The *Spitzer* Infrared Spectrometer view of V4334 Sgr (Sakurai’s Object)

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ABSTRACT

We present an observation of the very late thermal pulse object V4334 Sgr (Sakurai’s Object) with the Infrared Spectrometer (IRS) on the *Spitzer Space Telescope*. The emission from 5–38 μm is dominated by the still-cooling dust shell. A number of features are seen in absorption against the dust shell, which we attribute to HCN and polyyne molecules. We use these features to determine the 12C/13C ratio for the absorbing gas to be \( \sim 3.2^{+1.2}_{-1.0} \); this implies that, despite the H-content of the molecules, the hydrocarbon-bearing gas must have originated in material produced in the very late thermal pulse. We see no evidence of emission lines, despite the recently-reported optical and radio observations that suggest the effective temperature of the stellar remnant is rising.

Key words: stars; carbon – circumstellar matter – stars: evolution – stars: individual: V4334 Sgr – stars: individual: Sakurai’s Object – stars: mass-loss.

1 INTRODUCTION

V4334 Sgr (Sakurai’s Object) is a low-mass (\( \sim 0.5 \, M_\odot \)) star that is retraceing its post-asymptotic giant branch (AGB) evolution along the Hertzsprung–Russell diagram following a very late thermal pulse (VLTP) (Herwig 2001). The star was discovered in early 1996 (Nakano, Benetti & Duerbeck 1996), and was found to be at the centre of a faint planetary nebula (PN) of diameter 40 arcsec (e.g. Pollacco 1999). It first appeared as an F supergiant, possibly with a hot dust shell (Duerbeck & Benetti 1996).

Analysis of the optical spectrum for mid-1996 by Asplund et al. (1999) revealed that Sakurai’s Object had undergone a transformation to a hydrogen-deficient, carbon-rich star and that the elemental abundances of a range of species were close to those found in the R CrB stars. They also used the C2 (1–0) and (0–1) Swan bands at 4740 and 5635 Å, respectively, to determine that the 12C/13C ratio was in the range 1.5–5. Pavlenko et al. (2004) used the first-overtone CO bands to determine that the 12C/13C ratio was 4 ± 1. This is substantially less than the value in (for example) the Solar System (12C/13C = 70; Mathis 2000) and likely arises from second stage CNO cycling following He burning in the VLTP (Asplund et al. 1999).

In 1998, Sakurai’s Object was completely obscured by an optically thick dust shell from which (as of 2005 December) it has still not emerged. Indeed analysis of the infrared (IR) spectrum showed that dust emission has being making an increasing contribution to the IR emission since 1997 April (Pavlenko & Geballe 2002). Since the major dust event of 1998, the 1–5 μm spectrum is blackbody-like and is that of the ejected dust shell. Analysis of the post-1998 IR observations has shown that the dust is carbon, primarily in amorphous form (Tyne et al. 2002; Eyres et al. 2004). The 1–5 μm spectra during the period 1999–2001 were consistent with mass loss that increased from \( \sim 0.5 \times 10^{-5} \, M_\odot \, yr^{-1} \) to \( \sim 1.2 \times 10^{-5} \, M_\odot \, yr^{-1} \) for a gas-to-dust ratio 200, appropriate for solar abundances (note that a lower gas-to-dust ratio of 75 was suggested by Evans et al. (2004) for the hydrogen-deficient, carbon-rich wind of Sakurai’s Object). The maximum grain radius (in a grain size distribution \( n(a) \propto a^{-q} \, d \, a \), with \( q \approx 3 \)) increased by a factor \( \sim 3 \) (Tyne et al. 2002).

Submillimetre observations (Evans et al. 2004) show that the flux density at 450 and 850 μm was still rising in 2003, indicating that the mass loss was being maintained; the spectral energy distribution (SED) resembled a blackbody at 360 K.
Observations of N\,Ⅱ\,λ6548, 6583 and O\,Ⅱ\,λ7325 in the spectrum of Sakurai’s Object in 2002 (Kerber, Pirzkal & Rosa 2002) hinted that the stellar temperature had increased from \(\sim 5,500\) K in 1997 to \(\gtrsim 20,000\) K. The reheating seems to be confirmed by recent observations at 8.6 GHz with the Very Large Array (VLA; Hajduk et al. 2005), which detected free–free emission from the newly ionized gas.

We describe here observations of Sakurai’s Object with the Infrared Spectrometer (IRS) (Houck et al. 2004) on the Spitzer Space Telescope (Werner et al. 2003).

2 OBSERVATIONS

Sakurai’s Object was observed in STARE mode with the IRS on 2005 April 15 UT (PID 03362; AOR Key 10840320). Spectra were obtained with both low- and high-resolution modes, covering the spectral range of 5–38\,\mu m, and the RED peak-up array used to precisely centre the object in the IRS slits. We executed five 6-s ramps for a total observation time (including overheads) of 1042.6 s. The spectra in the wavelength range \(\sim 5.1–8.2\)\,\mu m were saturated and are not presented here. The spectrum was extracted from the version 12.3 processed pipeline data product using SPICE version 1.1 (Spice 2005). High-resolution segments were stitched together without any continuum normalization.

3 DISCUSSION

3.1 The continuum

The dust shell, which condensed and became optically thick in 1998 (Duerbeck 2002) still dominates the IR SED from 5–38\,\mu m, covering the wavelength range \(\sim 5.1–8.2\)\,\mu m (see Fig. 1a). Much of the scatter in the data in Fig. 1a consists of low-level features superimposed on the dust continuum (see Fig. 1b), and will be discussed in detail in a future paper. The depression in the SED around 13\,\mu m is due to the superposition of many ro-vibrational bands of hydrocarbon molecules (see Section 3.2.1 below).

We compare the Spitzer IRS spectrum with data obtained with the United Kingdom Infrared Telescope (UKIRT) and the James Clerk Maxwell Telescope (JCMT) (from Evans et al. 2004) in Fig. 2. Compared with the 2003 SED the peak emission has clearly shifted to longer wavelengths and the peak flux density has increased in 2005.

The cooling of the dust shell since 2003. The solid curve labelled ‘Spitzer’ is a fit to UKIRT (squares in the range 1–5\,\mu m) and JCMT (squares at 450 and 850\,\mu m) data obtained in 2003 (Evans et al. 2004); data labelled ‘Spitzer’ are reported here.

peaks at \(\lambda_{\text{max}} \sim 11.3\,\mu m\), implying a temperature for the dust ‘photosphere’ of \(\sim 210\) K if the (carbon) dust is amorphous with \(\beta \sim 1\) (where the \(\beta\)-index is defined such that the emissivity is \(\propto \nu^{\beta}\)), or is \(\sim 180\) K if the dust is graphic (\(\beta \simeq 2\)).

The integrated flux is \(1.77 \times 10^{-11}\,W\,m^{-2}\), yielding a bolometric luminosity \(L_\ast = 2 \times 10^3\,L_\odot\), for a distance of 1.9 kpc (Kimeswenger 2002). As the dust shell is still optically thick at short wavelengths, this radiation is effectively reprocessed stellar radiation and, assuming that there are no ‘holes’ in the dust distribution (see Section 4.1), a measure of the star’s bolometric luminosity. This is somewhat lower than the last reported \(L_\ast\) in Tyne et al. (2002), who found \(L_\ast = 4.47 \times 10^3\,L_\odot\). The modest decline in \(L_\ast\), accompanied by the reported rise in \(T_\ast\), is consistent with the evolution of Sakurai’s Object as predicted by Hajduk et al. (2005).

From the IRS spectrum, the ‘blackbody’ angular diameter (Gallagher & Ney 1976) was 85\,mas at the time of our observation, while that deduced from the 2003 UKIRT/JCMT data is 55\,mas. In Fig. 3 we plot the blackbody angular diameter as a function of time; earlier values are taken from the data of Tyne et al. (2002). The angular diameter data are consistent with linear expansion of the dust photosphere at the rate 0.0293 mas d\(^{-1}\), with the expansion starting at JD 2450763 (1997 November 10). Comparison with the visual light curve in Tyne et al. (2002) shows that this epoch coincides closely with the time when the light curve began its deep minimum (between JD 2450760 and JD 2450850, i.e., between 1997 November 7 and 1998 February 5).

Figure 1. (a) The Spitzer IRS spectrum of Sakurai’s Object in 2005. The curve is a dusty fit to the data; see text for details. (b) Detail in the spectrum in the wavelength range 12.5–16.5\,\mu m, plotted as \(\lambda^2 f_\lambda\) to emphasize the depression (which is indicated by horizontal line) around 13\,\mu m; much of the scatter is real, arising in ro-vibrational bands of the identified molecules.

Figure 2. The cooling of the dust shell since 2003. The solid curve labelled ‘360 K BB’ is a fit to UKIRT (squares in the range 1–5\,\mu m) and JCMT (squares at 450 and 850\,\mu m) data obtained in 2003 (Evans et al. 2004); data labelled ‘Spitzer’ are reported here.

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We fit the Spitzer dust SED using the dusty code (Ivezić & Elitzur 1999) with the downhill simplex routine we used to fit the 1–5 μm data for Sakurai's Object (Tyne et al. 2002), assuming a stellar temperature of 35 000 K (Kerber et al. 2002; Hajduk et al. 2005). We solve for visual optical depth (τv), graphitic carbon fraction f, maximum (a max) and minimum (a min) grain size in a distribution n(a) d a ∝ a−q d a, the exponent q, the temperature T1 at the inner radius r1, the radius of the star, and the ratio r1/R∗, where R∗ is the stellar radius. The fit is included in Fig. 1 and the derived parameters are listed in Table 1. For comparison, Table 1 also includes the corresponding parameters for the Dusty fit to the 2001 September 8 UKIRT data (Tyne et al. 2002).

There have been clear changes in the values of f, T1 and a max since 2001. While the change in f implies conversion of graphitic to amorphous carbon we should not, as noted by Tyne et al. (2002), interpret this change too literally as DUSTY computes average optical constants for a grain mix. The decrease in a max (Table 1) does however support our contention that a significant change in the character of both the dust mix and distribution has occurred since 2001. Some processing of the dust has undoubtedly taken place, possibly a result of the grains' exposure to the hardening radiation field (Kerber et al. 2002; Hajduk et al. 2005); similar changes are seen in the newly-condensed carbon dust around erupting novae (Gehrz et al. 1998).

Given the observed increase in the effective temperature of the star (Kerber et al. 2002; Hajduk et al. 2005), the change in T1 may imply that the inner boundary of the dust shell is receding from the stellar remnant, and that the condensation of new dust has ceased. If Lν were constant, then r1 ∝ T 1/2, implying (for no change in dust absorptivity) a ~4.5-fold increase in r1 since 2001. Note also the large increase in r1/R∗, in line with the rise in r1 and the decline in R∗, as the effective temperature of the star increases.

The increase in r1 is strong indication that the mass-loss rate (as measured by the dust) has declined since 2001. If this is the case then it augurs well for the dispersal of the dust and the imminent reappearance of the stellar remnant as the dust disperses. However, in view of the way in which DUSTY treats optical constants in a grain mix we again caution against overinterpretation of the results, other than to note the persistent decrease in T1, and the persistent rise in r1, since late 1997.

### 3.2 Spectral features

#### 3.2.1 Absorption features

The SED is far from smooth over the entire IRS wavelength range. There are several obvious absorption features superimposed on the dust continuum, at 13.688, 14.025, 14.135, 15.079, 15.918 and 16.085 μm (see Fig. 1b). The only plausible identifications for these features (see Table 2) are H12CN, H13CN, HC3N, and the carbon chain molecules (polyynes) acetylene (C2H2), diacetylene (HC4H) and triacetylene (HC6H).

We use the HCN features to estimate the columns of H12CN and H13CN and the temperature of the absorbing material. For H12CN we take Einstein coefficients and other relevant data from Harris, Polansky & Tennyson (2002), and partition functions from Barber, Harris & Tennyson (2002); the corresponding quantities for H13CN were kindly provided by Dr G. Harris (private communication). The optical depth in the HCN features was determined relative to a local continuum in the 13–17 μm wavelength region.

We consider an elementary model in which the absorbing gas is homogeneous and isothermal and located in front of the dust shell; each HCN transition is assumed to have intrinsic width 10 cm−1 (~2 × 10−5 μm) and broadened by a Gaussian having width corresponding to the resolution of the IRS. The column density temperature (N, T) parameter space was searched, independently for H12CN and H13CN, to find the best fit; we find (see Fig. 4)

\[
N_1 = 1.18^{+0.53 \times 10^{17}} \text{ cm}^{-2}, \quad T = 400 \pm 100 \text{ K} (\text{H}12\text{CN})
\]

and

\[
N_2 = 5.35^{+2.06 \times 10^{16}} \text{ cm}^{-2}, \quad T = 500 \pm 100 \text{ K} (\text{H}13\text{CN})
\]

The greatest uncertainty is in the column rather than temperature; the line profile is sensitive to the latter, while the former is more

### Table 2. Absorption features in Sakurai's Object; identifications from (Aoki, Tsuji & Ohnaka 1999) and (Cernicharo et al. 2001).

| λ (μm) | ID | Band | λ (μm) |
|------|----|--------|------|
| 13.688 | C2H2 | ν3 Q branch | 14.025 |
| 14.135 | H12CN | 2v2 1−v1 1 | 14.00 |
| 15.079 | HC3N | ν9 | 14.1605 |
| 15.918 | HC3H | ν9 | 15.926 |
| 16.085 | HC4H | ν9 | 16.067 |
| 16.095 | HC6H | ν11 | 16.095 |

### Table 1. Dust shell parameters for Sakurai's Object. T∗ is the stellar temperature assumed for the Dusty fit, r1 is the inner radius of the dust shell, R∗ is the radius of the star, τv is the visual optical depth through the dust shell, f is the graphitic carbon fraction, a min and a max are respectively the minimum and maximum grain radius, q is the exponent in the grain size distribution and T1 is the dust temperature at r1.

| Facility | UT Date | T∗ (K) | r1 (1014 cm) | r1/R∗ | τv | f | a min (μm) | a max (μm) | q | T1 (K) |
|----------|---------|-------|-------------|--------|-----|---|---------|---------|---|-------|
| UKIRT    | 2001-Sep-08 | 5 200 | 3.33 ± 1.2 | 57.9 ± 3 | 8.9 ± 0.3 | 0.80 ± 0.06 | 0.012 | 2.84 | 3.07 ± 0.09 | 854 ± 25 |
| Spitzer  | 2005-Apr-15 | 35 000 | 25.7 ± 0.5 | 13.4 × 103 | 8.8 ± 0.2 | 0.54 ± 0.02 | 0.005 | 2.00 | 2.9 ± 0.1 | 407 ± 10 |
Figure 4. Fit to the HCN and C₂H₂ features. Solid line, observed optical depth in HCN and C₂H₂ lines; broken line, optical depth for column density $N = 1.42 \times 10^{17}$ cm$^{-2}$ (H$_2$CN), $4.51 \times 10^{16}$ cm$^{-2}$ (H$_3$CN) and $9.0 \times 10^{17}$ cm$^{-2}$ (C$_2$H$_2$), and gas temperature 450 K. See text for details.

sensitive to the placement of the continuum. We do not expect the temperatures of the H$^{12}$CN and H$^{13}$CN regions to differ, and the above values of $T$ are consistent within the errors. For the purpose of discussion we take $T = 450$ K, for which $N = 1.42 \times 10^{17}$ cm$^{-2}$ (H$^{12}$CN) and $N = 4.51 \times 10^{16}$ cm$^{-2}$ (H$^{13}$CN; see Fig. 4). This immediately gives us the $^{12}$C/$^{13}$C ratio as $\sim 3.2^{+1.3}_{-1.2}$, consistent with the value $4 \pm 1$ obtained by Pavlenko et al. (2004) from fitting the first overtone CO bands in the near-IR, and with the VLT interpretation of Sakurai’s Object.

We note that the $\nu_3$ band of $^{13}$C$^{12}$CH$_2$ is blended with the corresponding $\nu_3$ band of $^{12}$C$^{12}$H$_2$ (Cernicharo et al. 1999) and, at the resolution of the Spitzer IRS, cannot be used to provide an alternative estimate of the $^{12}$C/$^{13}$C ratio. Similarly, we do not expect to see the effect of $^{12}$C $\rightarrow$ $^{13}$C substitution in the polyynes in our data. However, for $T = 450$ K and assuming the $^{12}$C/$^{13}$C ratio deduced from the HCN lines, the column density for C$_2$H$_2$ is $9.0 \times 10^{17}$ cm$^{-2}$, where we have taken partition functions from Gamache, Hawkins & Rothman (1990) and spectroscopic data from the HITRAN data base (Rothman et al. 1998).

3.2.2 Emission features

In view of the increased temperature of the stellar remnant (Kerber et al. 2002; Hajduk et al. 2005) we expect the appearance of IR fine structure lines as the wind is ionized. In the case of V605 Aql, which is $\sim 100$ yr ahead of Sakurai’s Object in its evolution, we clearly see Ne ii $\lambda 12.8$ μm (line flux $6.0 \times 10^{-17}$ W m$^{-2}$) and Ne iii $\lambda 15.5$ μm ($2.6 \times 10^{-16}$ W m$^{-2}$) in the Spitzer IRS spectrum, although the dust shell is clearly much cooler (see Fig. 5). However, there is no evidence for the presence of these emission lines in the Spitzer spectrum of Sakurai’s Object, to a limit of $3 \times 10^{-16}$ W m$^{-2}$ for both Ne ii and Ne iii, that we can attribute to increased ionization of the ejected gas as the effective temperature of the star increases.

4 DISCUSSION

4.1 The HCN features

The temperature of the dust ‘photosphere’ is $\sim 200$ K (see Section 3.1), so we seem to have the unphysical situation that the temperature of the absorbing gas ($\sim 450$ K) is greater than that of the dust. Cernicharo et al. (1999) note that the 14-μm HCN feature can appear in emission if the HCN-bearing material is close to the star.

The fact that it is in absorption in Sakurai’s Object indicates that this material is unlikely to be close to the star, while the kinetic temperature of 450 K indicates heating by ultraviolet photons in a thin layer of gas. For this to occur the radiation must penetrate the optically thick dust shell, which is possible only if the dust distribution has strong asymmetry.

The HCN column is $\sim 10^{17}$ cm$^{-2}$, but his should be regarded as a lower limit because, as noted above, the geometry of the dust and HCN is likely to be more complex than we have assumed here. Indeed, high-resolution IR spectroscopy (Tyne et al. 2000) around the He $\lambda 1.083$ line suggests that the distribution of matter in the outflow from Sakurai’s Object is not spherically symmetric, as our DUSTY modelling has assumed (again underlining that the dust properties and distribution are not well known). Rather the dust may be distributed in an equatorial ‘torus’, to which the He and HCN ‘wind’ is orthogonal. Although the Spitzer IRS does not give sufficient spectral resolution to determine a doppler shift for HCN, in the case of the He $\lambda 1.083$ line there is clear evidence of outflow. Tyne et al. (2000) found outflows with $\sim 600$ km s$^{-1}$.

However, the deduced $^{12}$C/$^{13}$C ratio should be relatively insensitive to the geometry.

4.2 The H-deficient wind

It is remarkable that the H-deficient, carbon-rich Sakurai’s Object should display absorption lines of H-containing species. The presence of H-bearing molecules in the Spitzer IRS spectra (Fig. 1b) might imply that these features form from material ejected by Sakurai’s Object prior to its current hydrogen-deficient state. However the $^{12}$C/$^{13}$C ratio clearly demonstrates that the absorbing material must be a product of the VLTP.

It is therefore of interest to consider the origin of these species. In the case of IRC+10 216, the proto-typical carbon-rich post-AGB star, chemistry takes place in the photo-chemistry zone and polynyes are produced via the reactions:

$$C_2H + C_2H_2 \rightarrow C_{n+2}H_2 + H$$

(Millar, Herbst & Bettens 2000). This requires the presence of C$_2$H, which is formed from C$_2$H$_2$ by photodissociation, i.e. polynyes do not form before C$_2$H$_2$ is present. Cernicharo (2004) has shown, in the context of the proto-planetary nebula CRL618, that carbon-rich molecules are formed in the presence of a strong photodissociating radiation field.

It generally seems the case therefore that the chemistry leading to these species requires the presence of radiation. Such an
environment might exist in the case of Sakurai’s Object along the ‘wind’ axis postulated in Section 4.1. However whether the chemistry that led to the hydrocarbons we see in Sakurai’s Object is a relatively recent phenomenon, or whether it is the result of earlier chemical processes whose products have been ‘frozen in’ is unclear.

5 CONCLUSIONS

We have reported an observation of V4334 Sgr (Sakurai’s Object) with the Spitzer IRS. We find that the IR SED is dominated by the optically thick dust shell that still enshrouds the stellar remnant. The dust shell ‘photosphere’ has a temperature $\sim 200$ K, while the temperature of the inner dust shell is inferred to be $\sim 400$ K. There is evidence that the condensation of new dust has ceased, and that the character of the dust has changed since 2001.

There are several prominent absorption features, which we attribute to HCN, acetylene and polynyes. The $^{12}$C/$^{13}$C ratio is $\sim 3$; this is substantially smaller than the Solar System value ($\sim 70$) and is consistent with (a) the CNO cycling following the VLTP, and (b) the value obtained from the IR first overtone CO bands.

We see no evidence for the presence of emission lines (such as Ne II $\lambda 12.8 \mu m$, Ne III $\lambda 15.5 \mu m$) that would be a signature of the anticipated increased $T_{\text{eff}}$ of the star.

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