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The Real-Time Evolution of Sakurai's Star (V4334 Sgr) and other (V)LTP Objects

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Abstract. We report on the progress of our on-going campaign to monitor the evolution of the VLTP objects V4334 Sgr and V605 Aql, as well as the suspected (V)LTP object CK Vul. V4334 Sgr does not show signs of increased ionization compared to our previous observations in 2004. We obtained the first radio detection of V605 Aql, indicating a strong increase in radio flux since 1987. We also present the first radio detection of CK Vul and discuss the expansion of the material ejected during the 1670 event.

Keywords. stars: AGB and post-AGB, stars: evolution, circumstellar matter, stars: winds, outflows

1. Introduction

Helium shell flashes punctuate the evolution of a star on the thermal pulsing Asymptotic Giant Branch (AGB). They occur whenever sufficient helium has accumulated from the preceding phase of hydrogen burning. Following the helium shell flash, a short phase of quiescent helium burning occurs, after which hydrogen burning resumes. Nearly all of these thermal pulses occur near the tip of the AGB, but approximately 20% of all low and intermediate mass stars are expected to suffer a final shell flash after they have left the AGB. If the event occurs while the hydrogen burning shell is still active, ingestion of the remaining hydrogen from the envelope into the helium burning shell is impossible and the event is called a Late Thermal Pulse (LTP). However, if the star is already on the cooling track and the hydrogen burning shell has ceased, the remaining envelope can be ingested, leading to additional rapid hydrogen-driven burning. This can result in an extremely fast real-time evolution following a double-loop structure in the Hertzsprung-Russell diagram (Herwig 2001, Hajduk *et al.* 2005). Such an event is called a Very Late Thermal Pulse (VLTP). A recent review of this process can be found in Herwig (2005).

Very few VLTP events have been observed: only V4334 Sgr (Sakurai's Object) and V605 Aql were discovered during their high-luminosity phase (respectively in 1996 and 1918). CK Vul (in 1670) is suspected to represent a third case (Evans *et al.* 2002) and may either be an LTP or VLTP event. We are currently involved in an effort to monitor the evolution of these objects. We presented results of this campaign for Sakurai's Object in Hajduk *et al.* (2005). Below we will give a brief update on the status of this campaign. We will also present first results for V605 Aql and CK Vul.

2. V4334 Sgr (Sakurai's Object)

V4334 Sgr was the core of a previously unknown planetary nebula (PN) when it erupted in 1992. In 2004 we obtained [O III] images using FORS1 on the VLT, and 8.6 GHz radio data with the VLA. The old PN has been detected in both data sets. This nebula is still visible because the O^{2+} ions did not have time yet to recombine. Hence the nebula has a "memory" of conditions before the VLTP. Analysis of this spectrum showed that the old PN had already entered upon the cooling track (Kerber *et al.* 1999, Pollacco 1999). During the VLTP event, the central star ingested part of the surface material into deeper layers where it was burned. The remainder has been ejected, exposing the hydrogen-deficient layers below. The expelled material is now moving away from the star at a velocity of ~ 350 km s^{-1} (Kerber *et al.* 2002) and will eventually form a new hydrogen-deficient planetary nebula. Initial spectra of the ejecta showed strong C_2 absorption bands, indicative of a carbon-rich molecular chemistry (Asplund *et al.* 1997), but no dust. Later dust formation did start, leading to significant circumstellar absorption. The central star is now very faint (V = 23 mag). The new ejecta have been detected in [N II] and [O II] lines (Kerber *et al.* 2002), as well as radio emission (Hajduk *et al.* 2005).

During 2005 we obtained new VLA data at 5 and 8 GHz in the AnB configuration. This configuration achieves higher angular resolution than our earlier observations. At 8 GHz we detected the source with a flux of 80 ± 30 μJy, in agreement with the 2004 observations. The deconvolved FWHM of the object is 1.0×0.5 arcsec, which is smaller than reported in Hajduk *et al.* (2005). The suspected bipolar morphology could not be confirmed. We did not detect Sakurai's object at 5 GHz with a 3σ upper limit of 50 μJy/beam. This indicates that the radio emission is optically thick at 5 GHz. Assuming $T_{\rm e} = 4500$ K (Hajduk *et al.* 2005) and a filling factor of unity this yields a diameter $\Theta \leqslant 20$ mas, which is much smaller than observed. This would imply a low filling factor, indicating the presence of a thin shell or a very clumpy medium.

In 2005 we obtained new optical spectra with FORS1 on the VLT. Full analysis of the spectra is not complete yet, but first indications are that there are no big changes w.r.t. to the Kerber *et al.* (2002) spectrum, although changes in the individual velocity components do appear to be present. In April 2005 we also obtained an infrared spectrum with IRS aboard the Spitzer Space Telescope (Evans *et al.* 2006). The spectrum shows absorption bands of HCN and polyyne molecules, but no atomic emission lines. In particular the [Ne II] 12.8 μm line has not been detected. This is one of the first lines that is expected to appear when reheating of the central star progresses.

3. V605 Aql

This star is sometimes called the "older twin" of Sakurai's Object. It erupted around 1917. It is the central star of an older planetary nebula (A58). The star is still very reddened and faint (V = 23 mag). It has a Wolf-Rayet type spectrum (Seitter 1987, Clayton *et al.*, these proceedings).

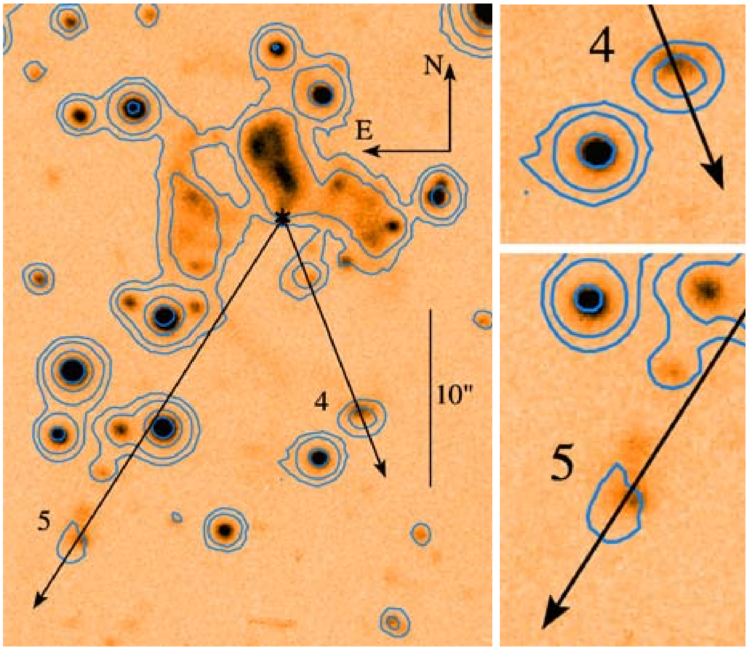

Figure 1. The expansion of the ejecta from the 1670 event in CK Vul. The negative image shows Hα observations from 1991 (Naylor *et al.* 1992), the contours are Hα observations from 2004 taken from the IPHAS survey (Drew *et al.* 2005). The asterisk marks the position of the radio source. Knots 4 & 5 are enlarged on the right.

We observed V605 Aql with the VLA on 4 April 2005. The flux was 440 $\pm$ 50 μJy at 5 GHz in the B configuration. The deconvolved FWHM was 0.7 $\times$ 0.3 arcsec, consistent with optical observations (e.g., Bond & Pollacco 2002). Previous observations by Rao *et al.* (1987) using the VLA only yielded upper limits of 150 μJy at 5 GHz, and 370 μJy at 15 GHz. Hence the radio flux has increased considerably since 1987. This could be due to a decrease in optical depth (expansion of the ejecta) or an increase in emission measure (e.g. due to increased stellar temperature). The latter is suggested by changes in the spectrum of the core (Kimeswenger 2003, see also Clayton *et al.*, these proceedings).

4. CK Vul

This object was first observed in 1670. Its nebula shows highly reddened emission lines of H I, [N II], [O III], and [S II], but the central star has not been found yet. This, and other unusual properties, make it unlikely that CK Vul is an ordinary nova. The observations better fit the hypothesis that this is an LTP or VLTP object (Evans *et al.* 2002).

We observed CK Vul with the VLA on 4 April 2005. The flux was 1.46 $\pm$ 0.05 mJy at 5 GHz in the B configuration, the diameter is less than 0.5 arcsec. The emission is placed at the center of the observed nebulosities (see Fig. 1). No Hα+[N II] counterpart of the radio emission is known. This could imply that there is significant circumstellar extinction or that the radio emission is non-thermal. Assuming the radio emission were optically thick and the filling factor unity would yield $\Theta = 0.1$ arcsec. Hence the upper limit for the angular extent implies that the optical depth at 5 GHz must be at least 0.04. Evans *et al.* (2002) reported on observations of the infrared spectral energy distribution of CK Vul. The observations are consistent with a two-component model: a bigger and cooler shell (25 K) with silicate grains, and a carbon-rich shell with a temperature of 550 K and

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very small diameter. Based on angular extent, the latter shell may be associated with the radio emission, but the evidence for this is not conclusive. The very compact nature suggests that this is a circumstellar disk. The slope of the SED between 450 μm and 850 μm is inconsistent with the dust emission model, suggesting that non-thermal radio emission is present at 850 μm.

Comparing the 2004 IPHAS Hα image with the 1991 observations of Naylor *et al.* (1992) reveals that knots 4 & 5 identified by Shara *et al.* (1985) have moved away from the central radio position at a projected velocity of roughly 100 and 200 km s^{-1} respectively, assuming a distance of 550 pc (Fig. 1). The arrows in Fig. 1 originate from the radio position and indicate that the knots are indeed moving away radially from this point. The rate of displacement of the knots is consistent with an origin during the 1670 event, as proposed by Shara *et al.* (1985). On the IPHAS Hα image we also identified a larger bipolar structure centered on the radio position. Future observations should clarify whether this structure is also connected to the 1670 event or if this could be the old PN.

5. Conclusions

• The radio detection of the new ejecta of V4334 Sgr has been confirmed. The radio source is more compact than previously thought and the suspected bipolar morphology could not be confirmed. There is no apparent evidence for an increase in ionization between 2004 and 2005.

• We obtained the first radio detection of V605 Aql at 5 GHz. The radio flux has increased considerably since 1987. The current rate of evolution is surprisingly steep considering the date of the VLTP event.

• We obtained the first radio detection of CK Vul. The radio source has no counterpart in our Hα+[N II] image and is unresolved. The radio emission may be non-thermal and associated with a circumstellar disk. The Hα+[N II] knots identified by Shara *et al.* (1985) are confirmed due to their proper motion as the ejecta from the 1670 event. We also detected a large bipolar structure around CK Vul that is centered on the radio position.

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References

Asplund, M., Gustafsson, B., Lambert, D. L., & Kameswara Rao, N. 1997, *A&A* 321, L17
Bond, H. E., & Pollacco, D. L. 2002, *Ap&SS* 279, 31
Drew, J. E., *et al.* 2005, *MNRAS* 362, 753
Evans, A., *et al.* 2002, *MNRAS* 332, 35
Evans, A., *et al.* 2006, *MNRAS* in press (astro-ph/0609083)
Hajduk, M., *et al.* 2005, *Science* 308, 231
Herwig, F. 2001, *ApJL* 554, L71
Herwig, F. 2005, *ARA&A* 43, 435
Kerber, F., Köppen, J., Roth, M., & Trager, S. C. 1999, *A&A* 344, L79
Kerber, F., *et al.* 2002, *ApJL* 581, L39
Kimeswenger S. 2003, *Rev. Mex. Astron. Astrofis. Ser. Conf.* 15, 75
Naylor, T., Charles, P. A., Mukai, K., & Evans, A. 1992, *MNRAS* 258, 449
Pollacco, D. L. 1999, *MNRAS* 304, 127
Rao N. K., Venugopal V. R., & Patnaik, A. R. 1987, *JA&A* 8, 227
Seitter, W. C. 1987, *ESO Messenger* 50, 114
Shara, M. M., Moffat, A. A., & Webbink, R. F. 1985, *ApJ* 294, 271