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The emergence of a [WC] star in Sakurai’s object

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ABSTRACT

Sakurai’s object provides a rare opportunity to observe stellar evolution on human time-scales. Since its born-again event and detection in 1996, its evolution has been extensively monitored, and recent optical spectroscopy has suggested the emergence of [WR]-type emission features. In this letter, we present a secure spectroscopic identification of its central star based on new VLT/FORS2 observations and NLTE expanding atmosphere models. Several observed emission lines arise in a [WR]-type stellar wind, establishing the central star as a [WR] object. The strongest stellar features are due to C II–III and He I. We derive the stellar and wind parameters of Sakurai’s object and discuss its evolutionary status. The [WR] star is much cooler ($T_{\text{eff}} \sim 30.5$ kK) than the born-again star V605 Aql ($T_{\text{eff}} \sim 95$ kK), which erupted about 80 yr earlier. The inferred temperature is lower than predicted by models suppressing convective mixing efficiency during the VLTP, but is consistent with higher time-resolution calculations involving slightly lower-mass ($\lesssim 0.6 M_{\odot}$) remnants. Continued spectroscopic monitoring and atmospheric modelling will be crucial for tracing its reheating curve and constraining the physics of this rapid evolutionary phase.

Key words: stars: atmospheres – stars: AGB and post-AGB – Stars: individual: Sakurai’s Object – stars: fundamental parameters – stars: mass-loss – stars: winds, outflows.

1 INTRODUCTION

Born-again stars are thought to result from a late helium-shell flash occurring at, or shortly after, the end of the asymptotic giant branch (AGB) phase. Depending on when the pulse occurs, it is classified as an AGB final thermal pulse (AFTP), a late thermal pulse (LTP; post-AGB), or a very late thermal pulse (VLTP; see M. M. Miller Bertolami 2024). In the most extreme case (VLTP), the star is already on the white-dwarf cooling track when the flash causes rapid expansion and cooling, accompanied by substantial mass ejection into the circumstellar environment. The star is thus “born again” and returns close to its former AGB position in the HR diagram. Subsequent evolution involves reheating, and possibly an additional cooling excursion, as the star evolves back

towards the white-dwarf domain with a markedly altered surface composition (T. M. Lawlor & J. MacDonald 2003).

Only two objects have been directly observed undergoing a VLTP: V605 Aql and Sakurai’s object (V4334 Sgr). Two others are thought to have undergone an LTP: FG Sge (B. Paczyński 1971; A. M. Genderen & A. Gautschi 1995; C. S. Jeffery & D. Schönberner 2006) and SAO 244 567 (N. Reindl et al. 2017; T. M. Lawlor 2021). FG Sge has evolved to become a cool supergiant. SAO 244 567 showed a sudden ionization event around 1980 and is currently cooling. In contrast, V605 Aql, discovered in 1919, evolved from an RCB-like star with $T_{\text{eff}} \sim 5000$ K in 1921 to a $\sim 95\,000$ K [WR] star by 2001 (G. C. Clayton et al. 2006).

Sakurai’s object (hereafter SO) has been extensively studied since its discovery in 1996 (S. Nakano et al. 1996). Following its outburst, the central star became completely obscured by circumstellar material (see P. A. M. Hoof et al. 2018, for a review). Later, radio and infrared observations continued to reveal its rapid evo-

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lution (e.g. M. Hajduk et al. 2005; P. A. M. Hoof et al. 2007; A. Evans et al. 2022). Although some observations were interpreted as evidence for reheating of the central star, the radio emission origin proved to be more complex than initially thought, and no [WR] features had been identified by 2020 (K. H. Hinkle et al. 2020; M. Hajduk et al. 2024). Recently, G. C. Van de Steene et al. (2025) reported the possible emergence and subsequent strengthening of [WR]-type emission features and proposed tentative identifications for the associated ions. Quantitatively confirming the emergence of the central star and tracking the evolution of its physical parameters can provide invaluable constraints on stellar evolution models.

In this letter, we present the first spectroscopic characterization of the central star of SO based on recent VLT/FORS2 observations and NLTE expanding atmosphere models.

2 OBSERVATIONS AND MODELS

VLT/FORS2 data were obtained through several campaigns by van Hoof (see G. C. Van de Steene et al. 2025). Here, we use a 2023 data set (ESO programme 111.24P1.001), which revealed the clearest stellar-like features despite strong nebular emission. The observations were acquired with the 300V+GG435 and 300I+OG590 set-ups, covering 4245–8870 Å and 5980–10310 Å, respectively, with $R \sim 350$. Each set-up consisted of nine exposures of 920 s with a 1.3 arcsec slit. Details about data reduction can be seen in P. A. M. Hoof et al. (2007). A comprehensive analysis of all available observations will be presented elsewhere.

We used the radiative transfer code CMFGEN (D. J. Hillier & D. L. Miller 1998), which solves the transfer equation in the co-moving frame of an expanding atmosphere coupled to the radiative and statistical equilibrium equations (NLTE). A full spectrum (continuum and lines) can be computed in the observer’s frame over a wide wavelength range (far-UV to the mid-IR) and is well suited to modelling WR stars with dense stellar winds.

The atomic data include hundreds of levels and thousands of transitions from He I–II, C II–IV, O I–IV, Ne II–IV, Mg II, Al II–III, Si II–IV, P V, S III–IV, and Fe II–V. Test models showed that including or excluding trace ions has little effect on the emergent spectrum. We therefore adopted this set, which provides adequate metal line blanketing without excessive computational cost.

2.1 Methodology

In principle, flux-calibrated data covering a broad wavelength range, combined with a reliable distance estimate, are sufficient to constrain the luminosity through SED fitting. For SO, however, this approach is severely limited. Distance estimates in the literature span 1.8–8 kpc, but recent studies favour ~ 2 to 4.4 kpc based, for example, on reddening or expansion velocity arguments, with 3.5 kpc being the most used value (see the review by K. H. Hinkle et al. 2020). Nevertheless, no direct distance determination is available. Such an uncertainty, together with the poorly constrained circumstellar extinction and corresponding colour excess (A. Evans et al. 2022), introduces strong degeneracies among luminosity, distance, and reddening. Moreover, the observed optical–near-IR flux cannot be straightforwardly attributed to the [WR] central star, as it is likely affected by circumstellar continuum emission and contaminated by strong nebular lines (see below). We therefore restricted our analysis to normalized optical VLT/FORS2 spectra.

During the modelling process, we adopted a luminosity of $5000 L_{\odot}$ and an initial temperature guess, from which the stellar radius follows via the Stefan–Boltzmann relation. The mass was fixed at $\sim 0.60 M_{\odot}$, as [WR] stars do not exhibit spectroscopic log g diagnostics. This value is the observed mean for white-dwarfs (see e.g. M. W. O’Brien et al. 2024). We adopted a chemical composition of $[\text{He}/\text{C}/\text{O}] \approx [43, 51, 6]$ (by mass), typical of [WR] stars and providing a good fit to the observed spectrum (see below). This differs markedly from what is inferred for SO shortly after its outburst, $[\text{He}/\text{C}/\text{O}] = [90, 7, 3]$ (M. Asplund et al. 1999), and likely results from proton ingestion and burning and mass-loss since then.

SO is likely associated with the Galactic thick disc (P. A. M. Hoof et al. 2007), whose stars typically have sub-solar metallicities (e.g. T. Bensby, S. Feltzing & M. S. Oey 2014). To assess the impact of this, we computed models with reduced metal content, scaling Fe to $\sim 1/4$ solar ($[\text{Fe}/\text{H}] \sim -0.6$). The resulting spectrum changes only slightly, indicating that our results are not strongly sensitive to plausible variations in the initial metallicity.

The main wind parameters are the mass-loss rate $\dot{M}$ and terminal velocity V_{∞} , which were adjusted to fit the observations. Clumping was included through a filling-factor formalism ($D = 10$), starting at a velocity of ~ 20 per cent of V_{∞} . In [WR] stars, the stellar temperature primarily determines the wind ionization and thus the dominant ions and relative line intensities. The transformed radius, $R_{\text{T}} \propto R_{\ast} (V_{\infty}/\dot{M})^{2/3}$, controls the emission-line strengths, while V_{∞} sets the line widths. Models with the same temperature and R_{T} produce similar rectified spectra (W. Schmutz, W.-R. Hamann & U. Wessolowski 1989). We used these properties to iteratively improve the fits and derive a first estimate of the stellar and wind parameters of SO after the born-again event. A different luminosity can still result in the same best fit, provided that R_{T} and temperature are kept constant. The radius and wind parameters would have to change.

2.2 Results

Fig. 1 compares synthetic spectra with the VLT/FORS2 spectrum of SO. Our best model is shown in the middle panel, while the other panels illustrate the effect of varying temperature at fixed R_{T} (see below). Several C II–III and He I features are identified. Those with labelled wavelengths are discussed below. Their identifications were quantitatively confirmed by computing spectra for individual ions.¹ A nebular contribution to the He I lines is possible but difficult to distinguish at the current spectral resolution. Forbidden nebular lines are also marked in Fig. 1. They contaminate several spectral regions, a situation similar to that encountered in the analysis of V605 Aql by G. C. Clayton et al. (2006).

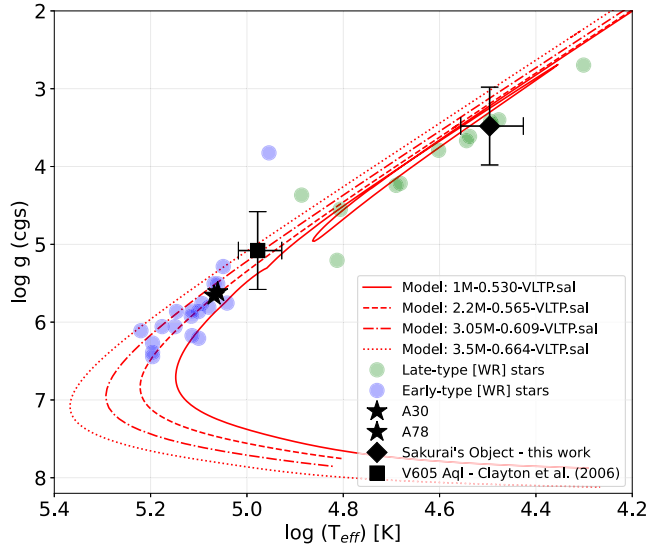
The C II–III features provide an estimate of the stellar temperature. The C III (C II) lines become stronger (weaker) than observed for values above $\sim 30\,500$ K, while the opposite occurs at lower temperatures. The C III $\lambda 5696$ line is particularly sensitive to this effect², as is the C II–III blend located just blueward of the

¹Initially, we extended the spectral calculations to 9500 Å , where G. C. Van de Steene et al. (2025) reported the emergence of features possibly associated with carbon (their Fig. 1). We did not find synthetic counterparts to these transitions. They remain unidentified and may instead arise from CN.

²C III $\lambda 5696$ is commonly used in spectral classification and gets stronger with temperature from late- to early-type [WR]. The observed FWHM is

Table 1. [WR] model parameters for Sakurai's object.

Parameter	Value	Comments
$\log(L/L_{\odot})$	3.7	Adopted
Clumping factor, D	10	Adopted
R_* ($\tau = 2/3$)	$2.5 R_{\odot}$	$R_* \propto L^{1/2}$
T_{eff} ($\tau = 2/3$)	30 550 K	
v_{∞} (km s^{-1})	500	
$\dot{M}$ ($M_{\odot} \text{ yr}^{-1}$)	1.1×10^{-6}	$\dot{M} \propto D^{-1/2} L^{3/4}$
He, C, O, other (solar)	0.425, 0.510, 0.059, 0.005	Mass fractions

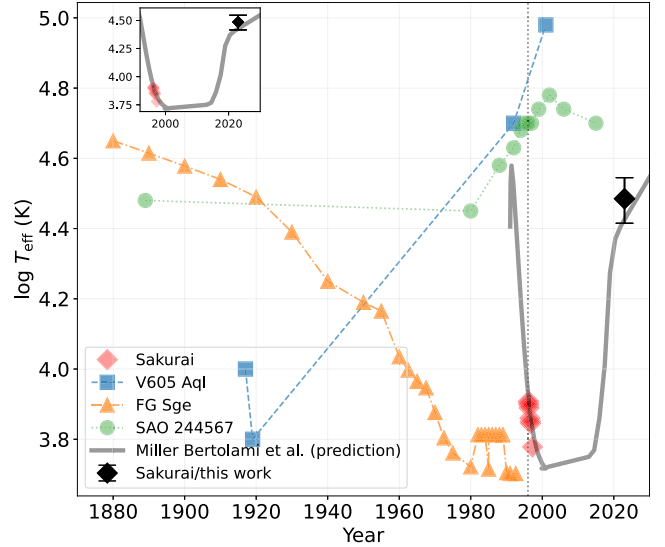
**Figure 2.** Kiel diagram with evolutionary tracks from M. M. Miller Bertolami & L. G. Althaus (2006). SO position is indicated by a black diamond. Late and early-type [WR] stars are also shown. The [WCE] outlier is PN RaMul 2.

SO lies in the range $27\,000\text{ K} \lesssim T_{\text{eff}} \lesssim 36\,000\text{ K}$. The remaining parameters of our preferred model are summarized in Table 1.

3 EVOLUTIONARY STATUS

Having inferred the stellar and wind parameters of SO, we can now discuss its evolutionary status. Fig. 2 shows a Kiel diagram including post-VLTP evolutionary tracks from M. M. Miller Bertolami & L. G. Althaus (2006) for initial (remnant) masses of 1 (0.53), 2.2 (0.565), 3.05 (0.609), and $3.5 M_{\odot}$ ($0.664 M_{\odot}$). The position of SO is indicated by a black diamond, while V605 Aql is shown as a black square based on the results of G. C. Clayton et al. (2006). We also include the more evolved born-again stars A 30 and A 78 (M. A. Guerrero et al. 2012; J. A. Toalá et al. 2015). For SO, the temperature uncertainty reflects the conservative range inferred in Section 2.2. The surface gravity was computed assuming $M = 0.6 M_{\odot}$ (see Section 2.1). Adopting masses between 0.5 and $0.7 M_{\odot}$ produces only minor shifts in the diagram. We estimated an uncertainty of ± 0.5 dex in $\log g$ by propagating the uncertainties in the derived T_{eff} and in the adopted luminosity. We assumed a 50 per cent uncertainty in the distance for the latter.

We also added results from the literature for early- and late-type [WR] stars in Fig. 2 using data from L. Koesterke (2001), W. L. F. Marcolino et al. (2007), G. R. Keller, L. Bianchi & W. J. Maciel (2014), V. M. A. Gómez-González et al. (2022), and J. A.

**Figure 3.** Evolution of the temperature of the stars undergoing the born-again phenomenon: SO, V605 Aql, SAO 244567, and FG Sge.

Toalá, H. Todt & A. A. C. Sander (2024). When the same object was analyzed in more than one study, we kept the latest result. V605 Aql is closer to early-type objects, whereas SO position is among late-type [WR] stars, suggesting a younger evolutionary status.

Fig. 3 shows the temperature evolution of SO, V605 Aql, SAO 244567, and FG Sge, using data from A. M. Gendreau & A. Gautschy (1995), T. M. Lawlor & J. MacDonald (2003), B. E. Schaefer & Z. I. Edwards (2015), and N. Reindl et al. (2014, 2017). For SO and V605 Aql, the most recent points correspond to our results and those of G. C. Clayton et al. (2006), respectively. We also display the model prediction by M. M. Miller Bertolami et al. (2006) for a $0.5842 M_{\odot}$ remnant star (see below). Our SO data point is the first after 1998.

The rapid cooling of SO can be reasonably reproduced by theoretical calculations in the literature, as well as its brightening time after the VLTP up to its discovery in 1996, the born-again time, which is about 5 yr (see e.g. M. Hajduk et al. 2005; M. M. Miller Bertolami et al. 2006). However, the calculations of F. Herwig (2001) and M. Hajduk et al. (2005) required a substantial reduction in the convective mixing efficiency within the He-flash zone; otherwise, the born-again time-scale would be about 350 yr (see F. Herwig 2001). In contrast, M. M. Miller Bertolami et al. (2006) and M. M. Miller Bertolami & L. G. Althaus (2007) showed that high temporal resolution ($\sim 10^{-5}$ yr) and slightly lower remnant masses ($\sim 0.58 M_{\odot}$) were sufficient to reproduce the rapid evolution of SO without artificially reducing the mixing efficiency.

Regarding the reheating of SO, M. Hajduk et al. (2005) predicted $\log T_{\text{eff}} \sim 4.95$ (~ 90 kK) by 2020, implying a much faster temperature increase than supported by our results. On the other hand, the model of M. M. Miller Bertolami et al. (2006) is broadly consistent with our measurements (see Fig. 3). In their calculations, temperatures above $\log T_{\text{eff}} \sim 4.80$ ($\gtrsim 60$ kK) are reached only about 100 yr after the VLTP, while $\log T_{\text{eff}} \sim 4.50$ is attained after ~ 35 yr (see also their fig. 5). However, these authors noted that the time-scales involved depend critically on the numerical treatment adopted once the models reach the Eddington limit.

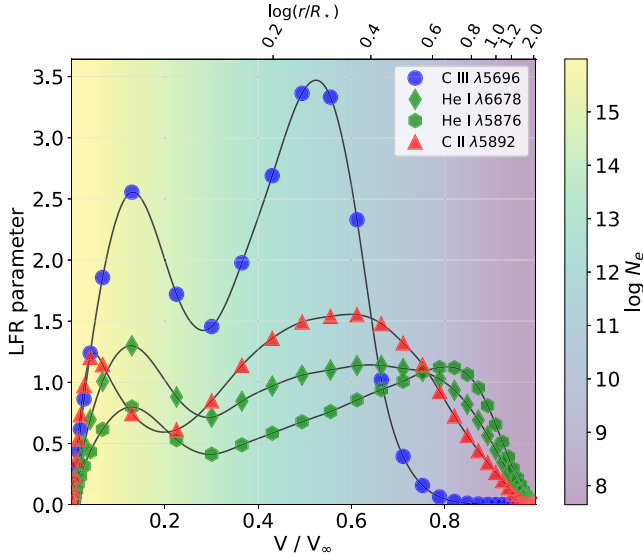


Figure 4. Line formation regions (LFRs) of selected lines. Note that the lines are not formed in a specific point, but over a large velocity and density interval. The LFR parameter informs how much of the profile is formed at a certain point (see D. J. Hillier 1987, for more details).

4 DISCUSSION

The analysis presented in Section 2.2 strongly suggests that several of the observed features originate in a stellar wind. Although some discrepancies remain, their relative intensities are reasonably well reproduced by our models. Nevertheless, one could argue that these features are instead formed in the ejecta produced during the VLTP event rather than in a stellar wind. Given the low spectral resolving power of the observations, synthetic wind-line profiles convolved to the instrumental resolution could potentially mimic emission features produced elsewhere, leading to an apparently satisfactory fit by coincidence.

The circumstellar material of SO has been mapped in the infrared with adaptive optics by K. H. Hinkle et al. (2020) and at radio wavelengths with ALMA by D. Tafuya et al. (2023). These observations revealed an equatorial disc and bipolar outflows forming an hourglass geometry. The projected velocities in the bipolar flows reach several hundred km s^{-1} (see Fig. 3 of D. Tafuya et al. 2023), comparable to the terminal velocity of our best model ($V_\infty = 500 \text{ km s}^{-1}$). However, it would be a remarkable coincidence if a spherically symmetric NLTE expanding atmosphere model reproduced the relative intensities of several observed features were they formed predominantly in the asymmetric ejecta rather than in a stellar wind.

The velocity, density, and temperature structure of a [WR] wind are expected to differ significantly from those of the born-again ejecta. Fig. 4 illustrates the formation regions of selected C II–III and He I transitions in our best model. The horizontal axis shows the wind velocity normalized to the terminal velocity, while the left vertical axis indicates the contribution to the line profile at a given velocity (for the quantitative definition of the LFR parameter, see D. J. Hillier 1987, Sect. IV); the right axis shows the electron density. The lines form over most of the wind volume, spanning a wide range of velocities and densities. Regions above ~ 80 per cent of v_∞ still contribute to the He I and C II lines, whereas C III forms mainly in the inner wind. This extended formation region reflects the stratified structure and accelerating

velocity field of a WR wind, conditions that would be difficult to reproduce in the ejecta while yielding comparable line intensities.

It is also instructive to compare the spatial scales implied by the ALMA observations with those of our atmosphere model. From H^{12}CN data, the ejecta reach velocities of $\sim 300 \text{ km s}^{-1}$ at $\sim 600 \text{ au}$. In contrast, our model extends to ~ 200 stellar radii, where the velocity reaches $\sim 500 \text{ km s}^{-1}$, corresponding to only $\sim 2 \text{ au}$. The entire [WR] spectrum is formed within this compact region, indicating that the line-forming zone probes a physical regime entirely distinct from the large-scale ejecta.

Note also that the C II–III features identified in our models, for example, are not produced under the same physical conditions as the nebular lines [N I–II], [O I–II], and [C I]. These forbidden transitions trace neutral or weakly ionized, low-density gas, whereas the C II–III recombination features require a denser and hotter environment. In particular, the upper level of C III $\lambda 5696$ can be efficiently populated only in dense stellar winds (D. J. Hillier 1989).

In summary, our analysis favours a stellar-wind origin for the broad C II–III features. The inferred stellar parameters correspond to a late-type [WR] object (see Section 3). The forbidden lines trace the surrounding ejecta.

5 CONCLUSIONS

Our VLT/FORS2 observations and NLTE models confirm the emergence of a [WC]-type spectrum in SO, first reported by G. C. Van de Steene et al. (2025), approximately 35 yr after its VLTP event. The relative intensities of several optical emission lines are reasonably reproduced by our synthetic spectra, indicating that most originate from C II–III and He I. The C II–III lines constrain the current temperature to a conservative range of $27\,000 \text{ K} \lesssim T_{\text{eff}} \lesssim 36\,000 \text{ K}$. The parameters of our preferred model are summarized in Table 1. Our results support a [WCL] classification for SO, placing it at an earlier evolutionary stage than V605 Aql. The inferred temperature is significantly lower than predicted by models that suppress the convective mixing efficiency (M. Hajduk et al. 2005), but broadly consistent with the calculations of M. M. Miller Bertolami et al. (2006).

Continued spectroscopic monitoring of SO remains essential. Born-again objects provide a rare opportunity to observe stellar evolution in real time and place unique constraints on VLTP evolution and the emergence of hydrogen-deficient central stars.

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DATA AVAILABILITY

The data underlying this article are available from the cited sources or by e-mail request to wagner@ov.ufrj.br.

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