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Strong helium 10 830-Å absorption in Sakurai's object (V4334 Sgr)

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ABSTRACT

We report the appearance and evolution during 1998 of strong neutral helium ^3S–$^3P^o$ absorption at ∼10 830 Å in Sakurai's Object (V4334 Sgr), which is believed to be a planetary nebula nucleus (PNN) undergoing a final helium shell-flash. First detected on 1998 March 18, the profile of the He I feature is P Cygni-like. The absorption depth has increased in three subsequent spectra in 1998. If this is owing to a wind, the profile indicates a wind velocity of $\sim 670 \pm 50\,\mathrm{km\,s^{-1}}$. The strong C I 10 690-Å line seen prior to the appearance of the helium feature has disappeared; however Sr II and CN absorption features remain present. We tentatively identify several new features as Si I. Taken together with other observations we suggest that the data are consistent with Sakurai's Object entering a phase in which it seems to have become a member of the R Coronae Borealis-type class of stars.

Key words: stars: AGB and post-AGB – circumstellar matter – stars: individual: Sakurai's object – stars: individual: V4334 Sgr – infrared: stars.

1 INTRODUCTION

The final helium shell flash of a star after it becomes a planetary nebula nucleus (PNN) is an important and rarely seen stage in the evolution of low- and intermediate-mass stars. The post-AGB (asymptotic giant branch) evolution of a star begins as a cool red giant which develops a superwind, resulting in the ejection of the envelope. This exposes the stellar core, and leads ultimately to a planetary nebula (PN). Subsequent rapid evolution to higher photospheric temperatures and the eventual end of nuclear reactions is followed by cooling towards the white dwarf region of the Hertzsprung–Russell (HR) diagram. During the late AGB phase, the core undergoes periodic helium-shell thermal pulses, or flashes. The final shell flash can occur after the star has already become a PNN, and the star will briefly return to the red-giant domain of the HR diagram, as a 'born-again' giant (B-AG hereafter; Iben et al. 1983). This is expected to be accompanied by the ejection of a new PN. If the outer H-burning shell has been extinguished at this time, a large amount of large-scale mixing is expected to occur. The latter event should lead to interactions between the B-AG envelope and the pre-existing PN.

Initially described as 'nova-like' when discovered on 1996 February 20 (JD 2450134; Nakano 1996), V4334 Sgr (= Sakurai's Object, SO hereafter) has since been identified as a B-AG, undergoing its final helium shell flash (Benetti et al. 1996). It is apparent that brightening was under way in 1995 January (Benetti et al. 1996), and perhaps as early as 1994 June 3 (JD 244 9507; Takamizawa, http://www.kusastro.kyoto-u.ac.jp/vsnet). SO is the first star to have been seen to be undergoing this stage of evolution in almost 80 years, and so it is the first one to be observable with current instruments. In particular, the many additional spectral bands available today will allow new insights into this stage of stellar evolution. Pollacco (1996) pointed out that infrared (IR) spectroscopy would first reveal the exposed Wolf–Rayet core. The first results from IR spectroscopy (Eyres et al. 1998a) found numerous atomic lines and molecular absorption bands, including C I, Sr II, CN, ^{12}CO, ^{13}CO, and C_2. A dust continuum consistent with graphitic carbon dust at 680 K was also apparent in an *ISO* spectrum from 1997 April. Weak visual He I 5875.6- and 5015.6-Å absorption lines were present in 1996 July, but had disappeared by 1996 October (Asplund et al. 1997; 1999). These lines behaved as expected for a photospheric origin, similar to the other visual absorption lines. Here, we report in detail the recent appearance of *non-photospheric* helium absorption at 10 830 Å (Eyres et al. 1998b), observed at the United Kingdom Infrared Telescope (UKIRT) in 1998.

2 OBSERVATIONS

Moderate and high-resolution spectra of SO were obtained on several occasions during 1997 and 1998 at UKIRT using the grating spectrometer CGS4. An observing log for those included

Table 1. Observation log.

Observation date (UT)	Julian date	Observation band/mode	Wavelength range (Å)	Resolution (Å)	Integration time (s)	Calibration star
1997 July 13	245 0643	J/grating	10 140–13 550	13	72	BS6496
1998 March 18	245 0891	J/grating	10 240–13 420	13	720	BS6310
1998 April 21	245 0925	J/grating	10 100–13 400	13	576	BS6310
1998 June 11	245 0976	J/grating	10 270–13 470	13	240	BS6310
1998 June 11	245 0976	Echelle	10 800–10 860	0.6	640	BS6679
1998 August 18	245 1044	J/grating	10 280–13 460	13	480	BS6496
1998 September 2	245 1059	Echelle	10 800–10 860	0.6	1152	BS6496

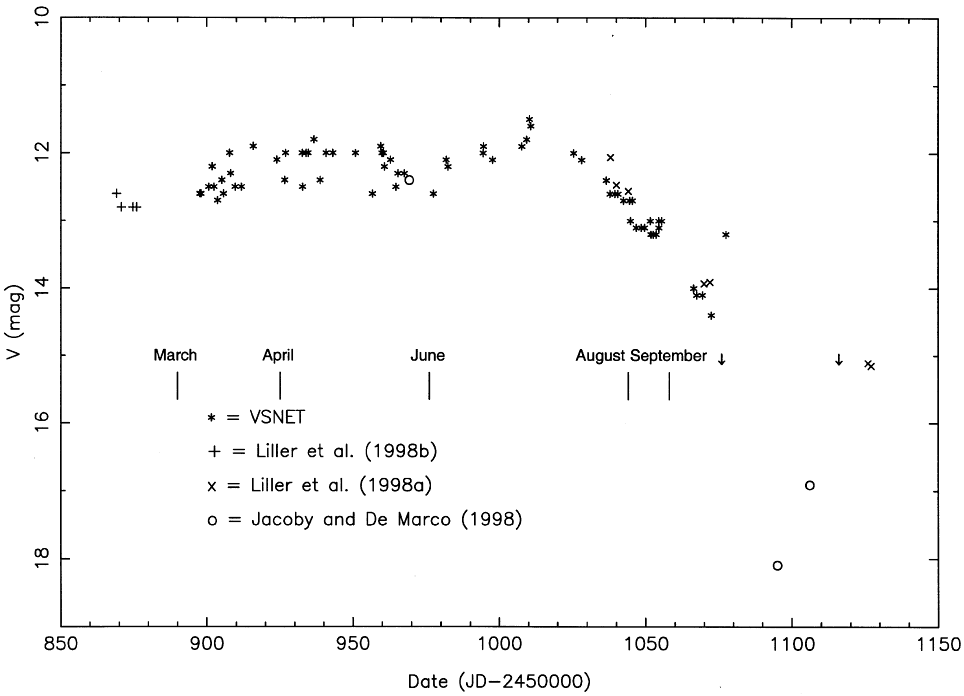

Figure 1. *V* magnitude light curve covering the period of our 1998 observations (see Table 1), extended to show the development of the RCB-type fading. Dates of our observations are marked with vertical lines, and by the month in 1998. Downward arrows indicate limits from Liller et al. (1998a); the sources of the other points are as indicated. During our observation in 1997 July, $V \simeq 11.1$ (Guinan, McCook & Magheim 1997).

here is provided in Table 1. We interpolated across the prominent H I absorption lines in the calibration stars prior to ratioing to produce flux–calibrated spectra. The flux calibrations used colours for the calibration stars derived from Koornneef (1984), and are probably accurate to 20 per cent. The wavelength calibrations are accurate to better than 2 Å ($\sim$55 km s^{-1}) for the moderate resolution spectra and better than 0.2 Å ($\sim$5.5 km s^{-1}) for the echelle spectra.

The times of our 1998 observations are marked on the visual light curve shown in Fig. 1. The first and third observations that year coincide with $\sim$0.5 mag drops in *V*, while the last two were during the decline to deep minimum reported by Liller et al. (1998a) and Jacoby & De Marco (1998). The 1997 July observation was made prior to any evidence of significant visual variations, when $V \simeq 11.1$ (Guinan, McCook & Magheim 1997); this observation has been previously published by Eyres et al. (1998a), and is included for comparison.

3 RESULTS

Fig. 2(a) shows the spectra taken between 1997 July and 1998 August in the wavelength range 10 280 to 11 500 Å. Clearly visible is the advent of the strong 10 830-Å absorption line between 1997 July 13 and 1998 March 18. The only plausible identification of this feature is He I ^{3}S–^{3}P^o triplet (at 10 829.081, 10 830.250, and 10 830.341 Å; Moore 1971). This is by far the strongest feature in the helium spectrum (Moore 1971). Thus even considering the enormous strength of the 10 830-Å absorption feature, we do not expect to see other He lines in the *JHK* bands; for example, the He I 20 580-Å line is $\sim$1 per cent of the 10 830-Å line. This may change if the lines are collisionaly excited, but such considerations are beyond the scope of this paper. Our *K* band spectra (to be reported elsewhere) do not show any evidence of other He I lines. Even if other He I lines are present, they are certainly obscured by the heavy blanketing.

Alternative explanations for the 10 830-Å absorption feature do not stand up to examination. For example, there is a Si I feature at 10 827.09 Å. If this was the origin of the observed absorption, we would expect lines of similar strength to appear, for example at 10 786.86 Å; these are not seen. The Si I lines which we have identified are much weaker than the 10 830-Å feature.

Determination of the equivalent width (EW) of the He I feature is hampered by the difficulty of assessing the continuum level. It is likely that the continuum is due primarily to C I bound–free (~50 per cent), with He^- free–free and C I free–free also contributing (~20 per cent each), but the heavy blanketing makes definitive statements impossible. Thus, we cannot easily determine the time-evolution of the line strength. However, we estimate an EW starting at ~9.5 Å in 1998 March 18, and increasing to ~11.5 Å in 1998 August 18; the upper limit in 1997 July 13 was ~0.1 Å. These values are useful in qualitatively emphasizing the clear increase in the strength of the absorption

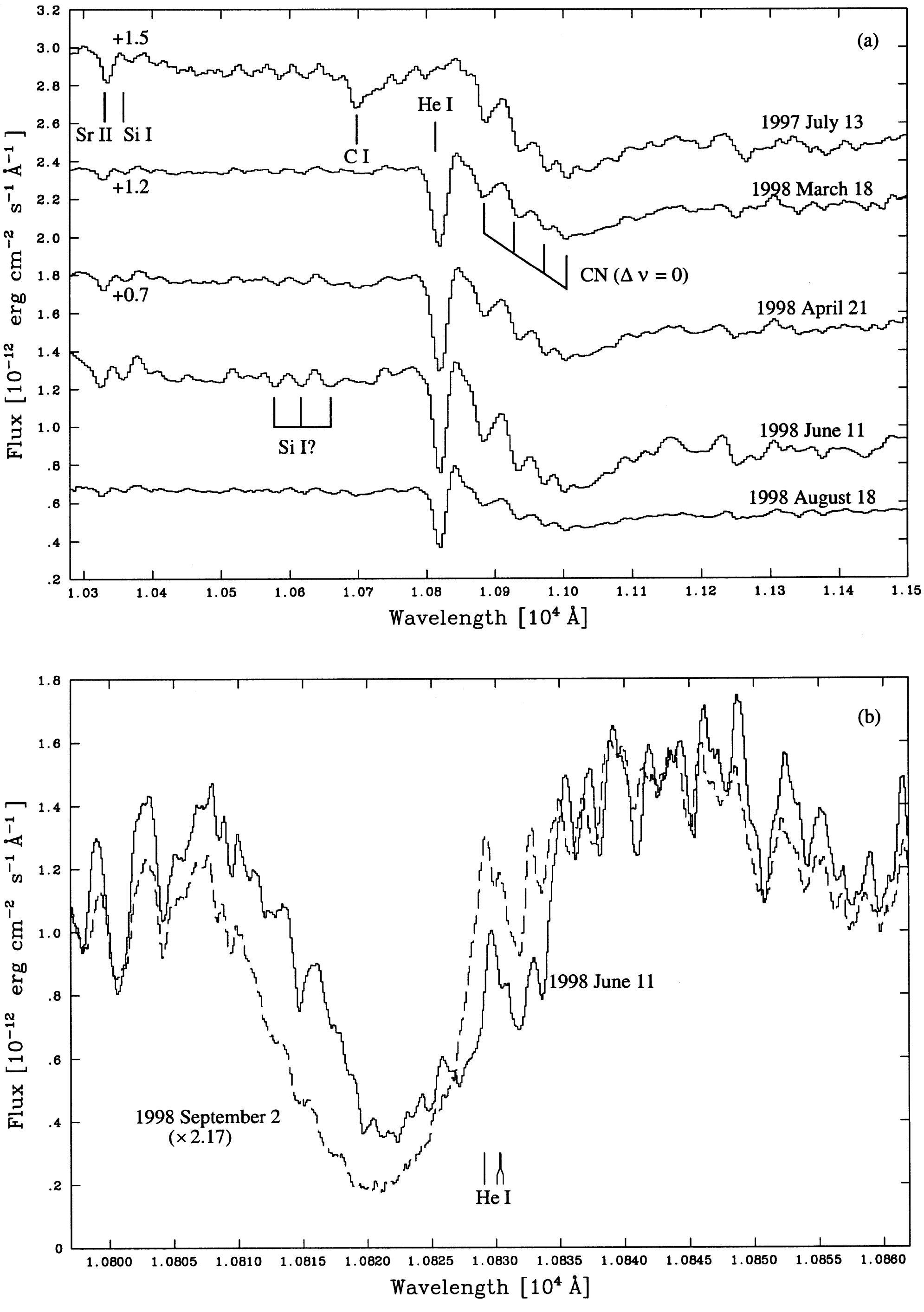

Figure 2. UKIRT CGS4 spectra. The spectra are dereddened assuming $E(B-V) = 1.15$ (Eyres et al. 1998c). The wavelengths are as measured; no correction has been made for any possible systemic motion. (a) Medium-resolution spectra. Vertical offsets are indicated in multiples of 10^{-12} erg cm^{-2} s^{-1} Å^{-1}, and are made for clarity. Observation dates are marked. Note the lack of He I 10 830-Å absorption in 1997 July 13, and the disappearance of C I 10 690 Å after 1997 July 13. (b) Echelle spectra for the region around the He I absorption feature on 1998 June 11 (solid line) and 1998 September 2 (broken line). The latter is rescaled by the factor indicated to aid comparison, according to the relative flux at 10 798 Å, and shifted by 1.1 Å to account for the change in the Earth's velocity towards SO between the two observations. The rest wavelengths of the three components of the He I triplet are marked.

over the 13-month period of our observations. It is noted that the C I absorption at 10 691 Å, reported by Eyres et al. (1998a), is no longer present by 1998 March 18 when the He I is first detected.

A P Cygni-type profile is apparent in the He I feature. This is especially so in the 1998 August 18 spectra, where the adjacent absorption bands from CN ($\Delta\nu = 0$), previously reported by Eyres et al. (1998a), have subsided somewhat. The echelle spectra of the He I 10 830 Å lines are shown in Fig. 2(b). The structure is dominated by numerous absorption features, a further indication of extremely heavy blanketing of the continuum. If the He I absorption is a P Cygni profile, the position of the blueward edge indicates a wind velocity of $\sim 550 \pm 50\,\mathrm{km\,s^{-1}}$. This is only a rough estimate, as the position of the blueward edge is difficult to assess; however, the high-velocity demonstrates that the emitting region is displaced from the star [which has a radial velocity of $\sim 115\,\mathrm{km\,s^{-1}}$ (Duerbeck & Benetti 1996)]; accounting for the stellar velocity, the wind velocity is $\sim 670\,\mathrm{km\,s^{-1}}$ (within the errors of our measurement). The absorption shifts bluewards by ~ 2 Å between our two echelle spectra. At the same time, the adjacent numerous absorption features do not move between the two observations.

We note that EW estimates indicate that the Sr II 10 330-Å feature and the CN ($\Delta\nu = 0$) bands are at their weakest in 1998 March 18, increasing through 1998 April 21 to a maximum in 1998 June 11, before declining again in 1998 August 18. At maximum, the CN bands appear slightly stronger than the pre-helium 1997 July 13, but the Sr feature is not as strong.

4 DISCUSSION

The huge width of the He I absorption, and the P Cygni profile, are both strong evidence that the line is not photospheric. In addition, for any reasonable effective temperature (T_{eff}) and surface gravity ($\log g$), the observed absorption would indicate an impossibly high He abundance, if the He I 10 830-Å lines were photospheric. A stellar atmosphere synthesis using parameters from Asplund et al. (1997) has little resemblance to the observed spectra. In particular, the modelled He I absorption EW was considerably smaller than our measurements show. This is consistent with the IR spectra not originating in photospheric conditions typical of the optical lines. Under local thermal equilibrium (LTE), the observed line strength requires a T_{eff} which is too high for the other observed spectral characteristics. This suggests non-equilibrium conditions, which may involve the pumping of the lower ^{3}S level of the He I transition.

The monochromatic optical depth at $\sim 10\,000$ Å is very similar to that in the visual. This means the He I lines cannot be formed in deeper layers than those where the optical continuum originates. Hence the lines are either formed in roughly the same region as the optical continuum, or above this. The P Cygni profile of the line suggests the latter. The optical and other IR lines are more consistent with $T_{\mathrm{eff}} \sim 6000$ K (see fig. 2 of Asplund et al. 1999, and also Eyres et al. 1998a) rather than 20 000 K required to form a pronounced 10 830-Å feature. Optical spectra from 1998 (Asplund et al., in preparation) show that the apparent cooling continued throughout that year.

Near-IR *IJK* photometry in 1997 March found a hot dust shell at ~ 1800 K (Kimeswenger et al. 1996). By 1998 March, L' M' N' narrowband photometry indicated that the dust may have cooled to ~ 1100 K (Lynch, Russell & Rice 1998). However, Eyres et al. (1998a) found a 2 to 10-μm continuum consistent with graphitic carbon grains at 680 K in 1997 April. The difference in temperature may be attributable to the different dust grain form assumed. *UBVRI* photometry found at least two episodes of optical fading and recovery, accompanied by changes in the colour indices (Liller et al. 1998a, 1998b; Jacoby & De Marco 1998) consistent with dust formation throughout 1998. The total drop of ~ 6 mag in V over ~ 120 days in the mid- to late-1998 dip, and the much smaller preceding dips, are similar to those seen in R Coronae Borealis-type (RCB) stars, which are associated with the formation of optically thick dust. The presence of such dust can only increase the optical depth at 10 000 Å, placing the He I emitting region even further from the photosphere.

In RCB stars, the development of broad *emission* lines is seen in connection with visual fading similar to that seen in SO. P Cygni profiles have been seen, most notably from He I 10 830 Å in R CrB itself (Querci & Querci 1978); broad emission (but not a P Cygni profile) was seen in the 1995–1996 decline (N. K. Rao, private communication). The development of dust in SO prior to the recent visual variations is consistent with fragmentary formation (i.e. the dust cloud subtends a solid angle $\ll 4\pi$), rather than the more uniformly obscuring dust seen, for example, in some classical novae (subtending a solid angle approaching 4π.) This is similar to what is believed to happen in RCB stars (Clayton 1996). We suggest that the broad He I line seen in SO orginates in shocked gas dragged outwards by accelerating dust. As dust formation is episodic, and the dust is continually accelerated, the coupled gas has a broad velocity dispersion, leading directly to broad lines. We also believe the He I line is collisionally excited, as the radiation field of a $T_{\mathrm{eff}} \sim 6000$ K photosphere is insufficient, consistent with our view of the dust–gas interaction. This model is also consistent with similar observations of RCB stars. A final point of similarity is seen in the chemical composition (Asplund et al. 1997, 1999). Thus, we suggest that in its current phase the appearance of SO is consistent with it being a member of the RCB class.

5 CONCLUSIONS

We have detected a strong absorption feature at 10 830 Å in the IR spectrum of SO. The only plausible identification is the He I triplet at 10 829.081, 10 830.250 and 10 830.341 Å. The centre of the absorption core is offset by ~ 9 Å from the central rest wavelength of the triplet. If the absorption is due to a wind, interpreting the feature as a P Cygni-type profile indicates a wind velocity of $\sim 670 \pm 50\,\mathrm{km\,s^{-1}}$. We note shift of ~ 2 Å over 83 d in the He feature between the two echelle observations.

The nature of the broad He I line and the activity at optical wavelengths is similar to that seen in RCB stars, particularly R CrB. The formation of dust indicated by IR observations and UVB colours is also consistent with that associated with visual variations in RCB stars. In addition, the possible explanation of the broadness of the He I line regarding the acceleration of the gas by dust is common to both SO and RCB stars. Hence, we suggest that the current phase of the evolution of SO is consistent with the object being in the RCB class. Given the dramatic changes seen in SO over the past three years, it remains to be seen if this situation will last for an appreciable time.

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