Recent Observations of Sakurai's Object

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Summary. We investigate the reheating of the very late thermal pulse (VLTP) object V4334 Sgr (Sakurai's Object) using radio observations from the Very Large Array, and optical spectra obtained with the Very Large Telescope. We find a sudden rise of the radio flux at 5 and 8 GHz — from ≤ 90 μJy and 80 $\pm$ 30 μJy, resp., in February 2005, to 320 μJy and 280 μJy, resp., in June 2006. The optical line emission is also evolving, but the emission lines are fading. The optical line emission and early radio flux are attributed to a fast shock (and not photoionization as was reported earlier) which occurred around 1998. The fading is due to post-shock cooling and recombination. The recent rapid increase in the radio flux is evidence for the onset of photoionization of carbon starting around 2005. The current results indicate an increase in the stellar temperature to 12 kK in 2006.

Key words: Stars: individual: V4334 Sgr - Stars: mass loss - Stars: evolution - Planetary nebulae: general

1 Introduction

Helium shell flashes dominate many aspects of the evolution of AGB (Asymptotic Giant Branch) and post-AGB stars. Helium flashes (or thermal pulses) are common on the AGB but the effects on the surface properties are mitigated by the thick hydrogen envelope. Very late thermal pulses (VLTPs), which can occur after hydrogen burning has ceased, lead to large and rapid changes in the star and are the best way to constrain the physics of these thermonuclear eruptions. The VLTP in Sakurai's Object (V4334 Sgr) has provided the first opportunity to observe such an event with modern instrumentation, and allows us to study poorly understood aspects, such as the post-VLTP mass loss and the mixing length theory [10].

Very few VLTP events have been observed: only V4334 Sgr [4] and V605 Aql [3, 20] were discovered during their high-luminosity phase (respectively in 1996 and in 1918). CK Vul (discovered in 1670) is suspected to represent a third case [11]. FG Sge also shows evidence for current post-VLTP evolution but its status is uncertain [15]. Another five central stars of planetary nebulae (PNe) show evidence for historical VLTP eruptions, based on the presence of hydrogen-poor gas near the central star [27].

V4334 Sgr showed a high luminosity phase with a cool stellar atmosphere ($T_{\rm eff} \sim 6000$ K) within a few years after the VLTP, during which the star became hydrogen poor and carbon rich. The speed of evolution from the VLTP to maximum brightness was surprising as pre-Sakurai models predicted timescales of more than 100 yr. The much faster evolution has been explained as caused by suppressed convection under explosive conditions [12, 19, 10]. However, [21] find that the numerical time step is important, and that smaller time steps are sufficient to predict much faster evolution. The problem of convection is studied further by [13]. The reheating timescale after maximum brightness is an important constraint to test the models. This evolution can be traced best by observing the ionization of the surrounding nebula. [8], [24], and [17] detected emission from atomic and ionized species around V4334 Sgr which is evidence for ionization. The existence of ionization was confirmed by [10] based on radio observations. In this paper we present new radio and optical observations, showing that this early ionization was due to a fast shock. Evidence for the onset of photoionization of carbon is also found, indicating that this started around 2005. We present photoionization models of the ejecta and compare the results to various VLTP evolutionary tracks.

2 Observations

2.1 Radio emission

We have been monitoring the radio flux of V4334 Sgr to test the temperature evolution of the star. Observations were carried out with the VLA array between 2004 and 2006, at 5 GHz and 8 GHz. We observed in the hybrid BnC (2004) and AnB (2005, 2006) arrays. This reduced confusion with emission from the old, extended PN. Integration times were 3-5 hours, with 1331+305 as the flux calibrator and 1733−130 as the phase calibrator. The assumed flux density of 1331+305 was 4.66 Jy at 5 GHz. Flux calibration was interpolated to V4334 Sgr. Observational parameters are summarized in Table 1. The resultant visibilities were Fourier transformed to the image plane and the dirty beam deconvolved. Convolution with a gaussian beam fitted to the dirty beam size gave images from which fluxes were measured. Natural weighting was used for the imaging. The FWHM of the gaussian beams are listed in Table 1.

Table 1. Observational parameters and results for the VLA observations. PA gives the position angle of the beam.

Date	Freq. [GHz]	FWHM Beam, PA	σ [μJy/b]	flux [μJy]
5 Feb 2004	8	$1.30''\times1.14''$, $+48°$	10	100 ± 30
4 Feb 2005	5	$1.37''\times0.96''$, $+68°$	16	< 90
6 Feb 2005	8	$0.78''\times0.54''$, $+76°$	14	70 ± 40
11 Jun 2006	8	$0.73''\times0.65''$, $+46°$	17	280 ± 50
12 Jun 2006	5	$1.43''\times1.05''$, $+2°$	19	320 ± 60

2.2 Optical spectroscopy

Line emission from the central ejecta in the optical wavelength regime was first detected in 2001 by [17] using the FORS1 instrument on the VLT. We continued to monitor the object with FORS1/2 in subsequent years. Details are given in Table 2. We averaged observations taken within the same semester. The spectra were bias subtracted, flatfielded, and wavelength calibrated in the standard way using the IRAF packages CCDRED and LONGSLIT. Sky lines were removed using the part of the long slit spectrum outside the old PN. The old PN also contributes to the line emission: this is strongly dependent on the position on the slit. The old PN lines were removed by interpolating the area around the central source. The response correction was done using various white dwarf flux standards. The line fluxes derived from the VLT spectra are listed in Table 2. The data were not corrected for reddening. The 2001 values are taken from [17].

Table 2. Line fluxes in units of 10^{-17} erg cm^{-2} s^{-1}. The 2001 fluxes are taken from [17]. *OR* means outside the observable range. Where appropriate 3-σ upper limits are given.

Line	2001.44[a]	2003.50[b]	2005.48[c]	2006.29[d]
[N I] 5198, 5200	8.	3.2 ± 0.5	2.6 ± 0.5	2.2 ± 0.7
[N II] 5755	2.	2.1 ± 0.7	< 1.5	< 2.2
[O I] 6300	30.	10. ± 1.5	5.5 ± 0.8	3.9 ± 0.8
[O I] 6364	8.	4. ± 1.2	2.5 ± 0.6	2.1 ± 0.7
[N II] 6548	40.	15. ± 1.9	7.6 ± 0.9	3.7 ± 0.6
[N II] 6583	121.	42. ± 4.2	21. ± 2.2	13.8 ± 1.5
[S II] 6716	2.5	< 1.9	< 1.6	< 1.3
[S II] 6731	2.	< 1.9	< 1.6	< 1.3
[O II] 7319, 7330	62.	20. ± 2.1	6.7 ± 1.6	4.2 ± 1.0
[C I] 8727	*OR*	13. ± 1.5	< 3.9	4.7 ± 0.8
[C I] 9824, 9850	*OR*	150. ± 15.	*OR*	*OR*

[a] 300V+GG375, 4500 – 8000 Å. [b] 150I, 4900 – 10075 Å; 150I+OG590, 6200 – 10075 Å; 1200R+GG435, 5875 – 7365 Å. [c] 300V+GG435, 4800 – 8900 Å. [d] 600V+GG435, 4520 – 6850 Å; 600I+OG590, 6500 – 9200 Å.

3 Discussion

3.1 Extinction distance

The FORS long slit spectra were used to extract the spectrum of the old PN, taking care not to include any field stars or the recent ejecta. The $\mathrm{H}\alpha/\mathrm{H}\beta$ ratio gives the interstellar extinction. Assuming a case B ratio of 2.85, we derive $E(\mathrm{B}-\mathrm{V}) = 0.86$, somewhat higher than found by [22]. The extinction-distance diagram for stars within a few arcminutes from V4334 Sgr is derived by [18]: it shows a linear rise with distance up to 1.8 kpc, followed by a constant extinction of $E(\mathrm{B}-\mathrm{V}) = 0.9 \pm 0.09$ between 1.8 and 5 kpc.

This suggests that V4334 Sgr is located beyond 1.8 kpc. The previously used value of 1.9 kpc (e.g. [6]) can be considered a lower limit. [5] suggests a distance d of $\sim$ 3–5.4 kpc based on the stellar luminosity. The line of sight reaches the scale height of the old disk at $d \approx 4$ kpc and this would provide a plausible distance.

3.2 Shock ionization

The line fluxes in Table 2 show a strong exponential decline with time (see also Fig. 1). The level of excitation is also decreasing, as the high excitation [O II] lines are decreasing faster than lines of lower excitation. The e-folding times are 1.81±0.13 yr for [O II] (the highest excitation line), 2.29±0.14 yr for [N II], 2.4±0.2 yr for [O I], and 3.7±0.9 yr for [N I]. This is clearly inconsistent with photoionization by an increasingly hot central star [17, 10]. The decrease in intensity as well as the level of excitation is consistent with a single shock that occurred somewhere before 2001 and then started cooling and recombining (cf. [16]). The [N II] line ratio in 2001 indicates an electron temperature $T_\mathrm{e} = 3200 - 5500$ K, depending on the electron density (Table 3). The [C I] ratio in 2003 indicates $T_\mathrm{e} = 2300 - 4300$ K assuming the same range in density. These low values indicate that cooling had already commenced by 2001.

The origin of the shock is not clear. No emission lines were seen during 1997. The earliest evidence for shock ionization is based on the He I recombination line, and dates from 1998 [8, 24]. High-velocity CO was seen starting late 1999 or early 2000 [7], with an outflow velocity around 290 $\mathrm{km\,s^{-1}}$. Optical shock emission with velocities up to -350 / $+200$ $\mathrm{km\,s^{-1}}$ was first seen in 2001 [17]. The shock occurred close to the time of the onset of dust formation [5]. Neutral molecule chemistry is slow in a hydrogen-deficient environment, while ion-molecule chemistry is much faster [26]. Hence UV radiation from the shock may have triggered dust formation elsewhere in the nebula through ionization of key molecular species. If the ejecta are bipolar, the dust formation could be taking place in the dense equatorial region (possibly an equatorial disk), while the shocks are internal to a fast polar outflow [6].

3.3 Photoionization

The radio flux was constant or decreased slowly between 2004 and 2005. This is consistent with the model of an early fast shock: the radio data trace the post-shock cooling and recombination of the shock and not a photoionized region. However, the

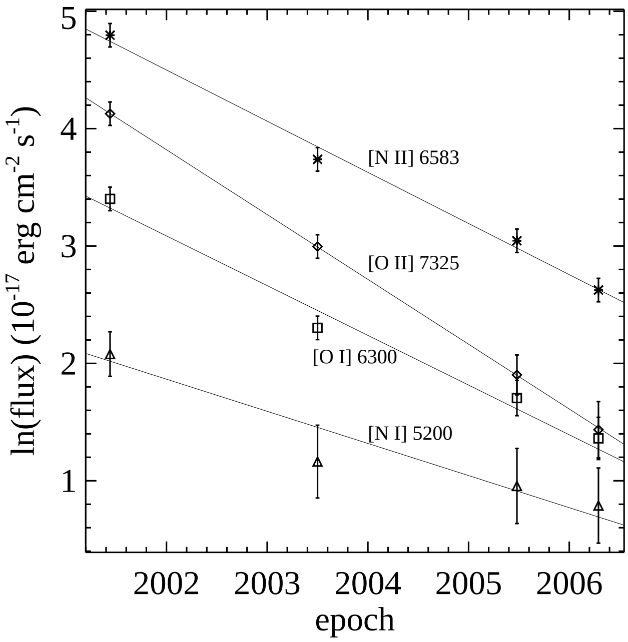

Fig. 1. Evolution of emission line strength. The lines show the least-squares fit to the data.

2006 observations show a strong increase in radio flux, by a factor of four within 16 months. The only optical line which appears to have strengthened is the [C I] 8727 line, but this is uncertain due to the low S/N of the 2005 data. The increase in radio flux in 2006 is therefore attributed to newly photoionized carbon which has the lowest ionization potential of all the major constituents in the gas. This process would not produce any noticeable changes in the optical or mid-IR spectrum.

We ran Cloudy models to investigate the origin of the radio flux using version c07.04.01 of the code, last described by [9]. The basic models are similar to those described in [10], with the following changes. (1) The angular diameter of the dust shell is discussed in [23] and [6]. Extrapolating their data to 2006 leads to an angular diameter of $\sim$ 100 mas. However, with such a small diameter the plasma would become optically thick at 5 GHz before the necessary emission measure could be reached to explain the observed radio flux. Based on the FORS2 1200R spectral image taken in 2003 (seeing $0.54''$) we measured a deconvolved (gaussian) FWHM of $0.27''$ for the [N II] emitting region. This indicates that the true diameter must be 0.3 – 0.5 arcsec [25]. We modeled both limits of this range. (2) Abundances from [1] (October 1996 values) were used, except for carbon where we used C/He = 0.1 by number (the value [1] used for their model atmospheres). (3) For the stellar spectrum we used the models of [2]. (4) We assumed a clumpy medium with a filling factor f of 0.1 or 0.01, and a $1/r^2$ density distribution. (5) The total dust mass was the same in all models with the same distance. We list four models in Table 3. The implied gas-to-dust mass ratio is $\sim 580\sqrt{f}$ for the $d = 1.9$ kpc models and $\sim 870\sqrt{f}$ for the $d = 4$ kpc models. The ionization of carbon begins around $T_{\rm eff} = 10$ kK. The radio flux (without the shock emission) as a function of $T_{\rm eff}$ is listed in Table 4. The observed radio flux is consistent with an increase in $T_{\rm eff}$ from $\lesssim 11$ kK in 2005 to $\sim$ 12 kK in 2006.

Table 3. Cloudy model parameters. The main constituents of the gas are helium (He/H = 250 by number) and carbon (C/H = 25 by number). The electron density in the ionized region is approximately $25\,n_{\rm H}$. $M_{\rm d}$ and $M_{\rm ej}$ are the dust mass and the total ejecta mass.

	model 1	model 2	model 3	model 4
d [kpc]	1.9	1.9	4.0	4.0
L [$L_\odot$]	2770	2770	12280	12280
Θ [arcsec]	0.3	0.5	0.3	0.5
$\log(r_{\rm in}[{\rm cm}])$	14.931	15.153	15.254	15.476
$\log(r_{\rm out}[{\rm cm}])$	15.630	15.852	15.953	16.175
$\log(n_{\rm H}[{\rm cm}^{-3}]/\sqrt{\rm f})$	4.45	3.85	4.3	3.7
$M_{\rm d}$ [10^{-6} $M_\odot$]	1.95	1.95	8.65	8.65
$M_{\rm ej}/\sqrt{f}$ [10^{-3} $M_\odot$]	1.05	1.22	6.92	8.05

Table 4. Predicted radio flux (not including the shock emission) at 8.435 GHz in μJy (valid both for $f = 0.1$ and 0.01).

$T_{\rm eff}$	model 1	model 2	model 3	model 4
10000	4	4	4	3
11000	24	24	24	24
12000	340	330	350	340
13000	830	790	850	820

3.4 Ejecta mass

If we write the diameter of the nebula as Θ, and the He/C mass ratio as m(He), the results from the Cloudy modeling can be summarized in the following formula for the ejected mass:

$$M_{\rm ej} = 6.0\ 10^{-4} \left(\frac{f}{0.01}\right)^{0.5} \left(\frac{d}{4\ {\rm kpc}}\right)^{2.5} \left(\frac{\Theta}{0.5''}\right)^{0.3} \frac{m({\rm He})}{2.5}\ M_\odot, \qquad (1)$$

The dominant uncertainty in the total ejecta mass comes from the distance, the volume filling factor, and the He/C mass ratio. In the Herwig models, the He/C ratio quickly evolves to a value of 2.5 after the star has reached the red end of the first loop. We take this value to determine the minimum ejecta mass, required by the photoionization models. Hence a very conservative lower limit to the ejecta mass is 6 10^{-4} $M_\odot$ at $d = 4$ kpc and 10^{-4} $M_\odot$ at $d = 1.9$ kpc assuming extreme clumping ($f = 0.01$). For a uniform outflow the lower limits would be a factor of

10 higher. The corresponding mass-loss rate over a period of roughly a decade is very high. It could be comparable to, or even exceed, the mass-loss rate during the superwind phase. A minimum ejecta mass of 5 10^{-3} $M_{\odot}$ is sufficient to expose the intershell region (e.g. Fig. 3 in [14]) where the C/He ratio reaches its peak value of 2.66 by mass. This would leave a central star with abundances compatible with those of [WC] and PG1159 stars. This could be consistent with the Cloudy models. The linear momentum in the ejecta far exceeds that in the stellar radiation (even when considering multiple scattering), so that the ejecta must be energy driven. This suggests that the ejecta may have been lost instantaneously.

4 Conclusions

The photoionization of carbon in the ejecta of V4334 Sgr has started around 2005. This is evident from a 4-fold increase in the 8 GHz radio flux observed in June 2006. Simultaneously the optical spectrum shows a continuing exponential decline, both in excitation and ionization. This indicates that the emission lines are formed in a shock which occurred around 1998 and is currently cooling and recombining. The models indicate that the star was at a temperature of 12 kK in 2006 and is currently evolving with a speed $\gtrsim 1$ kK yr^{-1}. This confirms that V4334 Sgr not only displays a fast return to minimum temperature, but also a fast reheating.

Acknowledgement. PvH acknowledges support from the Belgian Science Policy Office (grant MO/33/017). MH acknowledges support from the Polish research grant No. N203 024 31/3879. We wish to thank R. Blomme and D. Jevremović for stimulating discussions.

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