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Stellar Evolution in Real Time: The Exciting Star of the Stingray Nebula

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APN VI

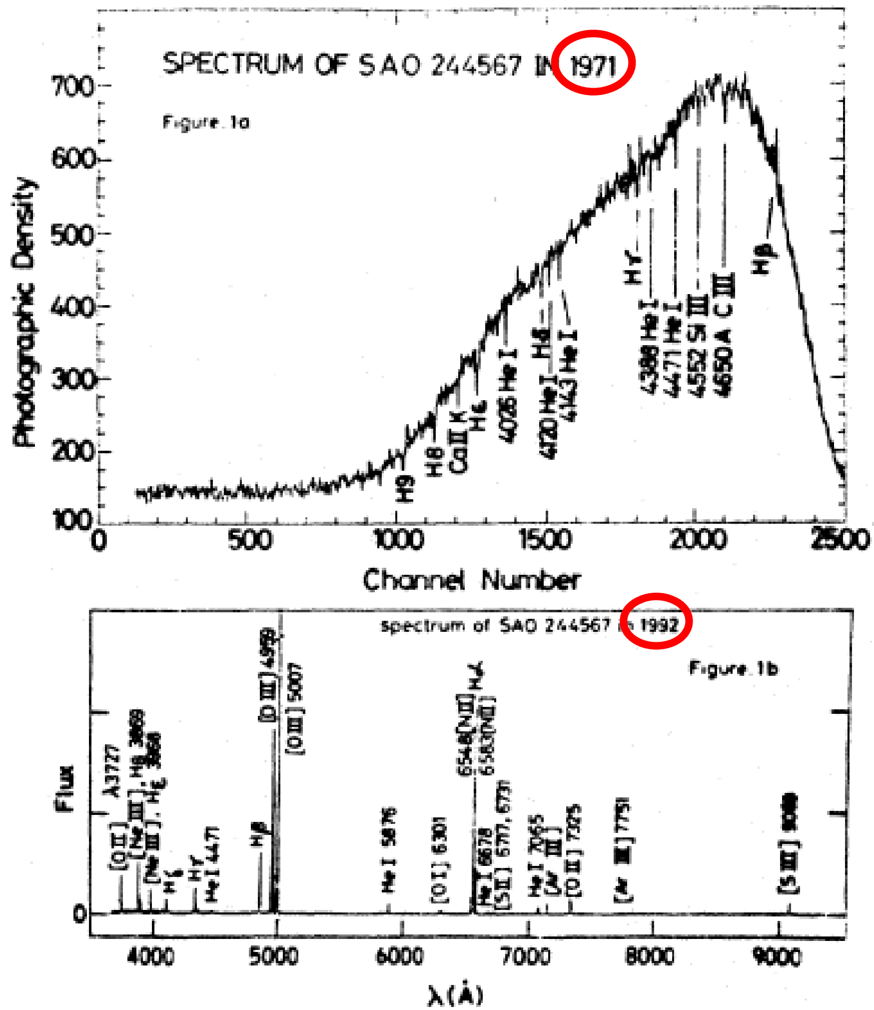
History of SAO 244567

- **~1950:** weak emission-type star with weak – moderate Hα emission, (Henize 1976)
- **1971:** Spectral classification based on optical spectrum (only Hβ relatively strong in emission) and UBV colors:

  → B-type supergiant with $T_{\rm eff}$ = 21 000 K

- Optical spectra (1990,1992), IUE spectra (from 1992 on), narrow-band HST imaging (1992):

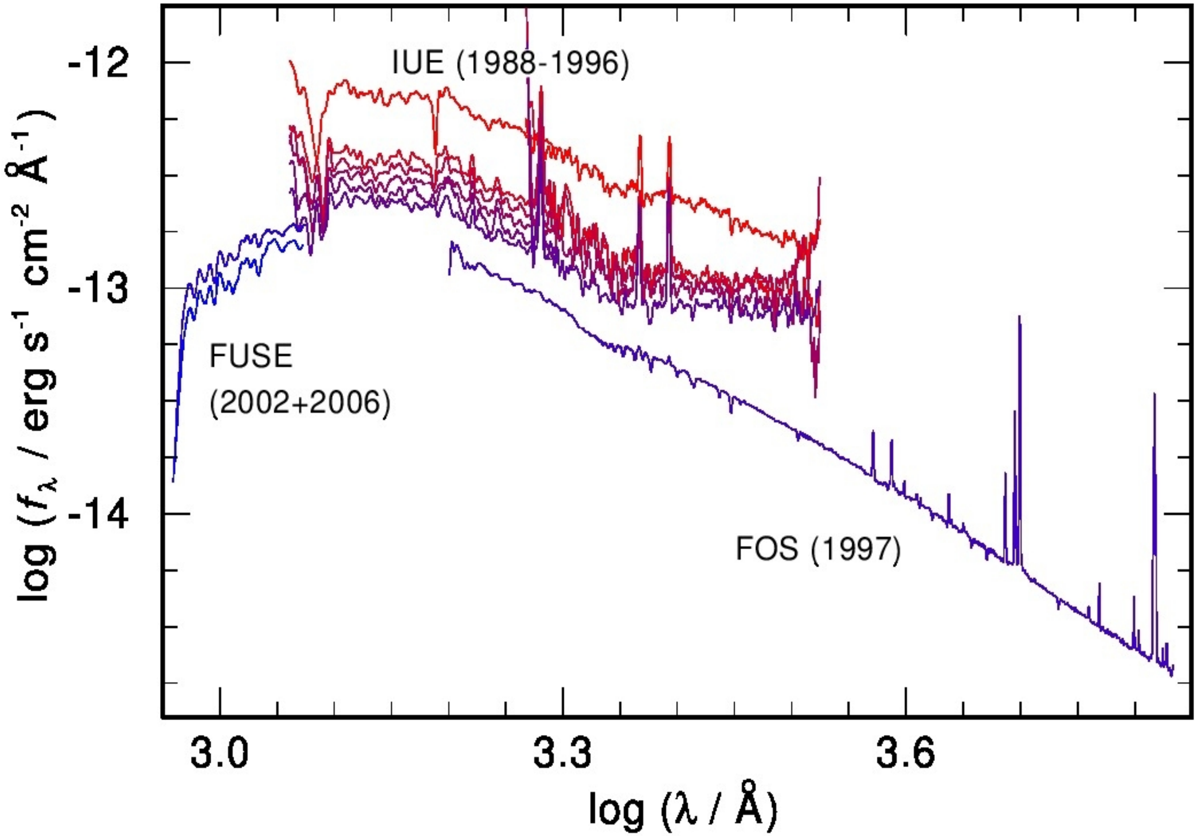
  SAO 244567 has turned into a CSPN within 20 years!



Parthasarathy 1995

Observations

- SAO 244567 was observed with various telescopes.
- Flux level seems to decrease continuously from 1988 to 1997.
- P-Cygni profiles became weaker with time
- Change of ionization equilibria
- Until now: No quantitative analysis of CS spectra



All available, reliably flux-calibrated observations of SAO 244567.

Spectral Analysis

- ***TMAP*** (Tübingen NLTE Model-Atmosphere Package, Werner et al. 2003), plane-parallel, metal-line blanketed, radiative and hydrostatic equilibrium

  → **effective temperature, surface gravity, abundances**

- Comparison with evolutionary tracks in the log g – log T_{eff} diagram

  → **mass, luminosity**

- ***PoWR*** (Potsdam Wolf-Rayet model-atmosphere code)

  → **mass-loss rate, terminal wind velocity, effective temperature, surface gravity**

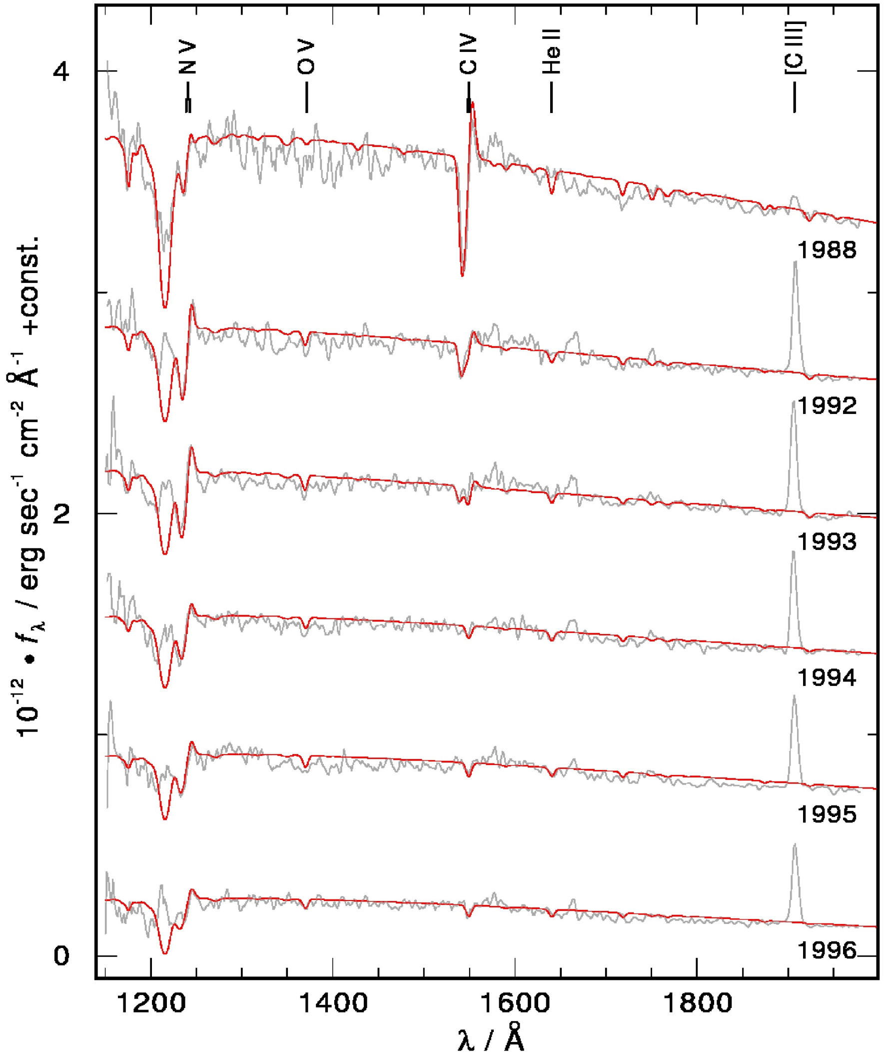
- Modeling the ISM line spectrum with ***owens*** (M. Lemoine, FUSE French Team)

TMAP Analysis

- H+He models for a coarse determination of T_{eff}, log g and the H/He ratio using the He II lines in the STIS and FOS spectra
- H+He+C models: T_{eff} determination using ionization equilibrium of C III / C IV, determination of C abundance (FOS, STIS, FUSE)
- Other ionization equilibria found in the FUSE spectra: N III / N IV, O III / O IV, and S IV / S V / S VI
- Determination of the N, O, Ne, Mg, Si, P, S, Fe, and Ni abundances

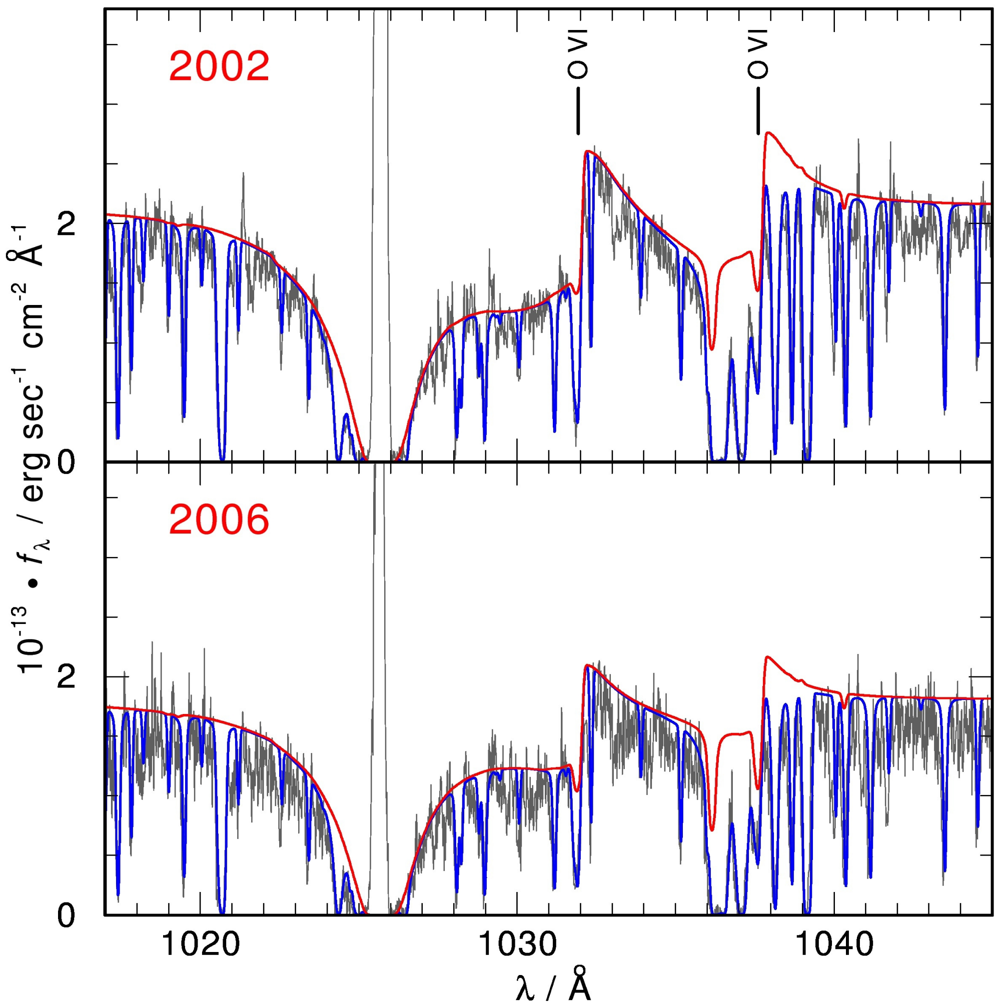
PoWR Analysis

- Element abundances from the *TMAP* analysis, mass and luminosity from evolutionary tracks
- Calculation of a grid, varying T_{eff}, $\dot{M}$, v_∞
- Comparison to the observed P-Cygni profiles of N **V** and C **IV** (IUE spectra), and O **VI** (FUSE)



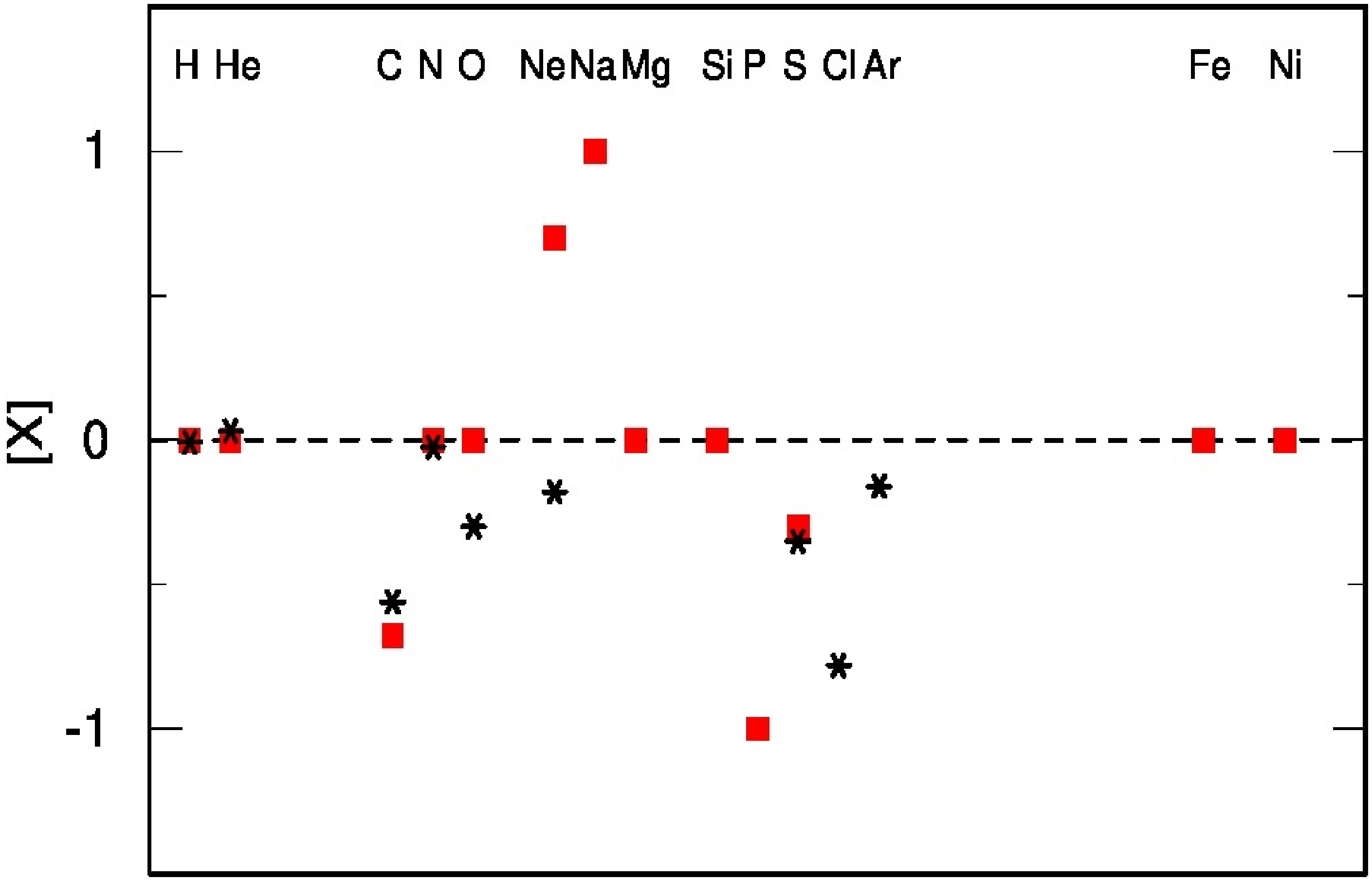
Comparison of our best-fit models (red) with the IUE spectra (gray)

PoWR Analysis



Comparison of our best-fit models (red: pure stellar spectrum, blue: stellar+ISM spectrum) with the observed O VI P-Cygni profiles in the FUSE spectra (gray).

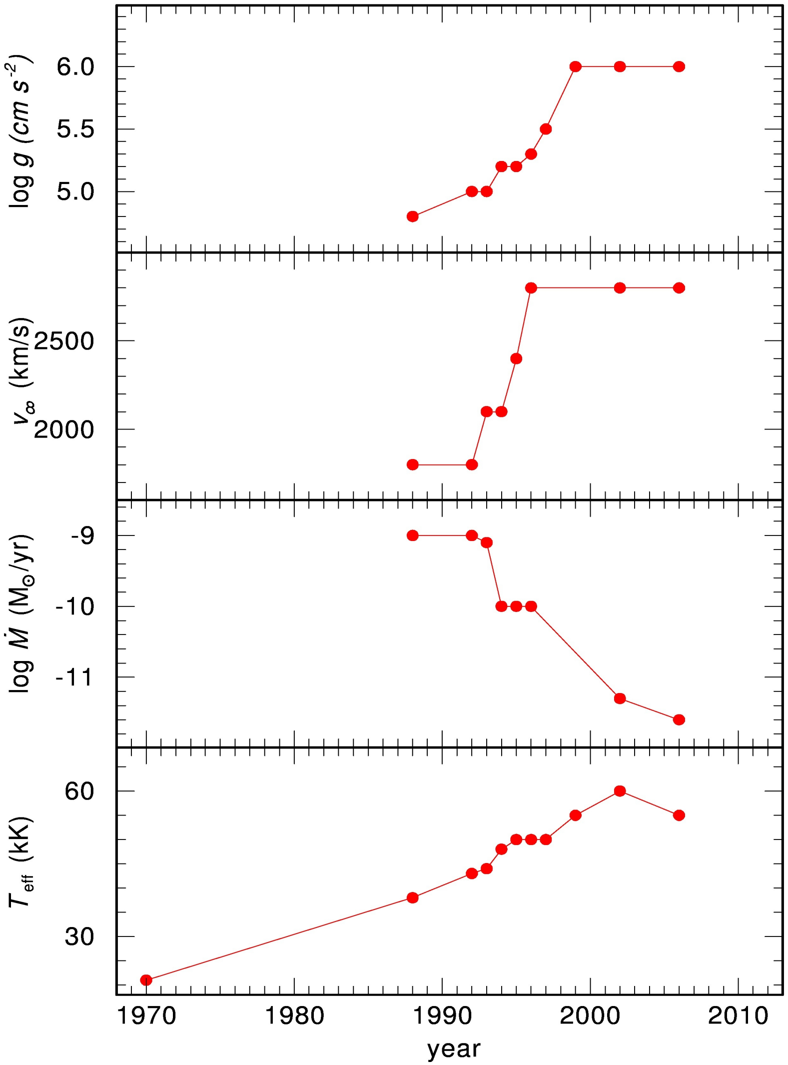
Element abundances



Element abundances of the CS (red squares) and its PN (black stars)

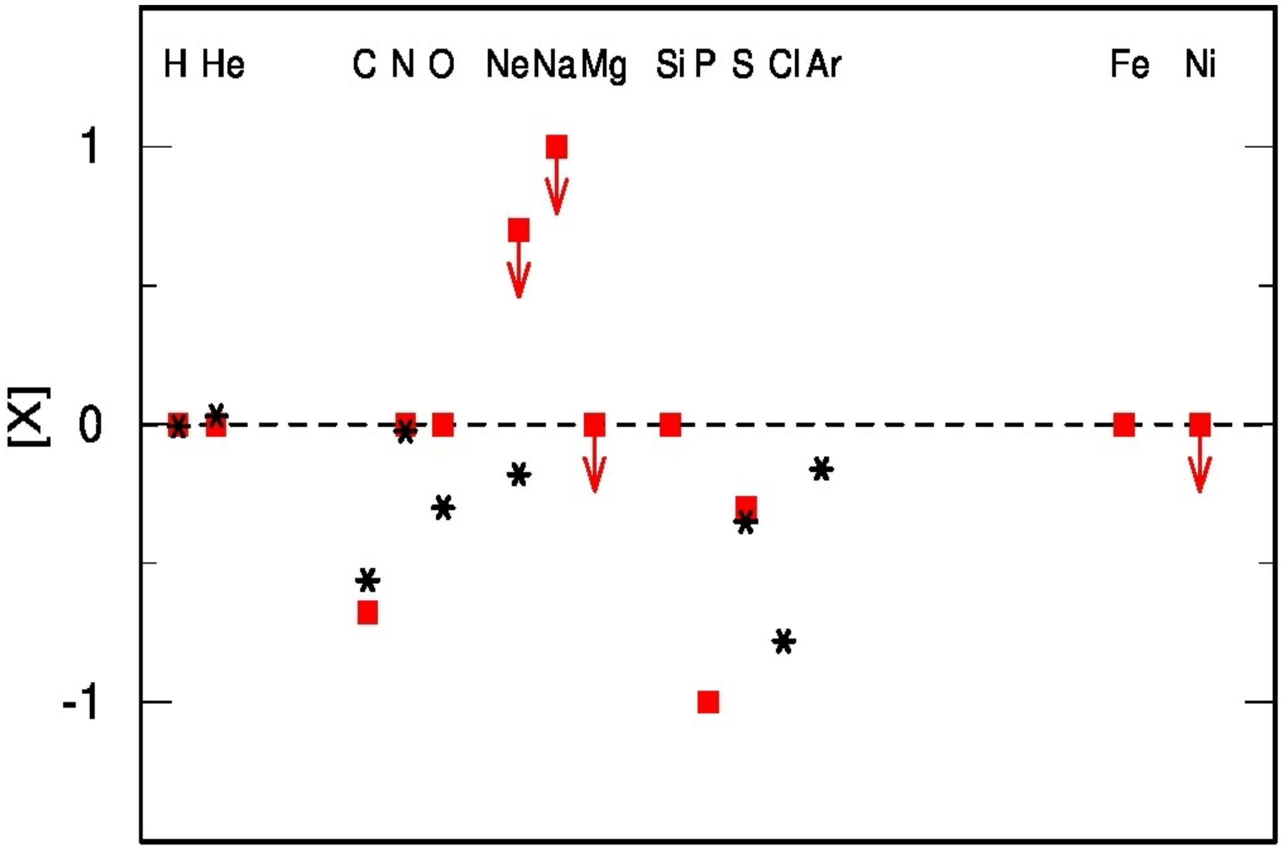
Results

- Increase of T_{eff} about 40 kK within 30 years only!
- Mass-loss rate dropped continuously from $10^{-9.0}$ in 1988 to $10^{-11.6}$ $M_{\odot}$/yr in 2006
- Mass-loss rate in 1988 in agreement with what is predicted by radiative-driven wind theory (Vink & Cassisi 2002)
- Terminal wind velocity increased continuously from v_{∞} = 1800 km/s in 1988 to v_{∞} = 2800 km/s in 2006
- Consistent with the contraction of the star (increase of log g)



Temporal evolution of T_{eff}, $\dot{M}$, v_{∞}, and log g.

Element abundances



Element abundances of the CS (red squares) and its PN (black stars)

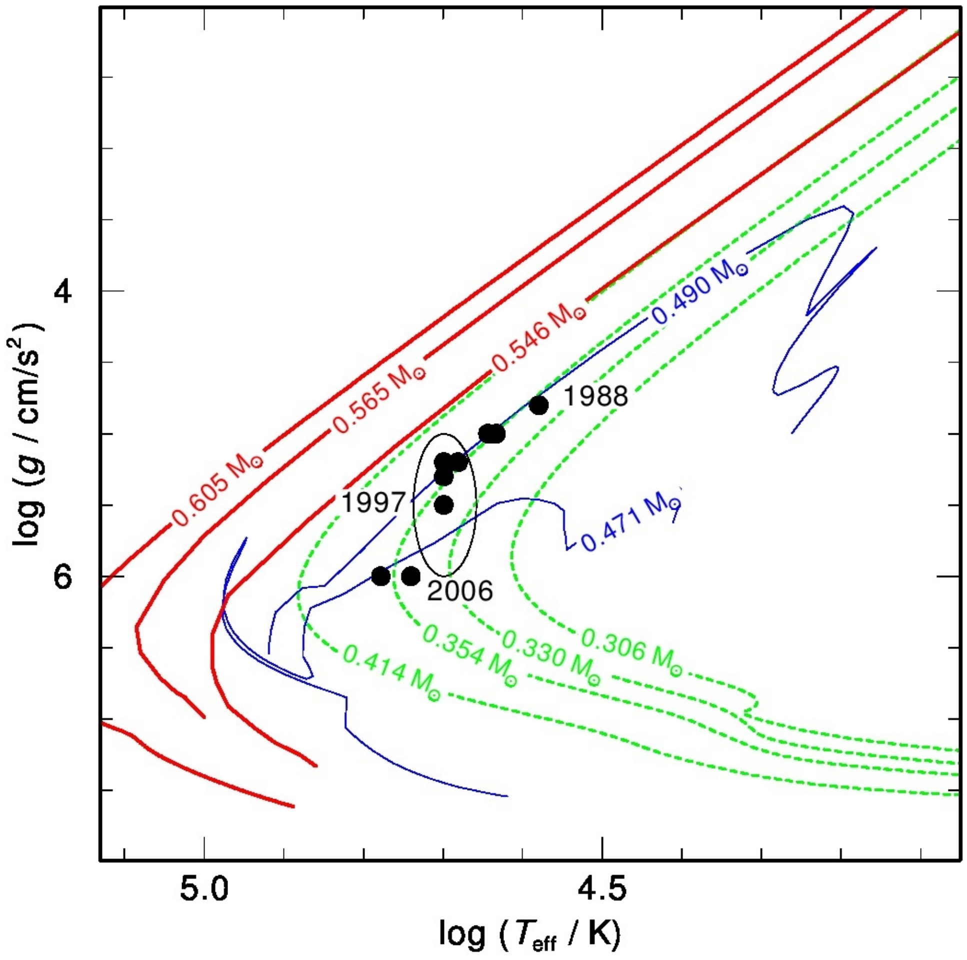
Distance

- Using the flux calibration of Heber et al. (1984), we found

$$\boldsymbol{d = 1.6\ \mathrm{kpc}, \quad z = 0.3\ \mathrm{kpc}, \quad R_{\mathrm{PN}} = 0.01\ \mathrm{pc}}$$

- Using an expansion velocity of 8.4 km/s (Arkhipova et al. 2013) the **kinematic age** of the PN is about **1000 years**

Evolutionary Status



Determination of the mass in the log g - log T_{eff} diagram

Post-AGB tracks (Blöcker 1995)

Post-EHB tracks (Dorman et al. 1993)

Post-RGB tracks (Hall et al. 2013)

→ SAO 244567 must be a low-mass star!

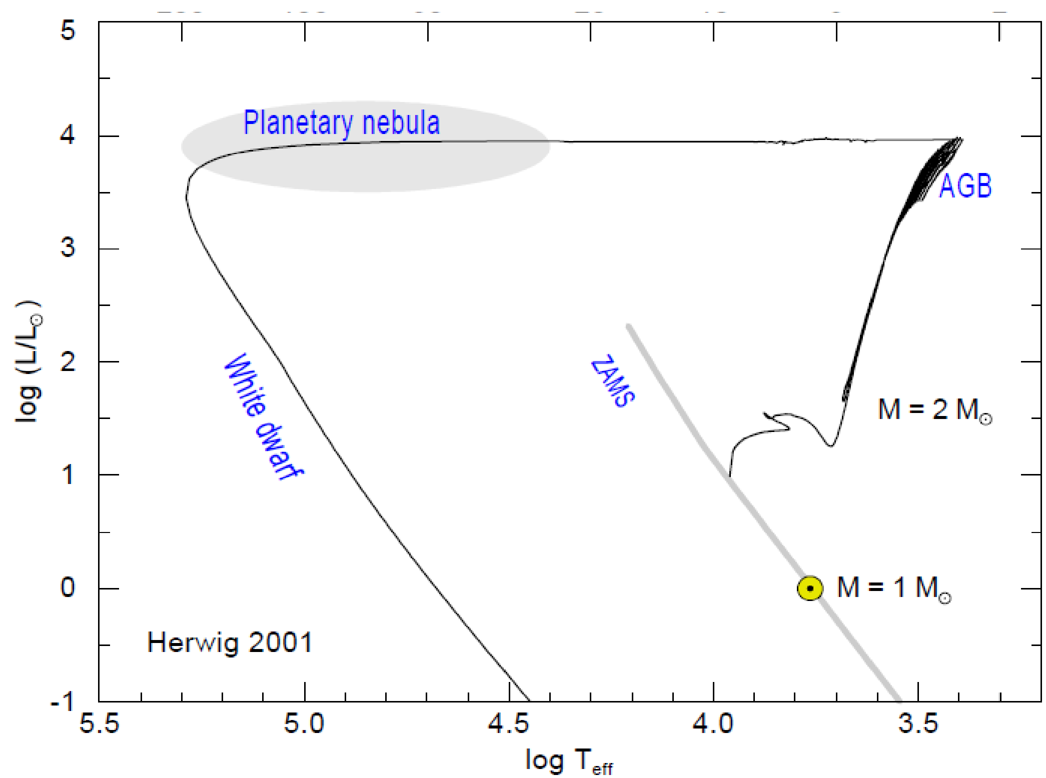
→ Based on the position in the log g – log T_{eff} diagram, SAO 244567 can be classified as an sdO star

Evolutionary Status

- Low-mass post-AGB star?

  → Normally, only post-AGB stars are expected to form a PN

  → Time scales correspond to a 0.87 $M_\odot$ star considering canonical post-AGB evolution (Blöcker et al. 1995)

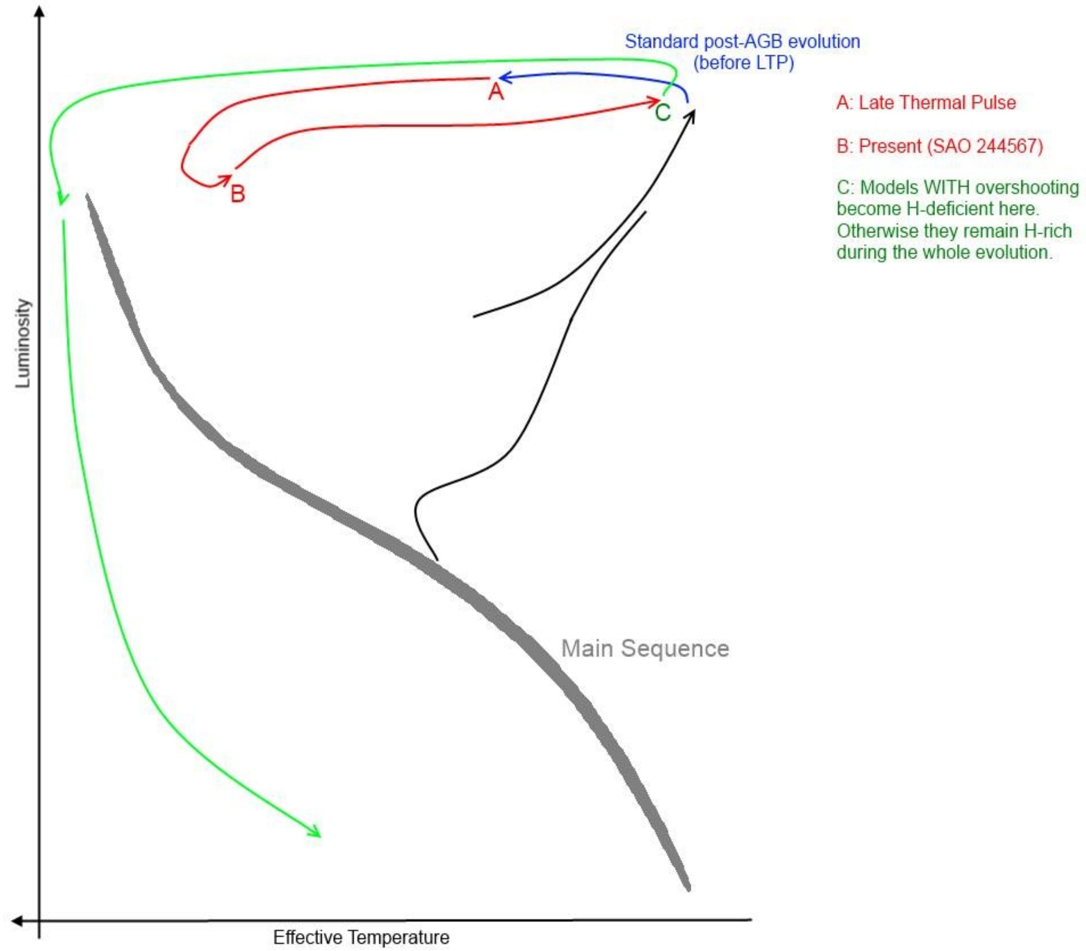


Evolutionary Status

- Late thermal pulse object?

→ Evolutionary time scales of (very) late thermal pulse objects (V605 Aql, V4334 Sgr, FG Sge) are of the order of decades

→ No sequences for low-mass stars exist



Sketch of a LTP sequence for SAO 244567 (Miller Bertolami, priv. comm.)

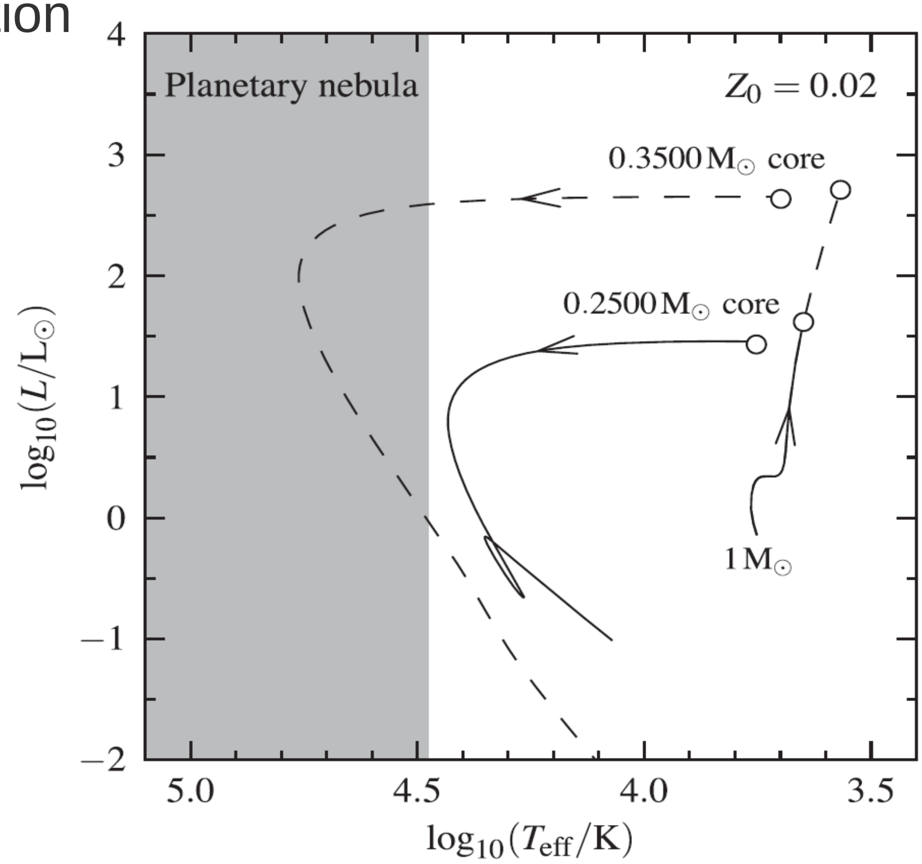
Evolutionary Status

- Post-RGB star?

→ Hall et al. (2013): low-mass ($M > 0.3\ M_\odot$) post-RGB can be CSPNe after a common-envelope ejection

→ Evolutionary time scales do not fit

→ higher mass-loss rate and if the remnant is in thermal non-equilibrium after the common-envelope ejection might increase the evolutionary speed



Hall et. al. 2013

Conclusions

- From our analysis, we found SAO 244567 must be low-mass, maybe even an AGB-manqué star
- None of the existing evolutionary models can explain the photospheric properties of this star
- The fast evolution of SAO 244567 gives us the unique possibility to study stellar evolution in real time
- The derived parameters establish constraints for stellar evolutionary theory

Paper has been submitted to A&A in Dezember 2013