed the basis of the investigation.

Since the present study of the May and October 1996 spectra is based on the same observations, spectral lines and model atmospheres as in Asplund et al. (1997b), the previously derived stellar parameters for May ($T_{\rm eff}=7\,500\pm300$ K, $\log g=0.0\pm0.3$, $\xi_{\rm t}=8.0\pm1.0$ km s^{-1}) and October ($T_{\rm eff}=6\,900\pm300$ K, $\log g=0.5\pm0.3$, $\xi_{\rm t}=6.5\pm1.0$ km s^{-1}) did not warrant a re-consideration. Within the framework of the present analysis

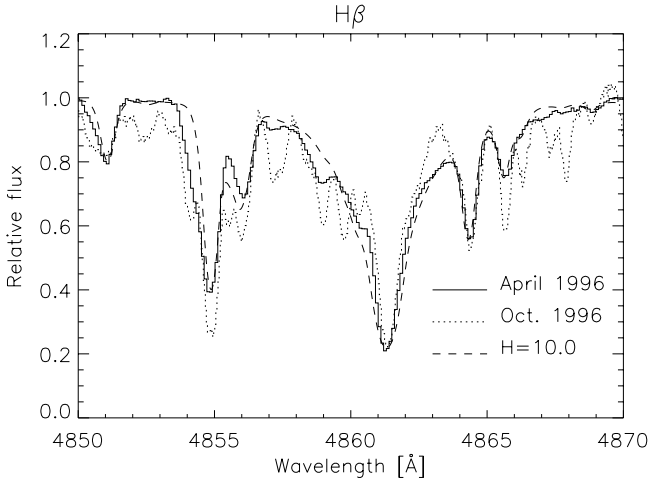

Fig. 1. Hβ in Sakurai's object in April (solid) compared with in October (dotted) 1996. The dashed line represents the spectral synthesis of the April spectrum using a H-abundance of 10.0. Note that all features but Hβ had became stronger in October as a result of the decreasing continuous opacity with a diminishing H-content and in some cases an increased elemental abundance (e.g. the s-elements)

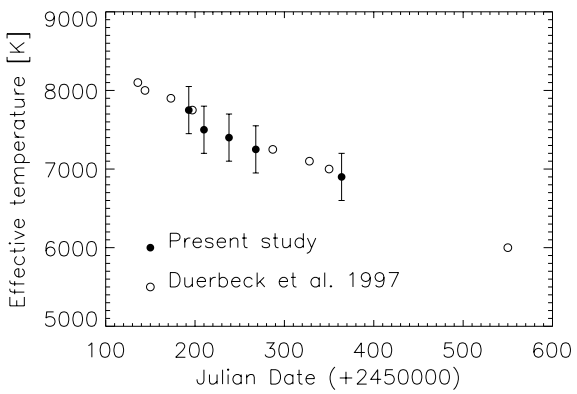

Fig. 2. The evolution of the effective temperature of Sakurai's object since discovery in 1996 and 1997 as judged from spectroscopy (present study) and $UBVRiz$ photometry (Duerbeck et al. 1997). The estimated temperatures reveal an essentially linear decrease with time. It should be noted that the last photometric data point is significantly more uncertain than the other estimates

the April spectrum is characterized by $T_{\rm eff} = 7\,750 \pm 300$ K, $\log g = 0.25 \pm 0.3$ and $\xi_{\rm t} = 10.5 \pm 1.0\,{\rm km\,s^{-1}}$. The June spectrum indicates $T_{\rm eff} = 7\,400 \pm 300$ K, $\log g = 0.4 \pm 0.3$ and $\xi_{\rm t} = 8.5 \pm 1.0\,{\rm km\,s^{-1}}$. Similarly the July spectrum is adequately described using $T_{\rm eff} = 7\,250 \pm 300$ K, $\log g = 0.5 \pm 0.3$ and $\xi_{\rm t} = 8.5 \pm 1.0\,{\rm km\,s^{-1}}$. The slight differences compared with the original analyses of Kipper & Klochkova (1997) and Shetrone & Keane (1998) are not alarming considering the very different adopted model atmospheres as well as the use of different $T_{\rm eff}$-$\log g$ criteria. The quoted uncertainties in the derived parameters represent the discrepancies between the various indicators; additional systematic errors are not accounted for. However, since the same criteria have been used, the systematic errors are likely very similar for the different observing epochs, and thus will not compromise our conclusions regarding the very rapid evolution of the star.

Table 1. The estimated stellar parameters for Sakurai's object in 1996

Epoch	$T_{\rm eff}$ [K]	$\log g$ [cgs]	$\xi_{\rm t}$ [km s^{-1}]	C/He
April 20–25	$7\,750 \pm 300$	0.25 ± 0.3	10.5 ± 1.0	10%
May 5–9	$7\,500 \pm 300$	0.00 ± 0.3	8.0 ± 1.0	10%
June 4	$7\,400 \pm 300$	0.40 ± 0.3	8.5 ± 1.0	10%
July 3	$7\,250 \pm 300$	0.50 ± 0.3	8.5 ± 1.0	10%
October 7	$6\,900 \pm 300$	0.50 ± 0.3	6.5 ± 1.0	10%

For all model atmospheres except for a few test cases, a C/He ratio (by number) of 10% has been adopted, following comparison of the C II and He I line strengths in the April and May spectra. It should be emphasized, however, that these lines do not provide a very accurate estimate of the C/He ratio in cool H-deficient stars such as Sakurai's object due to the sensitivity of the lines to the adopted stellar parameters and the significant contribution of blending C I lines with their unexplained "carbon problem" (see below) to the He I 5 876 Å triplet. The June and July spectra are consistent with the adopted C/He ratio of 10%, though a better agreement between the C II and He I lines would be obtained with a slightly higher ratio. The $T_{\rm eff}$ in October was too low to enable a determination of the C/He ratio through the high-excitation He I and C II lines.

In the H-deficient and C-rich photospheres of Sakurai's object and the R CrB stars, the continuous opacity at the flux-carrying wavelengths is no longer provided by hydrogen but by photoionization of highly excited levels of C I. Furthermore, carbon is by far the most important electron donor in the line-forming regions. The atmospheric structure is therefore essentially completely determined by C (Asplund et al. 1997a). Since the photospheric C abundance is derived from lines originating from levels with only slightly lower excitation energy than those providing the continuous opacity, the strengths of C I lines in these stars should be essentially independent on both the C abundance and the adopted $T_{\rm eff}$ and $\log g$, which is also confirmed by observations and theoretical calculations (Lambert et al. 1998). Therefore, the theoretical line strengths of weak C I lines should agree with observations since there are no free parameters to tune in order to achieve agreement as in normal analyses. Unfortunately both for the R CrB stars (Gustafsson & Asplund 1996; Asplund et al. 1997a; Lambert et al. 1998) and for Sakurai's object (Asplund et al. 1997b; Kipper & Klochkova 1997) there is a significant discrepancy between the predicted and observed line strengths: the derived abundance is about 0.6 dex smaller than the input C abundance for the model atmospheres. The explanation for this "carbon problem" is still unknown, but it may be related to inappropriate assumptions for the construction of the model atmospheres (1-D, static, flux-constant atmospheres in LTE) (Lambert et al. 1998).

Sakurai's object also shows the same discrepancy by on average 0.7 dex. As will be illustrated further below, the abun-

Table 2. Chemical compositions of Sakurai's object, the R CrB majority stars, the R CrB star V854 Cen and the Sun (normalized to $\log(\Sigma\mu_i\epsilon_i) = 12.15$). The errors quoted in the table are the standard deviations for the different lines of a species; in case the abundance is derived from a single line, no error is given. More uncertain values are marked with:

Element	Sun[a]	Sakurai's object in 1996					R CrB	V854 Cen[c]
		April 20–25	May 5–9	June 4	July 3	October 7	majority[b]	
H	12.00	10.0	9.7	9.7	9.6	9.0	< 4.1–6.9	9.9
He	10.93	11.4[d]	11.4[d]	11.4[d]	11.4[d]	11.4[d]	11.5[d]	11.4[d]
Li	3.31	3.6	3.6	3.6	4.0	4.2	< 1.1–3.5	< 2.0
C	8.52	$9.7^{e} \pm 0.2$	$9.7^{e} \pm 0.2$	$9.6^{e} \pm 0.2$	$9.7^{e} \pm 0.3$	$9.8^{e} \pm 0.3$	8.9^{e}	9.6^{e}
N	7.92	9.0 ± 0.3	8.9 ± 0.4	9.0 ± 0.4	9.2 ± 0.3	8.9 ± 0.2	8.6	7.8
O	8.83	9.2 ± 0.2	9.5 ± 0.3	9.3 ± 0.4	9.3 ± 0.1	9.4 ± 0.2	8.2	8.9
Ne	8.08	9.4 ± 0.2	9.4 ± 0.3	9.5 ± 0.3	9.5 ± 0.3			
Na	6.33	6.6 ± 0.1	6.7 ± 0.1	6.5 ± 0.1	6.6 ± 0.2	6.8 ± 0.1	6.1	6.4
Mg	7.58	6.5 ± 0.4	6.6 ± 0.4	$6.3 : \pm 0.4$	$6.3 : \pm 0.4$	6.5 ± 0.3	6.4	6.2
Al	6.47	6.5 ± 0.2	6.6 ± 0.2	6.5 ± 0.3	6.6 ± 0.3	6.3	6.0	5.7
Si	7.55	7.3 ± 0.0	7.1 ± 0.2	7.1 ± 0.2	7.1 ± 0.0	7.5 ± 0.2	7.1	7.0
P	5.45	6.2	6.2 ± 0.4	6.1 ± 0.4	6.3			
S	7.33	6.8 ± 0.1	6.6 ± 0.1	6.5 ± 0.2	6.7 ± 0.1	6.9 ± 0.1	6.9	6.4
K	5.12		4.9 ± 0.0	4.7	5.0 ± 0.1	5.0 ± 0.0		
Ca	6.36	5.2 ± 0.1	5.6 ± 0.3	5.4 ± 0.3	5.6 ± 0.4	5.5 ± 0.4	5.4	5.1
Sc	3.17	3.1 ± 0.1	3.1 ± 0.1	3.2 ± 0.1	3.3 ± 0.2	3.9 ± 0.2		2.9
Ti	5.02	4.0 ± 0.1	4.1 ± 0.2	4.2 ± 0.2	4.4 ± 0.2	4.6 ± 0.2		4.1
Cr	5.67	4.5 ± 0.1	4.5 ± 0.2	4.7 ± 0.2	4.8 ± 0.2	5.1 ± 0.2		4.2
Fe	7.50	6.4 ± 0.2	6.4 ± 0.2	6.4 ± 0.2	6.6 ± 0.2	6.6 ± 0.3	6.5	6.0
Ni	6.25	6.1 ± 0.3	6.1 ± 0.4	5.9 ± 0.2	6.0 ± 0.2	6.2 ± 0.2	5.9	5.9
Cu	4.21		5.0 ± 0.3	5.0 ± 0.2	5.1 ± 0.0	5.0 ± 0.1		
Zn	4.60	4.9 ± 0.2	4.8 ± 0.2	4.9	5.1	5.4	4.3	4.4
Rb	2.60		< 3.7	4.2		4.6		
Sr	2.97	$4.7 : \pm 0.1$	$4.9 : \pm 0.2$	$5.0 : \pm 0.4$		$5.4 : \pm 0.0$		2.2
Y	2.24	3.2 ± 0.3	3.3 ± 0.3	3.3 ± 0.3	3.7 ± 0.2	4.2 ± 0.2	2.1	2.2
Zr	2.60	3.0 ± 0.2	3.0 ± 0.3	3.2 ± 0.2	3.3 ± 0.2	3.5 ± 0.3		2.1
Ba	2.13	1.5 ± 0.1	1.5 ± 0.2	1.5 ± 0.2	1.8 ± 0.1	1.9 ± 0.4	1.6	1.3
La	1.17		< 1.6		1.3	1.5		0.4

[a] From Grevesse & Sauval (1998). For Li the meteoritic value has been adopted.
[b] From Lambert et al. (1998). The abundances are the mean from a sample of 14 stars; the four minority R CrB stars are not included here.
[c] From Asplund et al. (1998).
[d] Input C/He ratio for model atmospheres: C/He=10% estimated for Sakurai's object from the April and May spectra and V854 Cen and 1% assumed for R CrB stars.
[e] Spectroscopically determined C I abundance, which differs from the input model atmosphere C abundance, see text.

dances of most elements have remained the same throughout 1996, which suggests that the C/He ratio has not changed; an increasing C abundance would manifest itself as a decrease in derived abundances for all elements when assuming a constant C/He in the analysis unless for some reason X/C remained the same for all elements except for He. Fortunately, various tests (Lambert et al. 1998) suggest that although absolute abundances can be severely affected, abundance ratios such as [X/Fe] are largely immune to the carbon problem because of the similar sensitivity to the atmospheric structure of most elements; changing C/He from 10% to 1% introduces differences in [X/Fe] by $\lesssim 0.1$ dex (Asplund et al. 1998). Therefore, conclusions can still be drawn regarding the evolutionary history of Sakurai's object and the R CrB stars, in spite of the unsolved dilemma caused by the carbon problem.

4. Chemical composition

4.1. Elemental abundances

With the adopted stellar parameters described in Sect. 3, the resulting abundances under the assumption of LTE as observed throughout 1996 are listed in Table 2. To within the uncertainties the two April and the three May spectra give identical abundances. The abundances for May and October have been reanalysed for the present study, which has led to a few minor adjustments compared with the original study (Asplund et al. 1997b): the abundances of Ne, K, Fe, Cu and Zn have all increased by 0.1 dex for May, as a result of inclusion of additional lines, improved selection of lines and adoption of better atomic data.

From an inspection of Table 2 two important conclusions are immediately obvious. First, the abundances of most elements

(He, C, N, O, Ne, Na, Mg, Al, Si, P, S, K, Ca, Fe, Ni, Cu and La) have remained the same within the uncertainties (about 0.3 dex) throughout 1996. In most cases the total variation is only about 0.2 dex, which is remarkable considering the intrinsic uncertainties in the analyses. Given the good agreement, it is worthwhile emphasizing, that in all cases the adopted stellar parameters have been determined before considering the absolute abundances and their implications, and no a posteriori fine-tuning has been allowed in order to improve the consistency. Second, several elements show abundance alterations which significantly exceed the statistical scatter. This is true for H (decrease by 1.0 dex), Li ($+0.6$ dex), Sc ($+0.8$ dex), Zn ($+0.7$ dex), Rb ($> +0.9$ dex) and Y ($+1.0$ dex), and probably also Ti ($+0.6$ dex), Cr ($+0.6$ dex), Sr ($+0.7$ dex, though uncertain due to only based on very strong lines) and Zr ($+0.5$ dex). There is also some indication that the heavier s-element Ba increased steadily in 1996, though such a conclusion is not indisputable. Unfortunately, trustworthy abundances of other heavy s-elements throughout 1996 which could verify such a finding are lacking. The slightly larger variations (in total 0.4 dex) than the typical scatter for Si, S and Ca are less likely to be signs of real abundance variations, since no definite trend with time is apparent and only one of the epochs show a disparate value. We therefore attribute these variations to the uncertainties in the analyses.

For June and July the H abundance may be overestimated by $\sim$ 0.1–0.2 dex compared with the other epochs, since the abundances are derived solely from Hα as the spectra did not cover Hβ. For the other times the greatest weight has been given to Hβ, which in general needs slightly lower abundance than Hα for an acceptable fit to the extended line wings in Sakurai's object.

4.2. The reality of the abundance alterations

Considering the drastic abundance variations apparent in Sakurai's object, it is natural to ask whether perhaps they can be blamed on erroneous stellar parameters or inappropriate approximations in the analysis.

It is important to realize that no change in the adopted stellar parameters, no matter how large, can annull all abundance alterations simultaneously. The required $\Delta T_{\rm eff} \approx 1\,000$ K to invalidate most of the abundance changes would be clearly incompatible with the various $T_{\rm eff}$-log g criteria and furthermore would only introduce other severe modifications of the stellar abundances, which would be less easily explainable within the context of a born-again giant. There is no clear difference in sensitivity between the elements showing an increasing or decreasing abundance trend and the elements whose abundance has remained constant over the same time-span. The observation of a definite trend in abundance over time for all elements with a suspected abundance change, further supports the finding of a changing chemical composition. Likewise, the consistency between the different epochs for most elements also speaks against the stellar parameters being seriously in error.

Many of the spectral lines of the species with changing chemical content are by necessity relatively strong, which could cause problems in their interpretation as abundances. The effects of hyperfine and isotope splittings have been investigated for a few Li, Sc, Y and Ba lines but found to be insignificant except for the Li I D doublet; the Li abundances in Table 2 have been derived from such synthesis. Since the current analysis is based on the LTE approximation, departures from LTE may introduce spurious results which could be interpreted as abundance variations. However, we find it unlikely that such departures may be responsible for all of the observed drastic variations (in some cases 1.0 dex), since (1) in most cases the abundances are derived from lines of the dominant species in the atmosphere (exceptions: Li, Zn and Rb), (2) the line scatter of the relevant elements is similar or smaller than for the other elements, (3) in general the abundances are based on more lines than for the typical elements, (4) other elements with similar atomic structures, which thus should experience similar departures from LTE, do not show any abundance variations, and (5) it seems less likely that the relatively minor differences in stellar parameters between the four observing epochs could introduce *differential* NLTE effects of ~ 1.0 dex. Naturally though, it cannot be excluded that NLTE effects may be accountable for parts of the observed abundance alterations for some elements, e.g. for Ti and Cr (see below).

As will be further discussed below, the abundance variations can be naturally explained as a result of the mixing and nucleosynthesis which has occurred following the final He-shell flash – H-burning, Li-production and s-processing – which further supports the conclusion that the changes are real. The elements which should not participate to any significant extent in any nuclear reactions due to the He-shell flash do not show any abundance variations, thereby making the whole abundance pattern consistent with expectations.

In the absence of any plausible alternative explanation, we are thus forced to the conclusion that the observed changes in chemical composition are most likely real. The abundance alterations first noted by Asplund et al. (1997b) are thus confirmed by the present, more detailed analysis covering significantly more observational data.

4.3. Nucleosynthesis

The current chemical composition of Sakurai's object is clearly not pristine. The very evolved nature of the star is evidenced by the H-deficiency and high abundances of heavy elements, characteristic of neither disk dwarfs nor halo dwarfs (Edvardsson et al. 1993). Sakurai's object seem to have undergone H-burning, followed by He-burning and a second phase of CNO-cycling, as well as associated nuclear reactions such as Li-production and s-processing.

Sakurai's object is slightly metal-poor. With a C/He ratio of 10% the Fe mass fraction is 0.2 dex (mean of the four observing epochs) below solar, but had the input carbon abundance been used instead the mass fraction would be 0.7 dex lower as a result of the carbon problem. However, only [Mg/Fe]$= -0.1$, [Ca/Fe]$= 0.1$, [Ti/Fe]$= 0.2$ and [Cr/Fe]$= 0.0$ (mean of April, May, June and July for Ti and Cr) are consistent with such

an origin while all other elements seem to have been modified throughout the evolutionary history of Sakurai's object, with the possible exceptions of Si ([Si/Fe]$= 0.7$) and S ([S/Fe]$= 0.5$); also Ti and Cr seem currently to be modified (Sect. 5.1). The most obvious property is, of course, the presence of H-burning material due to the H-deficiency and high He-content. Furthermore, the high [Na/Fe]$= 1.4$ and [Al/Fe]$= 1.0$ abundance ratios can probably be explained by proton-captures on ^{22}Ne and ^{25}Mg. The significant C and O ([O/Fe]$= 1.4$) enhancements require He-burning through the 3α-process followed by subsequent α-captures.

The overabundant N ([N/Fe]=2.0) can not be accounted for by CNO-cycling of the initial CNO nuclei but requires a second phase of H-burning in which C and O produced by He-burning are converted to N. Such a conclusion is supported by the very high [Ne/Fe]$= 2.4$; Ne has presumably been synthesized from α-captures on products of He-burning and CNO-cycling (since Mg is not overabundant, Ne has more likely been formed from ^{14}N seeds rather than ^{16}O nuclei). Also the low ^{12}C/^{13}C ratio in Sakurai's object strongly suggests a second stage of CNO-cycling following He-burning, since the ^{13}C abundance should be very low after α-processing; the observed ^{12}C/^{13}C ratio ($1.5 \leq {}^{12}\mathrm{C}/{}^{13}\mathrm{C} \leq 5$) encompasses the equilibrium value of about 3.5 from CNO-cycling. The high ^{13}C/N ratio requires though that the proton supply was exhausted before conversion of the available C to N was completed. The Si and S abundances may also require nuclear processing, as in other H-deficient stars (Lambert et al. 1998), but the channels and conditions under which this would have occurred are still unclear. The observed Li has most likely been synthesized as a result of the Cameron-Fowler (1971) Be transport mechanism.

Sakurai's object is strongly enhanced in s-process elements, in particular the light s-elements. Also the very high abundance ratios [K/Fe]=0.8, [Sc/Fe]=1.6 (October), [Ni/Fe]=0.9, [Cu/Fe]=1.8 and [Zn/Fe]=1.7 (October) are likely explained by neutron captures of lighter seed nuclei (presumably mainly S, Ar, Ca and Fe), as previously suggested for R CrB stars (Asplund et al. 1998; Lambert et al. 1998) and FG Sge (Gonzalez et al. 1998). Very likely ^{13}C is the neutron source; the alternative reaction ^{22}Ne(α,n)^{25}Mg which ignites at higher temperatures, seems to be ruled out since the required neutron exposure (≈ 10 neutrons per Fe seed nucleus) is not consistent with the observed Mg/Fe (≈ 1) ratio. All the elements Ni-La could be synthesized with a *single* neutron exposure $\tau \sim 0.2 \pm 0.1\,\mathrm{mb}^{-1}$; the Sr/Rb ratio indicates a neutron density of $N_\mathrm{n} \sim 10^8\,\mathrm{cm}^{-3}$ (Malaney 1987). An exponential exposure of neutrons provides less good agreement. The fact that also the abundances of Ni, Cu and Zn are well explained with a single neutron exposure indicates that most of the envelope has been exposed to neutrons and little dilution has occurred with gas which has not suffered s-processing. Though [Ba/Fe]=0.6 is not atypical for AGB-stars, many of the light s-elements have very extreme ratios (e.g. [Sr/Fe]=3.0 and [Y/Fe]=2.2 in May) not observed in AGB-stars or post-AGB stars evolving towards the planetary nebula-phase for the first time. This may suggest that these elements have been synthesized following departure from the AGB. Indeed, both the Li and the (light) s-element abundances seem to have increased dramatically throughout 1996, due to mixing and processing which was initiated in connection with the final He-shell flash.

5. The evolution of Sakurai's object in 1996

5.1. Changes in chemical composition

Though most elemental abundances remained the same throughout 1996, a few elements are distinguished by their changing content within only a few months. These variations may be the result of either mixing of a previously modified chemical composition or current nuclear processing. The mixing time scale is determined by the convective time scale which is on the order of a couple of months for Sakurai's object. The nuclear burning time scale is comparable since it is determined by the rate at which convection brings fresh protons to H-burning temperatures. Thus, both processes may in principle be able to explain the extremely rapid evolution of Sakurai's object.

5.1.1. Mixing processes

Rather than reflecting current nucleosynthesis in the star, the elemental abundance variations may simply be due to mixing of the surface layers with gas from the interior. If the initial envelope abundances are significantly different from those of the interior, a changing chemical content may be observed without invoking present nuclear processing. Such a depth-dependent chemical composition may either be the result of previous nucleosynthesis (which must have occurred *during* the AGB-phase), or through dust-gas separation (which must have occurred *after* departure from the AGB).

Pure mixing of the envelope with the H-depleted gas of the interior could in principle explain the decreasing H-content. However, some amount of H-burning is expected after the final He-shell flash on theoretical grounds (Renzini 1979), since the flash should have caused an extensive convection zone ingesting the still H-rich envelope, which would bring the gas to H-burning temperatures. Though mixing may explain part of the diminishing H abundance, it is not possible to invoke mixing to explain the increasing Li content. Since Sakurai's object is H-deficient and H-burning necessarily destroys any present amount of the much more fragile Li, the observed high Li abundance can not have been inherited from a previous AGB-phase. The observed Li/H ratio ($10^{-6.1} - 10^{-4.8}$) far exceeds the value in even the most Li-rich AGB-stars ($\approx 10^{-8}$).

The observed changes of the light s-elements may be the consequences of mixing with gas exposed to neutrons in between the thermal pulses on the AGB now brought to the surface. Unfortunately, the exact nature of the last flashes immediately before the star departs from the AGB is poorly known, but a preferential production of the light s-elements is not inconceivable. Whether the very extreme [s/Fe] ratios (e.g. [Rb/Fe]=2.9, [Sr/Fe]=3.3 and [Y/Fe]=2.9 in October) could be accomplished remains to be shown, however. As noted in Sect. 4.3 the abundance distribution of the heavy elements is better described with a single neutron exposure than with an exponential exposure

as expected for thermal pulses in AGB-stars, which may indicate that the s-elements are not inherited from the previous AGB-phase. Even before the observed abundance alterations in 1996, the heavy element abundances in Sakurai's object are quite different from those observed in post-AGB stars evolving towards the planetary nebula-regime for the first time; this fact also seems to support our conclusion.

The observed abundance increases in Ti and Cr are more problematic to explain as a result of nucleosynthesis, whether from a previous phase or presently occurring. In principle, Ti and Cr could be synthesized through s-processing, as is the case with Sc. Both Ti and Cr are, however, preceded by elements (Sc and V respectively) which have significantly lower abundances. The neutron capture cross-sections (Beer et al. 1992) do not suggest a predominant build-up of Ti and Cr at the expense of the surrounding elements. (Though Zn succeeds the less abundant Cu for October 1996, the calculations of Malaney (1987) show that a single neutron exposure may produce such an abundance distribution due to the differences in cross-sections.) Furthermore, to explain the high Cr abundance for October, the Ca abundance would have had to decrease if it were the seed, which is not observed. Conceivably, repeated α-captures could explain the Ti and Cr abundance increases, in particular in the light of the high [Ne/Fe], [Si/Fe] and [S/Fe] ratios, but it would seem to require unreasonably high temperatures. Furthermore, Ca is not significantly enhanced. As a plausible nucleosynthetic explanation is lacking, it is not precluded that a combination of errors (e.g. NLTE effects, unaccountable blends) may have conspired to produce spurious results, especially since the interpretation of an abundance alteration of Ti and Cr is largely controlled by the October spectrum, while the [Ti/Fe] and [Cr/Fe] ratios for the other dates are representative of slightly metal-poor stars. For the moment, we are unable to find a nucleosynthetic explanation for the observed trends in Ti and Cr. We note that a similar problem of observed high [Ti/Fe] and [Cr/Fe] ratios also exists for some R CrB stars (Lambert et al. 1998).

Alternatively, mixing may cause variations not because the interior has undergone previous phases of nucleosynthesis, but because the surface layers have experienced dust fractionation, as e.g. suggested for post-AGB stars and FG Sge (Blöcker & Schönberner 1997). Such a suggestion may seem able to explain the observed increases in Sc, Ti, Cr and Y, since those elements can be heavily depleted in post-AGB stars (e.g. Gonzalez et al. 1997). However, the scenario is unlikely to be the main solution to the observed variations. Elements such as Al, Ca, Fe and Ni should then also show similar or stronger trends which are not observed, and the increase in Zn abundance is directly at odds with its inability to condense into dust (Cardelli 1994). Also, the variations in the H and Li content cause severe problems for the hypothesis of dust fractionation. Furthermore, dust depletion cannot explain the abundance ratios relative to Fe during the later times, in particular the extreme s-element ratios (e.g. [Rb/Fe]=2.9, [Sr/Fe]=3.3 and [Y/Fe]=2.9 in October), when the abundance pattern should be less affected by the action of dust fractionation. It is also hard to understand why exactly those elements which are likely to be synthesized in connection with a final He-shell flash (H, Li, and the s-elements) should be particularly modified while no other elements show similar trends. We therefore find such an explanation rather contrived. Similar arguments can be constructed against the suggestion of dust fractionation being responsible for the observed variations in the abundances of the s-elements in FG Sge (Langer et al. 1974; Blöcker & Schönberner 1997).

5.1.2. Nuclear processing

The most notable abundance alteration in 1996 is the decrease of the H-content by a factor of 10, due to the ingestion of the H-rich envelope in connection with the He-flash. Since most of the luminosity is now probably provided by H-burning rather than He-burning (Renzini 1990), the diminishing H-content reflects in fact the consumption of the nuclear fuel of the star. Not only is the generated energy sufficient to provide the high luminosity of the star, the released energy is also causing the expansion of the star to giant dimensions. Assuming a mass of $10^{-4}\,\mathrm{M}_{\odot}$ of the ingested material and an initial H content of $\log \epsilon_{\mathrm{H}} = 10.0$ (April), the energy generated over these months produces a luminosity which exceeds the classical Eddington limit by about a factor of 6 (see also Sect. 5.2). The energy generated during these months is less than the estimated binding energy of the stellar envelope outside the He-burning shell (assuming that the shell is located at a stellar radius of $\sim 2 \cdot 10^9$ cm and that its mass is $\sim 10^{-2}\,\mathrm{M}_{\odot}$, Renzini 1990). However, assuming instead an initial solar H-abundance prior to the He-shell flash in the ingested material is sufficient to provide the required energy for lifting the outer layers to produce a born-again giant. These simple-minded estimates naturally assume that the diminishing H-content only reflects the effects of H-burning rather than mixing of the envelope with previously H-depleted gas from the interior.

The increased Li abundance is most easily explained by Li-production through the Cameron-Fowler mechanism. Since H-burning also destroys present Li, the observed Li cannot have been generated in a previous AGB-phase but must be currently produced in the star, simultaneous with the consumption of H. Furthermore, since the required ^{3}He, which is produced during the main-sequence phase, is eradicated during He-burning, the Li-production must proceed in an environment not previously exposed to He-burning.

The high ^{13}C abundance provides an efficient neutron source for the s-processing through $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$. The abundance alterations of the light s-process elements (Zn, Rb, Sr, Y and Zr, as well as Sc) can be interpreted as being due to current synthesis in the star; it is less clear whether this is also true for the heavy s-elements though there are indications that Ba may have increased in 1996. As discussed above, the abundance distribution of the heavy elements suggests that the variations are not due to pure mixing, but rather to ongoing s-processing. If this interpretation is correct, however, it may pose a serious challenge for any theoretical modelling. The ignition of CN-cycling due to the onset of flash-driven envelope convection at a temperature of $T \lesssim 10^8$ K should cause a splitting of the shell into two con-

vective zones, the lower zone burning He at the bottom, while the upper zone experiences CN-cycling. As described above, Li can be produced in the upper zone ("hot-bottom-burning"), but the ^{13}C produced there does not release neutrons unless the temperature is significantly higher ($T \gtrsim 1.5 \cdot 10^8$ K), i.e. in conditions typical of the lower convection zone. A possible solution may be that H-burning has essentially run to completion during the peak He-burning phase, in which case the two convection zones would once again connect, and thereby bring down ^{13}C to the relevant high temperatures for neutron release to occur. No doubt, the final He-shell flash in Sakurai's object was a highly dynamical phenomenon with a very short timescale ($\lesssim$months), which may well have been severely inhomogeneous. Such asymmetric mixing may perhaps explain the simultaneous Li-production and s-processing. It is even possible that the surface layers may not have been chemically homogeneous during 1996 and further variations in the observed abundances of H, Li, ^{13}C and the s-elements could be expected.

As discussed in detail above, the increase in Ti and Cr abundances presents a problem when interpreting the variations as reflecting nuclear processing.

5.1.3. Summary

The most likely explanation for the observed changes in chemical composition of Sakurai's object is that they are the direct consequence of the combination of mixing and nuclear reactions which has occurred following the He-shell flash. These involve the following processes: ingestion and burning of the H-rich envelope through (interrupted) CN-cycling, Li production from the simultaneously ingested ^{3}He, and s-processing from neutrons liberated through α-captures on the available ^{13}C, which in turn has been produced from the concomitant proton captures on ^{12}C. In fact, the abundance alterations are in excellent accordance with theoretical expectations (Renzini 1990), but the exact details of how in particular the s-processing would have proceeded is less clear. However, we are at present unable to rule out convincingly the possibility that the s-elements have been synthesized in between previous He-shell flashes on the AGB and are now being brought to the surface purely through dredge-up. It is not possible, though, to invoke such mixing to explain the Li-enrichment or all of the diminishing H-content, as this requires current nucleosynthesis. Any way, the observed changes can only be understood if the final He-shell flash occurred *after* the H-burning shell had been extinguished in the post-AGB star, since otherwise the entropy barrier from H-burning would prevent ingestion of the H-rich envelope, and no substantial mixing or nucleosynthesis besides He-burning would occur. The observed variations of Ti and Cr are, however, not easily explained within this framework.

5.2. Changes in effective temperature and luminosity

Sakurai's object has evolved rapidly in effective temperature following its discovery, as is evident both from the spectroscopic analyses presented here for 1996 and from $UBVRiz$ photometry (Duerbeck et al. 1997) covering 1996 and early 1997, as illustrated in Fig. 2. The photometric temperatures have been derived using similar H-deficient model atmospheres as those applied here, which shows the good agreement between spectroscopic and photometric temperature estimates in 1996. Comparing the analysed spectra of Sakurai's object in 1996 reveals clear signatures of a decreasing $T_{\rm eff}$ which was already noted by Asplund et al. (1997b): from April to October pronounced C_2 and CN bands developed (Fig. 3) and the H lines became weaker as apparent from Fig. 1 (also due to the diminishing H-content). This evolution has continued in 1997 (Kerber et al. 1997) and 1998 (Fig. 4, though the recent development of heavy line-blanketing in the visual region makes the weakening of the H-lines less apparent). In the beginning of 1998 the

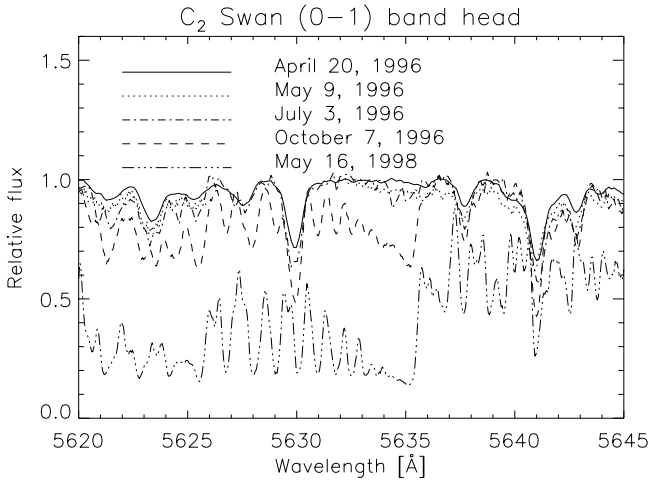

Fig. 3. The evolution of the C_2 0–1 Swan bandhead at 5635 Å in Sakurai's object during 1996, as well as a recent spectrum acquired in May 1998, illustrating the increasing strengths of molecular features due to the decreasing $T_{\rm eff}$. Note that the continuum placement for the May 1998 spectrum is highly uncertain due to the heavy blending

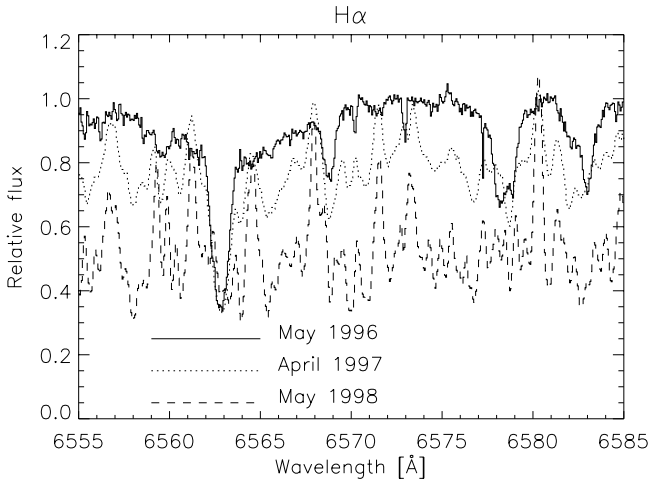

Fig. 4. The evolution of the Hα feature in Sakurai's object from just after discovery (May 1996), to April 1997 and May 1998. Note that the continuum placement for the May 1998 spectrum is highly uncertain due to the severe line-crowding

stellar spectrum resembled a carbon star (Figs. 3 and 4). The latter does not, however, imply similarly low $T_{\rm eff}$ as in carbon stars since the H-deficiency and C-enhancement make molecular features containing C very prominent (Asplund et al. 1997a). Rather $T_{\rm eff}$ is more likely to be around 5000–6000 K, though a detailed abundance analysis of these very crowded spectra will not be an altogether easy task, as is obvious from Figs. 3 and 4. This rapid cooling is the result of the stellar expansion caused by the drastically increased energy release after the final He-shell flash. A similar phenomenon is well-known to occur in novae in which the photosphere expands at roughly constant luminosity down to about 6000 K, when the expanding shell becomes optically thin. We would thus expect the luminosity to have remained roughly constant during the expansion.

From $UBVRiz$ monitoring of Sakurai's object, Duerbeck et al. (1997) find evidence for a luminosity increase of about 30%. It is, however, not unlikely that this conclusion may be compromised by adoption of inappropriate bolometric corrections for the star; considering the H-deficiency and its peculiar composition the line-blanketing will be very different compared with normal supergiants of similar temperatures. A constant luminosity can therefore in our opinion not be ruled out; clearly more detailed calculations of bolometric corrections for the star are needed.

Our stellar parameters offer information on the luminosity: $\mathrm{L} \propto T_{\rm eff}^4/g$ according to standard relations. Fig. 5 shows three loci of constant L in the log g versus $T_{\rm eff}$ plane together with the derived values. When taken at face value, the spectroscopic parameters suggest an evolution with a decreasing luminosity; however, the parameters are consistent with a constant luminosity and perhaps also with the modest increase suggested by Duerbeck et al. (1997) within the errors of measurement. Spectroscopic estimates of luminosity are dependent on the assumption about the stellar mass but the primary uncertainty may arise from the basic assumptions underlying the construction of the model atmospheres. As pointed out by Asplund et al. (1997b), the assumption of hydrostatic equilibrium for the star may be inappropriate. In particular, an underestimation of the surface gravity will result from neglecting the hydrodynamics due to, for example, an overall atmospheric expansion, or turbulent pressure (Gustafsson et al. 1975). The assumption of constant luminosity and the observed decrease in $T_{\rm eff}$ require e.g. the expansion velocity to have *increased* during 1996. This conclusion follows directly from the second derivative of the luminosity $L = 4\pi R^2 \sigma T_{\rm eff}^4$:

$$0 = \frac{2}{T_{\rm eff}}\frac{{\rm d}^2 T_{\rm eff}}{{\rm d}t^2} - \frac{2}{T_{\rm eff}^2}\left(\frac{{\rm d}T_{\rm eff}}{{\rm d}t}\right)^2 + \frac{1}{R}\frac{{\rm d}^2 R}{{\rm d}t^2} - \frac{1}{R^2}\left(\frac{{\rm d}R}{{\rm d}t}\right)^2 . \quad (1)$$

Due to the linear decrease in $T_{\rm eff}$ with time in 1996, ${\rm d}^2 T_{\rm eff}/{\rm d}t^2 = 0$ and thus the expansion velocity must have increased: ${\rm d}^2 R/{\rm d}t^2 = {\rm d}v_{\rm exp}/{\rm d}t > 0$. Duerbeck et al. (1997) arrived at the same conclusion based on an analysis of photometric data. The observed trend of a decreasing $\xi_{\rm t}$ also suggests that hydrostatic equilibrium may have been inapplicable directly following discovery. Furthermore, for both April and May the spectroscopically derived parameters are located at the classical Eddington luminosity for electron scattering (Asplund 1998). Thus, we cannot at present rule out an evolution at constant luminosity from the spectroscopy.

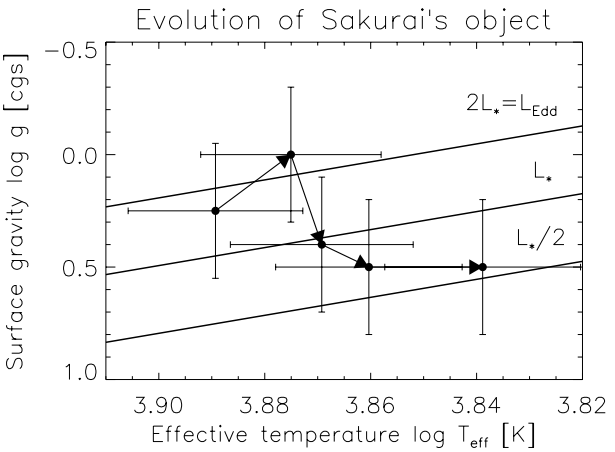

Fig. 5. The spectroscopically derived fundamental parameters of Sakurai's object in 1996 suggest an evolution at decreasing stellar luminosity when taken at face value (but see text). The solid lines illustrate slopes of constant luminosity each separated by a factor of 2. The middle line corresponds to $L_* = 10^{4.4}\,\mathrm{L}_\odot$ when assuming $M_* = 0.8\,\mathrm{M}_\odot$. The line denoted by $2L_*$ is identical to the classical Eddington limit (pure electron scattering for fully ionized gas) for H-deficient stars

Assuming a stellar mass of $0.8\,\mathrm{M}_\odot$ (see below), the spectroscopically derived parameters for October indicate a stellar luminosity of $10^{4.1}\,\mathrm{L}_\odot$, which is in very good agreement with predictions for born-again giants (Iben & MacDonald 1995; Blöcker & Schönberner 1997). This corresponds to a distance of about 7 kpc (using the above-mentioned $E(B-V) = 0.7$), which agrees with previously estimated distances of 5.5–8 kpc (Duerbeck & Benetti 1996; Duerbeck et al. 1997) but is in sharp contrast to the short distance of 1.1 kpc claimed by Kimeswenger & Kerber (1998) (see also Jacoby et al. 1998). Adopting the spectroscopic parameters of the earlier dates would require a larger distance. A distance of only 1.1 kpc would imply $\log g = 2.1$ for October, a value well outside the acceptable uncertainties in the spectroscopic analysis.

The very rapid evolution of Sakurai's object following discovery is significantly faster than that of FG Sge (van Genderen & Gautschy 1995) though seemingly similar to that of V605 Aql though available data are scarce (Lundmark 1921; Clayton & De Marco 1997). Throughout the last century, FG Sge has brightened visually while cooling, while V605 Aql reached peak brightness within only two years, before starting to show R CrB-type fadings and turning too faint for continued monitoring (Seitter 1987). Sakurai's object is currently evolving on a time scale of a few years; the star probably started to brighten in 1994 (Duerbeck et al. 1997). It is of interest to compare these short evolutionary time scales with theoretical predictions.

According to Renzini (1990) the time scale for burning the ingested H-envelope (which generates more luminosity than the initial He-burning which triggered H-burning) after the He-shell flash is

$$\tau_{\rm H-burn} \approx \frac{E_{\rm H}\Delta M_{\rm H}}{40 L_{\rm pl}}, \quad (2)$$

where $E_{\rm H}$ denotes the energy release from H-burning (CNO-cycling), $\Delta M_{\rm H}$ the amount of ingested H, and $L_{\rm pl}$ the luminosity plateau during the post-AGB evolution; the numerical factor takes into account that the H-burning proceeds at a luminosity roughly 40 times higher than $L_{\rm pl}$. For a typical case of a 0.6 $M_\odot$ post-AGB star, $\tau_{\rm H-burn}$ will be about 25 years (Renzini 1990), which is in good agreement with the only published numerical calculation of a final He-shell flash event by Iben & MacDonald (1995), in which the subsequent brightening occurred over 17 years Furthermore, the theoretical time scale is in agreement with the observed time scale for H-burning in Sakurai's object (Sect. 5.1). Different evolutionary time scales are expected with different stellar masses M_*, since $\Delta M_{\rm H}$ is a very sensitive function of M_* (e.g. Blöcker & Schönberner 1997). The very rapid evolution of Sakurai's object and V605 Aql can thus presumably be accomplished with a slightly higher M_* and therefore smaller $\Delta M_{\rm H}$. The main difference in evolutionary time scales between FG Sge on one hand and Sakurai's object and V605 Aql on the other is therefore probably due to different M_*.

The life-time of the quiescent born-again giant phase may be about a factor of 40 longer than $\tau_{\rm H-burn}$, since the generated energy will be radiated away at a luminosity not very different from $L_{\rm pl}$ (Renzini 1990). In reality, the life-time will be shorter (1) since the star can be found only part of the time in the giant regime and (2) due to the effects of mass-loss. A typical life-time as a bright giant of 100–1 000 years can thus be expected, which is not incompatible with the observational evidence; the visual brightness of V605 Aql has decreased greatly since the outburst in 1919 but the bolometric luminosity has probably remained roughly the same (Harrison 1996; Clayton & De Marco 1997). Judging from their similarities in rise-time and visual variability at peak brightness, it is not a bold speculation that soon Sakurai's object will also form an optically thick surrounding dust cloud, which will cause a visual fading it may not recover from; the development of an IR excess (Eyres et al. 1998) is certainly suggestive of such a prospect. The very rapid brightening of V605 Aql (and now Sakurai's object) may perhaps have caused a dynamical ejection of the outer envelope (Asplund 1998) which subsequently underwent dust condensation, while the more gentle brightening of FG Sge did not provide the necessary conditions for formation of a completely obscuring dust shell but only the irregular dust condensations typical of R CrB stars.

6. Relation to FG Sge, V605 Aql and the R CrB stars

Sakurai's object bears several striking similarities to the R CrB stars (Asplund et al. 1997b; Lambert et al. 1998), in particular to the R CrB star V854 Cen (Asplund et al. 1998); considering its abundances Sakurai's object can be classified as an R CrB star[1]. Recently, Sakurai's object has also been reported to show visual variability (Liller et al. 1998): in February 1998 the star had faded by almost two magnitudes which by April it had recovered from, a behaviour characteristic of the R CrB stars. The irregular variability has continued since then (H. Duerbeck, priv. comm.). Thus, Sakurai's object fulfills the two defining properties of the R CrB stars: a distinct H-deficiency and unpredictable visual dimming events, presumably due to dust formation episodes in the vicinity of the stars. For the first time, the "birth" of an R CrB star has therefore been witnessed, proving the "Final Flash" scenario (Renzini 1979) as a viable channel for the formation of R CrB stars, though perhaps not the only option.

The R CrB stars can be put into two groups by chemical composition: a homogeneous majority class and a relatively heterogeneous minority class (Lambert et al. 1998), which are distinguished by a lower metallicity (here: Fe/C) and several extreme abundance ratios, in particular [Si/Fe] and [S/Fe]. Sakurai's object, however, at present has traits of both groups. It is therefore not possible for the moment to identify which, if either, of the two R CrB groups evolved from a star experiencing a final flash. Sakurai's object lacks the extreme [Si/Fe] and [S/Fe] ratios of the minority, but has e.g. their low Fe/C ratio and high [Na/Fe] ratio. Furthermore, in no minority member has Li previously been detected, while it has been observed in four of the majority stars (UW Cen, R CrB, RZ Nor and SU Tau). Lithium, however, could conceivably be destroyed as Sakurai's object continues to evolve. Sakurai's object resembles most closely the R CrB star V854 Cen, whose status as a majority or minority member is also unclear (Asplund et al. 1998). The only property of Sakurai's object not known to be shared with the R CrB stars is the high ^{13}C content (Asplund et al. 1997b). Possibly, the high ^{13}C abundance is a transient feature. It should be noted too that even rough estimates of the ^{13}C abundance are not available for most R CrB stars.

Additional support for the final flash scenario comes from FG Sge and V605 Aql. Currently FG Sge is showing typical R CrB-like variability (Papousek 1992) and there are hints that it may be H-deficient (Gonzalez et al. 1998). Unfortunately the published abundance analyses (e.g. Kipper & Kipper 1993; Gonzalez et al. 1998) of FG Sge differ significantly, even in [X/Fe], which prevents a detailed comparison with Sakurai's object and the R CrB stars, in particular since a normal H-abundance has been assumed for the analyses. FG Sge is, however, also significantly enhanced in the heavy s-elements and not only in the lighter s-elements, as is the case in Sakurai's object. During outburst, the spectrum of V605 Aql resembled closely those of cool R CrB stars (Lundmark 1921; Ludendorff

[1] Due to the different adopted C/He ratios in the analyses of Sakurai's object and the R CrB stars, it is not possible to directly compare the *absolute* abundances, since those are proportional to the C/He ratio. Had C/He=1% been used instead for Sakurai's object, then all abundances would have been 1.0 dex lower to first order (Asplund et al. 1998). Therefore it is more appropriate to compare *relative* abundances for different stars.

1922; Clayton & De Marco 1997), though detailed information on its chemical composition is lacking.

The situation is therefore slightly unfortunate. All of the identified born-again giants Sakurai's object, FG Sge and V605 Aql show similarities with the R CrB stars, clearly suggesting that the final flash scenario is a possible route to forming R CrB stars. However, none of the three stars are readily identified with either the majority or the minority group. It is tempting to identify tentatively at least the minority stars as descendants of a final flash, because of their more heterogeneous nature and their possibly higher C/He ratios (Asplund et al. 1997b; Asplund et al. 1998; Lambert et al. 1998), as these would be in better agreement with theoretical predictions (Iben & MacDonald 1995; Schönberner 1996). By applying Occam's razor, one could speculate that *all* R CrB stars have indeed been formed through a final He-shell flash in a cooling pre-WD. Until the abundance differences between the stars can be explained either by their earlier nucleosynthetic evolution or through the work of dust-gas separation (Lambert et al. 1998), this conclusion seems premature. We are therefore happy to conclude that at least one R CrB star – Sakurai's object – is a final flash object. Given the striking similarities in terms of chemical composition between V854 Cen and Sakurai's object (Asplund et al. 1998) it is very likely that at least these two stars share the same origin.

7. Conclusions

An analysis of the available spectra, published and unpublished, of the born-again giant Sakurai's object from 1996 confirms the extremely rapid evolution of the star previously noted by Asplund et al. (1997b). Throughout 1996 Sakurai's object cooled significantly by about 1 000 K, which is also obvious from photometry (Duerbeck et al. 1997); the cooling has continued until the present (1998). Such cooling is presumably the result of the expansion of the photosphere following the drastically increased luminosity due to the He-shell flash. Even more spectacularly, the chemical composition of Sakurai's object shows definite signs of having significantly altered within only a few months (from April to October 1996). Again, these changes are can be interpreted as being most likely caused by the mixing and nuclear reactions which have ensued as a result of the final He-shell flash: ingestion and burning of the H-rich envelope, Li-production through the Cameron-Fowler mechanism, and s-processing of the light s-elements (including Sc). To our knowledge, Sakurai's object represents the fastest case of stellar evolution ever observed (leaving aside complete stellar disruptions such as supernovae).

Sakurai's object shows strong abundance similarities with the R CrB stars, not only a distinct H-deficiency and C-enhancement. In all respects, Sakurai's object would be classified as an R CrB star judging from a compositional perspective (Lambert et al. 1998). Since recently Sakurai's object has also started showing irregular fading episodes typical of the R CrB stars (Liller et al. 1998), it indeed seems to have evolved into an R CrB star. Thus, for the first time ever, the "birth" of an R CrB star may have been witnessed, which lends strong support for the final flash scenario as a probable channel for forming at least some of the R CrB stars. The exact relation between Sakurai's object and the majority and minority classes of the R CrB stars needs, however, to be clarified before one draws any conclusions on how many of the R CrB stars have been formed through a final He-shell flash in a post-AGB star on the WD cooling track.

Further studies of the future evolution of Sakurai's object are clearly needed. Judging from its rapid metamorphosis since its discovery in 1996, it is not unlikely that the star will provide astronomers with even more surprises and spectacular changes of appearance in the years to come. In this respect, both close photometric monitoring of the visual variability and spectroscopic studies of the changes in chemical composition after 1996 are of great importance. As long as the IR excess is not too disturbing (Eyres et al. 1998), it may be advantageous to use high-resolution near-IR spectrum for such abundance analyses. Furthermore, studies are needed on the chemical composition of FG Sge, in particular regarding its H-content, and the R CrB star U Aqr, which shows very pronounced s-element enhancements similar to FG Sge and Sakurai's object (Bond et al. 1979), in order to assess better the relationship between born-again giants and the R CrB stars. Finally and most urgently, the theoretical modelling of the final He-shell flash events needs to be extended to a wider range of stellar masses and initial conditions including a detailed study of the mixing processes and incorporating the relevant nuclear reactions such as CNO-cycling, He-burning, Li-production and s-processing, which will likely provide strong constraints on the models. Admittedly, such modelling is a Herculean task considering the dynamical nature of the event, but is unfortunately required in order to understand fully the rapid evolution of Sakurai's object and related stars.

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