The second death of Sakurai's Object (V4334 Sgr)

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Abstract. The discovery of Sakurai's Object, in 1996, provided the first modern observations of a very late thermal pulse. Models predicted that it would become a born-again planetary nebula over a few hundred years. It is however evolving very much faster: the first radio detection shows that ionization of the envelope has already started. To reproduce its unexpectedly fast evolution, we have developed a model in which convective mixing is strongly suppressed under the influence of flash burning. A strong prediction of this model is that the star will evolve back to very high temperatures at equally accelerated time scales. A CLOUDY photoionization model of the hydrogen-poor nebula indicates an ionized ejecta (carbon) mass of $\sim 10^{-3}\,M_\odot$, indicating that born-again objects may be significant contributors to carbonaceous dust in the galaxy.

Keywords: Stars: Post-AGB – evolution – individual: V4334 Sgr – circumstellar matter
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INTRODUCTION

About one fifth of post-AGB stars will also experience a final He-flash after reaching the cooling track [1]: a so-called very late thermal pulse (VLTP) event. The star retraces its post-AGB evolution [2], becomes hydrogen-poor, and experiences renewed mass ejection. The likely progeny of the born-again stars are the peculiar PG 1159 and [WC] PN central stars [3].

The discovery of Sakurai's object (V4334 Sgr) in 1996 [4] has provided the first modern opportunity to study such a VLTP event. In our Galaxy, a VLTP event is expected to occur once per decade [5]. But V4334 Sgr was only the third case where a VLTP was observed, after V605 Aql in 1918 [6], and possibly CK Vul in 1670 [7].

Following a VLTP, the small remaining H-rich envelope is convectively ingested into the He-shell, and burned. Models predicted that the stellar luminosity would increase, and temperature decrease, over a few hundred years [8]. However, V4334 Sgr evolved far faster. It became hydrogen poor during 1996 [9, 10], when it developed a strong, dusty wind. The discrepancy in time scales of a factor of 100 may be attributed to neglected physics in simulations. Revised stellar evolution models parametrically account for the buoyancy effect of rapid nuclear burning on convective turbulence in the He-shell flash zone [11]. This reduces the convective mixing efficiency, and accelerates the evolution because nuclear energy from fast proton capture is released closer to the stellar surface. These models predict that V4334 Sgr will reheat rapidly as well [12].

Reheating will ionize the new ejecta, forming a new, H-poor PN. Early indications for the onset of ionization in the new ejecta were found by Kerber et al. [13]. The formation of an H-poor PN had never been observed. V605 Aql formed a compact H-poor emission nebula after the 1919–1924 outburst [6, 14]. But the formation of this structure was not observed: like V4334 Sgr, circumstellar extinction rendered it invisible to 1920 astronomical tools. It was recovered 60 years later as a hot (about 50 000 K) WR-type star [15], with its H-poor nebula in place. Five PNe are known to have H-poor inner regions [5].

New radio data [16] now confirms the ionization of the obscured ejecta.

OBSERVATIONS

We observed Sakurai's Object with the VLA on Feb. 5th, 2004, at 8.6 GHz in the CnB configuration. Optical images of Sakurai's object were obtained using FORS1 on the ESO 8m VLT, on Oct. 2nd, 2002, usig an [O III] filter, and a redshifted [O III] filter for continuum subtraction. The pixel scale is 0.2 arcsec per pixel, and the seeing in the images is 1.2 arcsec. The continuum-subtracted image is shown in Fig. 1, with the 8.6 GHz radio contours superposed.

The extended nebula (the old PN) was detected, with integrated radio flux of 1.5 ± 0.2 mJy at 8.6 GHz. The 8.6 GHz map shows a central radio source, marginally resolved, which has no [O III] counterpart. The radio core has an integrated 8.6 GHz flux of $100\pm30\mu$Jy, with a

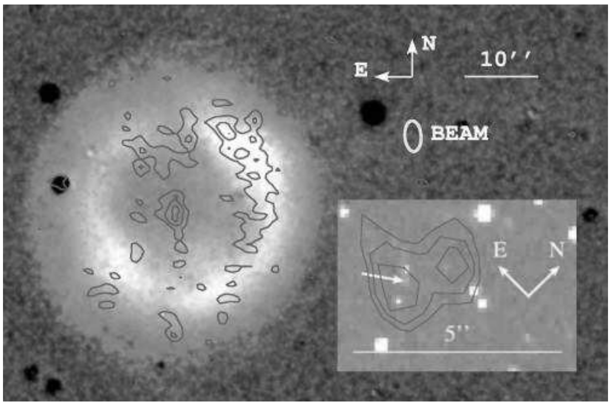

FIGURE 1. Large: The continuum subtracted O++ image, showing the extended, old PN. Radio (8.6 GHz) contours are shown superposed, at 30, 50 and 70 μJy/beam. A natural weighted map (beam of 4.2×2.4 arcsec) is shown. Small insert: An HST I-band (F814W) image, taken Aug 29, 2001 (PI: H. Bond). Sakurai's Object (fainter of the two components, 0.2 arcsec apart) is indicated by an arrow. The over-plotted radio data shows a uniform weighted map with contours at 25, 35, 45 μJy/beam.

peak flux of 67μJy/beam. We identify this source with the central star. Fig. 1 (insert) shows an HST image taken in 2001. The radio core of the newly formed ionised region is shown superposed as contours.

The resolved radio core shows an indication of a double structure. This may be caused by poor UV coverage and needs confirmation. Bipolarity is observed in the H-poor ejecta for A30 and A78 [17, 18], and in V605 Aql [19]. Causes of common bipolarity in VLTP outbursts could be stellar rotation and/or a magnetic field. Binarity is not likely to play a role, unless stellar accretion can affect VLTP's.

The distance is assumed at $d = 2$ kpc, corresponding to a source radius of 1400 AU.

DISCUSSION

The photoionization model

We modelled the central ionized region using the photoionization code CLOUDY version 96 beta 5. We assume that the central star has an effective temperature $T_{\rm eff} = 20000$ K [13], a luminosity $L = 2770\ L_\odot$ [20], and a distance of 2 kpc. Details are given in [16]. The chemical composition of the H-poor shell is assumed to be equal to that of the central star [10]. The radius of the ionized region is set at $0.7''$. Three different models were tried (Table 1).

The electron temperature and density predicted by the prefered model (IB) are shown in Fig. 2. The radio flux is predominantly due to ionized carbon. The radial stratification of the most dominant ions causes a steplike decrease in the electron density. The [N II] diameter is also smaller than the C^+ diameter: the latter determines the radio extent. Model IB predicts [NII] λ6584/Hα = 9.3, in fair agreement with observations, and [OII](7319+7330)/[NII](6584)= 8.0×10^{-4}, in disagreement with observations [13]. The electron temperature is insufficient to excite the upper levels of the [OII] transitions which are at ~ 58200 K. The [O II] lines may be shock excited.

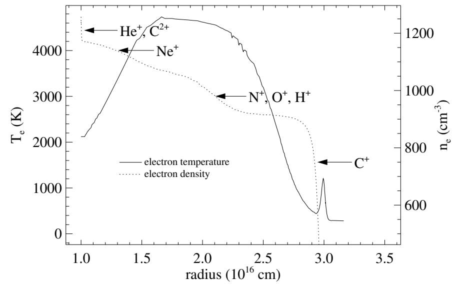

FIGURE 2. The ionization structure of the Cloudy model.

The ionized mass $M_{\rm ion}$ in Table 1 consists mainly of singly ionized carbon. The shell mass $M_{\rm sh}$ includes the neutral mass (mainly helium) within the ionized region. The mass estimate would reduce if a lower distance is adopted. Clumping in the gas would also reduce the mass estimate.

The He:C ratio [10] is based on 1996 spectra taken while the star became H-poor. Assuming a mass ratio X(C):X(He)~ 1, as predicted for the He layer [1] would half the shell mass. The total mass of the shell implies a mass loss rate of the order of $> 2 \times 10^{-4}\ M_\odot\,{\rm yr}^{-1}$. Mass-loss rates have increased over time, to $\sim 3 \times 10^{-5}\ M_\odot\,{\rm yr}^{-1}$ during 2003 [21]. This discrepancy may indicate a high degree of clumping.

Using the results above, we find that Sakurai's Object ejected $\sim 5 \times 10^{-4}\,M_\odot$ of primary carbon; 20% of this

TABLE 1. Three photo-ionization models: DB=density bounded, IB=ionization bounded, SM=small model

	$\log(r_{in})$ cm	$\log(r_{\rm str})$ cm	n_H cm^{-3}	$M_{\rm ion}$ $M_\odot$	$M_{\rm sh}$ $M_\odot$	$M_{\rm dust}$ $M_\odot$
DB	16.000	16.322	59	6.0e-4	2.4e-3	3.2e-5
IB	16.000	16.477	36	1.0e-3	4.7e-3	1.9e-4
SM	15.500	16.000	100	4.1e-4	1.8e-3	1.0e-4

is located in carbonaceous dust. (Note that clumping reduces the mass but continuing mass loss will increase it.) Sakurai's Object shows an extreme isotope ratio of $^{12}C/^{13}C \approx 4$ [22]. Together with novae, VLTP events may be the dominant ^{13}C source in the Universe.

Stellar evolution models

Fig. 3 shows the full evolutionary model tracks. Details can be found in Hajduk et al. [16]. A good fit for the recent evolution is obtained if we assume that the thermal pulse occured in 1992 (the fast brightening in early 1995 may be caused by the rapid temperature evolution). V4334 Sgr is currently on the first, fast loop of the double-loop evolution that is characteristic for the revised models with suppressed convective mixing [23]. The revised H-ingestion flash models place it at the beginning of a very rapid increase in temperature. The detection of radio emission only 12 years after the very late He-flash may signal the onset of this rapid heating. Continued monitoring over the next few years is essential to further test the evolutionary predictions.

Conclusion

The interpretation of the presented data is open to question. The ionization may contain a shock component, and the lack of an [Ne II] line suggests the star is slightly cooler than assumed here [13]. The variability seen before full obscuration is indicative of fluctuating temperatures–short-term changes may differ from a long-term trend.

It is also interesting that two stars (V605 Aql and V4334 Sgr) show identical, accelerated evolution, wilst a third case (FG Sge) evolves much more sedately. CK Vul may test the further evolution, if indeed it suffered a VLTP in AD 1670. Its star has not yet been recovered, but we recently found a central radio source, without an Hα counterpart (Hajduk, in preparation). The next decade(s) in the evolution of V4334 Sgr will be a crucial test bed of the physics of the VLTP. The second death of Sakurai's Object is likely to show new, further surprises.

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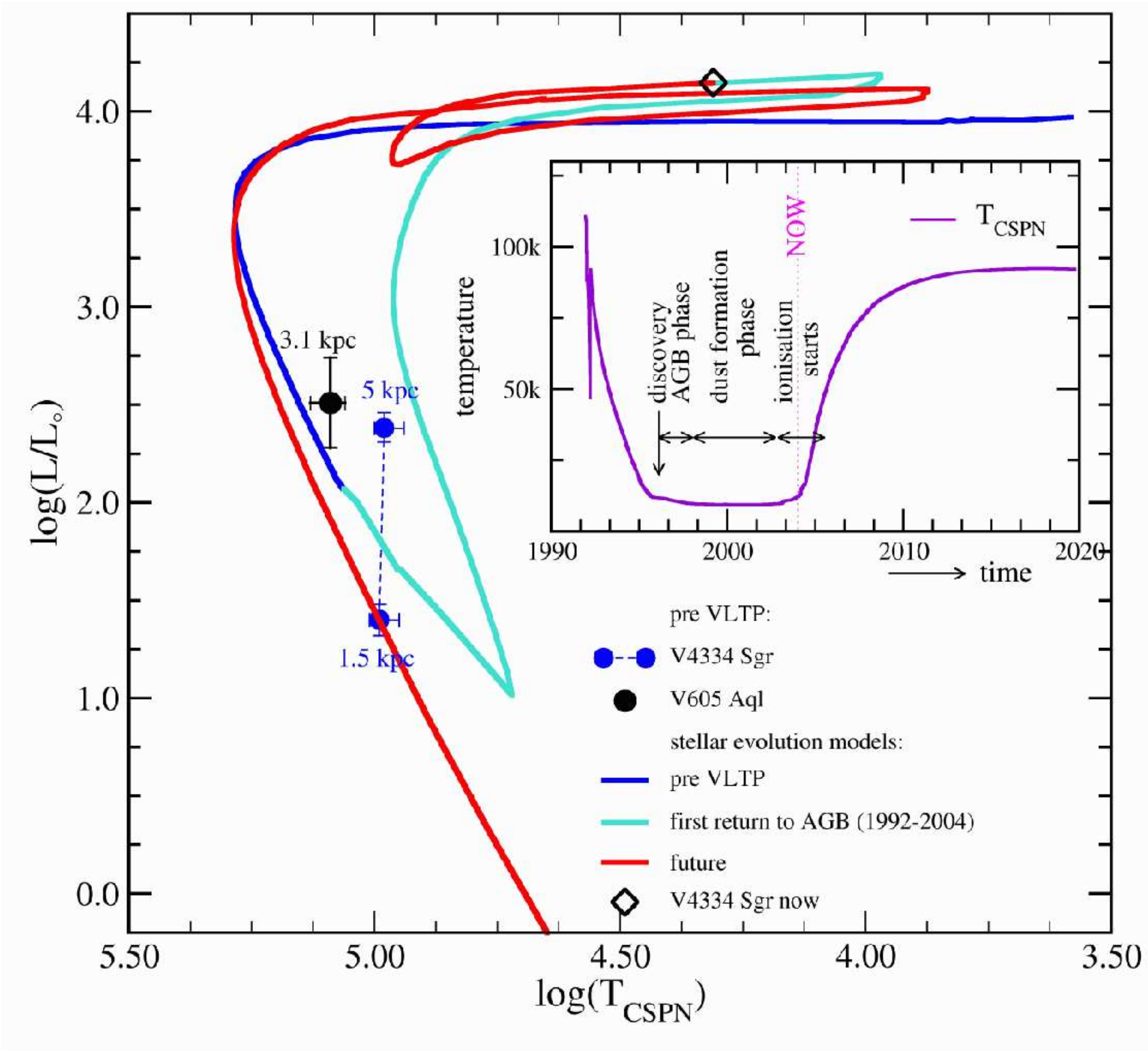

FIGURE 3. The stellar model sequence of the past and future temperature and luminosity evolution of Sakurai's object. Two loops are predicted: the first corresponds to the hydrogen ingestion flash, and the second much slower loop corresponds to the helium flash. Sakurai's Object is currently at the start of a fast temperature increase. The peculiar PG 1159 and [WC] central stars [3] will be mostly on the second, slower loop. The pre-flash positions of V4334 Sgr and V605 Aql are based on the ionization structure of their old nebulae [14].