Astron. Astrophys. 350, L27–L30 (1999)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

ISO* observations of dust formation in Sakurai's object

Monitoring the mass loss of a very late Helium flash star

F. Kerber[1,2], J.A.D.L. Blommaert[3], M.A.T. Groenewegen[4], S. Kimeswenger[2], H.U. Käufl[5], and M. Asplund[6]

[1] Space Telescope European Coordinating Facility, European Southern Observatory, 85748 Garching, Germany
[2] Institut für Astronomie der Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria
[3] ISO Data Centre, ESA, Villafranca, 28080 Madrid, Spain
[4] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 85748 Garching, Germany
[5] European Southern Observatory (ESO), Karl-Schwarzschild-Strasse 2, 85748 Garching, Germany
[6] Uppsala Astronomical Observatory, Box 515, 75120 Uppsala, Sweden

Received 27 May 1999 / Accepted 2 September 1999

Abstract. We present ISOCAM observations of Sakurai's object (V4334 Sgr) covering the wavelength range of 4 to 15 μm in seven filters. The photometry shows that in the period from February 1997 to February 1998 the flux over the whole wavelength range has increased by a factor of about ten. Combined with ground-based data we conclude that this increase is the result of mass loss from Sakurai's object and the formation of hot dust around it. Using a spherically symmetric dust radiative transfer model we obtain a quantitative result of a variable and increasing mass loss rate reaching some 10^{-7} $M_{\odot}$/yr, a value not uncommon among stars during the Asymptotic Giant Branch (AGB) evolution. This is in agreement with the notion that Sakurai's object is retracing its own evolutionary history as a consequence of a very late Helium flash. We conclusively demonstrate that significant mass loss is associated with such an event and foster the link to the other few known examples of final Helium flashes.

Key words: stars: AGB and post-AGB – stars: evolution – stars: circumstellar matter – ISM: planetary nebulae: individual: Sakurai's Object (V4334 Sgr)

1. Introduction

Sakurai's object (V4334 Sgr) most likely is a star undergoing a final Helium flash, the first example since V605 Aql/A 58 in 1919. Details of its discovery and evolution are found in Duerbeck et al. (1996, 1997), Kerber et al. (1999a) and references therein. This is the first such event that can be studied with modern technology and at wavelengths other than optical. Most recently two studies of the old planetary nebula (PN) surrounding Sakurai's object (Kerber et al. 1999a; Pollacco 1999) have demonstrated that a very late Helium flash is under way, i.e. one that happened when the star was highly evolved (T $\approx$ 100 000 K) and had already entered the white dwarf cooling track. This result is in full agreement with the quantitative analysis of Asplund et al. (1999) who show that Sakurai's object is hydrogen-poor and hydrogen is still being removed from the photosphere as it is ingested and burned, whereas s-process elements become more abundant.

The theory of a very late Helium flash (Iben et al. 1983) predicts that such stars will return to the AGB and retrace their own post-AGB evolution for a second time ("born-again"). This will lead to the formation of a second PN composed of hydrogen-poor material and dust (Harrington 1996). The prototypes of these PNe are A 30 and A 78 (Jacoby & Ford 1983; Hazard et al. 1980) but also V605 Aql/A 58 (Seitter 1987), GIJC-1 (Gillett et al. 1989) in M 22 and IRAS 15154$-$5258 (Manchado et al. 1989) belong to this class. Therefore both theory and the known examples of very late Helium flashes suggest that significant mass loss is associated with such an event.

2. Observations and data reduction

Sakurai's object has shown fast and massive changes in its spectrum as carbon bearing molecules have formed (Asplund et al. 1997; Kerber et al. 1997) very much comparable to V605 Aql (Clayton & de Marco 1997). We were the first to discover a strong infrared excess (Kimeswenger et al. 1997) as a direct result of mass loss (Kerber et al. 1999b). Using general and discretionary time on ISO we have obtained a homogeneous set of photometric observations spanning the full ISOCAM (Cesarsky et al. 1996) LW wavelength range and covering a full year from February 1997 to 1998 in four epochs, closely monitoring the

Send offprint requests to: F. Kerber (fkerber@eso.org)

* ISO is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, The Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

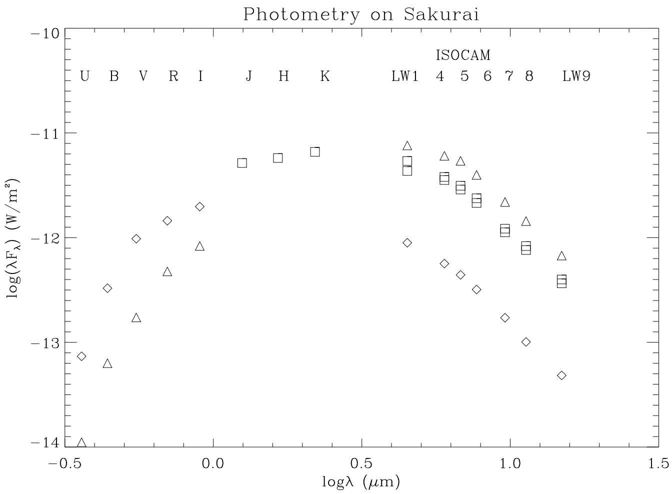

Fig. 1. ISOCAM photometry of Sakurai's object at different epochs. Diamonds are from Feb 1997, squares from Sept and Oct 1997 and triangles from Feb 1998. $UBVRi$ and JHK data are by us and from the literature (see text).

evolution of Sakurai's object in the mid-IR, see Table 1 for a summary of the observations. The ISOCAM observations were performed in staring mode. The error for the flux is between 2 and 8 per cent, with the latter applying to filters LW 1, 4 & 5, which showed saturation in the central pixel for epoch 4. The data was reduced in the Cam Interactive Analysis (CIA) package (Ott et al. 1996). The reduction steps included deglitching, dark correction (time dependent model) and averaging over the stabilized part of the readouts. The images were flatfielded using the calibration file flatfields. Fluxes were determined with aperture photometry, corrected for the size of the PSF, and using conversion factors of the Off Line Processing (OLP) v7 calibration file. For details see Blommaert (1998).

3. The formation of hot dust

The ISOCAM data clearly confirmed the existence of a strong – and steadily increasing - IR excess, see Fig. 1. We conclude that this is the signature of very hot dust that has recently formed in an extended, optically thin shell around the star. Furthermore there is indication of change in the spectral energy distribution (SED), getting redder over time. In addition, 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. One conclusion is that the formation of dust is continuing but at variable rates or in an episodic manner.

For two reasons the dust observed in Sakurai's object must have formed most recently: First Sakurai's object has not been detected as an IRAS source in the 80s (compare with Table 1), second the location of the dust excludes an age older than the He-flash because dust from the AGB is much further out and does not remain intact so close to a PN central star.
Moreover we recorded an unprecedented increase in the IR flux by a factor of ten over one year. This of course is an indication of continuous or episodic mass loss.

Table 1. Log of the ISOCAM observations

Date	Flux (LW1, 4, 5, 6, 7, 8, 9) [Jy]	$t_{\rm int}$
25.02.97	1.34, 1.13, 1.00, 0.82, 0.55, 0.38, 0.24	2.1 s
05.09.97	6.5, 7.1, 6.53, 5.5, 3.6, 2.87, 1.82	2.1 s
11.10.97	8.1, 7.6, 7.1, 6.1, 3.9, 3.13, 1.98	2.1 s
27.02.98	11.4, 12.1, 12.28, 10.2, 7.01, 5.42, 3.35	2.1 s

Fig. 2 shows a fit to ISO and $UBVRi$ data for February 1997 and February 1998 using a spherically symmetric dust radiative transfer model (Groenewegen 1993). The observational data are the ISO fluxes discussed above, and $UBVRi$ photometry from the literature. For Feb. 1997 they are interpolated from values listed in Duerbeck et al. (1997), for Feb. 1998 they are from Liller et al. (1998). The near-IR data shown in Fig. 1 is our data taken with the 1.5m Carlos Sanchez telescope (Tenerife). We adopt a visual foreground extinction of 2.2 mag (Pollacco 1999).

For the central star we use a state of the art H-deficient model atmosphere of a temperature appropriate for the respective epoch (see Asplund et al. 1997, 1999 for details), specifically we have used $T_{\rm eff}$ = 6000 K for Feb. 1997, $T_{\rm eff}$ = 5500 K for Feb. 1998. For the dust we used amorphous carbon grains (optical constants from Rouleau & Martin (1991) for the "AC" species). Since the laboratory species may not be fully representative of astronomical dust, the opacity used may not be appropriate.

The fit to the Feb. 1997 data assumes a dust condensation temperature of 1500 K. A good fit could *only* be achieved using a finite value for the outer radius of the dust shell. This is not surprising as the dust shell has been expanding for a very limited time. Eyres et al. (1998) report a mean temperature of 680 K (Apr. 97) for the dust using a Planck fit to SWS data. For a distance of 1.5 kpc (Kimeswenger & Kerber 1998; Kerber et al. 1999a), we derive a luminosity of 650 $L_\odot$ and a mass loss rate of 2.3 $\times 10^{-8}$ $M_\odot$/yr. For a distance of 5.5 kpc, these numbers are 8750 $L_\odot$ and 8.4 $\times 10^{-8}$ $M_\odot$/yr, respectively. These numbers assume a gas-to-dust ratio of 200 and an expansion velocity typical for AGB stars of 10 km s^{-1}. If the expansion velocity is larger (see below) the mass loss rate is larger by the same factor. The inner shell radius is 17.2 stellar radii (which follows from the effective temperature of the star and the dust condensation temperature), and the outer radius is 25 times the inner dust radius. The latter number is accurate to within a factor of 1.5. For a distance of 1.5 (5.5) kpc this implies that the dust has traveled about 7.2 (26.2) $\times 10^{14}$ cm from the star since the Helium flash occurred, assuming radial expansion. Normalized to a time-scale since the flash of two years, this implies a typical expansion velocity of 110 (420) km s^{-1} to within a factor of 1.5. This indicates an expansion velocity much higher than in AGB stars, but is quite similar to the velocity found for the ejecta in A 58 (Pollacco et al. 1992).

The fit to the Feb. 1998 data is less good, and required some fine-tuning. In the model shown the dust at the inner radius has a temperature of 875 K, and the (assumed constant) mass loss

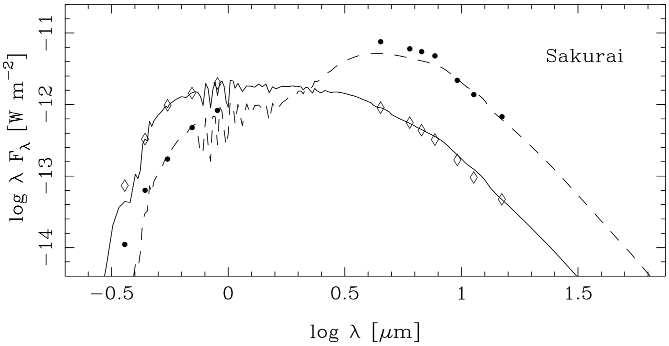

Fig. 2. ISOCAM photometry of Sakurai's object with a fit to the SED, February 1997 (solid line) and February 1998 (dashed line).

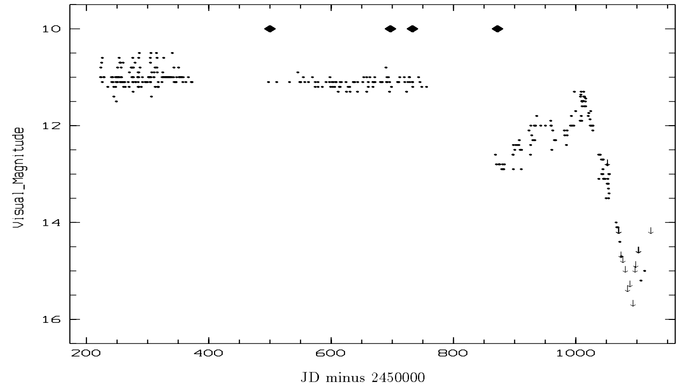

Fig. 3. Visual light curve of Sakurai's object (provided by the AAVSO). The arrows denote limits, while the solid diamonds represent the epochs of the four ISOCAM observations.

rate is 9.0 $\times 10^{-7}$ $M_{\odot}$/yr (3.3 $\times 10^{-6}$ $M_{\odot}$/yr for a distance of 5.5 kpc). There was no need to change the luminosity. Since we actually show that the mass loss rate has increased by a factor of 40 over a time-scale of a year, more sophisticated modeling should include a time-dependent mass loss rate. This is beyond the scope of the present paper. The fit to the ISO data can be improved by adopting a higher condensation temperature. The fit in the optical becomes much worse then, but one could then invoke non-spherical mass-loss, as seen in some of the other late He-flash objects (see next section). Mid-IR observations by Käufl & Stecklum (1998) from June 98 using TIMMI show more change indicating that the dust formation is time dependent.

Combining our near-IR observations and those reported by Kamath & Ashok (1999) a period of relative stability, lasting from late March to late May 97 seems to exist; that is exactly between two ISO epochs (Feb 97 and Sept 97) which show a strong increase in the mid-IR. It would be tempting to speculate that the rate of mass loss varies on rather short time scales of weeks or few months, but comparison of the two fits in Fig. 2 clearly show that the near-IR is the region of least change. Apparently the effects of dust formation and cooling counteract, making conclusions based on the near-IR alone very difficult.

The observed dimmings in the visual, - as the dust became optically thick - are therefore the direct consequence of this mass loss, see Fig. 3 for the light curve provided by the AAVSO (Mattei 1999). The observed light curve and physical mechanism resemble those of R CrB stars (Clayton 1996), which produce clouds of dust at irregular intervals, which only become (visually) apparent when blocking our line of sight. The lack of change in the visual between epochs 1 and 2, could then be interpreted as an indication of non-spherical mass loss as seen in R CrB stars.

4. Evolutionary status and outlook

In order to understand Sakurai's object it might be helpful to compare it to other objects that experienced a very late Helium flash. Given the small number of examples known and the dynamic nature of the flash only qualitative comparison can be made. Both A 30 and A 78 show extended second PNe, as result of a Helium flash thousands of years ago. Optical images taken with HST (Borkowski et al. 1993, 1995) beautifully demonstrate the knotty structure of this hydrogen-poor ejecta. In both cases the knots show "cometary" tails, signs of erosion of these knots by the fast wind of the central star, which has become hot again. They seem to form an equatorial disk with some polar knots also apparent. This is strong evidence that the matter lost in connection with the Helium flash was not ejected in a uniform shell. HST observations of V605 Aql/A58 reveal a very small (0.7 arcsec) inner knot (Bond et al. 1993; Clayton & de Marco 1997). For an ejection velocity of about 100 km s^{-1} (Pollacco et al. 1992) the observed size is in agreement with the matter being ejected in 1917 when the flash presumably happened. Using ISOCAM Kimeswenger et al. (1998) have been able to observe a hot dust component in both A 78 and A 58, thereby strengthening the connection between a very late Helium flash, mass loss and dust formation. With our ISO observations we have undoubtedly witnessed an episode of heavy mass loss associated with the very late Helium flash in Sakurai's object. The evolution of Sakurai's object is similar to the example set by V605 Aql in 1921 to 1924 based on the sketchy data we have for that event. It also developed molecular features in the spectrum a few years after the flash (Clayton & de Marco 1997). It has shown R CrB like dimmings while declining (Harrison 1996) and is now deeply enshrouded in an envelope of hot dust. Most recent (March and June 99) observations by Jacoby et al. (1999) and us find Sakurai at a V magnitude of 20 indicating that dust formation continues and might lead to a similarly "buried" star. One word of caution concerning the status of Sakurai's object in terms of stellar evolution seems to be in order. While Sakurai's object could definitely be called an R CrB star right now, the star it resembles most, V605 Aql is a very hot, possibly a WR-type, star today. In contrast the known R CrB stars show only limited evolution (e.g. shortening of pulsational period in RY Sgr, Kilkenny 1982).

5. Conclusions

Sakurai's object is undergoing a very late Helium shell flash, the first such event that can be observed with modern instrumentation. ISO has provided essential data through the monitoring (one full year) of the mid-IR region enabling us to demonstrate that significant mass loss is associated with such an event. We have found that the freshly formed dust cooled over time and derived a variable mass loss rate of a few 10^{-7} $M_{\odot}$/year, a typical value for AGB stars. This gives further credibility to the notion that final Helium flash stars return to the AGB retracing their own history (born-again scenario). Monitoring in all accessible wavelength regions will remain absolutely vital in order to follow the fast-paced evolution of the object. Ground-based infrared observations of Sakurai's object will be indispensible to record the evolution of the dust, even more so due to the current faintness in the optical. To improve quantitative insight more sophisticated modeling is required. One important improvement will be to take properly into account the dust chemistry and variable mass loss rate.

Acknowledgements. We thank the referee D. Pollacco for his valuable suggestions. The ISOCAM data presented in this paper was analysed using 'CIA', a joint development by the ESA Astrophysics Division and the ISOCAM Consortium. The ISOCAM Consortium is led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matière, C.E.A., France. In this research, we have used, and acknowledge with thanks, data from the AAVSO International Database, based on observations submitted to the AAVSO by variable star observers worldwide. We also acknowledge the use of the archive of the CADC. This work is supported by the Fonds zur Förderung der wissenschaftlichen Forschung (FWF), project P-11675.

References

Asplund, M., Gustafsson, B., Kiselman, D., Eriksson, K., 1997, A&A 318, 521
Asplund, M., Gustafsson, B., Lambert, D.L., Kameswara Rao, N., 1997, A&A 321, L 17
Asplund, M., Lambert, D.L., Kipper, T., Pollacco, D., Shetrone, M.D., 1999, A&A 343, 507
Blommaert, J., 1998, 1. Österreichischer ISO Workshop, eds. F. Kerber & J. Hron, p. 59
Bond, H.E., Meakes, M.G., Renzini, A., 1993, in Planetary Nebulae, IAU Symp. 155, eds. R. Weinberger and A. Acker (Kluwer, Dortrecht), p.499
Borkowski, K.J., Harrington, J.P., Tsvetanov, Z.I., Clegg, R.E.S., 1993, ApJ 415, L47
Borkowski, K.J., Harrington, J.P., Tsvetanov, Z.I., 1995, ApJ 449, L143
Cesarsky, C.J., Abergel, A., Agneŝe P., et al., 1996, A&A 315, L32
Clayton, G.C., 1996, PASP 108, 225
Clayton, G.C., de Marco, O., 1997, AJ 114, 2679
Duerbeck, H.W., Benetti, S., 1996, ApJ 468, L 111
Duerbeck, H.W., Benetti, S., Gautschy, A. et al., 1997, AJ 114, 1657
Eyres, S.P.S., Evans, A., Geballe, T.R., Salama, A., Smalley, B., 1998, MNRAS 298, L37
Fluks, M.A., Plez, B., The, P.S., de Winter, D., Westerlund, B.E., Steenham, H.C., 1994, A&AS 105, 311
Gillett, F.C., Jacoby, G.H., Joyce, R.R., el al., 1989, ApJ 338, 862
Groenewegen, M.A.T., 1993, Chapter 5, Ph.D. thesis, University of Amsterdam
Harrington, P.J., 1996, ASP Conference Ser. 96, Hydrogen-Deficient Stars, C.S., Jeffery and U. Heber (eds.), p.193
Harrison, T.E., 1996, PASP 108, 1112
Hazard, C., Terlevich, R., Morton, D.C., Sargent, W.L.W., Ferland, G., 1980, Nature 285, 463
Iben, I., Kaler, J.B., Truran, J.W., Renzini, A., 1983, ApJ 265, 605
Jacoby, G.H., Ford, H.C., 1983, ApJ 266, 298
Jacoby, G.H., Ciardullo, R., Feldmeier, J., Hinkle, K., Joyce, R., 1999, IAU Circ. 7155
Käufl, H.U., Stecklum, B., 1998, IAU Circ. 6938
Kamath, U.S., Ashok, N.M., 1999, MNRAS 302, 512
Kerber, F., Köppen, J., Roth, M., Trager, S.C., 1999a, A&A 344, L79
Kerber, F., Blommaert, J.D.A.L., Kimeswenger, S., Groenewegen, M.A.T., Käufl, H.U., 1999b, ISO's View on the Universe, Cox P. Kessler M. (eds.), in press
Kerber, F., Gratl, H., Kimeswenger, S., 1997, IAU Circ. 6601
Kessler, M.F., et al., 1996, A&A 315, L27
Kilkenny, D., 1982, MNRAS 200, 1019
Kimeswenger, S., Kerber, F., 1998, A&A 330, L 41
Kimeswenger, S., Kerber, F., Weinberger, R., 1998, MNRAS 296, 614
Kimeswenger, S., Gratl, H., Kerber, F., Fouqué, P., Kohle, S., Steele, S., 1997, IAU Circ. 6608
Liller, W., Janson, M., Duerbeck, H.W., van Genderen, A., 1998, IAU Circ. 6825
Mattei, J.A., 1999, Observations from the AAVSO International Database, private communication
Manchado, A., Garcia-Lario, P., Pottasch, S.R., 1989, A&A 218, 267
Ott, S., Abergel, A.,Altieri, B. et al., 1997, ASP Conference Series, Vol. 125, 34
Pollacco, D., Lawson, W.A., Clegg, R.E.S., Hill, P.W., 1992, MNRAS 257, 33p
Pollacco, D., 1999, MNRAS 304, 127
Rouleau, F., Martin, P.G., 1991, ApJ 377, 526
Seitter, W.C., 1987, ESO Messenger 50, 14