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The i process in the post-AGB star V4334 Sgr

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Abstract. V4334 Sgr is a post-AGB star that underwent a VLTP a few years before 1996. During the event the hydrogen-rich outer layer was ingested into the He shell, creating conditions where i-process nucleosynthesis could take place. The enriched material was ejected almost immediately afterwards to form a new, hydrogen-deficient PN inside the old PN. In this paper we describe theoretical work to study the convective mixing during the VLTP event, as well as our observational campaign to study the ejecta.

Key words. Nuclear reactions, nucleosynthesis, abundances – Convection – Stars: AGB and post-AGB – Stars: evolution – Stars: individual: V4334 Sgr – planetary nebulae: general

1. Introduction

V4334 Sgr (Sakurai's object) is the central star of an old PN that underwent a very late thermal pulse (VLTP) a few years before its discovery in 1996 (Nakano et al., 1996). The evolution back to the AGB took until 1997. V4334 Sgr baffled scientists with this very fast evolution, much faster than pre-discovery models predicted. Herwig (2001) first reproduced very fast evolution by making the assumption that the efficiency for element mixing in the He-flash convection zone during the VLTP is 100 times smaller than predicted by mixing-length theory. A more detailed explanation is that during the VLTP, the central star ingested its remaining hydrogen-rich envelope into the He-

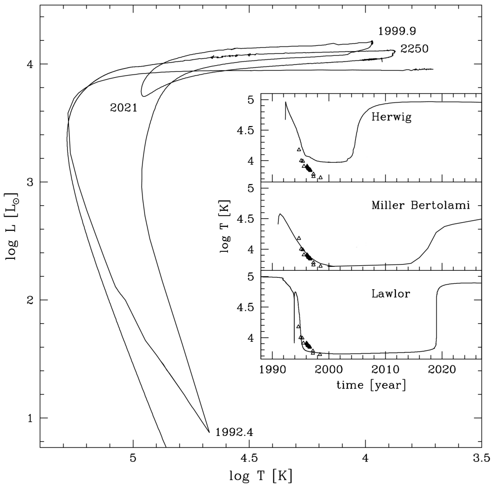

Fig. 1. The evolutionary model by Herwig (Hajduk et al., 2005; van Hoof et al., 2007), showing the double loop in the HR diagram. Sakurai's object is currently near the start of the first loop. The insets compare the observed values of the stellar temperature to various evolutionary models.

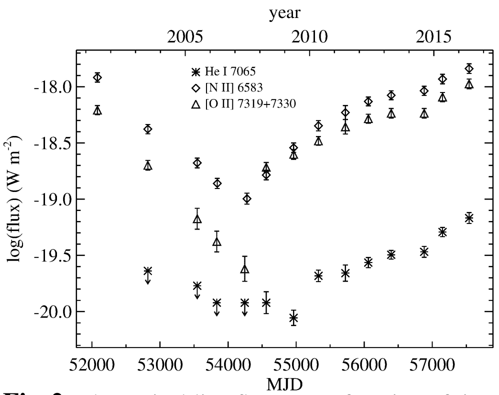

Fig. 2. The optical line fluxes as a function of time of selected nebular lines. (van Hoof et al., in prep.)

burning shell. This results in a separate hydrogen ingestion flash (HIF) in the upper layers of the He shell which produces i-process nuclear burning (with $^{13}C(\alpha,n)^{16}O$ as the neutron source). A fascinating feature of V4334 Sgr is that the i-process enriched material is ejected almost immediately afterwards to form a new, hydrogen-deficient nebula inside the old PN. This creates a rare opportunity to directly observe the products of the i process in space!

2. Evolutionary models

The ingestion of the remaining hydrogen-rich envelope causes the star to experience a double loop in the HR diagram (Fig. 1). The first loop is the result of the HIF and is very fast (on the order of decades) while the second loop results from the regular helium flash deeper in the helium shell. The second loop is slower (on the order of centuries). Several authors have produced evolutionary models for Sakurai's object. These models (Lawlor & MacDonald, 2003; Miller Bertolami et al., 2006; Herwig et al., 2011, 2014) could be improved by constraining them with the temporal evolution of the central star temperature.

3. Optical Monitoring

When the star heats up, it will start to photoionize the recently ejected material. This will produce dramatic changes in the emitted spectrum. We have been monitoring the evolution of the optical emission lines since 2001 using spectra obtained with FORS1&2 at ESO-VLT (Fig. 2). The goal of this monitoring program is to derive the stellar temperature as a function of time (van Hoof et al., 2007, 2008, 2015). From 2001 through 2007 the optical spectrum showed an exponential decline in flux and the level of excitation also dropped. We see this as evidence for a shock that occurred around 1998 and started cooling shortly afterwards. The line fluxes have been rising again since 2008. We ascribe these to a bow shock associated with the formation of the bipolar lobes discovered by Hinkle & Joyce (2014). To date we have found no evidence for photoionization.

4. Hydrodynamical simulations

We have been modeling the HIF with full 3D hydrodynamical simulations to study the evolution of the convective areas. These models have been described in Herwig et al. (2006, 2011, 2014). Herwig et al. (2011) show that standard mixing theory produces insufficient neutrons to explain the abundance pattern seen by Asplund et al. (1999). Based on 3D hydrodynamical models we adopted a delayed convective split that would separate the HIF from the regular helium flash. Using this informa-

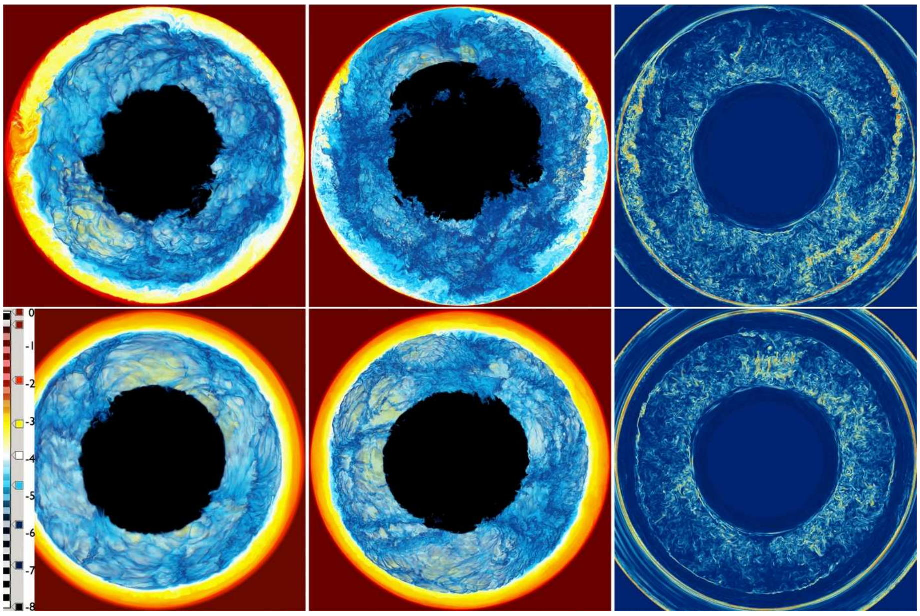

Fig. 3. Hydrodynamical models showing the convective mixing of H into the He burning shell in Sakurai's object. The left column shows a thick slice of the model using 768^3 cells, the middle column shows a model using 1536^3 cells, and the right-hand column the vorticity in the 1536^3 model. The top row is a snapshot at t=960 min and the bottom row at t=1100 min. The colors represent the H-rich H+He fluid, while black is the initially ^{12}C-rich core. (Herwig et al., 2014).

tion in evolutionary models, a sufficient neutron flux for the i process to take place could be reached and thereby explain the observed abundance pattern. In Herwig et al. (2014) the hydrodynamical models were improved, concentrating on the hydrodynamical aspects of the convection triggered by the HIF. A new instability was found, the Global Oscillation of Shell H-ingestion (GOSH), which however is not the convective split adopted in the 1D nucleosynthesis models (Fig. 3).

5. ALMA observations

The i-process enriched material that was ejected during the VLTP has since formed molecules and dust. We obtained ALMA observations where we detect the presence of CO, CN, HC_3N, and ^{13}C isotopologues (Fig. 4). Unfortunately we did not detect any other isotopes that would allow us to constrain the i process simulations further (the ^{12}C/^{13}C ratio was already known from Asplund et al., 1999). The ALMA data show that the CN emission has a bipolar distribution very similar to the bipolar lobes seen by Hinkle & Joyce (2014). The other molecules are spatially unresolved and most likely reside in the circumstellar disk discovered by Chesneau et al. (2009).

6. Binary evolution

In Denissenkov et al. (2017) it is shown that a rapidly accreting white dwarf in a close binary system can produce the necessary conditions to activate the i process and produce abundance patterns very similar to those in Sakurai's object. This opens the possibility to explain Sakurai's object as the result of binary evolution. However, it remains to be shown that a binary evolution channel can reproduce the temperature evolution of Sakurai's object.

7. Summary

V4334 Sgr is a post-AGB star that underwent a VLTP a few years before 1996. During the

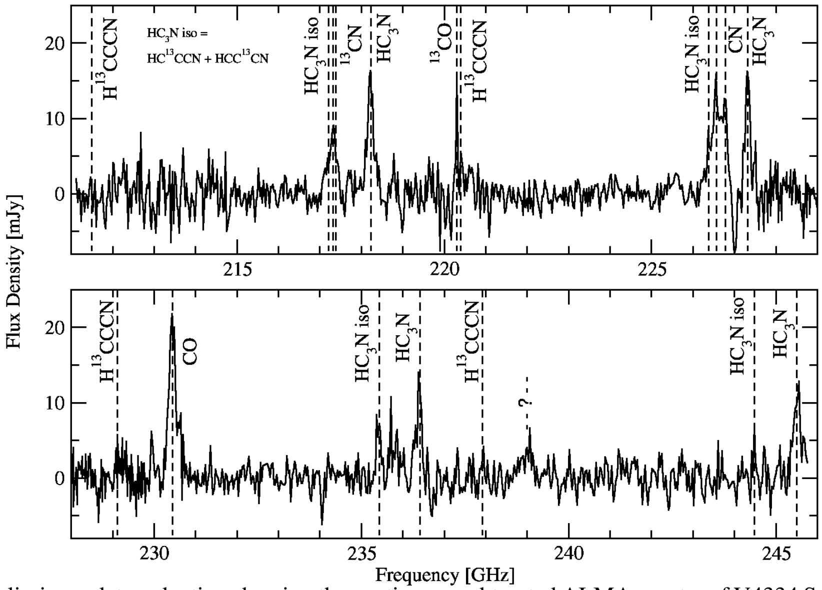

Fig. 4. Preliminary data reduction showing the continuum subtracted ALMA spectra of V4334 Sgr obtained in 2015. (Kimeswenger et al., in prep.).

event the hydrogen-rich outer layer was ingested into the He shell, creating conditions where i-process nucleosynthesis could take place. The enriched material was ejected almost immediately afterwards to form a new, hydrogen-deficient PN inside the old PN.

Detailed hydrodynamical simulations of the convection zone were undertaken, confirming that the HIF creates a split in the convection zone which separates the HIF from the regular helium flash. This produces a double-loop evolution in the HR diagram.

Both a single or a double-star channel could explain the i-process abundance patterns seen in V4334 Sgr. The latter could be consistent with the bipolar shape of the new PN. A campaign to obtain additional constraints for the evolutionary models using ESO-VLT and ALMA has so far not yielded new constraints. This campaign will be continued.

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