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Letter to the Editor

The distance of Sakurai's Object

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Abstract. Sakurai's Object seems to be undergoing a very late Helium-flash, making it a unique observational event with very important implications for our understanding of late stellar evolution. We present the first individual distance determination: using the extinction method we have derived a distance of 1.1 kpc for the planetary nebula surrounding the star. This accurate distance will be a crucial step forward in our efforts to understand the nature and the evolution of Sakurai's Object.

Key words: ISM: planetary nebulae: individual: Sakurai's Object – stars: AGB and post-AGB

1. Introduction

Sakurai's Object ($\alpha = 17^{\rm h}52^{\rm m}32\overset{\rm s}{.}69$, $\delta = -17^\circ 41' 07\overset{''}{.}7$, J2000.0) was discovered by the Japanese amateur astronomer Y. Sakurai in February of 1996 (Nakano et al. 1996). First classified as a slow nova, this new star showed a highly unusual spectrum dominated by a wealth of absorption lines from carbon, nitrogen and oxygen, but displays only weak hydrogen Balmer lines (Benetti et al. 1996). This finding and the discovery of a faint old planetary nebula (PN) surrounding the star, led Duerbeck & Benetti (1996) to the idea that Sakurai's Object may be a star undergoing a late He-flash. Despite the fact that 10 to 20 % of all low mass stars should experience such a phase (Iben & MacDonald 1996), it is an exceedingly rare observational event due to its extremely short duration. In historic times there are only two other likely candidates: the first is V 605 Aql, the central star of A 58 that showed a strong brightening in 1919 (Harrison 1996, see Clayton & De Marco 1997 for a review). The second example is the peculiar star FG Sge that has crossed the HRD over the last 100 years, while showing an almost continuous increase in brightness; see van Genderen & Gautschy (1995) for a summary of its evolution. FG Sge's behaviour has most recently been explained by Blöcker & Schönberner (1997) by a He-flash that happened during the plateau phase of the PN evolution (late He-flash). He-flashes on the cooling track towards the white dwarf region (very late He-flash) develop much faster and are therefore a very short-lived phase. Sakurai's Object gives us a unique opportunity to study such a very late He-flash with the full array of modern equipment. Monitoring has already led to a number of important discoveries; Asplund et al. (1997) and Kipper & Klochkova (1997) have been able to derive accurate abundances for Sakurai's Object, thereby establishing the hydrogen-poor nature of the object. Kerber et al. (1997a) have discovered dramatic changes in the optical spectrum, where strong molecular bands of C_2 and CN were found. Similarly Kimeswenger et al. (1997) identified a strong NIR excess due to hot dust. This was confirmed by recent ISO observations (Kerber et al. 1997b). All these observations seem to be in agreement with the notion that Sakurai's Object is indeed experiencing a very late He-flash and is undergoing an episode of mass loss. A reliable and accurate distance will be vital in order to learn as much as possible from this example of stellar evolution in "real time“.

2. The problem of distance determination

Conventional distance methods, like spectroscopic parallaxes can not be applied in this case as our current understanding of stellar evolution can not be used to predict the physical properties of such a very late He–flash with any degree of certainty. To the contrary, once a distance is known, accurate values can be derived to check the validity of theory. The existence of an old PN around Sakurai's Object gives us an alternative means of determining the distance. The physical connection between the star and the PN is confirmed by measurements of the radial velocity ($\approx 100\,\mathrm{km\,s^{-1}}$) which give very similar results for both (Duerbeck & Benetti 1996, Kerber et al. 1997c). In addition, Sakurai's Object is almost perfectly located in the centre of the PN. Using a PN for distance determination may sound like a losing proposition when one considers that PN distances are notoriously difficult to obtain and that the results often remain unreliable

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(Terzian 1993). In fact statistical means of distance determination - like a distance scale derived from the Shklovsky method - contain large uncertainties. Van de Steene & Zijlstra (1995) explicitly warn against using them for distance determination of individual objects. Individual distance methods generally are more reliable but often make use of a special property of the object, like e.g. cluster membership (Dufour 1984). An individual method that does not make any assumptions about the object itself is the extinction or reddening method. It has successfully been employed by a number of authors (Acker 1978, Gathier et al. 1986, Martin 1994, Saurer 1995) This method requires that the reddening as a function of distance be determined from photometry of stars in the field surrounding the PN. The details of the method including potential problems – in particular the influence of the inhomogeneity of the interstellar medium – are discussed e.g. in Gathier et al. (1986).

3. Observations and data analysis

We obtained BVRI$_c$ photometry of the field around Sakurai's Object using the HSHT 60 cm telescope of the Toronto Southern Observatory (UTSO) in Las Campanas, Chile in April 1996 and April 1997 and the Dutch 90 cm telescope at ESO/La Silla in March 1997. During the latter run a set of deep exposures were taken even if Sakurai's Object was overexposed, to obtain a better signal to noise ratio for faint stars. We only used stars within the field of a single CCD frame (3.5 by 3.5 arcmin) centered on Sakurai's Object, thereby minimizing the effect of inhomogeneities in the interstellar medium. It is well established that the interstellar has an irregular distribution resulting in a patchy pattern of extinction (e.g. Burton 1991 and references therein). The basic assumption of the extinction method requires that all stars used belong to the same reddening vs. distance relation. For a small field this is virtually garanteed and we have also found no indication of inhomogeneous reddening from star counts in the frame. The stars used are identified by numbers in Fig. 1, which can also serve as a finding chart. For the determination of color equations, extinction coefficients and instrumental calibration a set of standard stars (Landolt 1992) were taken throughout the whole night. A spectrum of one unusual star was obtained with the 2.5 m du Pont telescope of the Las Campanas Observatory, Chile in April 1997. For obtaining spectral type and luminosity class from the BVRI$_c$ photometry we used a newly developed method (a (V-I) vs. (V-R)-(R-I) diagram) which is similar in approach to the one described by Dean et al. (1978) and extensively investigated for the determination of extinction distances of planetary nebulae by Pollacco & Ramsay (1992). The (V-R)-(R-I) parameter is nearly identical to the extinction free parameter Q:= (V-R) - 1.72 (R-I). Defining the errors on the (V-R)-(R-I) axis by gaussian errors gives us

$$\sigma_{\text{(V-R)-(R-I)}} := \sqrt{\sigma_{\rm V}^2 + 4\ \sigma_{\rm R}^2 + \sigma_{\rm I}^2}$$

while that one for Q is given by

$$\sigma_{\rm Q} := \sqrt{\sigma_{\rm V}^2 + 7.4\ \sigma_{\rm R}^2 + 3\,\sigma_{\rm I}^2}.$$

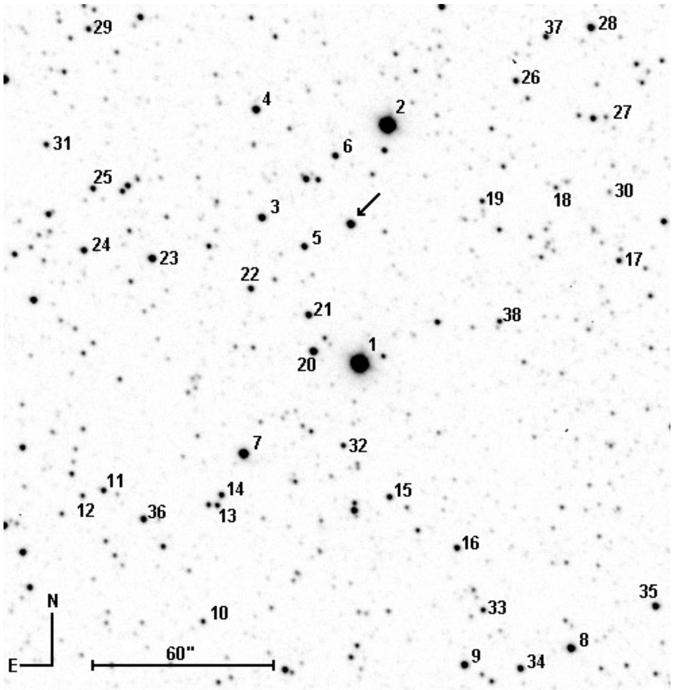

Fig. 1. R band image of the field around Sakurai's Object (1) identifying all stars used in the photometry. The star maked by an arrow was investigated spectroscopically.

Assuming similar rms errors σ on all bands this results in an error that is about 1/3rd samller than that for the Q parameter. The fact that the angle between main sequence and extinction direction is nearly identical at both diagrams lead us to the choice mentioned above. This method gives a quite good separation of dwarfs. This enables us to reliably classify the vast majority of stars in the field, most of which are late–type stars. We therefore can use the typical stellar population for establishing the reddening vs distance relation and do not have to rely on early–type stars none of which was found in the field. Details of the method will be presented in an upcoming paper.

4. Results and discussion

The photometric results for all stars are given in Table 1 along with the derived stellar classification and the resulting reddening values. All stars with useable results have been used to construct a reddening vs. distance relation. Additionally, photometric data and MK classification for HD 162740 (square at 1 kpc), located 16.4 arcminutes from Sakurai's Object, were taken from SIMBAD. The particularly red star (arrowed) was observed spectroscopically and classified as a Mira–like M giant in about the distance of the bulge. The resulting reddening vs. distance relation can be seen in Fig. 2. We derive a distance of 1.1 kpc with errors allowing a range of 0.9 to 1.5 kpc. Distances larger than 2 kpc can be excluded for the measured reddening of E$_{(B-V)}$ = $0\overset{m}{.}54$. Reddening as a function of distance rises steeply up to a distance of 2 kpc. Such a behaviour is well known from extragalactic studies and can nicely be explained in terms of the

Table 1. Photometry, extinction and adopted spectral types from CCD photometry:

Nr.	V	(B-V)	(V-R)	(V-I_c)	E_{B-V}	Sp.
1	11.13	0.88	0.56	1.18	-	Sakurai
2	10.60	0.36	0.29	0.49	0.32	A2V
3	14.90	1.45	0.93	1.64	0.27	K3-4V
4	14.52	0.96	0.66	1.18	0.20	K0-1V
5	15.63	1.52	1.07	1.88	0.81	G3-5III
6	15.65	1.70	1.08	1.82	1.00	G2-3III
7	13.94	1.79	1.06	1.84	0.77	K0III
8	14.52	1.34	0.82	1.39	0.77	F0-5V
9	15.35	2.19	1.26	2.21	0.84	K3III
10	16.26	1.17	0.67	1.19	0.27	K0-2V
11	16.05	1.39	0.94	1.69	0.27	K4-5V
12	16.86	1.89	1.13	1.98	0.94	K0III
14	15.82	1.46	1.01	1.74	0.87	G0III
15	15.57	1.07	0.63	1.07	0.67	A8-F1V
16	16.13	2.22	1.30	2.33	0.81	K2-4III
17	15.84	1.19	0.68	1.26	0.47	G5-6V
18	16.50	0.98	0.78	1.28	0.87	A5-6V
19	16.10	1.09	0.70	1.29	0.47	G0-2V
20	15.13	2.30	1.36	2.48	0.81	K5III
21	15.77	2.08	1.42	2.56	0.84	K4-5III
22	16.20	2.21	1.40	2.48	0.92	K3-4III
23	15.48	2.29	1.54	2.79	0.87	K5III
24	15.85	2.04	1.25	2.16	0.94	K0-1III
25	15.91	1.59	0.93	1.64	0.27	K3-5V
26	16.05	1.81	1.00	1.80	0.29	K5-6V
27	16.56	1.18	0.79	1.67	?	?
28	15.24	1.93	1.11	1.99	?	?
29	16.15	1.81	1.04	1.81	0.84	G8III
30	16.98	1.33	0.69	1.35	?	?
31	16.44	1.78	1.14	2.02	0.90	G8-K0III
32	16.74	2.24	1.41	2.44	1.06	K2III
33	16.50	2.08	1.17	2.11	0.39	K5-7V
34	15.86	2.06	1.32	2.26	0.94	K2III
35	15.78	2.09	1.55	2.86	0.87	K7-M0III
36	16.39	2.21	1.80	3.38	1.16	M0-2V
37	16.32	2.22	1.18	2.17	0.35	K5-8V
38	16.43	1.97	1.24	2.23	0.42	K5-8V

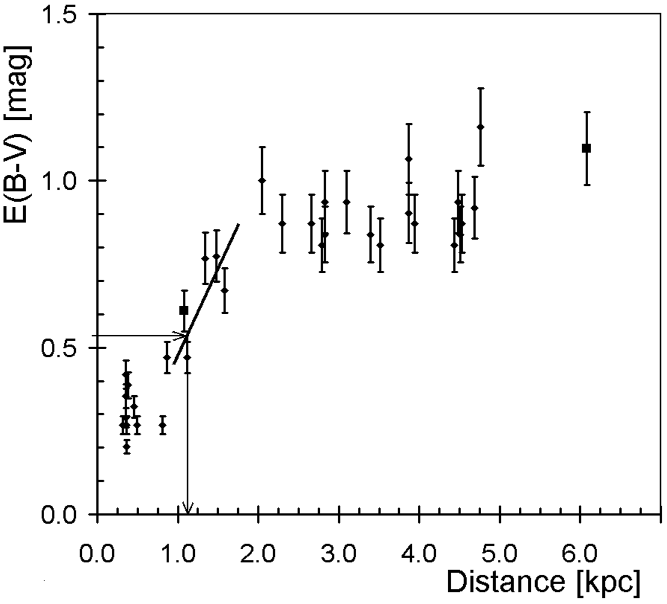

Fig. 2. Extinction vs. distance of all field stars (diamonds) classified. The filled square near 1 kpc indicates the position of HD 162740; the one beyond 6 kpc the position of the spectroscopically investigated red giant star (see text).

galactic structure. At the location of Sakurai's Object ($l = 10.^\circ48$, $b = 4.^\circ41$) the line of sight will first pass through the galactic disk resulting in a rather uniform increase in reddening for the first two kpc. Assuming a scale height of $\leq$ 100 pc for the dust in the galactic plane (Kimeswenger et al. 1993), the distance z from the galactic plane for the field exceeds 150 pc at about a distance of 2 kpc onwards, therefore only minimal additional reddening occurs farther out, as is observed. Due to the small galactic latitude of the field, stars can be found out to bulge distances. The unusually red star investigated spectroscopically and classified as a Mira–like star confirms the "asymptotic" reddening of ca. $1.^{m}0$ out to 7 kpc. Most of the stars at large distances in Fig. 2 are assumed to be giants. This find is consistent with star count models (Cohen 1993 and references therein, Ruhpy et al. 1997).

With the distance derived above we obtain an absolute magnitude range of $M_V = -0.^{m}8$ ($-0.^{m}4$ to $-1.^{m}5$). Assuming the same effective temperature $T_{\rm eff} = 7250$ as taken in Duerbeck & Benetti (1997) and for the post–AGB star HR 4049 ($T_{\rm eff} = 7500$, Bakker et al. 1996) and the typical absolute magnitude of an F2 supergiant we come up with the radius to be 9 to 15 times smaller than that one of such a F2 supergiant (4 to 6 times smaller than HR 4049). The old PN around Sakurai's Object has a diameter of $32''$, corresponding to 0.17 (0.14 – 0.23) pc at 1.1 kpc, which results in a kinematic age of 4200 (3400 – 5600) years assuming an expansion velocity of about $20\,{\rm km\,s^{-1}}$. The distance found by us is significantly smaller than those reported so far. Duerbeck & Benetti (1996) obtain a value of 5.5 kpc on grounds of a statistical method using the 5 GHz flux derived from the observed H_β. In support of a large distance they state that field 154 from Neckel & Klare (1980) indicates distances larger than 2 kpc for the measured reddening of $E_{(B-V)} = 0.^{m}54$. Unfortunately there seems to be a mix-up here. The field closest to the position of Sakurai's Object (number 242) is very large ($\approx$ 300 square degrees) which makes it highly vulnerable to variations in the reddening. More recently a distance of 8 kpc was given by Duerbeck et al. (1997) placing Sakurai's Object at bulge distance. This is the result of a pulsational analysis of the observed photometric variability which requires a high luminosity, high mass ($0.8\,M_\odot$) central star. Such a star implies a small age of the nebula, which is difficult to reconcile with the physical dimensions of the nebula at bulge distance, assuming a normal expansion velocity. Furthermore the distribution of bulge PNe shows a pronounced cut–off at diameters of 10 to $12''$, for a discussion of the properties of bulge PNe see Pottasch (1990), Stasinska et al. (1991) and Pottasch & Zijlstra (1992). While one might argue that the very low surface brightness of the nebula prevented it from being discovered, the nebula would still be unusually large (1.2 pc) for a bulge object. Furthermore it would rank among the faintest bulge PNe observed judging from the H_β flux. No such problem exists for a distance of 1.1 kpc.

5. Conclusion

We present the first individual distance determination of the PN around Sakurai's Object using the extinction method. The reddening vs. distance relation established using stars in a very small field is in full agreement with galactic structure. The value of 1.1 kpc obtained results in an absolute magnitude of $M_V = -0\overset{m}{.}4$ to $-1\overset{m}{.}5$. For the old PN we find a diameter of 0.17 pc and a kinematic age of about 4200 years. This comparatively small distance is compatible with all available data, while much larger distances lead to discrepancies. We are confident that a reliable distance value will help us to gain new insights in the very late He-flash phenomenon which is taking place right before our eyes.

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