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The hidden past of Sakurai's object

Stellar properties before the final helium flash

F. Kerber[1,2], J. Köppen[3,4,5], M. Roth[6], and S.C. Trager[6]

[1] Space Telescope European Coordinating Facility, European Southern Observatory, D-85748 Garching, Germany
[2] Institut für Astronomie der Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria
[3] UMR 7550, Observatoire Astronomique, 11 Rue de l'Université, F–67 000 Strasbourg, France
[4] International Space University, Parc d'Innovation, F–67 400 Illkirch, France
[5] Institut für theoretische Physik und Astrophysik der Universität, D–24 098 Kiel, Germany
[6] The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, USA

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Abstract. We derive the properties of Sakurai's object before its sudden evolutionary change by studying the remnant ionization of the old planetary nebula (PN) surrounding it. The star must have had a surface temperature of $98\,000 \pm 7000$ K ($95\,000 \pm 7000$ K). For a distance of 1.5 kpc (5.5 kpc) the luminosity should have been $25 \pm 5\,\mathrm{L}_\odot$ ($240 \pm 40\,\mathrm{L}_\odot$). The central star thus was highly evolved and had already reached the tip of the white dwarf cooling track. Sakurai's object indeed is an example of a star undergoing a very late helium flash.

Key words: Stars: AGB and post-AG – Stars: evolution – (Stars:) Hertzsprung-Russel (HR) diagram – (ISM:) planetary nebulae: individual: Sakurai's Object

1. Introduction

Sakurai's object (V4334 Sgr) presumably is a star undergoing a final helium flash. Details of its discovery and observed evolution are found in Duerbeck et al. (1996, 1997), Kerber et al. (1998) and references therein.

The idea that a final (late or very late) helium flash is taking place is based on several observational facts:

- the star is surrounded by a round nebula showing a spectrum typical for an evolved planetary nebula (PN).
- its photosphere is highly deficient in hydrogen but rich in heavier elements (Asplund et al. 1997, Kipper & Klochkova 1997). This composition also changes in time with hydrogen becoming further depleted, while s-process elements have been seen to increase (Asplund et al. 1999).
- the time evolution of the brightness is in general agreement with both the model (Iben et al. 1983) for a *very late* helium flash (i.e. after the end of H-burning, in contrast to a *late* flash which happens while H-burning is still active (suggested for FG Sge, by Blöcker & Schönberner 1997)) and the other possible historic example for a very late helium flash, V605 Aql the central star of A 58 (Seitter 1987).
- the formation of molecular features (Asplund et al. 1997, Kerber et al. 1997) and of copious amounts of hot dust as deduced from a strong IR strong excess is also in line with expectations (Kimeswenger et al. 1997; Kerber et al. 1999). The recently observed dimmings in the visual (Liller et al. 1998a, 1998b; Jacoby et al. 1998b) - as the dust became optically thick - were therefore not unexpected (Duerbeck et al. 1997; Arkhipova et al. 1998) and are similar to the example set by V605 Aql in 1921 to 1924 (Clayton & De Marco 1997). These dimmings together with the H-deficiency make Sakurai's object a bona fide R CrB star.

Hence, all observational facts available today are in agreement with the notion of Sakurai's object having undergone a very late helium flash. What is currently missing is information about the properties of Sakurai's object before the presumed helium flash. Such information will be hard to come by directly as the only observations on record are Schmidt survey plates which might just show it at the plates' limit of 21 mag in R.

However, the low density PN around the Sakurai's object keeps a memory of the ionization when the star was still hot enough to ionize it. This is what we shall exploit in this work.

2. Basic Data and Observations

The angular diameter of $D = 32''$ was given by Duerbeck & Benetti (1996). This is in full agreement with the size of our [O III] and Hα images which show a rather well defined outer edge. Figure 1 depicts an image of the nebula using an Hα filter (bandwith 70 Å) obtained in March 1997 at

Send offprint requests to: F. Kerber, email: fkerber@eso.org

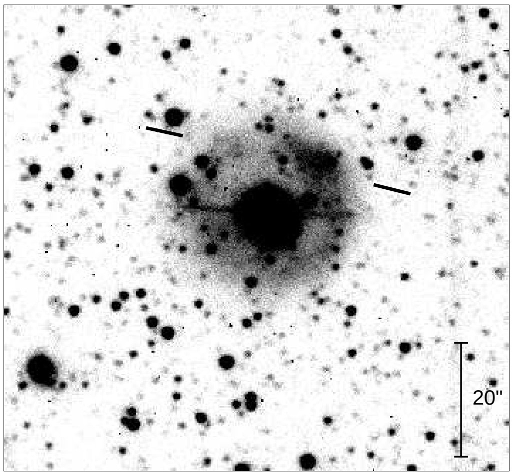

Fig. 1. Hα image of the PN surrounding Sakurai's object. The star itself is heavily saturated, resulting in the E-W oriented spikes. The two lines in the NW part indicate the position of the spectrographs's slit.

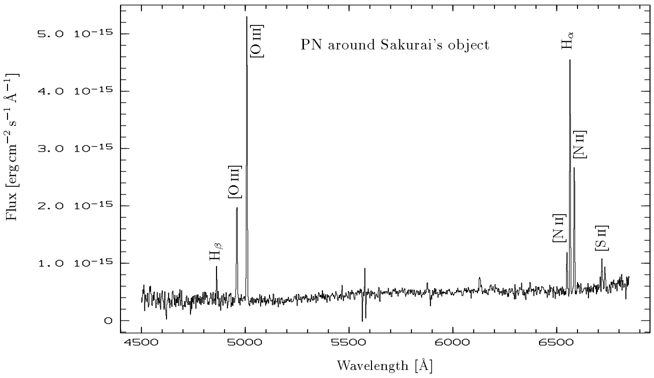

Fig. 2. The spectrum of the PN surrounding Sakurai's object.

the du Pont 2.5 m at Las Campanas Observatory. Using the TEK 5 CCD gave us a scale of $0.25''$/pix. The exposure time was 1800 s. The nebula is quite round, has a rather mottled appearance, and a brighter segment in the NW sector. Jacoby et al. (1998a) have clearly detected emission outside of this radius. For the purpose of this work we shall still use a diameter of $32''$ as the images demonstrate that the faint outer envelope extending to at least $44''$ (Jacoby et al. 1998a) does not significantly contribute to the total flux.

The Hβ-flux of 2.08×10^{-14} erg cm^{-2} s^{-1} from the entire nebula was measured rather indirectly by Duerbeck & Benetti (1996). Our spectrum gives 6.9×10^{-14} erg cm^{-2} s^{-1} which is probably higher, because the slit cut across the bright north-western segment (cf. Fig. 1). Nonetheless, we shall use this value in our analysis. The interstellar extinction had been estimated rather indirectly as E(B-V) = 0.54 by Duerbeck & Benetti (1996). A much higher value of E(B-V) = 1.15 from radio observations has been reported by Eyres et al. (1998). Pollacco (1999) derives E(B-V) $= 0.71 \pm 0.09$ (i.e. the logarithmic balmer decrement $c = 1.1$), and N. Kameswara Rao obtains 0.7 from the strengths of the diffuse interstellar bands (both quoted in Asplund et al. (1999)). With this value we revise the extinction distance of Kimeswenger & Kerber (1998) slightly upwards, to 1.5 ± 0.2 kpc. Note that large (e.g. galactic bulge) distances can still be excluded for the extinction distance.

We obtained long slit spectra of the PN using the 2.5 m du Pont telescope at Las Campanas Observatory. Using the modular spectrograph (Modspec) we cover wavelengths from 3800 to 7200 Å at a resolution of 2 Å/pix. The exposure time was 1800 s. The slit length is about $2.5'$ projected on the sky, its width $1.2''$. The spectra are flux-calibrated with standard stars from the list of Hamuy (1992, 1994). The slit is placed roughly east-west intersecting the bright NW segment (see Fig. 1).

The spectrum is presented in Fig. 2. The measured line fluxes are collected in Table 1. From the intensity ratio Hα/Hβ we obtain with an electron temperature of 10 000 K a reddening of $c = 1.5$, somewhat larger than Pollacco's. The intensity ratio of the [O III] lines 5007 and 4959 Å is 2.78, quite lower than the expected value of 3.05 (Acker et al., 1989). This ratio, being independent of physical conditions, is a direct measure for the somewhat limited quality of our spectrum. We corrected the line intensities with the c-value obtained from this spectrum.

Table 1. Measured line fluxes (in 10^{-15} erg cm^{-2} s^{-1}) and intensities relative to $I(\mathrm{H}\beta) = 100$, corrected with an extinction of $c = 1.5$

λ	ID	F	$I/I(\mathrm{H}\beta)$
4861	Hβ	2.27	100
4959	[O III]	9.59	391
5007	[O III]	26.66	1044
6548	[N II]	3.28	46
6563	Hα	20.64	287
6583	[N II]	11.69	160
6717	[S II]	2.30	30
6731	[S II]	1.65	21

3. Simple Analysis

A rough initial analysis of the stellar luminosity can be done by computing the total number of hydrogen recombinations taking place in the nebula and what must be the minimum luminosity of the central star to keep the nebula ionized. We assume a spherical, homogeneous, and isothermal nebula of density n and electron temperature $T_e = 10\,000$ K at a distance d. Given the angular diameter D (in arc sec), the measured total Hβ-flux $F(\mathrm{H}\beta)$, and the interstellar extinction c, the relation between nebular density and distance

$$n(\mathrm{H}^+) n_{\mathrm{e}} d = \frac{4\pi F(\mathrm{H}\beta)\, 10^c}{\epsilon_{\mathrm{H}\beta}(T_{\mathrm{e}})\, 4\pi((D/2)/206265)^3/3} \qquad (1)$$

with the total emission (Case B assumed) $\epsilon_{\mathrm{H}\beta}(T_{\mathrm{e}}) = 4\pi j_{\mathrm{H}\beta}/(n_{\mathrm{p}} n_{\mathrm{e}}) = 1.24 \times 10^{-25}$ erg cm^3 s^{-1} per proton and electron for the Hβ -line (cf. Osterbrock 1990). Setting $n \approx n(\mathrm{H}^+) \approx n_e$ suffices for the intended first estimate. The number of recombinations $\mathcal{N}$ is

$$\mathcal{N} = \frac{4\pi F(\mathrm{H}\beta)\, 10^c\ d^2\ \alpha_{\mathrm{A}}(T_{\mathrm{e}})}{\epsilon_{\mathrm{H}\beta}(T_{\mathrm{e}})} \qquad (2)$$

with the recombination coefficient $\alpha_{\mathrm{A}} = 4.18 \times 10^{-13}$ cm^3 s^{-1} to all levels of hydrogen (Osterbrock 1990), as the nebula will turn out to be density bounded (see below).

Assuming a reasonable estimate for the distance $d = 1.5$ kpc, see above, we use Eq. 1 to derive the gas density to be 100 cm^{-3}, and $\mathcal{N} = 7.9 \times 10^{44}$ recombinations per sec. With $d = 5.5$ kpc we get $n = 50$ cm^{-3} and $\mathcal{N} = 1.1 \times 10^{46}$.

The density of 100 cm^{-3} is compatible with the intensity ratio of the [S II] 6717/31 Å lines measured from our spectrum of 1.3 which is very close to the lower density limit. Therefore we shall use this value for the further analysis, but any density below 200 cm^{-3} would be acceptable. We note that for such a nebula the recombination time scale is about 400 years or longer.

To have the deduced number of recombinations per sec in an optically thick Strömgren-sphere in photoionization equilibrium about a blackbody central star of 100 000 K temperature, the central star should have a luminosity of 11 (or 145) L$_\odot$. The value for L_* is quite insensitive to stellar temperature in this range. As the nebula might well be optically (partially) thin, this luminosity represents a lower limit. We note that $\mathcal{N} \propto Fd^2\alpha_{\mathrm{A}}/\epsilon_{\mathrm{H}\beta}$ depends somewhat strongly on d but weakly on T_e. For other values of $T_e = 5000 \ldots 20\,000$ K, we get ($d = 1.5$ kpc): $n = 75 \ldots 135$ cm^{-3}, $\mathcal{N} = 7.2 \ldots 8.9 \times 10^{44}$ phot/s, and $L_* = 9.9 \ldots 12.1$ L$_\odot$, respectively.

4. Photoionization Models

The available spectrum shows only the strongest lines, and lacks all lines necessary for a proper determination of the chemical composition with the means of the normal plasma diagnostics. It also lacks any definitive indication for helium lines, in particular He II 4686 Å which would be an essential clue to the temperature of the ionizing radiation.

However, scant as the spectrum may be, photoionization models can help to interpret the spectrum, if one makes some further assumptions. Preliminary tests had shown that if one wanted to explain the spectrum by models optically thick in the hydrogen Lyman continuum, [O III] required an enhanced oxygen abundance, while both [N II] and [S II] needed abundances substantially lower than would be acceptable in a normal picture of galactic chemical evolution. An alternative would be to weaken the low ionic species by accepting that the nebula is optically thin.

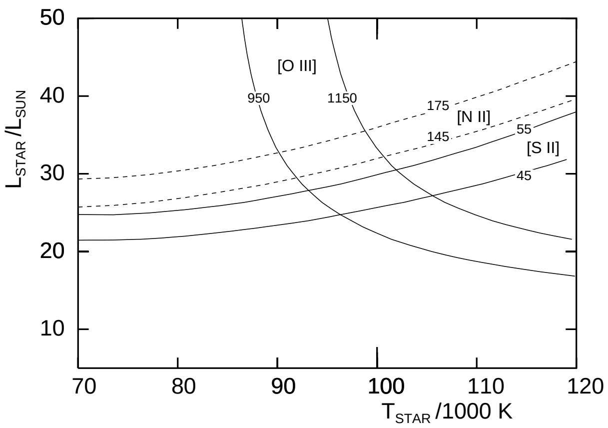

Fig. 3. Combinations of temperature and luminosity for a blackbody central star (d = 1.5 kpc) that match the observed intensities of [O III] 5007, [N II] 6583, and [S II] 6717+6731 Å lines (given in units of Hβ = 100).

If one makes the rather reasonable assumption that the nebula has a solar chemical composition, one can achieve a rather good fit. That nebulae around hydrogen-deficient central stars have perfectly normal abundances, is shown by K 1-27 and LoTr 4 (Rauch et al. 1994, 1996).

With the photoionization code GWYN (Köppen 1979; Rauch et al. 1996) we compute a grid of spherically symmetric models of solar composition nebulae, all having an angular diameter of 32″ at a distance of 1.5 kpc (5.5 kpc), with a density of 100 cm^{-3}. Figure 3 shows for which combinations of temperature and luminosity of the blackbody central star the [O III], [N II], and [S II] line intensities are matched. There are two regions where the [O III] lines and either of the other are reproduced. We have a slight preference for the intersection with the [S II] locus, as the nitrogen abundance can be affected by nucleosynthesis in the progenitor star. The best fit is given by $T_* = 98\,000 \pm 7000$ K and $L_* = 25 \pm 5$ L$_\odot$. For 5.5 kpc the diagram resembles very closely Fig. 3 but with the best fit at $T_* = 95\,000 \pm 7000$ K and $L_* = 240 \pm 40$ L$_\odot$. For these ranges we assume a relative error of 10 percent in the intensities, but the overall error bars are certainly larger. The structure of the plots does not change with distance, thus no constraint on d can be obtained from the nebula spectrum.

Taking the 'best' model, we would expect an intensity of He II 4686 of about 20 percent of Hβ. Due to the noise in our spectrum a line of this strength cannot reliably be identified. The measurement of the He II line intensity by a higher quality spectrum could thus be a crucial test for the validity of our present preliminary model. This is planned using the VLT at ESO.

5. Evolutionary status and outlook

So far the pre-flash evolutionary status of Sakurai's object had not been well constrained. Duerbeck & Benetti assume a temperature between 50 000 and 60 000 K, while Jacoby et al. (1998a) derive a hydrogen Zanstra temperature above 45 000 K.

From the level of ionization in the nebula we obtain a temperature close to 100 000 K and a luminosity of a few tens $L_\odot$ to a few hundred depending on the distance. Because of its low density, the nebula changes its ionization on time scales of at least 400 yrs, much longer than the currently observed evolution of the central star. Our results show that Sakurai's pre-flash position in the HRD was indeed that of a highly evolved PN central star, entering the white dwarf cooling tracks. Thus, it is truly a case of a very late helium flash.

It is tempting to compare Sakurai's pre-flash properties with theoretical tracks of post-AGB evolution (Iben et al. 1983; Blöcker 1995). Given the preliminary nature of our analysis, we restrict ourselves to stating that the position in the HRD is in the range of the tracks for remnant masses between $0.8\,M_\odot$ (d = 1.5 kpc) and $0.55\,M_\odot$ (d = 5.5 kpc). The higher mass is consistent with estimates based on the observed time scales for the return to the AGB after the flash (Asplund et al. 1999). While this paper was under revision the referee pointed out a work by Pollacco (1999) he had just received as a preprint. Using similar material he finds $\log(T_*/K) = 5.1 \pm 0.2$ and $\log(L_*/L_\odot) = 3.3 \pm 1.3$ (d > 5 kpc), values quite similar to ours albeit with larger error margins. The reason for this probably is the slightly different approach using photoionization models to fit the full spectrum and deriving abundances, whereas we focus on the stellar parameters using key line ratios. While, due to the larger errors, he does no specifically call it a very late flash he also concludes that Sakurai's object was highly evolved before the final helium flash supporting our result.
The kinematical age of a few thousand years for the nebula given by Jacoby et al. (1998a) is smaller than the evolutionary time calculated for both masses, but in light of the uncertainties involved we feel that this discussion can only be done properly when the position in the HRD is known more precisely.

6. Conclusions

From analysis of the old PN surrounding it, we derive the properties of Sakurai's object before the helium flash. This is possible, because the nebula has not yet had the time to recombine since it was last ionized by the pre-flash central star. For a distance of 1.5 kpc (5.5 kpc) the star had a temperature of 98 000 K (95 000 K) and a luminosity of about $25\,L_\odot$ ($240\,L_\odot$). Thus, it was located already on the white dwarf cooling track, when the final flash occurred.

The spectrum available to us was of a rather limited quality. Observing time at the VLT has been granted, and will serve to obtain a spectrum with a significantly improved S/N. This will permit tighter constraints on the PN's properties and on the past of Sakurai's object.

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