The Very Fast Evolution of the VLTP Object V4334 Sgr

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Abstract. V4334 Sgr (Sakurai’s object) is an enigmatic evolved star that underwent a very late thermal pulse a few years before its discovery in 1996. It ejected a new, hydrogen-deficient nebula in the process. Emission lines from the newly ejected gas were first discovered in 1998 (He\textsc{i} 10830 Å) and 2001 (optical). We have monitored the optical emission spectrum since. From 2001 through 2007 the optical spectrum showed an exponential decline in flux, consistent with a shock that occurred around 1998 and started cooling soon after that. In this paper we show that since 2008 the line fluxes have been continuously rising again. Our preliminary interpretation is that this emission comes from a region close to the central star, and is excited by a second shock. This shock may have been induced by an increase in the stellar mass loss and wind velocity associated with a rise in the stellar temperature.

1. Introduction

V4334 Sgr (a.k.a. Sakurai’s object) is the central star of an old planetary nebula (PN) that underwent a very late thermal pulse (VLTP) a few years before its discovery in 1996 (Nakano et al. 1996). During the VLTP it ingested its remaining hydrogen-rich envelope into the helium-burning shell and ejected the processed material shortly afterwards to form a new, hydrogen-deficient nebula expanding at a velocity of approximately 300 km s\textsuperscript{-1} inside the old PN. The star brightened considerably and became a very cool, born-again asymptotic giant branch star with a spectrum resembling a carbon star. After a few years, dust formation started in the new ejecta and the central star became highly obscured. Emission lines were discovered: first He\textsc{i} 10830 Å in 1998 (Eyres et al. 1999), later in 2001 also optical forbidden lines from neutral and singly ionized nitrogen, oxygen, and sulfur, as well as very weak H\textalpha{} (Kerber et al. 2002). The distance to V4334 Sgr is poorly known, but is likely around 3 – 4 kpc.
2. Evolutionary Models

Sakurai’s object baffled the scientific community with its very fast evolution, must faster than pre-discovery models predicted. Three evolutionary models have been proposed to explain the fast evolution, all focusing on the hydrogen ingestion flash (HIF) in the helium burning shell. Herwig (2001) and Lawlor & MacDonald (2003) assume that hydrogen burning takes place close to the stellar surface due to the suppression of convection by the HIF. This is investigated further by Herwig using full 3D hydro models (Herwig et al. 2011, 2014). These models show that the hydrogen ingestion proceeds through a global non-radial instability, which facilitates the transition from one spherically symmetric state into another one, and could never be computed in 1D models. Lawlor & MacDonald (2003) were the first to predict the double-loop evolution in the HR diagram, later confirmed by Herwig’s model in Hajduk et al. (2005). Miller Bertolami et al. (2006) claim that they can reproduce very fast evolution by using very small time steps, but without changing the mixing physics. All of these models could be improved by constraining them with the temporal evolution of the stellar temperature. This was reasonably straightforward when the central star was still directly observable, but is much more difficult now that the star is heavily obscured.

![Figure 1](image_url)  
Figure 1. The evolution of the flux of various selected lines as a function of time.

3. Optical Observations

We have been monitoring the evolution of the optical emission line spectrum since 2001 using low-resolution spectra taken with FORS1 and FORS2 on the ESO-VLT. The goal of this monitoring program is to derive the central star temperature as a function of time. First progress reports can be found in van Hoof et al. (2007, 2008).
The optical lines initially showed an exponential decline in intensity, and also a decreasing level of excitation. This trend continued until 2007. Between 2001 and 2007 the optical spectrum is consistent with a shock that occurred before 2001, and started cooling and recombining afterwards. The low electron temperature derived from the [N ii] lines in 2001 (3200 – 5500 K) and the [C i] lines in 2003 (2300 – 4300 K) is consistent with this (van Hoof et al. 2007). The earliest evidence for this shock is the detection of the He i 10830 Å recombination line in 1998 (Eyres et al. 1999). This line was absent in 1997. The shock must have occurred around 1998 and must have stopped soon after, leaving cooling and recombining gas in its wake.

All line fluxes have been increasing since 2008! This is shown in Fig. 1 for some selected strong lines. The spectrum we observed in 2013 is shown in Fig. 2. This confirms the trend for the [C i] 9824 and 9850 Å doublet reported by Hinkle & Joyce (2014). There are two exceptions: [O i] 6300 Å already started increasing in 2007 and the [N i] 5198 and 5200 Å doublet still decreased in flux in 2008. However, these exceptions may not be real as the lines in question suffer from strong telluric contamination. Also note that there is a strong discontinuous jump in the [O ii] flux in 2008.

Here we report the first detection of several helium lines in 2008 (He i 5876 and 7065 Å) and 2009 (He i 6678 Å). Since 2010 the [S ii] 6716 and 6731 Å doublet is detected again. This is the first time this doublet is seen since 2001. This is due to a better signal-to-noise ratio in the spectra and the fact that the lines are brightening.
again. Kerber et al. (2002) detected Hα at 5% of the strength of [N ii] 6583 Å. Our spectra confirm this detection with a slightly greater strength of 7% of the [N ii] line.

4. Discussion

Hinkle & Joyce (2014) believe that the reheating of the central star has started, mainly based on an increase in the blackbody temperature of the dust. This suggests that an onset of photoionization could be the cause of the rising line fluxes. However, in the most recent VLA observations V4334 Sgr was only barely detected at around 50 µJy in 2012 and around 150 µJy in 2013, indicating that the radio flux must have dropped since the detections presented in Hajduk et al. (2005) and van Hoof et al. (2007, 2008). The last value they reported was 550 µJy in 2007. This seems inconsistent with an onset of photoionization. Alternatively, the sudden jump in the [O ii] flux in 2008 could point to a second shock as the cause of the rising fluxes and we will adopt this as our working hypothesis.

Kerber et al. (2002) observed two components in the shock-excited [N ii] 6548 and 6583 Å lines, one at a radial velocity of −350 km s\(^{-1}\) and one at +200 km s\(^{-1}\) relative to the central star. The blueshifted component was much stronger, resulting in the fact that the unresolved lines appeared blueshifted in the FORS spectra at about −270 km s\(^{-1}\) relative to the central star. However, since 2011 we see a clear shift in radial velocity and the emission lines now appear at about −120 km s\(^{-1}\) relative to the central star. This indicates that the emission lines seen up to 2007 came from a different region than those seen later on. Doing spectro-astrometry on the recent spectra indicates that the emission comes from a region less than 100 mas in size in the EW direction. Hinkle & Joyce (2014) find a larger extent in the (roughly) NS direction. This suggests that the bipolar structure seen by Chesneau et al. (2009) and Hinkle & Joyce (2014) could be the origin of the shock emission.

In Fig 3 we show various line ratios as a function of time. Note that these ratios are not corrected for extinction! The left panel shows two diagnostic ratios that are sensitive to electron temperature. Both indicate a decrease in electron temperature since
2008, assuming that the extinction is not increasing over time. This is inconsistent with photoionization and points to the presence of a shock. The line ratios suggest however that the electron temperature has been constant since 2012.

The right-hand panel of Fig. 3 shows line ratios of ionized over neutral species from nitrogen and oxygen. These ratios are more difficult to interpret. A change in density would affect the degree of ionization in the gas, and if the density is high enough, the line ratios would also be affected by a changing degree of collisional de-excitation. The latter doesn’t appear to be a problem as the observed $[\text{S} \text{ii}]$ line ratio indicates an electron density well below the critical density of all lines. The gas density could be dropping due to expansion of the nebula, or could be rising due to compression by the shock. Both line ratios indicate a drop in the degree of ionization (assuming that the extinction is not decreasing) at least since 2012. This is inconsistent with photoionization and would point to either the strength of the shock diminishing or the density of the gas increasing. Either interpretation would point to the presence of a shock.

If the central star temperature is indeed rising, as suggested by Hinkle & Joyce (2014), it could have caused an increase in the mass loss and wind velocity from the central star, which is now causing shock emission in the bipolar structure. The sudden jump in the $[\text{O} \text{ii}]$ flux, as well as the dropping electron temperature point to a shock. The rising flux could be due to the fact that the interaction area between wind and the bipolar structure is still growing and is now approaching a maximum. We would like to emphasize that the analysis of our data is not yet complete, and all scenarios presented here are preliminary.

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