SAKURAI'S OBJECT: ISO WITNESSES STELLAR EVOLUTION IN "REAL-TIME" *

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ABSTRACT

We present ISOCAM observations of Sakurai's Object covering the wavelength range of 4 to 15 μm in seven filter bands. The photometry shows that over the period from February 1997 to February 1998 the flux over the whole range has increased by a factor of about ten. On basis of the ISOCAM and ground-based data we conclude that this increase is the result of recent mass loss from Sakurai's object and the formation of hot dust around it. Using a spherically symmetric dust radiative transfer model we get a very preliminary quantitative result for the mass loss rate of a few 10^{-7} M$_\odot$/year, a rather typical value for stars on the Asymptotic Giant Branch. This is in agreement with the notion that Sakurai's object is retracing its own evolutionary history as a consequence of a final helium flash.

Key words: ISO; final helium flash; mass loss; dust formation.

1. WHAT IS SAKURAI'S OBJECT ?

Discovered by Japanese amateur astronomer Y. Sakurai in February of 1996 (Nakano et al. 1996) Sakurai's object ($\alpha = 17^{\rm h}52^{\rm m}32.7^{\rm s}$, $\delta = -17{\rm d}41'08''$, J2000.0) was first classified as a slow nova. Spectroscopy revealed that this new star showed a highly unusual spectrum dominated by a wealth of absorption lines from carbon, nitrogen and oxygen, and showing only weak hydrogen Balmer lines (Duerbeck & Benetti 1996; Kerber et al. 1998). Soon thereafter an old planetary nebula (PN) surrounding Sakurai's object was dicovered on narrow–band images ([O III] and Hα).

At that point it became quite clear that Sakurai's object is undergoing a final He–flash at this very moment. Despite the fact that 10 to 20 per cent of all low mass stars should experience such a phase (Iben & MacDonald 1996), it is an exceedingly rare observational event due to its extremely brief duration.

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2. WHAT IS SAKURAI'S OBJECT DOING ?

Sakurai's object gives us a unique opportunity to study 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.
The energy distribution as it was in 1996 could be explained by a 7000 K blackbody in agreement with the observed spectrum, resembling a F-type supergiant.

In March 1997 we discovered dramatic changes in the optical spectrum of Sakurai's object using the 2.5 m Du Pont telescope at Las Campanas, Chile. The dominating features now were the prominent bands of CN (bandheads at 388.8 and 421.6 nm) and C_2 (Swan-Bands at 439.2, 473.7, 516.5, 558.5 and 565.5 nm, Kerber et al. 1997b) that were not evident the year before (Duerbeck & Benetti 1996; Kerber et al. 1998), see Figures 1 and 2.

Still in 1997 we discovered another dramatic change, the development of a strong IR excess from DENIS observations (Kimeswenger et al. 1997). The 1997 energy distribution could no longer be described by a single Planck curve, but a second, cooler, component was required. Using Open and Discretionary time on ISO we followed the evolution of Sakurai's object for a full year.

2.1. The ISO observations

The observations were performed in staring mode. See Table 1 for an overview of the used parameters. In the last observation we changed the Pixel Field Of

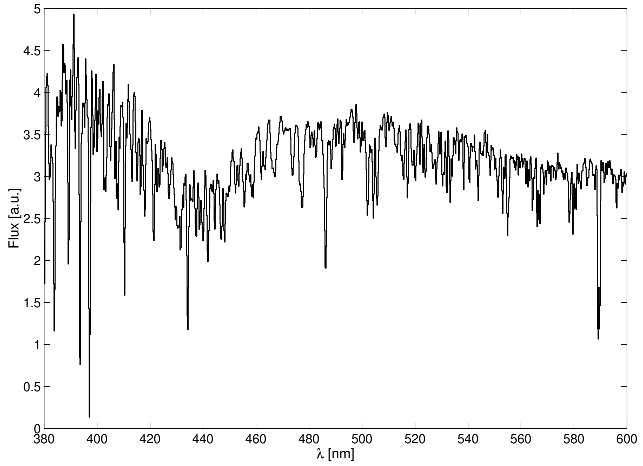

Figure 1. Spectrum of Sakurai's object in April 1996.

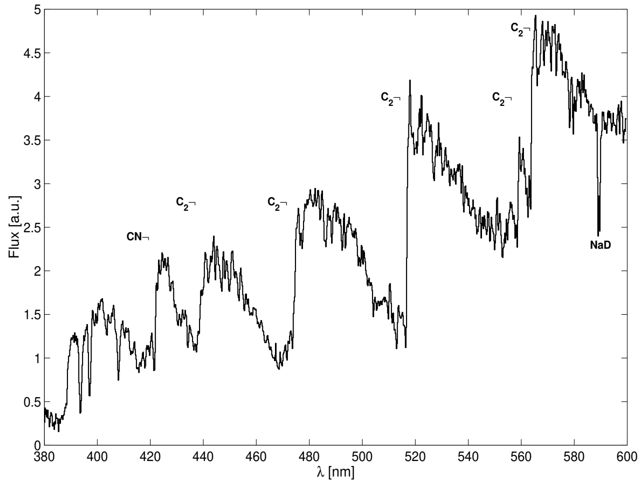

Figure 2. Spectrum of Sakurai's object in March 1997.

Table 1. Log of the ISOCAM observations

Date	Filter	PFOV	Tint	Gain
25. Feb 1997	LW1, 4 – 9	3	2.1 s	2
05. Sep 1997	"	3	2.1 s	2
11. Oct 1997	"	3	2.1 s	2
27. Feb 1998	"	1.5	2.1 s	1

View (PFOV) from 3 to 1.5$''$ and reduced the gain to one to avoid a possible saturation of the detector. The data was reduced in the Cam Interactive Analysis (CIA) package (Ott et al. 1997). The reduction steps included deglitching, dark correction (using the time dependent model) and averaging over the stabilized part of the readouts for each filter. The images were flatfielded using the Calibration Library. Fluxes were determined with aperture photometry, corrected for the size of the psf, and using the signal to flux density conversion factors of the Off Line Processing (OLP) v7 Calibration file. For details of the procedures see Blommaert (1998).
The ISOCAM data clearly confirmed the existence of a strong - and steadily increasing - IR excess, see Figure 3.

We conclude that this is the signature of very hot dust that has recently formed in an extended, optically thin shell around the star. Recent episodes of fading (spring of 1998 and most recently during the last two months) in the visual indicate that the dust becomes optically thick on occasions (Liller et al. 1998a, 1998b), a behaviour resembling that of R CrB stars.
The lack of an excess in the ISO filter centered on the 7.7 μm PAH feature indicates that the dust is formed in an H-poor environment.

2.2. Dust around Sakurai's object

For two reasons the dust observed in Sakurai's object must have formed most recently: First Sakurai's object has not been detected as a source by IRAS in the 80s, second the location of the dust excludes an age older than the He-flash because dust so close to a PN central star would have been destroyed long ago. Moreover we recorded an unprecedented increase in the IR flux by a factor of ten in just one year. This of course is an indication of continuous or episodic mass loss.
Figure 4 shows a fit to ISO and BVRI data for February 1998 using a spherically symmetric dust radiative transfer model (see e.g. Groenewegen et ak. 1998). The central star was a F6 I model atmosphere (Fluks et al. 1994), but this is not very well constrained.
The dust optical depth in the V-band for this model is 4.0. For an assumed expansion velocity of 10 km s^{-1}, a dust condensation temperature of 1500 K and a gas-to-dust ration of 200, the corresponding mass loss rate is 4×10^{-7} M$_\odot$/year.
We did not yet consider a mass loss rate that changes with time or that the mass may preferentially be lost in a disk. For an assumed distance of 1.1 kpc (Kimeswenger & Kerber 1998) we found a luminosity of 840 L$_\odot$. From the peak of the SED and Wien's law one immediately finds that the colour temperature decreased from about 2900 to 1150 K between February 1997 and February 1998.
Yet the ratios of the different filters for a given epoch vary. This certainly is an indication of structural changes in the SED. One conclusion is that the formation of dust is continuing but at variable rates or in an episodic manner.
An other explanation is the formation of dust features. Sakurai's object evidently is poor in hydrogen and rich in carbon , therefore the freshly formed dust is likely to be mostly amorphous carbon.

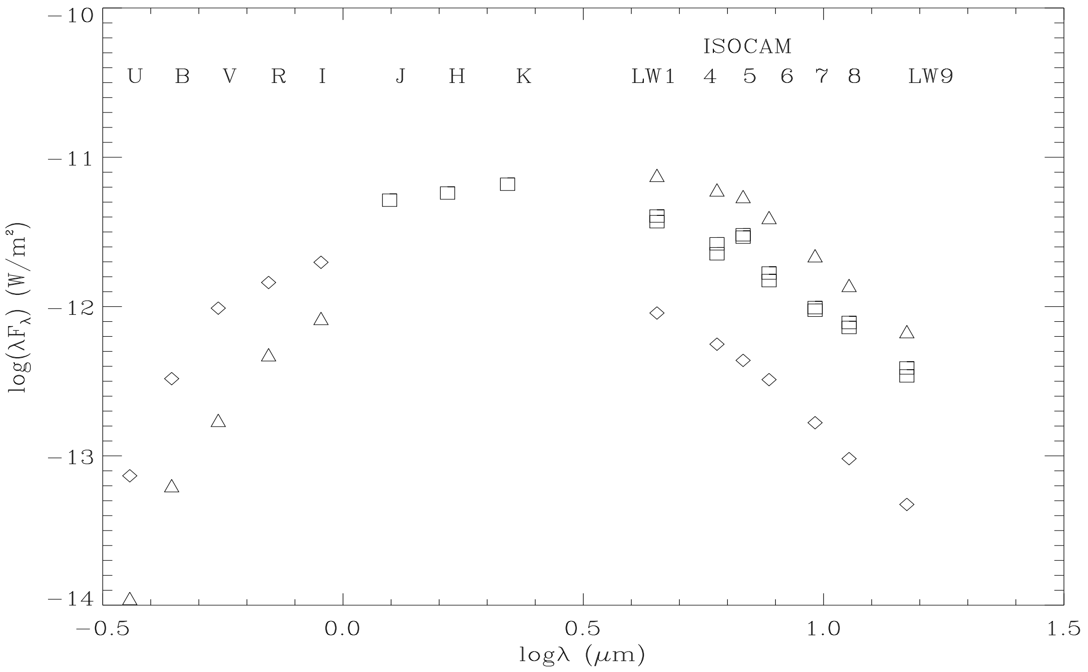

Figure 3. ISOCAM photometry of Sakurai's object at different epochs. Diamonds are from Feb 1997, squares from Sept and Oct 1997 and triangles from Feb 1998. UBVRI data are from the literature.

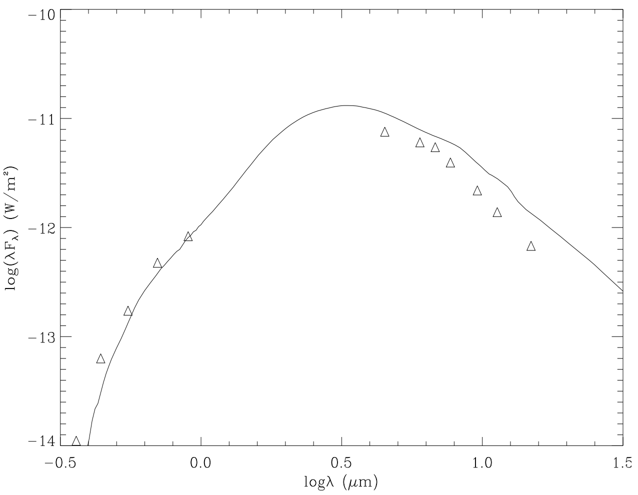

Figure 4. ISOCAM data from Feb 1998 and the fit to the SED, see text for details

To further investigate this topic we have started ground-based monitoring using TIMMI (Käufl et al. 1994) at ESO's 3.6m. First result are reported in Käufl & Stecklum (1998). A flux of 5.7 Jy measured in a SiC filter in June 1998 is significantly smaller than the earlier (March) observed value of 8.3 Jy. Further observation will be obtained during the next season in order to monitor the evolution of this freshly formed dust.

3. SAKURAI'S OBJECT IN TERMS OF STELLAR EVOLUTION

All currently known facts about Sakurai's object are in agreement with the idea that it is undergoing a final He-flash. Theory predicts that about 10 to 20 per cent of all low mass stars should experience such an episode (Iben & MacDonald 1996). Still it is an exceedingly rare observational event, due to its brevity.
In fact only two other likely examples are known.

FG Sge, the unique central star of He 1-5, has traveled throughout the Hertzsprung-Russell diagram (HRD) over the last 100 years, changing from spectral type O3 in 1880 to K2 in the 1990s, while brightening by about 4.5 mag. For a detailed review of FG Sge's behaviour see van Genderen & Gautschy (1995).
Recently Blöcker & Schönberner (1997) have explained this evolution as a *late* He-flash that occurred at high luminosities on the horizontal part of the evolutionary track. The most important difference to Sakurai's object is that the pace of evolution is much slower and that FG Sge does not seem to be H-deficient. So the two objects are probably not two of a kind.

The other candidate is V605 Aql, the central star of A 58. This star erupted as a "nova" in 1919 and faded quickly. It showed two more brightness maxima during the decline separated by about two years each. Today V605 Aql seems to be a WR-type PN nucleus deeply embedded in dust, making it a very faint target. A spectrum taken by Lundmark in 1921 shows a striking similarity to Sakurai's spectrum in 1997, (Clayton & De Marco 1997).

Unfortunately the development of V605 Aql could not be monitored after 1923, until it was again observed in the early 80s, resulting in a gap of 60 years and so its development to its present state is not documented.
It has been suggested by Seitter (1987) that this is a case of a *very late* flash that happened on the cooling track towards the white dwarfs. The much faster pace of evolution and the spectrum suggest that this may be a case similar to Sakurai's object.
It should be noted that the only calculation for the very late He-flash observed in Sakurai's object was done by Iben et al. (1983) and predicts a time span of 17 years from the onset of the flash to the AGB (0.3 mag/y).
Even this astronomically very brief period seems to be too long by at least a factor of three compared with the rate of change observed for Sakurai: 1 mag/y.
While rapid change is expected for such a star, Sakurai's object literally outpaces all predictions made by current theory.
The final outcome of such an evolution should be a second, inner nebula of H-deficient chemical composition as has been found in A 30 and A 78 (Jacoby 1981). Both PNe probably suffered a final He-flash thousands of years ago.

A final He-flash is one of the scenarios under discussion for formation of R CrB stars (Clayton 1996). Interesting similarities between Sakurai's object and these rare stars are noted by Clayton & De Marco (1997) and in particular by Asplund et al. (1998) for V854 Cen and its chemical composition.

4. CONCLUSION

Sakurai's object is undergoing a final Helium shell flash. This is a unique opportunity to study such a truly rare and remarkable event in the stellar evolution of intermediate mass stars.
Observations are the key to the understanding of this phenomenon and ISO has provided some essential data through the monitoring of the mid-infrared.
Monitoring in all accessible wavelength regions will remain absolutely vital in order to follow the fast-paced evolution of the object.
In the infrared, observations of Sakurai's object will continue from the ground to record the formation and evolution of the dust. In an attempt to establish quantitative insight into the physical conditions, we have shown - as a first step - the results of a simple radiative transfer model from which we have derived a mass-loss rate. The resulting value of a few 10^{-7} $M_\odot$/year is quite typical for stars on the asymptotic giant branch.

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