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Abundance similarities between the R CrB star V854 Cen and the born-again Sakurai's object

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Abstract. The elemental abundances of the mildly hydrogen-deficient R Coronae Borealis (R CrB) star V854 Cen have been estimated. The R CrB stars have been divided into majority and minority classes judging by their abundance patterns. Class assignment has previously been unambiguous but V854 Cen has traits of both the minority and majority class. Neither V854 Cen nor the three obvious minority members show any clear abundance signatures of having been affected by e.g. dust-gas separation as often observed in post-AGB stars. By chemical composition, V854 Cen closely resembles Sakurai's object, which has probably recently experienced a final He-shell flash. Therefore V854 Cen and Sakurai's object may share the same evolutionary background, which would add support for the final-flash scenario as a viable origin of the R CrB stars. Most of the few differences in abundance ratios between the stars could if so be attributed to milder H-ingestion in connection with the final He-shell flash of V854 Cen. The identification of either the majority or the minority group, if any, as final flash objects, remain uncertain, however, due to the unclear membership status of V854 Cen.

Key words: stars: individual: V854 Cen – stars: variables: R Coronae Borealis – stars: abundances – stars: AGB and post-AGB – stars: evolution – stars: individual: Sakurai's object

1. Introduction

The extreme hydrogen-deficiency of the R Coronae Borealis (R CrB) stars together with overabundances of elements produced at the time of helium burning suggest that these stars are in late evolutionary stages. A removal of essentially all of the hydrogen-rich envelope prior to leaving the asymptotic giant branch (AGB) is very unlikely in the context of single star evolution for low- and intermediate-mass stars. Furthermore, due to the short time-scale following evolution off the AGB and the lack of significant pre-planetary nebula material, the stars cannot readily be identified with a phase immediately after departing from the AGB. Instead, the R CrB stars are likely to be re-born stars, i.e., stars that evolved off the AGB to the white dwarf cooling regime but now show brief re-appearances as luminous giants.

Two proposals for re-born stars have garnered most attention: the "final flash" (Renzini 1979) and the "double degenerate" (Webbink 1984) models. In the former a final He-shell flash in a post-AGB star descending the white dwarf cooling track briefly expands the stellar envelope to giant dimensions once again. This He-shell flash quickly depletes the envelope of hydrogen to create an R CrB-like supergiant. Examples of such stars may be the recently discovered Sakurai's object (Asplund et al. 1997b) and FG Sge (Gonzalez et al. 1998). The second model involves a merger of a He white dwarf and a C-O white dwarf. Close white dwarf binaries such as WD 2331+290 and WD 0957-666 may merge within a Hubble time and produce hydrogen-deficient giants (Iben et al. 1997). The pros and cons of each scenario are discussed in Iben et al. (1996) and Schönberner (1996). Possible progenitors and descendants to the R CrB stars are the hydrogen-deficient carbon (HdC) stars (Warner 1967) and the extreme helium (EHe) stars (e.g. Jeffery 1996), respectively, which may subsequently evolve into the helium sub-dwarf O (HesdO$^+$) stars.

The two suggested scenarios will probably produce different atmospheric chemical compositions. Estimates of the elemental abundances are therefore essential for placing the stars in the correct context of stellar evolution. In two companion articles the compositions of 17 R CrB stars and two EHe stars (Lambert et al. 1998) and Sakurai's object (Asplund et al. 1997b) have been determined. V854 Cen is discussed separately being a 'peculiar' (!) R CrB star with two special characteristics: a relatively high hydrogen abundance and a propensity to undergo frequent declines. In the present paper the composition of V854 Cen is

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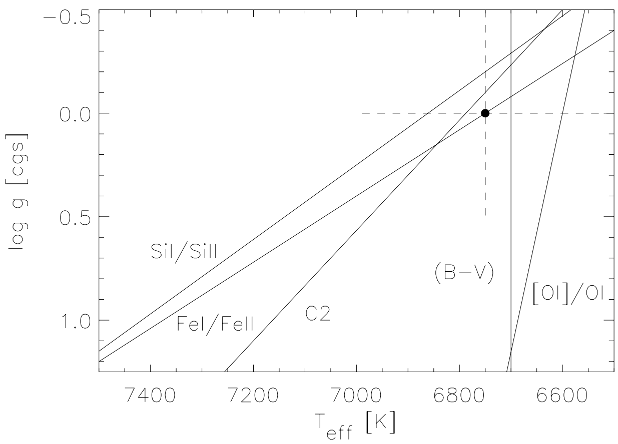

Fig. 1. The loci provided by the different $T_{\rm eff}$-log g indicators for C/He=10%. The adopted stellar parameters $T_{\rm eff}$ = 6750 K and log g = 0.0 [cgs] are denoted by •, with the estimated uncertainties shown by dashed lines. Consistent parameters which are not shown in the figure were also obtained from the excitation balance of Fe I and II lines and the hydrogen lines

analysed. Similarities and differences with the compositions of R CrB stars and Sakurai's object are investigated and discussed in light of the proposed evolutionary scenarios.

2. Observations

V854 Cen was observed in July 1989 with the Cassegrain echelle spectrograph on the CTIO 4m reflector, together with many other R CrB stars which form the basis for the analysis described in Lambert et al. (1998). At the time, the star was at or close to maximum light. Both red (5500-6840 Å) and blue (4200-4900 Å) spectra were obtained at a resolution of about 0.3 Å. The signal-to-noise of the different spectra is 100 or higher over most of the observed bandpass.

For the C_2 Swan 0-1 band, the He I triplet and the hydrogen lines, synthetic spectroscopy were used to fit the spectral features. Otherwise, equivalent widths of seemingly unblended lines were measured. A list of all lines used for the analysis can be found in Table 4.

3. Abundance analysis

The abundance analysis of V854 Cen is based on line-blanketed, hydrogen-deficient model atmospheres similar to those described in Asplund et al. (1997a). The input abundances for the model atmosphere calculations were determined in an iterative fashion, such that all abundances of the final adopted model were consistent with the results from the abundance analysis, with one important exception, namely carbon, which will be discussed further below.

The stellar parameters $T_{\rm eff}$ = 6750±250 K, log g = 0.0±0.5 and $\xi_{\rm turb}$ = 6.0 ± 1.0 km s^{-1} were determined utilizing a range of spectral features. The ionization balances of Fe I/Fe II and Si I/Si II provide loci in the $T_{\rm eff}$-log g diagram, which run essentially parallel with the solution from the C_2 Swan band strengths. The excitation balance from high-excitation, permitted O I lines and low-excitation forbidden [O I] lines provide an additional temperature indicator with a minor gravity dependence. Also the excitation balance of Fe I and Fe II lines and $B - V$ photometry (adopting $(B - V)_0$ = 0.50, N.K. Rao unpublished research) provide estimates of $T_{\rm eff}$. V854 Cen has only a small light amplitude due to pulsations and the non-simultaneous photometry compared with the spectroscopy is therefore unlikely to introduce any significant errors. The loci in the $T_{\rm eff}$-log g diagram of the various indicators are shown in Fig. 1. The microturbulence parameter $\xi_{\rm turb}$ was derived from Fe II and Ti II lines of various strengths.

With the estimated $T_{\rm eff}$ and log g, the H abundance was determined using the wings of Hβ. Hγ was also used but is more affected by blending and was therefore given a lower weight, though the derived abundance was consistent with the value obtained from Hβ. Synthetic spectra of Hα was not attempted since the line is often distorted by emission components even at maximum light for R CrB stars (Rao & Lambert 1997). For the computed H line profiles, data were taken from Seaton (1990 and private communication). The weak Balmer lines in V854 Cen, compared to normal supergiants of similar temperature, require a significant H-deficiency, since the strengths of the H line wings remain unchanged or even *increase* with a decreasing H abundance until another element but H takes over as the dominant opacity source (Böhm-Vitense 1979). The Balmer line profiles give additional information on $T_{\rm eff}$ and log g, which for V854 Cen were consistent with those of the other indicators.

The continuous opacity at visual wavelengths in atmospheres of R CrB stars is predicted to be provided largely by photoionization of C I from highly excited levels (Searle 1961; Asplund et al. 1997a). Then, the equivalent widths of C I lines from similarly excited levels must be almost independent of the atmospheric parameters $T_{\rm eff}$ and log g. This expectation is confirmed by the fact that the equivalent widths of weak C I lines are almost the same from one R CrB star to another. However, the analyses of the R CrB stars has revealed a significant discrepancy between the observed and predicted line strengths of the C I lines (Gustafsson & Asplund 1996; Lambert et al. 1998): all observed lines are weaker than predicted to the extent that the derived C abundance is on average 0.6 dex less than the input abundance with a small scatter between the stars. The reason for this so called "carbon problem" is still unknown, but it may be related to inappropriate assumptions for the model atmospheres (one-dimensional, static, flux constant models in LTE) on which the analyses are based (Lambert et al. 1998). Fortunately, various tests suggest that abundance ratios such as [X/Fe] [1] will in general be little affected by the carbon problem. As in the previous studies, we have chosen to adopt a C abundance for the model atmospheres, which results in a "carbon problem" of 0.8 dex.

[1] The abundance ratios are defined by the customary [X/Fe]=log (X/Fe)$_*$ − log (X/Fe)$_\odot$

Despite the fact that C dominates the continuous opacity, He is the most abundant element. In principle, the He abundance may be determined from the presence of the He I 5876 Å triplet. The predicted He I D_3 triplet (with the blending C I lines taken into account using synthetic spectroscopy, Lambert et al. 1998) is too strong with an assumed C/He ratio of 1% by number, which is the value determined for most of the EHe stars (Jeffery 1996) and deemed appropriate for the R CrB stars by Lambert et al. (1998). A ratio of 10% seems more suitable, which is the value found for Sakurai's object (Asplund et al. 1997b). The C/He ratio in V854 Cen is uncertain, however, due to the significant contribution of the blending C I lines, and possible departures from LTE for this high-excitation transition. The derived stellar parameters are independent to first order of the C/He ratio, since He is acting only as an inert element, only contributing to the gas pressure except for at large depths. The effects of the uncertainty in C/He will thus be minor; typically, the [X/Fe] ratios differ by < 0.05 dex when using 1% instead of 10% for the C/He ratio, though smaller absolute abundances will be derived, as is clear from Table 1.

A list of the lines used for the abundance analysis with relevant data is shown in Table 4. The adopted *gf*-values are the same as in Lambert et al. (1998), i.e. mainly from a compilation kindly provided by R.E. Luck. For the Fe I and II lines, data were taken from Lambert et al. (1996). For the C I lines, Opacity Project *gf*-values (Seaton et al. 1994; Luo & Pradhan 1989) were used assuming LS-coupling, as well as data from Hibbert et al. (1993) for intermediate coupling. Most of the lines used for abundance determination are weak and hence little affected by microturbulence and hyperfine structure, except for Mg, Sc, Ti, Cr, Sr and Ba. For two of the Ba II lines we have investigated the effects of hyperfine structure, with relevant data taken from Magain (1995) for λ4554.04 Å and Villemoes (1993) for λ6496.90 Å. Isotope shifts were not included, since they are expected to play a minor role (Cowley & Frey 1989). The hyperfine structure affects the derived abundances from the lines by only ≤ 0.02 dex, due to the fact that $\xi_{\rm turb}$ is large relative to the hyperfine splitting. Thus, the neglect of hyperfine structure will probably not compromise our conclusions regarding the chemical composition.

4. Chemical composition and comparison with the other R CrB stars

4.1. Elemental abundances

The derived abundances from the LTE analysis are listed in Table 1. The given errors are the formal standard deviations from the different lines; for elements with only a single line, no error is given. Errors introduced by the uncertainties in the adopted stellar parameters are given in Table 2, from which we judge the accuracy of most determined abundances to be better than 0.3 dex, except for Ca, Ni, Zn, Sr and Ba where the errors may be slightly larger. Abundance ratios such as [X/Fe] will in general be much less vulnerable to errors in the parameters.

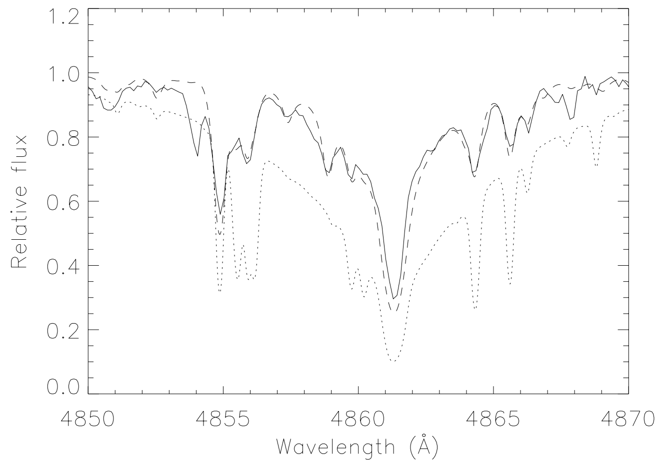

Fig. 2. Hβ in V854 Cen (solid) compared with synthetic spectra with normal hydrogen abundance (dots) and H-deficient by 2.1 dex (dashed). The stellar parameters used for the predicted profiles are $T_{\rm eff}$ = 6750 K, $\log g$ = 0.00 [cgs] and $\xi_{\rm turb}$ = 6.0 km s^{-1}. For the H-deficient model C/He=10% has been used

According to Table 1 V854 Cen is metal-poor. Assuming C/He=10%, the Fe mass fraction is 0.6 dex below solar if the spectroscopic C abundance is adopted (1.4 dex with the input C abundance). In fact, the Fe/C ratio is the lowest of all analysed R CrB stars with the exception of DY Cen. Had the usual C/He=1% ratio (Lambert et al. 1998) been assumed, the derived metallicity might have been problematic considering the galactic location of the star: Z = 800 pc (assuming $M_{\rm bol} = -5$, Lambert et al. 1998). The latter suggests that it may belong to the thick disk population, and thus not metal-poor by a large factor. If C/He=1% is still to be preferred, V854 Cen may have acquired the metal-poorness (then 1.6 dex below solar) through chemical processes. One chemical process – the separation of dust and gas – will be investigated in detail below.

Compared to other R CrB stars, V854 Cen is only mildly hydrogen-deficient. Only the hot R CrB DY Cen with $\log \epsilon_{\rm H}$ = 10.8 has a higher H abundance (Jeffery & Heber 1993). The H abundance of V854 Cen is $\log \epsilon_{\rm H}$ = 9.9 for C/He=10% and 8.9 for C/He=1% which is the spectroscopically determined C/He value for DY Cen. The next least H-deficient R CrB star is V CrA with $\log \epsilon_{\rm H}$ = 8.0 for an adopted C/He=1%. Synthetic spectra of the Hβ profile in V854 Cen is shown in Fig. 2. A solar hydrogen abundance is clearly excluded since it would require unreasonably low $T_{\rm eff}$ and $\log g$. V854 Cen accentuates the anti-correlation between the H and Fe abundances found for R CrB and EHe stars (Heber 1986; Lambert et al. 1998), which Sakurai's object also follows (Asplund et al. 1997b).

Nitrogen when considered as a [N/Fe] ratio is slightly less overabundant in V854 Cen ([N/Fe]=1.4) than in the R CrB majority stars (mean of 14 stars [N/Fe] = 1.6). The [N/Fe] ratio in V854 Cen is roughly consistent with a complete conversion of the original CNO nuclei in a slightly metal-poor star to N through CNO-cycling. Some additional N may also have been produced subsequently by proton-capture on ^{12}C synthe-

Table 1. Chemical compositions of V854 Cen, the R CrB stars, Sakurai's object and the Sun. The customary normalization $\log(\Sigma\mu_i\epsilon_i) = 12.15$ has been adopted for the abundances

Element	Sun[a]	V854 Cen		Sakurai's object[b]		R CrB	R CrB minority			
		C/He=1%	C/He=10%	May	October	majority[c]	V CrA[c]	V3795 Sgr[c]	VZ Sgr[c]	DY Cen[d]
H	12.00	8.9 ± 0.1	9.9 ± 0.1	9.7	9.0		8.0	< 4.1	6.2	10.8
He	10.99	11.5	11.4	11.4[e]	11.4[e]	11.5[e]	11.5[e]	11.5[e]	11.5[e]	11.5
Li	3.31[a]	< 1.0	< 2.0	3.6	4.2					
C	8.55	$8.7^{f} \pm 0.3$	$9.6^{f} \pm 0.3$	9.7[f]	9.8[f]	8.9[f]	8.6[f]	8.8[f]	8.8[f]	9.5
N	7.97	6.8 ± 0.1	7.8 ± 0.1	8.9	8.9	8.6	8.6	8.0	7.6	8.0
O	8.87	7.9 ± 0.1	8.9 ± 0.1	9.5	9.4	8.2	8.7	7.5	8.7	8.8
Na	6.33	5.4 ± 0.1	6.4 ± 0.1	6.7	6.8	6.1	5.9	5.9	5.8	
Mg	7.58	5.2	6.2	6.6	6.5	6.4	6.6	6.1		7.3
Al	6.47	4.7 ± 0.1	5.7 ± 0.1	6.6	6.3	6.0	5.3	5.6	5.4	5.9
Si	7.55	6.1 ± 0.2	7.0 ± 0.2	7.1	7.5	7.1	7.6	7.5	7.3	8.1
S	7.23	5.5 ± 0.1	6.4 ± 0.1	6.6	6.9	6.9	7.6	7.4	6.7	7.1
Ca	6.36	4.2 ± 0.2	5.1 ± 0.2	5.6	5.5	5.4	5.1	5.3	5.0	
Sc	3.17	1.9 ± 0.1	2.9 ± 0.1	3.1	3.9	2.7	2.8	2.8		
Ti	5.02	3.1 ± 0.2	4.1 ± 0.2	4.1	4.6	4.0	3.3	3.5		
Cr	4.00	3.2 ± 0.2	4.2 ± 0.2	4.5	5.1			4.2		
Fe	7.50	5.0 ± 0.1	6.0 ± 0.1	6.3	6.6	6.5	5.4	5.6	5.8	5.0
Ni	6.25	4.9 ± 0.1	5.9 ± 0.1	6.1	6.2	5.9	5.2	5.8	5.2	
Zn	4.60	3.4 ± 0.3	4.4 ± 0.3	4.7	5.4	4.4	4.0	4.1	3.8	
Sr	2.97	1.2	2.2	4.9	5.4:					
Y	2.24	1.2 ± 0.2	2.2 ± 0.2	3.3	4.2	2.1	0.6	1.5	2.8	
Zr	2.60	1.1 ± 0.2	2.1 ± 0.2	3.0	3.5	2.0			2.5	
Ba	2.13	0.3 ± 0.1	1.3 ± 0.1	1.5	1.9	1.6	0.7	0.9	1.4	
La	1.17	-0.6 ± 0.1	0.4 ± 0.1	< 1.6	1.5					
Ce	1.58	-0.5 ± 0.2	0.5 ± 0.2							

[a] From Grevesse et al. (1996). For Li the meteoritic value is adopted.
[b] From Asplund et al. (1997b)
[c] From Lambert et al. (1997). The majority is an average of 14 stars, with little scatter except for O, Y and Ba. For Mg, Sc, Ti and Zr the mean is based only on a few majority stars
[d] From Jeffery & Heber (1993).
[e] Input C/He ratio for model atmospheres: 10% estimated for Sakurai's object and C/He=1% assumed for the R CrB stars, except for DY Cen where it was determined spectroscopically to be 1%.
[f] Spectroscopically determined C I abundance, which differs from assumed input abundance by typically 0.6 dex.

sized from He-burning. The [O/Fe] ratio for V854 Cen, which is greater than seen in the R CrB majority stars, would seem to require additional production of O through He-burning.

[Na/Fe], [Al/Fe] (see Fig. 3), [Si/Fe], [S/Fe], and to some degree [Ca/Fe], are all overabundant relative to the Sun. In particular, [Na/Fe]=1.6 is very high, which suggests that Na has been synthesized through ^{22}Ne(p,γ)^{23}Na; of the analysed R CrB stars only V CrA has a higher [Na/Fe]. At the same time Al should have been produced by ^{25}Mg(p,γ)^{26}Al, but [Al/Fe] is not unusually high compared with the other R CrB stars. A possible explanation is that the proton captures occurred in gas enriched in ^{22}Ne. This is quite possible as CNO-cycling converts all C, N, and O to ^{14}N, which at higher temperatures is converted by successive α-captures to ^{22}Ne. Ne is destroyed in He-burning but, in a convective situation as may occur when H-rich gas is mixed into the final He-shell, some may survive and be available for conversion to Na. In steady conditions, Ne is converted to Mg in a He-shell. Unfortunately the low $T_{\rm eff}$ prevents a determination of the Ne abundance, but since [Mg/Fe] is only solar in V854 Cen the explanation seems plausible.

The ratios [Si/Fe]=1.0 and [S/Fe]=0.6 are higher than expected for a dwarf star with the metallicity of V854 Cen (i.e.[Si/Fe] $\simeq$ [S/Fe] $\simeq 0.2$) but similar to what has been determined for the R CrB majority. Apparently, either Si and S have been synthesized or Fe has been depleted (Lambert et al. 1998). The slight Ca overabundance ([Ca/Fe]=0.2) is as expected for a mildly metal-poor dwarf (Edvardsson et al. 1993).

Of the Fe-group elements, Sc and Ti are overabundant while Cr has a solar abundance relative Fe: [Sc/Fe]=1.2, [Ti/Fe]=0.5 and [Cr/Fe]=0.0. In particular Sc is very overabundant, which

Table 2. Abundance errors due to uncertainties in the stellar parameters of V854 Cen, defined by $\Delta(\log \epsilon_i) = \log \epsilon_i$(perturbed) - $\log \epsilon_i$(adopted). The adopted parameters are $T_{\rm eff}$ = 6750 K, $\log g$ = 0.00 [cgs] and $\xi_{\rm turb}$ = 6.0 km s^{-1}

Element	$\Delta T_{\rm eff}$ = 250 [K]	$\Delta \log g$ = 0.5 [cgs]	$\Delta\xi_{\rm turb} = -1.0$ [km s^{-1}]
H I	−0.10	−0.20	< 0.05
C I	+0.08	−0.06	+0.07
N I	−0.13	+0.18	+0.03
O I	−0.07	+0.09	+0.10
Na I	+0.27	−0.27	+0.06
Mg I	+0.29	−0.26	+0.13
Al I	+0.25	−0.26	+0.00
Si I/II	+0.25/ − 0.06	−0.25/ + 0.05	+0.00/ + 0.33
S I	+0.17	−0.15	+0.00
Ca I	+0.37	−0.30	+0.01
Sc II	+0.12	+0.13	+0.22
Ti II	+0.12	+0.03	+0.22
Cr II	+0.03	+0.07	+0.16
Fe I/II	+0.34/ + 0.03	−0.28/ + 0.07	+0.01/ + 0.08
Ni I	+0.34	−0.29	+0.00
Zn I	+0.31	−0.26	+0.05
Sr II	+0.31	−0.06	+0.23
Y II	+0.18	+0.00	+0.11
Zr II	+0.13	+0.03	+0.05
Ba II	+0.41	−0.17	+0.26
La II	+0.28	−0.04	+0.01
Ce II	+0.25	−0.03	+0.01

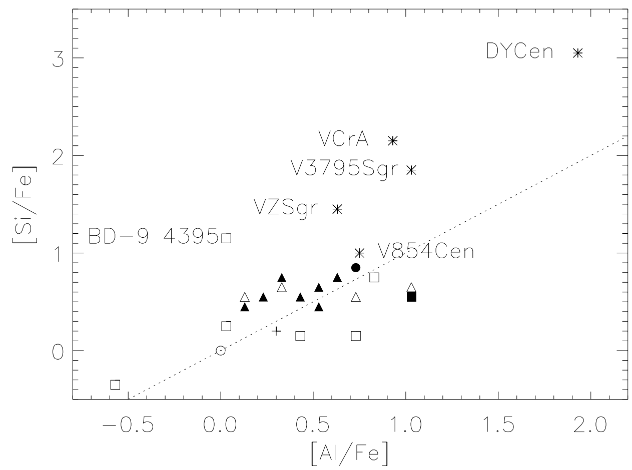

Fig. 3. [Si/Fe] vs [Al/Fe] for H-deficient stars. The symbols correspond to Li-rich majority R CrB stars (△), other majority members (black triangles), the minority (including DY Cen) (∗), Lambert et al.'s (1998) EHe stars (black squares), Jeffery's (1996, see further references therein) 'best' EHe stars (□), Sakurai's object in October 1996 (•) (Asplund et al. 1997b), the Sun (⊙) and typical halo dwarf abundances for [Fe/H] $\simeq -1.0$ (+). The dotted curve correspond to a 1-to-1 slope passing through the solar values

Table 3. Elemental abundance ratios in V854 Cen compared to predictions from s-processing calculations for different neutron exposures τ_0

Element ratio	observed ratio	Single exposure[a]		Exponential exposure[b]	
		τ_0 = 0.1	0.3	0.05	0.1
Ni/Fe	-0.1	-0.7	+0.3	-1.0	-0.7
Zn/Fe	-1.6	-1.7	+0.2	-1.9	-1.3
Sr/Fe	-3.8	-3.8	-1.2	-3.6	-2.2
Y/Fe	-3.8	-4.7	-2.3	-4.6	-3.1
Zr/Fe	-3.9	-4.6	-2.4	-4.5	-2.9
Ba/Fe	-4.7	-4.6	-3.7	-4.8	-4.0
La/Fe	-5.6	-5.8	-4.8	-6.1	-5.3
Ce/Fe	-5.5	-5.6	-4.4	-5.7	-5.0

[a] From Malaney (1987a).
[b] From Malaney (1987b).

suggests synthesis by the s-process such that the Sc abundance is raised by neutron captures on the much more abundant Ca nuclei. This is supported by the observed enhancements of the s-elements. A similar phenomenon has been observed in the related stars FG Sge (Acker et al. 1982; Gonzalez et al. 1998) and Sakurai's object (Asplund et al. 1997b). [Ti/Fe] is slightly higher than for metal-poor dwarfs, for which [Ti/Fe] $\simeq$ 0.3 is expected (Edvardsson et al. 1993), though it could be due to observational errors. Cr behaves similarly to Fe, as anticipated for a low metallicity star.

Both [Ni/Fe]=1.1 and [Zn/Fe]=1.2 (see Fig. 4) are distinctly non-solar, which cannot be attributed to an initial metal-poor composition for V854 Cen. Furthermore, the light s-process elements Y and Zr are significantly enhanced ([Y/Fe]=1.4 and [Zr/Fe]=1.0) and to lesser degree the heavy s-elements ([Ba/Fe]=0.6, [La/Fe]=0.7 and [Ce/Fe]=0.5), which are all more abundant than for metal-poor dwarfs where [s/Fe] $\simeq$ 0.0 is characteristic (Edvardsson et al. 1993). According to Malaney's (1987a) calculations of s-processing in a single exposure, the elements Ni-Ce suggest that V854 Cen has suffered a mild neutron exposure of $\tau_0 = 0.1 - 0.2$ mb^{-1}, as shown in Table 3. Since also Ni and Zn are well fit by the predictions, the stellar atmosphere may consist predominantly of material exposed to neutrons. If instead the elemental abundances are to be explained as the result of s-processing by an exponential exposure, the derived abundances suggest $\tau_0 = 0.05 - 0.1$ mb^{-1} (Malaney 1987b). In this case, the observed [Ni/Fe] is not well reproduced. The estimated neutron exposure is similar to what seems appropriate for most of the R CrB stars (Lambert et al. 1998), and indicates either that the formation of an R CrB star in general produces an environment capable of mild s-processing, or that the atmospheres have retained the s-process characteristics from the previous thermally pulsing AGB-phase. The latter possibility may likely be discounted as s–process enriched AGB stars generally show a much more severe exposure to neutrons, say $\tau_0 \approx 0.2 - 0.4$ mb^{-1} (Busso et al. 1995). A final He-shell flash in a post-AGB star is clearly able to produce these abundance patterns, as demonstrated by Sakurai's object. It is more uncertain whether this is also possible in the merger of two white dwarfs.

4.2. Minority or majority status for V854 Cen?

The first survey of compositions of R CrB stars (Lambert & Rao 1994) led to the definition of the two classes: majority and minority. The latter were principally characterized by high [Si/Fe] and [S/Fe] ratios and a low spectroscopic metallicity. The minority is also distinguished by their high [Na/Fe], [Al/Fe], [Ca/Fe] and [Ni/Fe] ratios. [2]

With the abundances determined here, V854 Cen is mainly located in between the three minority stars and the majority group, as shown in e.g. Fig. 3. Only in [Si/Fe] vs [Na/Fe] is V854 Cen distinctly different from the majority. In particular, the [S/Fe] ratio is as expected for the majority and far from the very high characteristic ratios of the minority. The high [Ni/Fe]=1.1 and [Zn/Fe]=1.2 (see Fig. 4) ratios are also atypical of the majority (on average 0.6 and 0.7, respectively) but typical of the minority for which both ratios show a large range. The results for V854 Cen may suggest that there is a gradual difference between the two groups introduced perhaps by varying degree of dust depletion rather than reflecting different evolutionary backgrounds.

4.3. Iron-depleted rather than iron-deficient?

The peculiar abundances relative to Fe of V854 Cen may suggest that the star was not born as metal poor as its Fe abundance indicates. Dust depletion has been proposed to explain the observed abundance patterns in several post-AGB stars (cf. Bond 1991; Lambert 1996) and λ Boötis stars (Venn & Lambert 1990), as well as in the hot R CrB star DY Cen (Jeffery & Heber 1993); elements that condense readily into grains are now underabundant in these stellar photospheres.

It is tempting to identify the low Fe abundance of the minority stars as the result of a dust-gas separation that either occurred in the post-AGB progenitor or is occurring in the R CrB star. The temptation is especially strong for V854 Cen which is frequently in decline with its surface obscured by dust. A high [S/Fe] ratio is readily explained as S does not easily condense. Moreover, a high [S/Fe] ratio is characteristic of those post-AGB stars for which a severe separation of dust and gas has occurred. However, the high [Si/Fe] is not naïvely expected, in particular not if the dust-gas separation occurred in the C-rich gas of an R CrB star because in such an environment a likely condensate is SiC. The [Si/Fe] ratio of the extreme minority stars DY Cen, V CrA, and V3795 Sgr greatly exceed the [Si/Fe] ratios seen in even those post-AGB stars most severely affected by the dust-gas separation. In Fig. 5 the observed depletions, defined here as the stellar abundance relative to the solar value, are shown for the minority members, as a function of the observed depletions for the ζ Oph main cloud (Cardelli 1994). The latter cloud is taken as being representative of the ISM depletions. Note that the observed depletions using this definition do not necessarily reflect the exact amount of removed material, since the initial

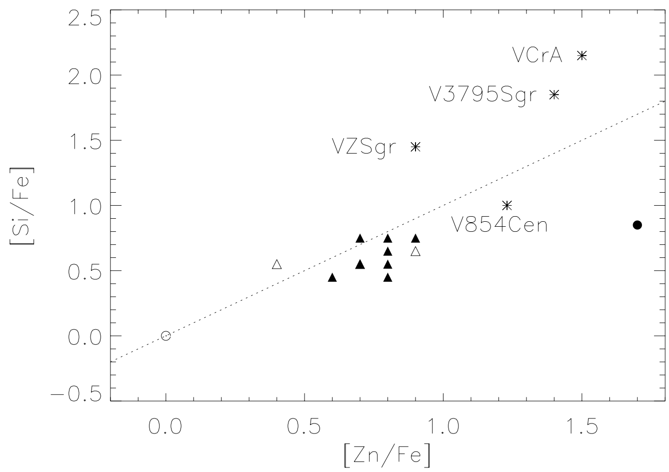

Fig. 4. [Si/Fe] vs [Zn/Fe] for H-deficient stars. The symbols have the same meaning as in Fig. 3

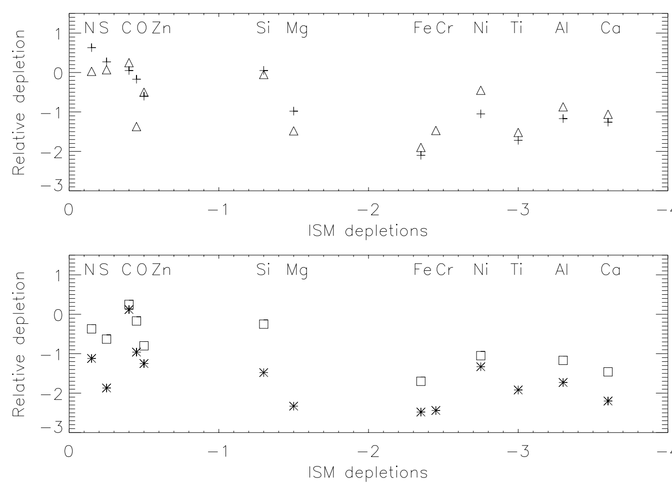

Fig. 5. The depletions of the minority R CrB stars vs the observed ISM depletion (see text). The stellar depletion is here defined by the stellar abundance relative to the solar abundance. The symbols correspond to V3795 Sgr ($\triangle$), V CrA (+), VZ Sgr ($\square$) and V854 Cen ($*$). The different elements are indicated on top

[2] Rao & Lambert (1996) placed V854 Cen in the minority group based on a preliminary analysis that overestimated the hydrogen abundance. As a result the continuous opacity and resultant abundances were overestimated. In particular, the high [Si/Fe] suggested a membership of the minority, but the more accurate analysis presented here gives a lower [Si/Fe] ratio. The difference in [X/Fe] ratios is attributed to differences in temperature gradients of the model atmospheres. With the lower hydrogen content estimated here, the continuous opacity will be lower, and hence backwarming will be more pronounced.

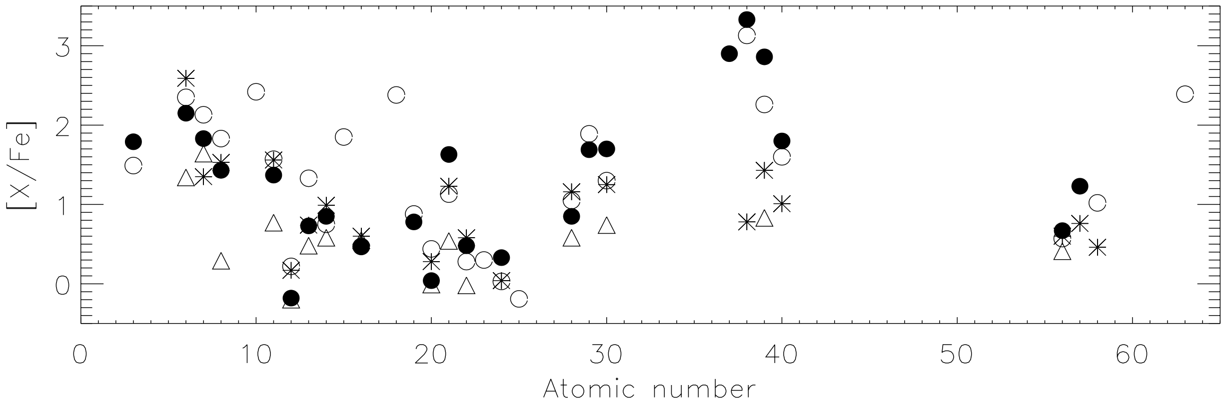

Fig. 6. The elemental abundance ratios [X/Fe] in V854 Cen ($*$) compared with Sakurai's object in May ($\circ$) and October ($\bullet$) 1996 (Asplund et al. 1997b) and the mean of the majority R CrB stars ($\triangle$) (Lambert et al. 1998). Note that the apparent changes in [X/Fe] for Sakurai's object between the two dates do not necessarily reflect the real alterations in *absolute* abundances obvious in Table 1, since the abundance of Fe is not the same, which may or may not be real since it is still within the observational uncertainties

metallicity may not have been solar, but indicate the differential depletion between different elements.

Though there is some tendency for the abundances to follow the ISM depletions as seen in Fig. 5, the correlation is not conclusive. The differential depletion for the different elements for each star does not seem to exceed about 1.0 dex. Judging from Fig. 5, all elements, if depleted, seem to have been altered roughly by the same amount, except possibly Si, S, Ni and Zn. In the case of S and Zn this might be expected but not for Si and Ni. A further complication is that the initial abundances of, e.g., the s-process elements, such as Ni and Zn (see above), and the proton-capture elements like Na and Al, have likely been modified by nucleosynthesis. This is exemplified by a slightly greater depletion of S than Al in V854 Cen, while in the ISM S reflects the initial metallicity and Al being one of the most depleted elements.

Before drawing any definite conclusions more condensation calculations for H-deficient and C-rich environments are needed. Such a special composition may well cause significant changes in expected dust depletions compared to what is found in the H- and O-rich ISM.

5. Abundance similarities with Sakurai's object

In many respects V854 Cen is similar to Sakurai's object, which has probably recently experienced a final He-shell flash. Sakurai's object is H-deficient and C-rich, like the R CrB stars. Furthermore the abundances of some elements, most notably H, Li and the light s-process elements, seem to have changed significantly within only five months in 1996, presumably as a result of mixing of material exposed to nucleosynthesis with the stellar surface layers following an ingestion of the H-rich envelope (Asplund et al. 1997b). The abundances of Sakurai's object in May and October 1996 are listed in Table 1. As shown in Fig. 6, the differences in [X/Fe] between V854 Cen and Sakurai's object in May and October 1996 do not exceed 0.3 dex for the elements studied besides H, Li, N, and the s-process elements, and possibly C and Al. As has already been mentioned, the H abundances are also higher in these stars relative to the R CrB stars in general. Indeed, V854 Cen is more similar to Sakurai's object than any of the other R CrB stars, which suggests a similar evolutionary background as final flash objects for the two stars.

Most of the abundance differences between the two stars could be interpreted as a result of less amount of H ingestion in connection with the He-shell flash. The proton supply may not have been sufficiently high to raise the ^{13}C abundance significantly (Renzini 1990), which in turn prevented $^{13}C(\alpha,n)^{16}O$ from being as efficient a neutron source for s-processing as seems to have been the case in Sakurai's object. Unfortunately, the C_2 Swan bands are too weak in V854 Cen to admit a useful estimate of the $^{12}C/^{13}C$ ratio but a high ratio would not be surprising. More severe s-processing probably explains the higher [Sc/Fe] in Sakurai's object in October 1996 as well. Li production is dependent on the amount of ^{3}He in the envelope and on physical conditions, especially the convective velocity, at the time the Cameron-Fowler (1971) mechanism is initiated. It is not surprising that two stars with otherwise similar compositions may differ in their Li abundances. The lower N abundance in V854 Cen cannot, however, be attributed to reduced CNO-cycling in connection with the final flash, since the low observed $^{12}C/^{13}C$ and N/C ratios in Sakurai's object are not consistent with a significant simultaneous synthesis of N (Asplund et al. 1997b). The difference in [N/Fe] must therefore have been inherited from earlier CNO-cycling and He-burning episodes. As already noted, the derived [C/Fe] ratios are somewhat suspicious in light of the "carbon problem".

A possible problem with this interpretation is the slightly larger [Na/Fe] ratio in V854 Cen by 0.2 dex compared with Sakurai's object, which might indicate more proton captures. This minor difference can presumably be attributed to uncertainties in the analyses or that V854 Cen might be of lower initial metallicity which would increase [Ne/Fe] and [Na/Fe].

Table 4. Lines used for the abundance analysis. For the hydrogen and helium lines synthetic spectroscopy is used

Species	λ [Å]	χ [eV]	log gf	W_λ [mÅ]	Species	λ [Å]	χ [eV]	log gf	W_λ [mÅ]	Species	λ [Å]	χ [eV]	log gf	W_λ [mÅ]
H I	4861.32	10.20	-0.02	synt	S I	6757.16	7.87	-0.29	43	Fe II	4576.33	2.84	-3.04	191
	4340.46	10.20	-0.45	synt	Ca I	5590.12	2.52	-0.57	27		4582.84	2.84	-3.10	172
He I	5875.63	20.87	0.74	synt		5598.49	2.52	-0.09	68		6084.10	3.20	-3.80	38
Li I	6707.80	0.00	0.17	< 10		5601.29	2.52	-0.52	48		6147.74	3.89	-2.74	86
C I	5813.51	8.87	-2.73	114		6122.22	1.89	-0.32	84		6149.25	3.89	-2.75	92
	5817.70	8.87	-2.86	75		6162.18	1.90	-0.09	100		6247.55	3.89	-2.34	137
	5850.25	8.77	-2.68	97		6166.44	2.52	-1.26	11		6331.97	6.22	-1.64	17
	5864.95	8.77	-3.55	57		6439.08	2.52	0.39	81		6369.46	2.89	-4.36	32
	5877.31	8.77	-2.14	104		6449.81	2.52	-0.50	23		6432.68	2.89	-3.58	71
	5963.99	8.64	-2.64	133		6462.57	2.52	-0.26	66		6442.95	5.55	-2.46	16
	5969.33	7.95	-3.08	110		6493.78	2.52	-0.39	30		6446.39	6.22	-1.99	8
	6292.37	9.00	-2.19	186	Sc II	4354.61	0.60	-1.56	239		6516.08	2.89	-3.29	136
	6335.70	8.77	-2.80	87		4431.37	0.60	-1.88	170	Ni I	5578.73	1.68	-2.74	25
	6337.18	8.77	-2.33	137	Ti II	4350.83	2.06	-1.81	134		5592.28	1.95	-2.57	20
	6342.32	8.77	-2.11	142		4450.49	1.08	-1.45	281		5831.61	4.17	-0.96	10
	6378.79	8.77	-3.29	76		4488.32	3.12	-0.82	196		6643.64	1.68	-2.48	43
	6578.77	9.00	-2.60	143		4493.53	1.08	-2.83	100		6767.78	1.83	-2.17	49
	6586.27	9.00	-2.02	152		4501.27	1.12	-0.75	340		6772.32	3.66	-0.98	18
	6591.45	8.85	-2.41	110		4518.30	1.08	-2.64	123	Zn I	4810.53	4.08	-0.17	122
	6595.24	8.85	-2.41	90		4529.46	1.57	-2.03	169		6362.00	5.79	0.27	64
	6611.35	8.85	-1.84	195		4544.01	1.24	-2.40	145	Sr II	4215.52	0.00	-0.16	460
	6641.96	9.03	-3.46	39		4545.14	1.13	-2.46	157	Y II	4398.01	0.13	-1.00	240
	6650.97	8.85	-3.52	45		4563.76	1.22	-0.96	330		4682.32	0.41	-1.51	156
	6671.82	8.85	-1.66	217		4568.31	1.22	-3.03	112		4786.58	1.03	-1.29	134
	6817.95	9.17	-2.43	105		4571.97	1.57	-0.53	382		4823.31	0.99	-1.12	186
	6828.12	8.54	-1.51	229		4589.96	1.24	-1.62	220		5473.40	1.74	-1.02	123
N I	6440.94	11.76	-1.14	5		4779.99	2.05	-1.37	207		5497.42	1.75	-0.58	176
	6484.80	11.76	-0.76	15		4805.10	2.06	-1.10	249		5521.56	1.74	-0.91	61
	6644.96	11.76	-0.88	14		4874.02	3.10	-0.79	166		5662.93	1.94	0.20	232
	6793.84	11.84	-1.11	6		4911.20	3.12	-0.34	214		5728.89	1.84	-1.12	54
O I	5958.48	10.99	-0.87	88	Cr II	4275.57	3.86	-1.52	120		6613.73	1.74	-1.10	87
	6156.77	10.74	-0.44	135		4558.66	4.07	-0.45	219		6795.41	1.73	-1.55	48
	6158.18	10.74	-0.29	179		4588.22	4.07	-0.63	180	Zr II	4317.32	0.71	-1.38	50
	6363.79	0.02	-10.25	31		4616.05	4.07	-1.22	103		4359.74	1.23	-0.56	94
Na I	5682.63	2.10	-0.71	152		4824.08	3.87	-1.22	185		4379.78	1.53	-0.35	128
	5688.20	2.10	-0.40	191		4876.37	3.86	-1.46	154		4403.36	1.18	-1.12	57
	6154.22	2.10	-1.57	50	Fe I	5569.62	3.42	-0.49	70		4440.45	1.21	-1.19	66
	6160.75	2.10	-1.27	75		5586.77	3.37	-0.10	104		4454.80	0.80	-1.35	132
Mg I	4702.99	4.33	-0.38	166		5569.63	3.42	-0.49	70		4494.41	2.40	0.07	114
Al I	6696.03	3.14	-1.32	13		6065.49	2.61	-1.53	42		4495.44	1.20	-1.42	42
	6698.67	3.14	-1.62	5		6136.62	2.45	-1.40	47		4496.97	0.71	-0.81	163
Si I	5708.41	4.95	-1.47	46		6137.70	2.59	-1.40	36		6114.78	1.66	-1.48	7
	5772.26	5.08	-1.78	24		6230.74	2.56	-1.28	40	Ba II	4554.04	0.00	0.17	288
	6091.92	5.87	-1.40	8		6252.55	2.45	-1.69	18		5853.68	0.60	-1.00	134
	6125.03	5.61	-1.51	29		6430.85	2.18	-2.01	20		6141.73	0.70	-0.08	276
	6145.02	5.61	-1.48	17	Fe II	4351.76	2.71	-2.10	250		6496.90	0.60	-0.38	250
Si II	6347.09	8.12	0.26	324		4508.23	2.86	-2.21	263	La II	4322.51	0.17	-1.05	17
	6371.36	8.12	-0.05	237		4522.63	2.84	-2.03	306		4429.90	0.24	-0.37	42
S I	5706.11	7.87	-0.80	21		4541.52	2.86	-3.05	174	Ce II	4460.21	0.48	0.17	35
	6743.58	7.86	-0.70	23		4555.80	2.83	-2.29	264		4562.37	0.47	0.32	24
	6748.79	7.86	-0.44	33										

It should be emphasized that Sakurai's object has continued to evolve since October 1996, and its future composition may therefore not resemble V854 Cen's. Our spectroscopic monitoring reveals that the star has become cooler in 1997, which is apparent from the development of conspicuous molecular bands. The cooling is also evident from photometry (Duerbeck et al. 1997). The change in $T_{\rm eff}$ has probably caused an increased extension of the convective zone to deeper layers where further processed material could possibly be dredged up. This may, however, not necessarily imply a significant alteration of the elemental abundances, though further studies of possible changes in the chemical composition of the star is definitely encouraged. We note that V854 Cen resembles Sakurai's object more closely than any other R CrB star, both for May and October 1996, in spite of the modifications of the abundances during 1996. According to Fig 6, some [X/Fe] ratios seem to evolve towards the observed ratios in V854 Cen, while other ratios apparently become less similar. The latter are at least partly due to a slight increase in the absolute abundance of Fe between the two dates, which may or may not be real since it is still within the observational uncertainties. Also, the significant amount of mixing of s-processed material that occurred in Sakurai's object during 1996 explains the diverging ratios for the s-elements. As already mentioned, the differences between V854 Cen and Sakurai's object can largely be attributed to differing degree of H-envelope ingestion. Therefore, the continued evolution of Sakurai's object, even if it induces further abundance changes, does not necessarily contradict the possible interpretation of a similar background for the two stars. In particular, the resemblance between the two is based largely on elements unlikely to be modified by further nuclear processing and such similarities will likely still remain.

6. Conclusions

The derived chemical composition for V854 Cen suggests that it belongs to the minority group of the R CrB stars, though less extreme than the other three minority members. One is tempted to term it a minority-majority transition object. As an R CrB star, V854 Cen is not only one of the stars with the lowest Fe/C ratio but also one of the least H-deficient. V854 Cen accentuates the anti-correlation between the H and Fe abundances found for the R CrB and EHe stars (Heber 1986; Lambert et al. 1998). Like most R CrB stars, V854 Cen shows indications of a mild neutron exposure.

Perhaps, the most interesting result is the abundance similarities between V854 Cen and the final He-shell flash candidate Sakurai's object (Asplund et al. 1997b). In fact, V854 Cen resembles Sakurai's object more closely than any of the other R CrB stars. This might suggest that the two stars also share the same evolutionary background. Most of the abundance differences could if so be attributed to less amount of H-envelope ingestion in connection with the final flash for V854 Cen.

If V854 Cen is indeed a final flash object, a search in optical or IR for a fossil shell from a previous planetary nebula stage could be rewarding. In this context we note that nebular emission lines of [O I], [N II], [S II] and Hα, have already been observed for the star during a decline (Rao & Lambert 1993). A connection between V854 Cen and Sakurai's object would suggest that the final flash scenario is a viable channel to form R CrB stars. Unfortunately, the status of V854 Cen regarding class assignment as a minority or majority member is unclear. It is therefore difficult to associate either group, if any, with being final flash objects. An alternative interpretation is that all R CrB stars have been formed through the same mechanism but e.g. dust-gas separation have introduced the differences in abundances between the two groups, though such dust depletion must then have proceeded quite differently than in the ISM. Further theoretical predictions for the two proposed models regarding the resulting chemical compositions for different initial conditions are clearly desirable in order to discriminate between them, as well as work on the expected results of a dust depletion in H-deficient and C-rich environments. A continued monitoring of possible abundance changes in Sakurai's object is clearly also a priority.

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