The sub-millimetre evolution of V4334 Sgr (Sakurai’s Object)

A. Evans\textsuperscript{1}, T. R. Geballe\textsuperscript{2}, V. H. Tyne\textsuperscript{1}, D. Pollacco\textsuperscript{3}, S. P. S. Eyres\textsuperscript{4}, B. Smalley\textsuperscript{1}

\textsuperscript{1}Department of Physics, Keele University, Keele, Staffordshire, ST5 5BG
\textsuperscript{2}Gemini Observatory, 670 N. A’ohoku Place, Hilo, HI 96720
\textsuperscript{3}Department of Pure & Applied Physics, Queen’s University of Belfast, Belfast, BT7 1NN
\textsuperscript{4}Centre for Astrophysics, University of Central Lancashire, Preston, PR1 2HE

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ABSTRACT

We report the results of monitoring of V4334 Sgr (Sakurai’s Object) at 450\,\mu m and 850\,\mu m with \textsc{scuba} on the James Clerk Maxwell Telescope. The flux density at both wavelengths has increased dramatically since 2001, and is consistent with continued cooling of the dust shell in which Sakurai’s Object is still enshrouded, and which still dominates the near-infrared emission. Assuming that the dust shell is optically thin at sub-millimetre wavelengths and optically thick in the near-infrared, the sub-millimetre data imply a mass-loss rate during 2003 of \( \sim 3.4 \pm 0.2 \times 10^{-5} \, \text{M}_\odot \, \text{yr}^{-1} \) for a gas-to-dust ratio of 75. This is consistent with the evidence from 1–5\,\mu m observations that the mass-loss is steadily increasing.

Key words: stars, individual: V4334 Sgr – stars, individual: Sakurai’s Object – stars: evolution

1 INTRODUCTION

V4334 Sgr (Sakurai’s Object) continues to be the subject of intense interest. It is a low-mass (\(< 0.7 \, \text{M}_\odot \)) star that is re-tracing its evolution along the Hertzsprung-Russell diagram following a very late thermal pulse (Herwig 2001). The star is at the centre of a faint planetary nebula (PN) of diameter 40′ (e.g. Pollacco 1999; Bond & Pollacco 2002) and, after an early incarnation as an F-type star, it underwent a transformation to a carbon star in 1997.

Little is known observationally about the evolution of the star since mid-1998, when it was completely obscured by an optically thick dust shell from which (as of April 2004) it has still not emerged; a dramatic illustration of the obscuration is given by Bond & Pollacco (2002). Since the major dust event of 1998 the 1–5\,\mu m spectrum is black-body-like and is simply that of the dust shell. Analysis of the post-1998 infrared (IR) observations has shown that the dust is carbon, primarily in amorphous form (Geballe et al. 2002; Tyne et al. 2002; Eyres et al., in preparation). The 1–5\,\mu m spectra during the period 1999-2001 were consistent with a mass-loss that increased from \( \sim 1.8 \times 10^{-6} \, \text{M}_\odot \, \text{yr}^{-1} \) to \( \sim 4.4 \times 10^{-6} \, \text{M}_\odot \, \text{yr}^{-1} \) (for the gas-to-dust ratio of 75 we adopt here; see §3 below), while the maximum grain radius in a grain size distribution \( n(a) \, da \propto a^{-q} \, da \) (\( q \approx 3 \)) increased by a factor \( \sim 3 \) (Tyne et al. 2002).

We first observed V4334 Sgr at sub-millimetre wave-lengths with the \textsc{scuba} instrument (Holland et al. 1999) on the 15-m James Clerk Maxwell Telescope (JCMT) in 2001 August, and reported marginal detections at both 450\,\mu m and 850\,\mu m (Evans et al. 2002, hereafter Paper I).

We report here the results of our continued monitoring of Sakurai’s Object at these wavelengths.

2 OBSERVATIONS AND DATA REDUCTION

We have observed Sakurai’s Object on the dates given in Table 1, in which we include our 2001 August observation from Paper I. On each occasion atmospheric extinction was regularly monitored by taking skydip measurements, and pointing sources in the observatory catalogue were used to check telescope pointing and focussing; Uranus and Mars were used as calibrators. The beamwidths at 450\,\mu m and 850\,\mu m are 7′′ and 14′′ respectively.

\textsc{scuba} was used in \textsc{photometry} mode, which provides simultaneous observations at 450\,\mu m and 850\,\mu m; the observations were carried out in good (sub-millimetre) weather conditions to ensure that data at both 450\,\mu m and 850\,\mu m were obtained. However, as is well-known (Holland et al. 1999), radiation at the shorter wavelength is severely affected by atmospheric water vapour, and hence detection and calibration is always more problematic at 450\,\mu m even when weather conditions are favourable. The observations...
consisted of 2 (or 4) sets of 50 integrations, to give total on-source integration time of 30 (or 60) minutes. First order sky subtraction was achieved by chopping 60$''$ in azimuth.

The data were reduced using the surf package (Jeness & Lightfoot 2000). The frames were flat-fielded and corrected for atmospheric extinction, and the outer bolometers in the array were used for second order sky subtraction; ‘spikes’ in the data were clipped to remove any points further than 3$\sigma$ from the mean. The flux conversion factors at 850$\mu$m and 450$\mu$m, together with the detection levels (the signal-to-noise ratios in the measured signal) for Sakurai’s Object are listed in Table 1.

Sakurai’s Object was strongly detected at both 450$\mu$m and 850$\mu$m, and the flux densities $f_\nu$ are listed in Table 1. As usual, a significant fraction of the uncertainty in the flux densities for Sakurai’s Object listed in Table 1 arises from the uncertainty in the flux calibration, particularly at 450$\mu$m. In the Table the flux errors include both statistical errors and calibration uncertainties. The measurement at 450$\mu$m for 2003 June 16 is marginal and is not used in what follows.

3 DISCUSSION

The 450$\mu$m and 850$\mu$m light curves are shown in Fig. 1. We see a consistent and significant rise in the 850$\mu$m flux density between 2001 August and 2003 September; the behaviour of the 450$\mu$m data is consistent with the rise at 850$\mu$m, but of course the 450$\mu$m calibration is less certain. In Paper I we considered the possibility that the 450/840$\mu$m emission detected in 2001 August might have originated in the old PN but we concluded that the emission originated in material ejected in the 1995 event. The fact that the sub-millimetre flux densities rise so dramatically is consistent with this conclusion.

We first note that the sub-millimetre data may imply a drop in the $\beta$-index of the dust (defined in the usual way such that the dust emissivity at frequency $\nu$ is $\propto \nu^\beta$), from $\sim 1.5$ in 2001 August to $\sim 0$ in 2003. This may indicate changes in (a) the nature of the dust (e.g. as grains grow, or are processed) and/or (b) the dust distribution, allowing hotter grains (which have flatter emissivities, cf. Mennella et al. 1998) to contribute more to the observed flux. However any conclusion along these lines must await detailed modelling combining both UKIRT (e.g. Tyne et al. 2002, Eyres et al., in preparation) and JCMT datasets; such an analysis will be reported elsewhere.

The referee has pointed out that the sub-millimetre rise could be due to the anticipated rise in effective temperature as the star retraces its post-AGB evolution towards the PN phase, and the consequent heating of the inner dust shell. While observational evidence that this process may have started has been presented by Kerber et al. (2002), we do not consider that this accounts for the rise in the sub-millimetre flux for reasons which may be discerned from Fig. 2.

In this Figure we plot the JCMT data from 15 June 2003 (Table 1), together with the 2–5$\mu$m data obtained in September 2003 from our UKIRT programme (Eyres et al., in preparation); we assume that variations are sufficiently slow that the data can be combined. Both sets of data are reasonably fitted by a $\sim 360 \pm 10$ K black-body (cf. Equation (2) below, and 350 $\pm 30$ K for the UKIRT data alone; Eyres et al. 2004), suggesting that the 2–5$\mu$m and sub-millimetre emission have common origin.

We might envisage a scenario in which the sub-millimetre emission in Fig. 2 comes from inner, hotter, dust whose near-IR emission does not penetrate the outer region.

### Table 1. Sub-millimetre flux densities $f_\nu$ of V4334 Sgr. Errors are 1$\sigma$.

| Date MJD | FCF (mJy mV$^{-1}$) | $f_\nu$(450$\mu$m) (mJy) | Detection level ($\sigma$) | $f_\nu$(850$\mu$m) (mJy) | Detection level ($\sigma$) | Comment |
|----------|---------------------|--------------------------|--------------------------|--------------------------|--------------------------|---------|
| 18/08/2001 | 2140 | 309 $\pm$ 72 | 219 $\pm$ 30 | 96.6 $\pm$ 37.5 | 3.2 | 10.6 $\pm$ 3.4 | 3.5 | Paper I |
| 09/01/2003 | 2649 | 378 $\pm$ 49 | 193 $\pm$ 5 | 55.2 $\pm$ 14.9 | 4.2 | 35.7 $\pm$ 2.4 | 17 |
| 05/05/2003 | 2765 | 322 $\pm$ 3 | 202 $\pm$ 1 | 157.6 $\pm$ 25.8 | 4.1 | 52.1 $\pm$ 2.7 | 20 |
| 15/06/2003 | 2806 | 440 $\pm$ 5 | 217 $\pm$ 2 | 213.2 $\pm$ 29.1 | 7.4 | 61.3 $\pm$ 2.9 | 28 |
| 16/06/2003 | 2807 | 401 $\pm$ 2 | 213 $\pm$ 1 | 113 $\pm$ 41 | 2.8 | 58.3 $\pm$ 3.2 | 18 |

**Figure 1.** The 450$\mu$m (left) and 850$\mu$m (right) light curves of Sakurai’s Object.
of the dust shell, while the observed near-IR emission comes from dust in the outer shell having very steep $\beta$-index. However such a situation would be ad hoc and contrived. Indeed that the $\beta$-index is close to zero in late 2003 is supported both by the 450/850 flux ratio, and by the closeness of the 2–850 $\mu$m data to a black-body at $\sim 360$ K (see Fig. 2).

We therefore make the assumptions that (i) the emission we detect at 450 $\mu$m and 850 $\mu$m is from the dust shell (any emission at these wavelengths from the star – whatever its effective temperature – is at the few $\mu$Jy level at most), (ii) the dust shell is optically thin at sub-millimetre wavelengths and (iii) the sub-millimetre emission is on the Rayleigh-Jeans tail.

We justify (ii) by noting that the optical depth $\tau$ at wavelength $\lambda$ (in $\mu$m) is $\sim 0.55 \tau(0.55/\lambda) \ll 1$, since the optical depth in the visual is $\sim 10$ (see Tyne et al. 2002), and (iii) is valid if the dust temperature is $\gtrsim 200–300$ K. Eyres et al. (2004) find that a 1–5 $\mu$m spectrum of Sakurai’s Object obtained on 2003 September 8 is well-described by a black-body at temperature $\sim 350\pm30$ K, consistent with continued cooling of the dust shell; thus (iii) is certainly justified. We therefore have that

$$M_d T_d = \frac{f_\nu D^2 \lambda^2}{2\gamma \kappa K},$$

$$\simeq \frac{A}{\gamma} \left( \frac{f_\nu}{\text{mJy}} \frac{D}{2 \text{kpc}} \right)^2 M_\odot \text{ K},$$

(1)

where the constant $A = 9.60 \times 10^{-7}$ for 450 $\mu$m, and $6.23 \times 10^{-6}$ for 850 $\mu$m. In Equation (1) $M_d$ is the dust mass, $D$ is the distance of Sakurai’s Object (see Kimeswenger 2002), $T_d$ is an appropriate value for the dust temperature (see below), $\kappa$ is the absorption coefficient for the dust, and $\gamma$ depends on physical conditions in the dust shell (e.g. $\gamma \equiv 1$ for an optically thin, isothermal shell).

Although Equation (1) applies to an optically thin, isothermal shell, it is also accurate, to within a factor $\simeq 2/(1 + (R_i/R_o)^{1/2}) \leq 2$ (where $R_i, R_o$ are respectively the inner and outer radii of the dust shell), to the case of a dust shell with grain density law $n(r) \propto r^{-2}$ that is optically thick at short ($\sim$ optical/near-IR) wavelengths, optically thin in the sub-millimetre, and for which the dust temperature depends on distance $r$ from the star as $T_d \propto r^{-1/2}$ (see Ivezić & Elitzur 1997). In this case $T_d$ in Equation (1) is the temperature of the coolest dust; we take this to be the dust seen in the 1–5 $\mu$m data, which still detect the dust ‘pseudophotosphere’ (Tyne et al. 2002, Eyres et al., in preparation). It is not unreasonable to assume that the dust shell around Sakurai’s Object is geometrically thick, so that $R_i/R_o > 1$; for this case $\gamma = 2$ and we use this value here (see also below).

For the distance, we take $D = 2$ kpc (see Kimeswenger 2002), and we have taken $\kappa$ from Mennella et al. (1998; their $\kappa$ values for amorphous carbon at 295 K, which is likely to be close to that appropriate for Sakurai’s Object).

We give values of $M_d T_d$, computed from Equation (1), in Table 2 for both wavelengths. For each epoch, we have estimated the temperature $T_d$ of the coolest dust by (i) fitting a black-body to 1–5 $\mu$m data obtained in the course of our IR monitoring programme (see Tyne et al. 2002, Eyres et al. 2004, and paper in preparation) and (ii) fitting an exponential decline to the time-dependence of $T_d$. We find:

| Date  | MJD  | $M_d T_d$ (10^{-5} M_\odot K) | $T_d$ (K) | $M_d$ (10^{-7} M_\odot) | $M_{cs}$ (10^{-5} M_\odot) |
|-------|------|-----------------------------|----------|-------------------------|-------------------------|
|       |      | 450 $\mu$m | 850 $\mu$m | 450 $\mu$m | 850 $\mu$m |
| 18/08/2001 | 2140 | 4.6 ± 1.8 | 3.3 ± 1.1 | 504 | 0.9 ± 0.4 | 0.7 ± 0.2 |
| 09/01/2003 | 2649 | 2.7 ± 0.7 | 11.1 ± 0.8 | 418 | 0.6 ± 0.2 | 2.7 ± 0.3 |
| 05/05/2003 | 2765 | 7.5 ± 1.2 | 16.2 ± 0.8 | 401 | 1.9 ± 0.4 | 4.0 ± 0.5 |
| 15/06/2003 | 2806 | 10.2 ± 1.4 | 19.1 ± 0.9 | 395 | 2.6 ± 0.4 | 4.8 ± 0.5 |
| 16/06/2003 | 2807 | – | 18.2 ± 1.0 | 395 | – | 4.6 ± 0.5 | – |

Figure 2. Combined UKIRT/JCMT data for Sakurai’s Object in late 2003 to give the 2.5–850 $\mu$m spectral energy distribution; the UKIRT data have been binned for clarity. The curve is a 360 K black-body, fitted by eye. See text for details.

Figure 3. Increase in circumstellar mass around Sakurai’s Object as deduced from 450 $\mu$m data (squares) and 850 $\mu$m data (triangles), for a gas-to-dust ratio of 75. Lines are included to guide the eye. See text for details.
lengths have increased steadily over the period 2001 August to 2003 June. These data, combined with dust temperatures obtained from our IR monitoring programme, lead to a mass-loss in 2003 of $\sim 3.4 \pm 0.2 \times 10^{-7} M_\odot \text{ yr}^{-1}$, consistent with a continuing rise since our IR observations of 1999-2003.

Monitoring of this object at sub-millimetre wavelengths is continuing and further observations will be presented elsewhere.

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