11th Pacific Rim Conference on Stellar Astrophysics IOP Publishing
Journal of Physics: Conference Series **728** (2016) 032006 doi:10.1088/1742-6596/728/3/032006

The rapid evolution of the central star of the Stingray Nebula – latest news from the HST

Nicole Reindl[1], **Thomas Rauch**[1], **Marcelo M. Miller Bertolami**[2] and **Klaus Werner**[1]

[1] Institute for Astronomy and Astrophysics, Kepler Center for Astro and Particle Physics, Eberhard Karls University, Sand 1, 72076 Tübingen, Germany
[2] Instituto de Astrofísica de La Plata, UNLP-CONICET, La Plata, Buenos Aires, 1900, Argentina

E-mail: `reindl@astro.uni-tuebingen.de`

Abstract. SAO 244567 is an unusually fast evolving star. Within twenty years only, it had turned from a B-type supergiant into the central star of the Stingray Nebula. Space- and ground-based observations obtained over the last decades have revealed that its spectrum changes noticeably over just a few years, showing stellar evolution in real time. The low mass of SAO 244567 is, however, in strong contradiction with canonical post-asymptotic giant branch evolution. Thus, its fast evolution has been a mystery for decades. We present preliminary results of the non-LTE spectral analyis of the recently obtained HST/COS observations, which finally allow us to shed light on the evolutionary history of this extraordinary object.

1. Introduction

Rapid changes of the observable properties of SAO 244567 were at first noticed by [1, 2]. Based on a spectral classification of the optical spectrum obtained in 1971 and the UBV colors, they concluded that SAO 244567 was a B-type supergiant with an effective temperature of $T_{\rm eff} \approx 21\,{\rm kK}$. However, the optical spectra from 1990 and 1992 as well as UV spectra from 1992 on display many nebular emission lines, indicating that SAO 244567 has ionized its surrounding nebula only two decades later. [3] and [4] presented the first spatially resolved images of the planetary nebula (PN) and named it Stingray Nebula.

In [5] the first quantitative spectral analysis of all available spectra from 1988 to 2006, that were taken with various space-based telescopes, was presented. It was found that the central star has steadily increased its $T_{\rm eff}$ from 38 kK in 1988 to a peak value of 60 kK in 2002. During the same time, the star was contracting, as concluded from an increase in surface gravity from $\log g = 4.8$ to 6.0 and a drop in luminosity. Simultaneously, the mass-loss rate declined from $\log(\dot{M} / M_\odot\,{\rm yr}^{-1}) = -9.0$ to -11.6 and the terminal wind velocity increased from $v_\infty = 1800\,{\rm km/s}$ to $2800\,{\rm km/s}$. The surface composition is largely solar with the exception of slightly subsolar C, P, and S, indicating that the possible asymptotic giant branch (AGB) phase of the star was terminated before the third dredge-up. We confirmed previous findings, that SAO 244567 must be a low mass star ($M < 0.55\,M_\odot$). This low mass, however, contradicts the rapid heating if a canonical post-AGB evolution is assumed [2, 4], because for such a rapid evolution the core mass should be around $0.7\,M_\odot$ [6]. [5] speculated that the star might had experienced a late thermal pulse (LTP) shortly after leaving the AGB, because the evolutionary speed of late He-shell flash objects is very high. Within the next decades an LTP scenario would predict for SAO 244567 an evolution back to the AGB, i.e., a cooling of the star. To follow the evolution of the surface properties of SAO 244567 and verify the LTP hypothesis, we applied for further observations with HST/COS.

2. Observations and spectral analysis

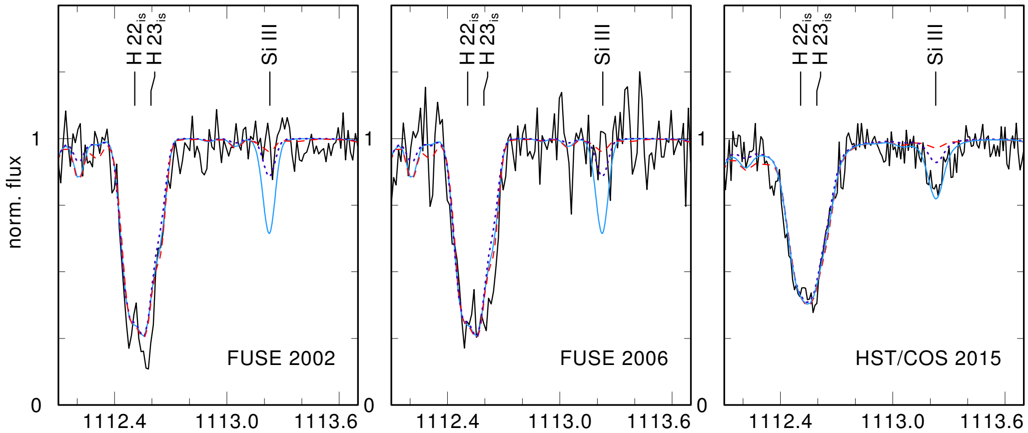

Figure 1. Emergence of Si III λ 1113.2 Å in the HST/COS observation taken in 2015 (right). This line was not visible in the FUSE observation in 2002/2006 (left/middle) when the star was about 10/5 kK hotter. The dotted red / dashed purple line corresponds to TMAP models with $T_{\mathrm{eff}} = 60/55$ kK (best fit for 2002/2006), while the solid blue line represents a model with $T_{\mathrm{eff}} = 50$ kK (best fit for 2015). Note that the differences in the line profiles are caused by the instruments' line spread functions.

The observations were successfully performed on August 9, 2015, more than nine years after the star was observed by an UV telescope the last time. We obtained FUV medium-resolution (grating G130M) and low-resolution FUV and NUV spectra (gratings G140L and G230L) spectra.

The new observations reveal that the flux level decreased by a factor of 1.55/1.4 compared to FUSE observations in 2002/2006. Thanks to the good signal-to-noise ratio (S/N), we could identify lines of Cr and Ni for the first time. Furthermore, we find that the N V resonance lines show blue shifted absorption wings, which might indicate the presence of a very weak stellar wind. Finally, we discovered the emergence the Si III λ 1113.2 Å line in the new HST/COS spectra (Fig. 1). This line was not visible in the previous FUSE observations, which cover this wavelength range as well and have about the same resolving power ($R \approx 20\,000$).

For the quantitative spectral analysis we used the Tübingen non-LTE Model-Atmosphere Package (TMAP, [7, 8, 9]), which allows the computation of fully metal-line blanketed model atmospheres in radiative and hydrostatic equilibrium. Our model grid included opacities of the elements H, He, C, N, O, Si, P, S, Cr, Fe, and Ni. The model atoms were taken from the Tübingen Model-Atom Database TMAD and calculated (Cr, Fe, Ni) via the Tübingen IRon Opacity interface TIRO [10]. In addition, we employed the program OWENS to model the ISM line-absorption spectrum.

We found, that Si III λ 1113.2 Å was not visible in the FUSE observation in 2002, because the star was about 10 kK hotter in 2002 compared to 2015 where we find the best fit at $T_{\mathrm{eff}} = 50$ kK. This value is also confirmed by evaluating additionally the ionization equilibria of C III / C IV, N III / N IV, O III / O IV / O V, and S IV / S V / S VI. The good S/N allows to reduce the error on T_{eff}

to ±2.5 kK. We conclude that the star has cooled significantly since 2002. The newly identified lines of Cr and Ni allowed to measure their abundances for the first time. They are solar. Moreover, we confirm the abundance values of all the other elements derived in our previous analysis, i.e., no hint of a change in the chemical abundances was found.

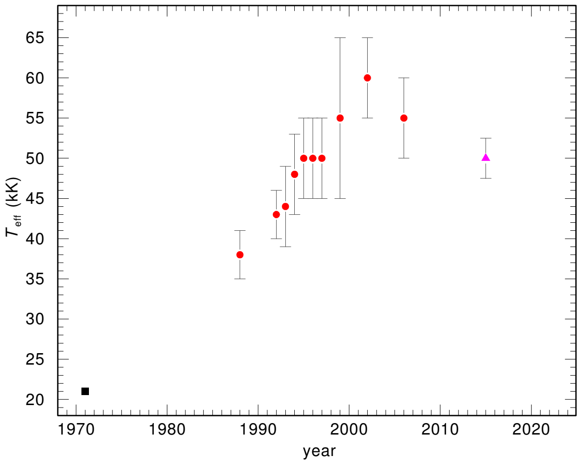

Figure 2. Temporal evolution of $T_{\rm eff}$. The square indicates the $T_{\rm eff}$ estimate of [2] when SAO 244567 was still a B-type supergiant. Dots correspond to $T_{\rm eff}$ values as derived by [5] and the triangle is the value measured with the new HST/COS observations performed in 2015. Note that the cooling rate of SAO 244567 (770 ± 580 K/yr) is similar to that of FG Sge (350 K/yr, [14]), the only other hitherto known LTP object.

3. Conclusions

SAO 244567 provides us with the rare opportunity to study stellar evolution in real time. Its primarily rapid heating (heating rate from 1988 to 2002: 1570 ± 570 K/yr, Fig. 2), followed by the rapid cooling (−770 ± 580 K/yr, Fig. 2) strongly supports the LTP evolutionary scenario (Fig. 3). LTPs are expected to occur to a significant fraction of the post-AGB stars while evolving with roughly constant luminosity from the AGB towards the white dwarf domain. Differently to very LTPs, which occur only on the early white dwarf cooling track and produce a hydrogen-free stellar surface already during the flash, a normal surface composition holds up after an LTP. Only when the star evolves back to the Hayashi limit on the AGB ($T_{\rm eff} \lesssim 7000\,{\rm K}$), envelope convection can set in again [11, 12, 13]. This was actually observed in case of FG Sge, the only other star known to date that certainly must have suffered an LTP. This star has been transformed over an interval of 120 years from a hot, hydrogen-rich post-AGB star into a very luminous cool supergiant (Fig. 3). [14] showed that, after its return to the AGB, the surface H fraction of FG Sge got diluted significantly (from 0.9 to 0.01, by number) while s-process abundances increased.

We note that SAO 244567 must be in an earlier evolutionary stage than FG Sge, as it was observed during its heating as well as its cooling phase. Moreover, the numerous UV observation taken over three decades as well as the use of sophisticated non-LTE model atmosphere codes allowed us to precisely record the evolution of this extraordinary object. Therefore the derived surface parameters will establish constraints for LTP evolutionary calculations. These calculations in turn may not only explain the nature of SAO 244567, but they could also provide a deeper insight in the formation process of hydrogen-deficient stars, which make up about a quarter of the post-AGB stars and white dwarfs.

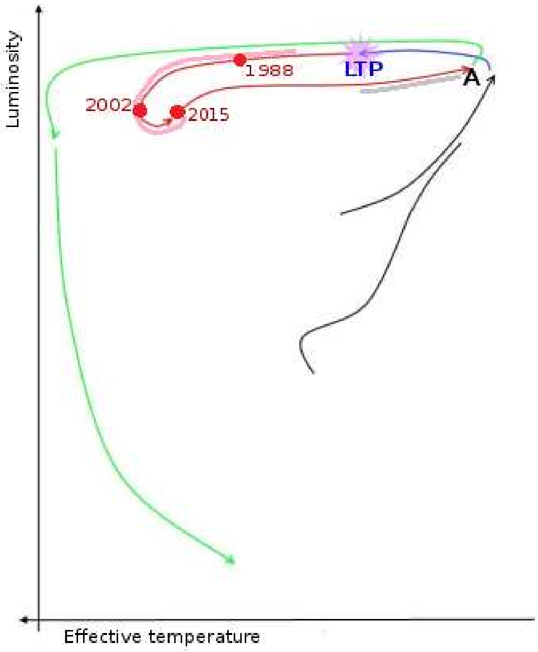

Figure 3. Sketch of an LTP evolution of SAO 244567 in the Hertzsprung-Russell diagram. The observed evolutionary path of SAO 244567 is indicated by the pink line, whereas the observed path of FG Sge is shown in gray. “A” corresponds to the point when the star reaches the Hayashi limit on the AGB and becomes H-deficient. “A” also corresponds to the recent position of FG Sge.

Acknowledgments

N.R. and T.R. are supported by the German Aerospace Center (DLR, grant 50 OR 1507).

References

[1] Parthasarathy M, Garcia-Lario P, Pottasch S R, Manchado A, Clavel J, de Martino D, van de Steene G C M, Sahu K C 1993 *Astron. Astrophys.* **267** L19
[2] Parthasarathy M, Garcia-Lario P, de Martino D, Pottasch S R, Kilkenny D, Martinez P, Sahu K C, Reddy B E, Sewell B T 1995 *Astron. Astrophys.* **300** L25
[3] Bobrowsky M 1994 *Astrophys. J. Lett.* **426** L47
[4] Bobrowsky M, Sahu K C, Parthasarathy M and García-Lario P 1998 *Nature* **392** 469
[5] Reindl N, Rauch T, Parthasarathy M, Werner K, Kruk J W, Hamann W-R, Sander A and Todt H 2014 *Astron. Astrophys.* **565** A40
[6] Miller Bertolami M M 2015 *Astron. Astrophys.* **588** A25
[7] Werner K, Dreizler S and Rauch T 2012 *Astrophysics Source Code Library* [record ascl:1212.015]
[8] Werner K, Deetjen J L, Dreizler S, Nagel T, Rauch T and Schuh S L 2003 *Stellar Atmosphere Modeling* eds Hubeny I, Mihalas D and Werner K (ASP Conf. Series vol 288) p 31
[9] Rauch T and Deetjen J L 2003 *Stellar Atmosphere Modeling* eds Hubeny I, Mihalas D and Werner K (ASP Conf. Series vol 288) p 103
[10] Müller-Ringat E 2013 Dissertation, University of Tübingen, Germany, `http://nbn-resolving.de/urn:nbn:de:bsz:21-opus-67747`
[11] Blöcker T and Schönberner D 1996 *Memorie della Societa Astronomia Italiana* **67** 665
[12] Blöcker T and Schönberner D 1997 *Astron. Astrophys.* **324** 991
[13] Schönberner D 2008 *Hydrogen-Deficient Stars* eds Werner W and Rauch T (ASP Conf. Series vol 391) p 139
[14] Jeffery C S and Schönberner D 2006 *Astron. Astrophys.* **459** 885