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The Real-Time Evolution of 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. The source has been observed continuously since, at many wavelengths ranging from the optical to the radio regime. In this paper we evaluate these data and discuss the evolution of this object. We reach the conclusion that we have seen no evidence for photoionization of the nebula yet and that the spectral features we see are caused either by shocks or by dust. These shocks are an integral part of the hydrodynamic shaping that is now producing a new bipolar nebula inside the old planetary nebula (PN), implying that we have a detailed observational record of the very early stages of the shaping of a bipolar nebula.

Keywords: stellar mass loss; stellar evolution; planetary nebulae; circumstellar dust

1. Introduction

V4334 Sgr (also referred to as Sakurai's object, after the Japanese amateur astronomer who discovered this 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 [1]. As a result of the thermal pulse, the star brightened considerably and became a very cool, born-again asymptotic giant branch star with a spectrum resembling a carbon star. 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 inside the old PN. After a few years, dust formation started in the new ejecta, and the central star became highly obscured. An [O III] image of the old PN overlaid with contours showing the first detection of free-free emission from the new ejecta in the center can be found in Hajduk et al. [2]. The contours were derived from 8.6 GHz radio continuum observations obtained with the Very Large Array (VLA). The VLA data traced the old PN quite reasonably, while the central emission has no counterpart in the [O III] image and was only marginally resolved.

Emission lines of ionized species were discovered as follows: first He I 1083 nm was discovered in 1998 [3], and later, in 2001, optical forbidden lines from neutral and singly ionized nitrogen, oxygen, and sulfur, as well as very weak Hα were found [4]. Chesneau et al. [5] observed Sakurai's object using the Very Large Telescope Interferometer (VLTI) at the European Southern Observatory (ESO) Paranal site. They detected a thick and dense dust disk with dimensions of 30 $\times$ 40 mas. This equates to 105 $\times$ 140 AU, assuming a distance of 3.5 kpc. Hinkle and Joyce [6] discovered bipolar lobes using deconvolved *Ks* images taken with the NIRI/Altair instrument on Gemini in 2010 and 2013 (see Figure 2 in their paper). The expansion of the bipolar structure was clearly visible. Also, the central star seems to be brightening in the near-infrared wavelength range. Note that the old PN has a round shape, while the new ejecta are bipolar.

2. Optical Observations

V4334 Sgr stunned the scientific community with its very fast evolution that was much faster than pre-discovery models predicted. To constrain the evolutionary models, we decided to derive the evolution of the central star temperature over time. The expectation was that the rising stellar temperature would result in forbidden lines from different ions emerging with time. 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. A subset of these data was also discussed in earlier progress reports [7–12].

The optical lines initially showed an exponential decline in intensity and also a decreasing level of excitation (see Figure 1). This trend continued until 2007. Between 2001 and 2007, the optical spectrum was 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) was consistent with this [7]. The earliest evidence for this shock was the detection of the He I 1083 nm recombination line in 1998 [3]. This line was absent in 1997. Hence, the shock must have occurred around 1998 and must have stopped soon after, leaving cooling and recombining gas in its wake. In van Hoof et al. [7], the size of the [N II] emitting region was estimated to be 0.3–0.5 arcsec.

All line fluxes have been increasing since 2008. This is shown in Figure 1 for some selected strong lines. There are some minor exceptions for He I, [N I] and [O I] which are likely due to measurement errors and/or telluric contamination. This confirms the trend for the [C I] 982.4 and 985.0 nm doublet reported by Hinkle and Joyce [6]. Note that there was a strong discontinuous jump in the [O II] flux in 2008.

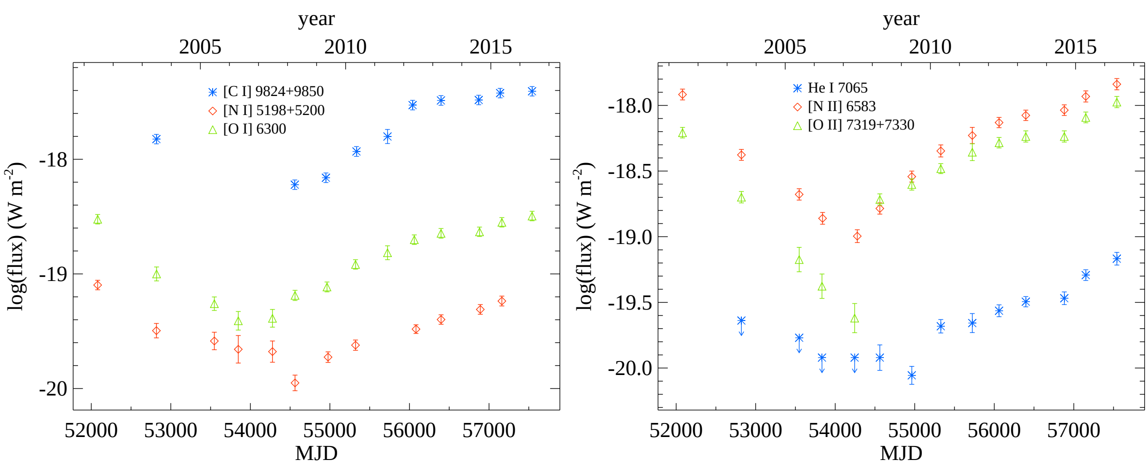

Figure 1. The flux evolution of selected lines in V4334 Sgr.

In 2015, we obtained a medium resolution echelle spectrum of V4334 Sgr using the Xshooter instrument at the ESO VLT. The slit was aligned along the bipolar axis (i.e., the position angle was PA = 13° east of north). In Figure 2, we show a position–velocity diagram of the [N II] 658.3 nm line. One can clearly see that the blue and red emissions come from different regions. The red-shifted and blue-shifted emission regions are +0.24 arcsec and −0.18 arcsec displaced with respect to the continuum source. This pattern is also seen in other forbidden and recombination lines (together referred to as nebular lines). From this, we conclude that the nebular emission lines originate in the bipolar lobes seen by Hinkle and Joyce [6].

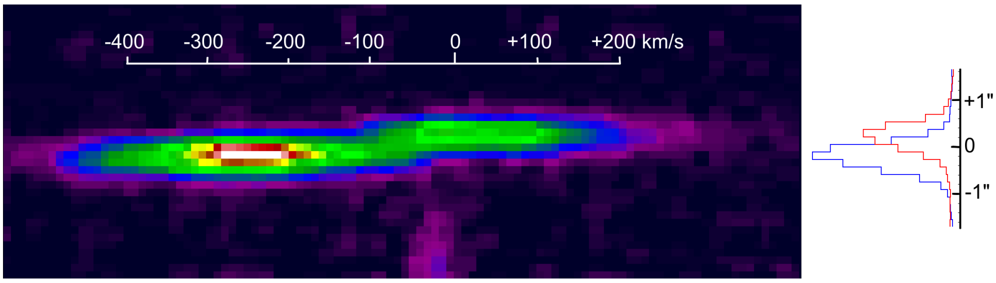

Figure 2. Position–velocity diagram of the [N II] 658.3 nm line taken at PA = 13°. Velocity runs along the x-axis, while position runs along the y-axis.

Since 2013, a complex of new lines has been emerging in the red. Many of these lines are still unidentified. The most prominent feature is shown in Figure 3. We have tentatively identified some of these as electronic transitions in CN (the 1,0 and 0,0 lines of A $^2\Pi_1 \rightarrow$ X $^2\Sigma^+$; the 0,0 lines would be the unidentified lines reported by Hinkle and Joyce [6]). We also identified the Na I doublet at 589.0 and 589.6 nm. The continuum is steadily rising, as was already reported by Hinkle and Joyce [6].

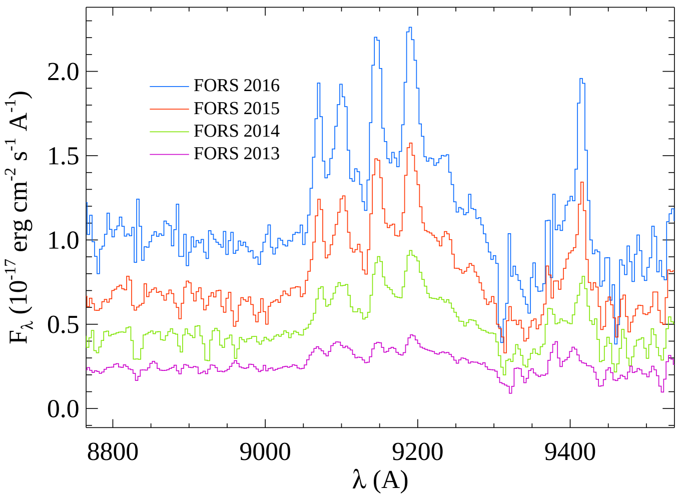

Figure 3. A complex of new emission lines that has been emerging since 2013. Note that the spectra have not been shifted.

3. Radio and ALMA Observations

Between 2004 and 2007, the 8 GHz radio flux was increasing. In van Hoof et al. [7], we interpreted this as evidence for the onset of photoionization of carbon. Since then, there has been a big gap in radio observations, but recently, we obtained new data that showed that the source has faded. The flux has dropped back to the levels of 2004 and 2005. This is inconsistent with photoionization of carbon, and the only plausible explanation is that the flux rise was due to a shock.

In 2015, we obtained Atacama Large Millimeter Array (ALMA) data of V4334 Sgr. The data set comprised a band 6 spectral scan, an incomplete band 7 spectral scan that was eventually rejected in quality control, and a continuum image. The band 6 spectral scan is shown in Figure 4 of van Hoof et al. [12]. We detected lines of CO, ^{13}CO, CN, likely ^{13}CN (blended), HC_3N, $HC^{13}CCN$, $HCC^{13}CN$, and possibly $H^{13}CCCN$. We also found CN absorption and a line at 239 GHz that was tentatively identified as CP.

We also created integrated images of the emission in each of the main emission lines. These are shown in Figure 4 where we also include the 2013 *Ks* image of Hinkle and Joyce [6] for comparison. One can see that the CN emission is spatially extended and coincides very nicely with the bipolar lobes detected by Hinkle and Joyce [6]. On the other hand, the CO, HC_3N, and the ALMA continuum image are nearly point-like and coincide with the central emission detected by Hinkle and Joyce [6]. This implies that these lines, as well as the dust emission, originate close to the central star, presumably from the disk detected by Chesneau et al. [5]. This implies that there is no dust emission detected in the bipolar lobes.

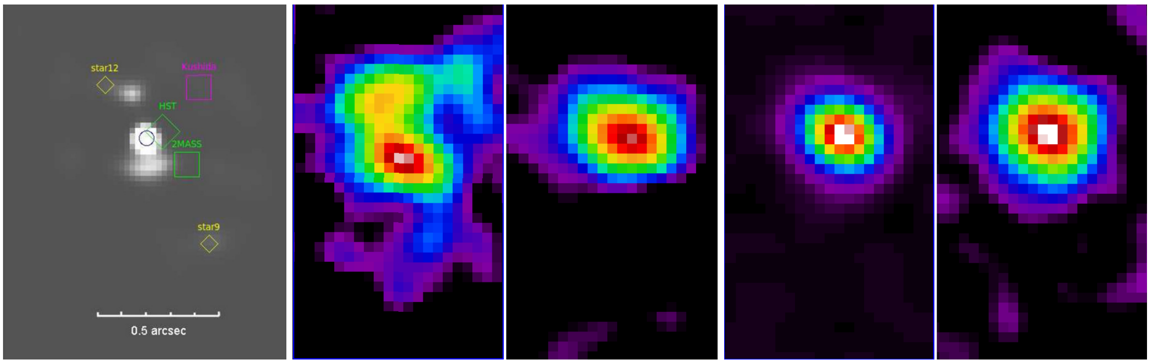

Figure 4. Panels from left to right: (1) the 2013 *Ks* image taken from Hinkle and Joyce [6] (© AAS, reproduced with permission); (2) the integrated CN emission observed with ALMA; (3) the integrated CO emission; (4) the continuum image; (5) the integrated HC_3N emission.

4. Preliminary Discussion

Using the data that have been presented in this paper, we reconstructed the following sequence of events. V4334 Sgr underwent a VLTP a few years before its discovery in 1996. It ejected a new hydrogen-deficient nebula in the process. The geometry of the source was clarified by Chesneau et al. [5] who discovered the presence of a dense and thick dust disk with dimensions of 30×40 mas using VLTI. All the dust was in the disk. The disk must have formed in the VLTP event (since there are no indications of the presence of hydrogen-rich material in the disk) and was already in place in 1997 (since it is responsible for obscuring the central star). It may be a Keplerian disk. Hinkle and Joyce [6] discovered the presence of bipolar lobes in the *Ks* band. These appear to be expanding. The total extent of these lobes along the major axis is approximately 0.4 arcsec.

Emission lines were first discovered in 1998 (He I 1083 nm) and 2001 (optical). The optical emission spectrum has been monitored since, initially showing an exponential decline in flux, while the level of excitation also dropped. We see this as evidence for a brief shock that occurred around 1998. A plausible explanation is that this is the fastest material ejected in the VLTP, hitting slower ejecta from the same event. Between 2005 and 2007, the 8 GHz radio emission showed a marked increase. The radio flux has returned to pre-2005 levels since. We see no counterpart for this behavior in the optical data. Our hypothesis is that this behavior was due to a shock in an obscured region. The optical line fluxes have started to increase again since 2008. The sudden jump in the [O II] flux in 2008 could point to a second shock as the cause of the change in behavior. Possibly this is the same shock that was already detected in radio emission and which now breaks out of the obscured region.

Our working hypothesis is that the central star wind is collimated into a bipolar jet and is now interacting with the lobes. So, the formation of the bipolar lobes may have started in 2008. The nebular lines were formed in the terminating bow shock. This was confirmed by Xshooter spectra. The optical spectrum shows new lines which have been emerging since 2013. Some have tentatively been identified as electronic transitions of CN and Na I. The optical CN lines, as well as the other lines that are emerging with them, formed close to the central star (based on Xshooter data that are not shown), possibly in the disk. If the optical CN lines are pumped by UV radiation from the central star, this is an indication that the reheating has started. Alternatively this could be a C-shock where the outflow is collimated by the disk into jets. In ALMA spectra, we detected the presence of CO, CN, HC_3N, and ^{13}C isotopologues. The CO and HC_3N (+isotopologues) emission is unresolved, so most likely comes from the disk. The ALMA CN and ^{13}CN emission was resolved and matched the bipolar lobes. A possible explanation is that CN is formed via shock-induced dissociation of HCN in the lobes. What is clear from these data is that we have a very detailed record of the very early stages of the hydrodynamic shaping of a bipolar nebula.

A more in-depth analysis of the available data will be presented in van Hoof et al. (A&A, in preparation).

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