Late Helium Flashes and Hydrogen-Poor Stars

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Outline

- Introduction
- He-shell flashes and nucleosynthesis in AGB stars
- Consequences of a late He-shell flash in post-AGB stars
- Observational results: Element abundances in the hottest H-poor post-AGB stars
- Conclusions

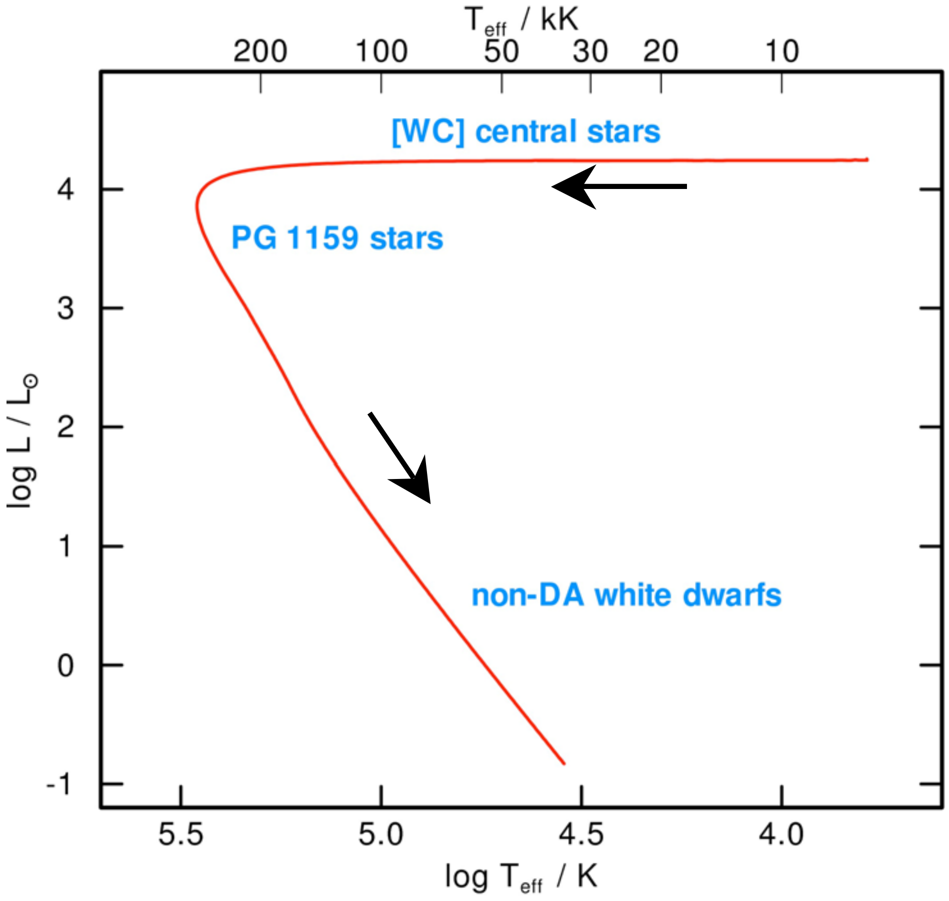
- There exists a H-deficient evolutionary sequence of post-AGB stars

→ Wolf-Rayet [WC]-type
central stars of planetary nebulae
→ PG1159-type (pre-) white dwarfs

} similar surface chemistry
(He-C-O dominated)

→ non-DA white dwarfs

pure-He surface (gravitational settling)



- Origin of H-deficiency: late He (shell) flash during post-AGB evolution → ingestion and burning (or dilution) of hydrogen

Focus of this talk: determination of element abundances in PG1159 stellar atmospheres; surface composition reflects chemistry of region between H- and He-burning shells in precursor AGB star

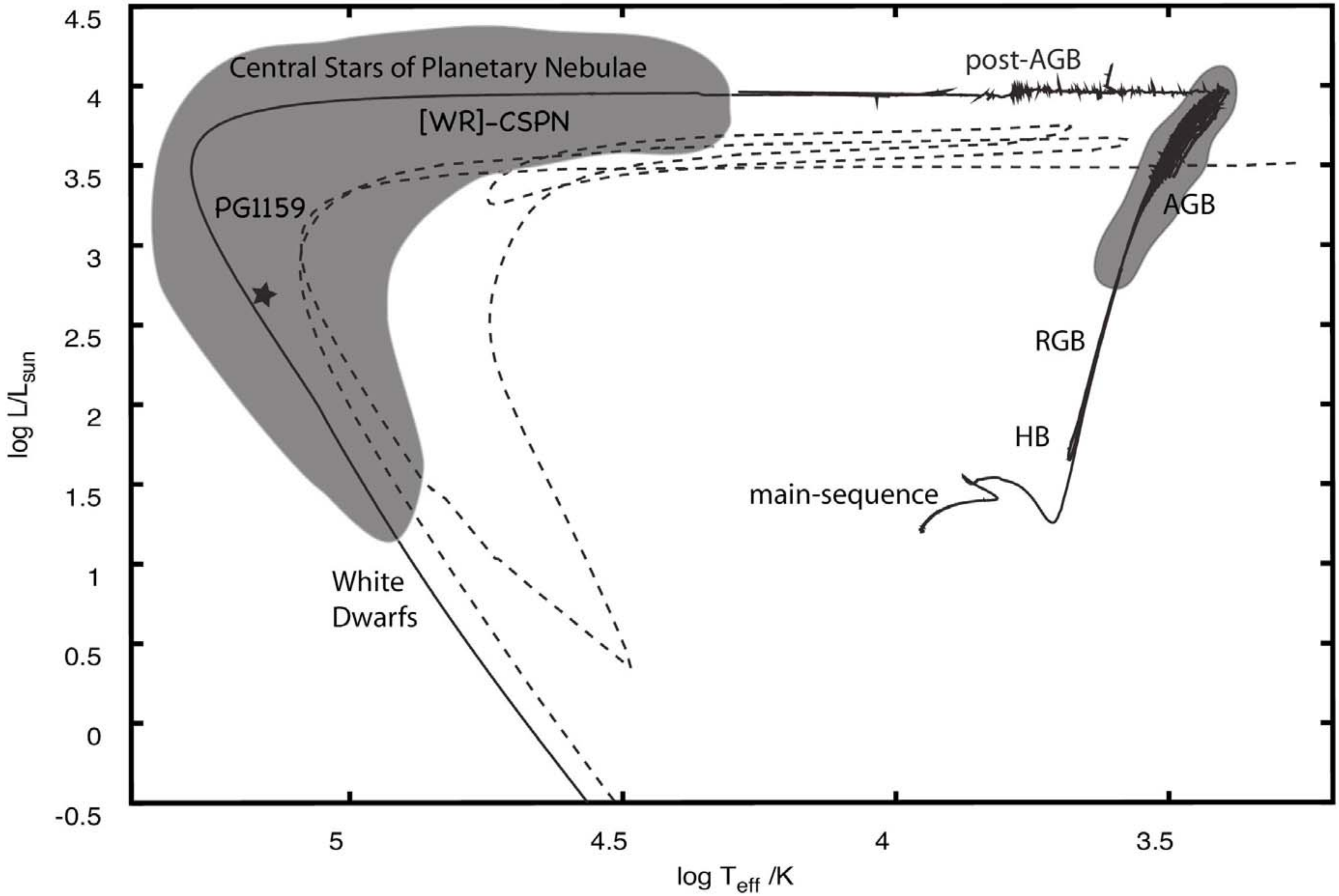
Out of focus: detailed course of late He-flash (see talk by Ken Shen)

- Why are abundance studies interesting?
- Abundance analysis reveals details of nucleosynthesis and mixing processes in AGB-star interiors
- Constrains uncertainties in shell-flash physics (e.g. convective overshoot)
- Useful verification of stellar evolution models: do they predict correct yields for modeling Galactic chemical evolution?

We use the outcome of a *late He-shell flash* as a tool to study the characteristics of AGB stars that perform thermal pulses *(=He shell flashes)*

Modeling of PG1159-star atmospheres is an interesting and challenging task:

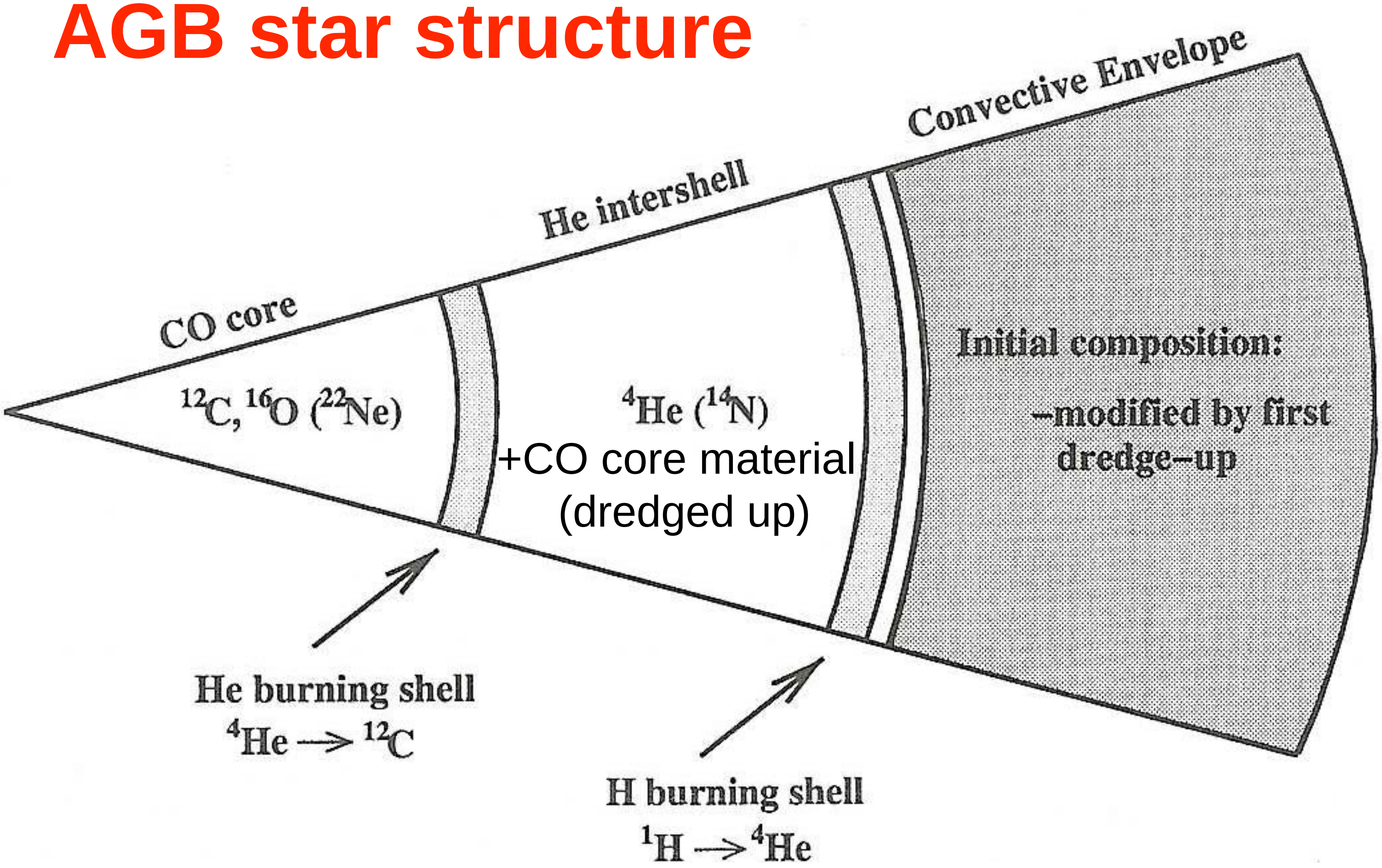
- They are the hottest stellar atmospheres (except neutron stars), non-LTE modeling is essential
- Most spectral lines are from highly ionized elements (e.g. Ne VIII)
    - Line identification means “entering new territory”
    - UV spectroscopy necessary (HST, FUSE; hard to get)
    - Problems with atomic data: level energies, f-values are often hidden in literature, or inaccurate, or simply non-existing



Evolutionary tracks for a 2 $M_\odot$ star. Born-again track offset for clarity.

(Werner & Herwig 2006)

AGB star structure



from Lattanzio (2003)

s-process in AGB stars

Main neutron source is reaction starting from ^{12}C nuclei (from 3α-burning shell):

$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)^{16}O$ protons mixed down from H envelope

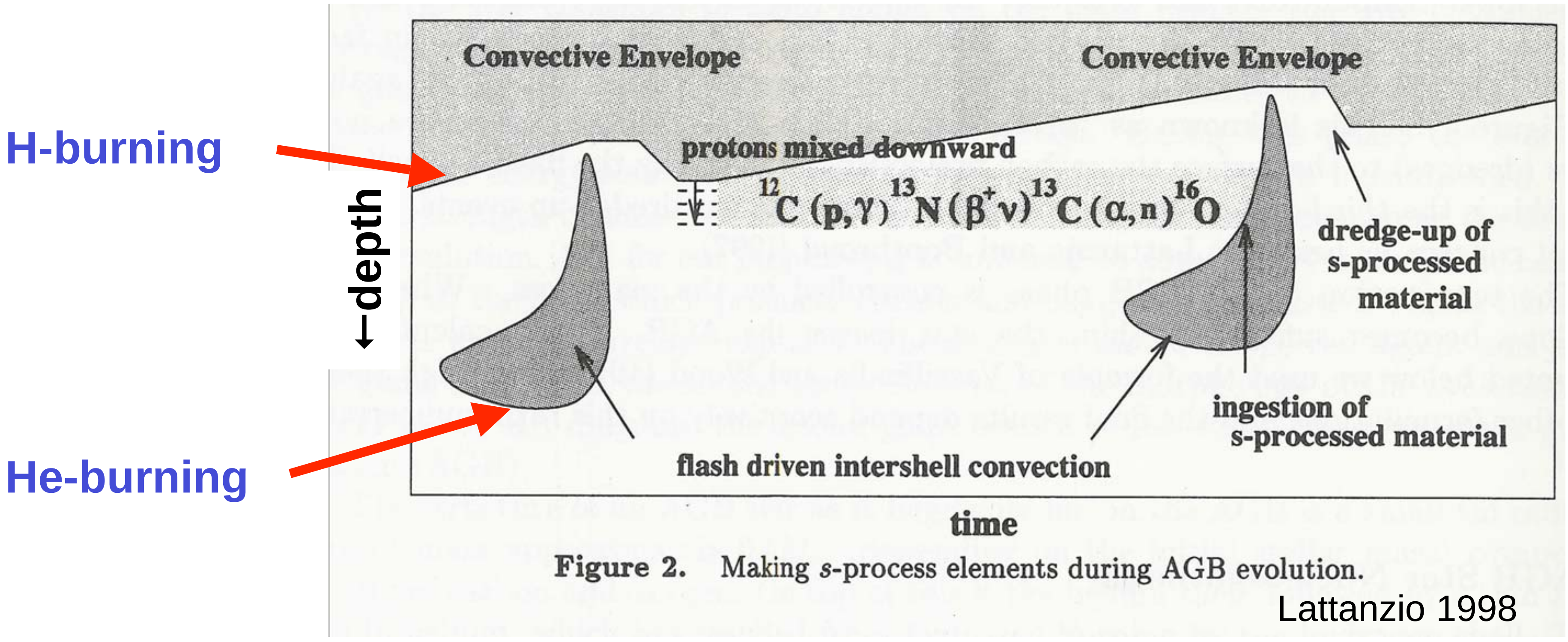


Figure 2. Making *s*-process elements during AGB evolution.

Lattanzio 1998

- Nucleosynthesis products of s-process in intershell layer not directly visible

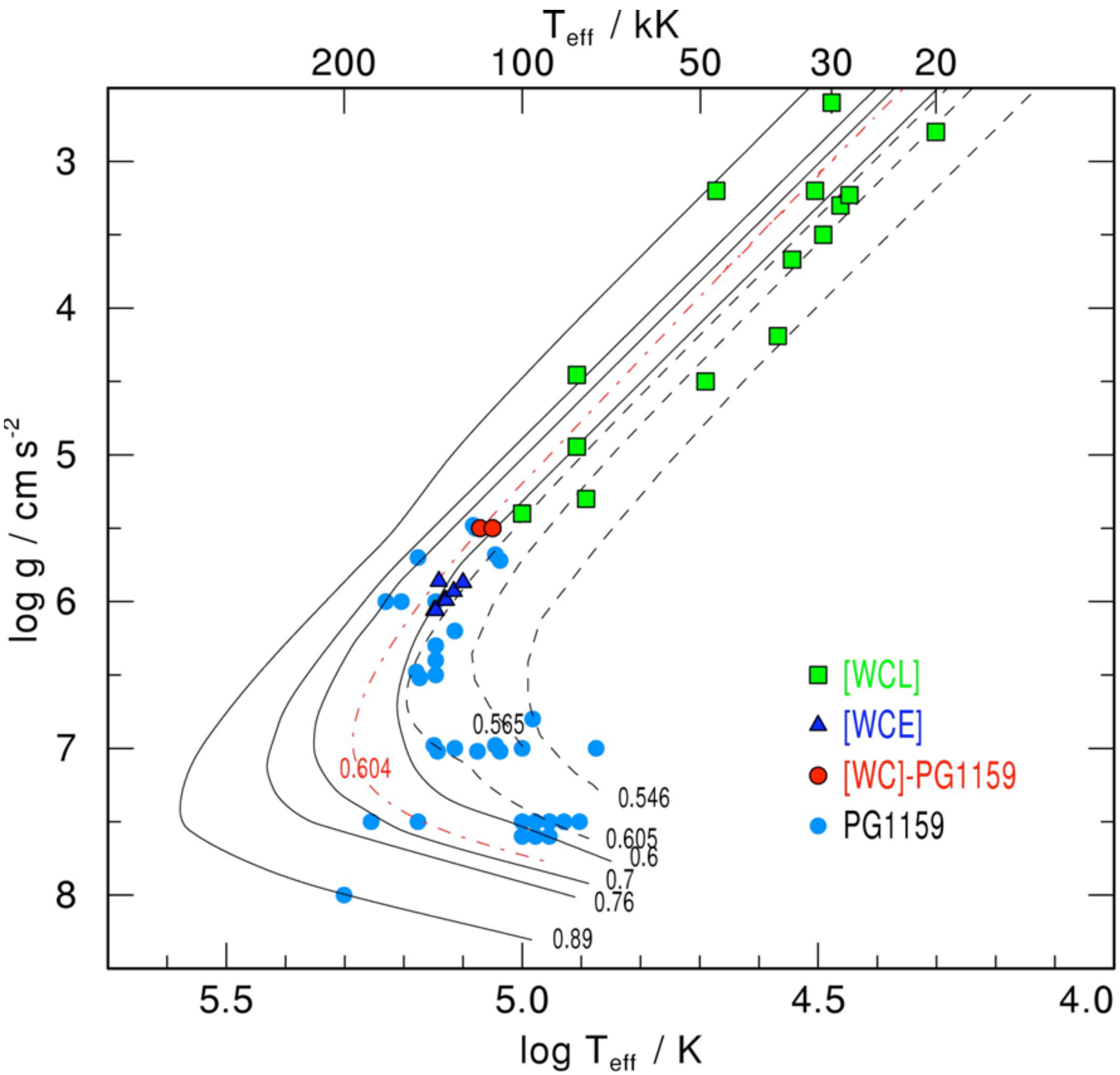
- Intershell matter is hidden below massive, $10^{-4}\ M_{\odot}$, convective hydrogen envelope

- Dredge-up of s-processed matter to the surface of AGB stars, spectroscopically seen

- In principle: Analysis of metal abundances on stellar surface allows to conclude on many unknown burning and mixing processes in the interior, but: difficult interpretation because of additional burning and mixing (hot bottom burning) in convective H-rich envelope

- Fortunately, nature sometimes provides us with a direct view onto processed intershell matter: exposed by H-deficient post-AGB stars as consequence of late He-shell flash

- Our work concentrates on PG1159 stars; famous progenitors are FG Sge and Sakurai's star, suffering late flashes in 1894 and 1996, respectively



PG1159 stars

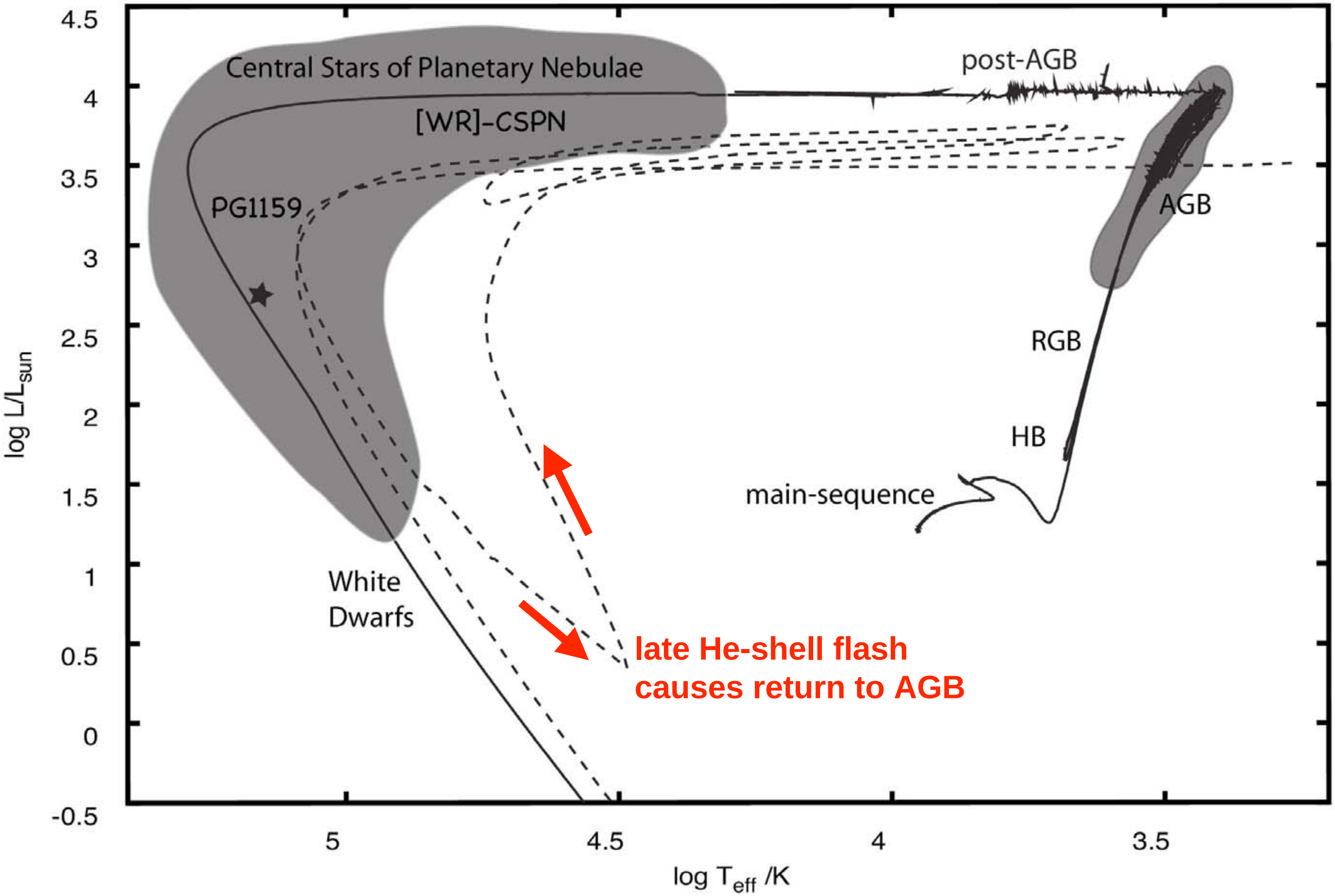
40 objects known

Mean mass **0.57 $M_\odot$**

Atmospheres dominated by C, He, O, and Ne, e.g.

He=33%, C=48%, O=17%, Ne=2% (mass fractions)

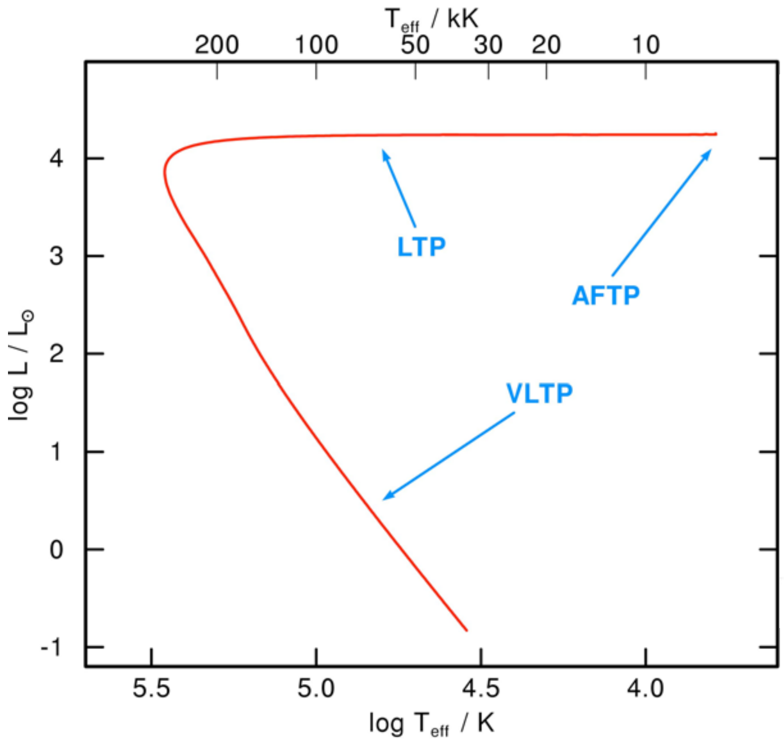
= chemistry of material between H and He burning shells in AGB-stars (intershell abundances)

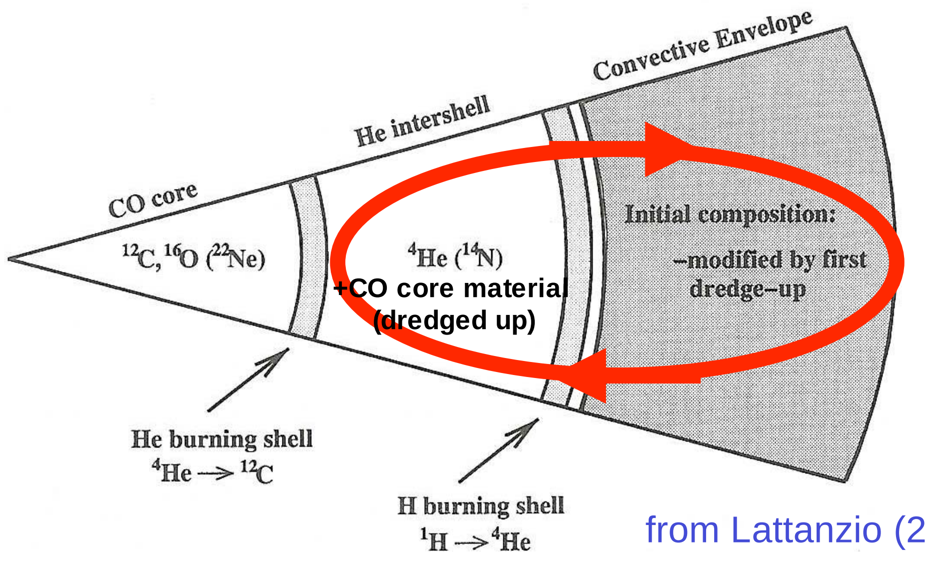


late He-shell flash causes return to AGB

Evolutionary tracks for a 2 $M_\odot$ star. Born-again track offset for clarity.

(Werner & Herwig 2006)





from Lattanzio (2003)

1. Very late thermal pulse (**VLTP**): He-shell burning starts **on WD cooling track**. Envelope convection above He-shell causes ingestion and burning of H. No H left on surface.

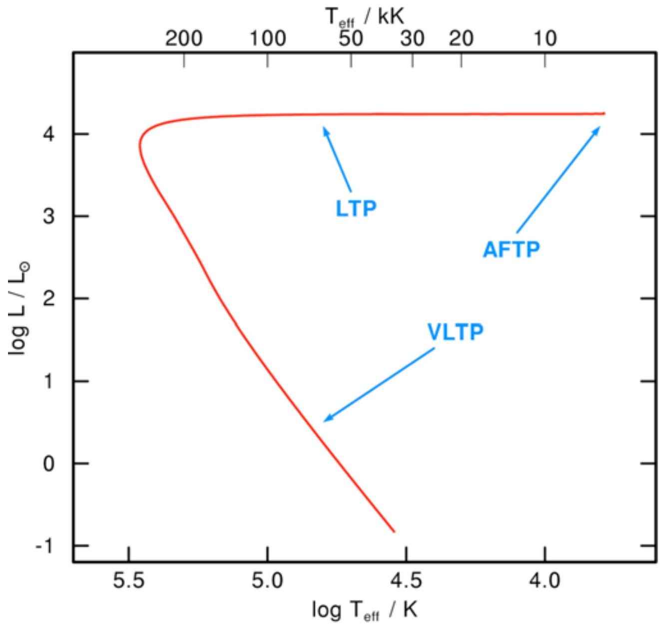
2. Late thermal pulse (**LTP**): He-shell burning starts **on horizontal part of post-AGB track** (i.e. H-shell burning still "on"). Envelope convection causes ingestion and dilution of H. Very few H left on surface (below 1%), spectroscopically undetectable in PG1159 and [WC] stars.

3. "AGB final" thermal pulse (**AFTP**): He-shell burning starts just at the moment **when the star is leaving the AGB**. Like at LTP, H is diluted but still detectable: H≈20%.

Element abundances in PG1159 stars from spectroscopic analyses

- Abundances of main constituents, He, C, (O) usually derived from optical spectra (He II, C IV, O VI lines)
- Trace elements: almost exclusively from UV spectra (HST, FUSE)
- Model atmospheres: Plane-parallel, hydrostatic, radiative equilibrium, NLTE

Hydrogen and nitrogen



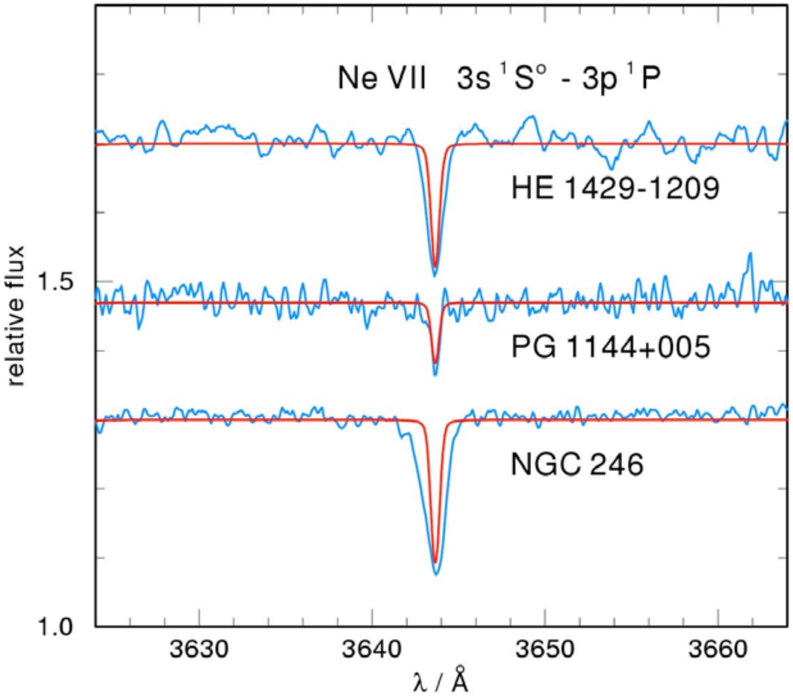
- Hydrogen discovered in four PG1159 stars, so-called “hybrid PG1159s”, Balmer lines, H=0.35
- Can be explained by AFTP evolution models

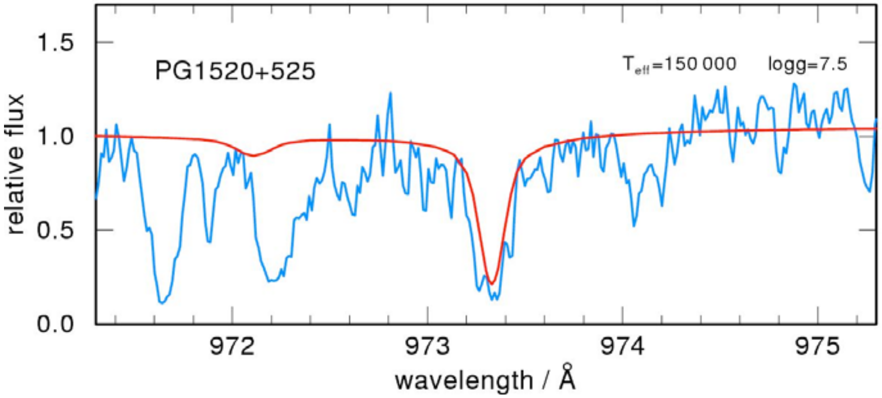
- Nitrogen: Discovered in some PG1159 stars, N=0.001-0.01, strict upper limits for some stars: $N<3\cdot10^{-5}$
- Nitrogen is a reliable indicator of a LTP or VLTP event: $N<0.001 \Rightarrow$ LTP, $N \approx 0.01 \Rightarrow$ VLTP (nitrogen produced by H ingestion & burning)

Hence: From H and N abundances we can conclude when the star was hit by late TP

Neon

- Synthesized in He-burning shell starting from ^{14}N (from previous CNO cycling) via $^{14}N(\alpha,n)^{18}F(e^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne$
- Evolutionary models predict Ne≈0.02
- Confirmed by spectroscopic analyses of several NeVII lines



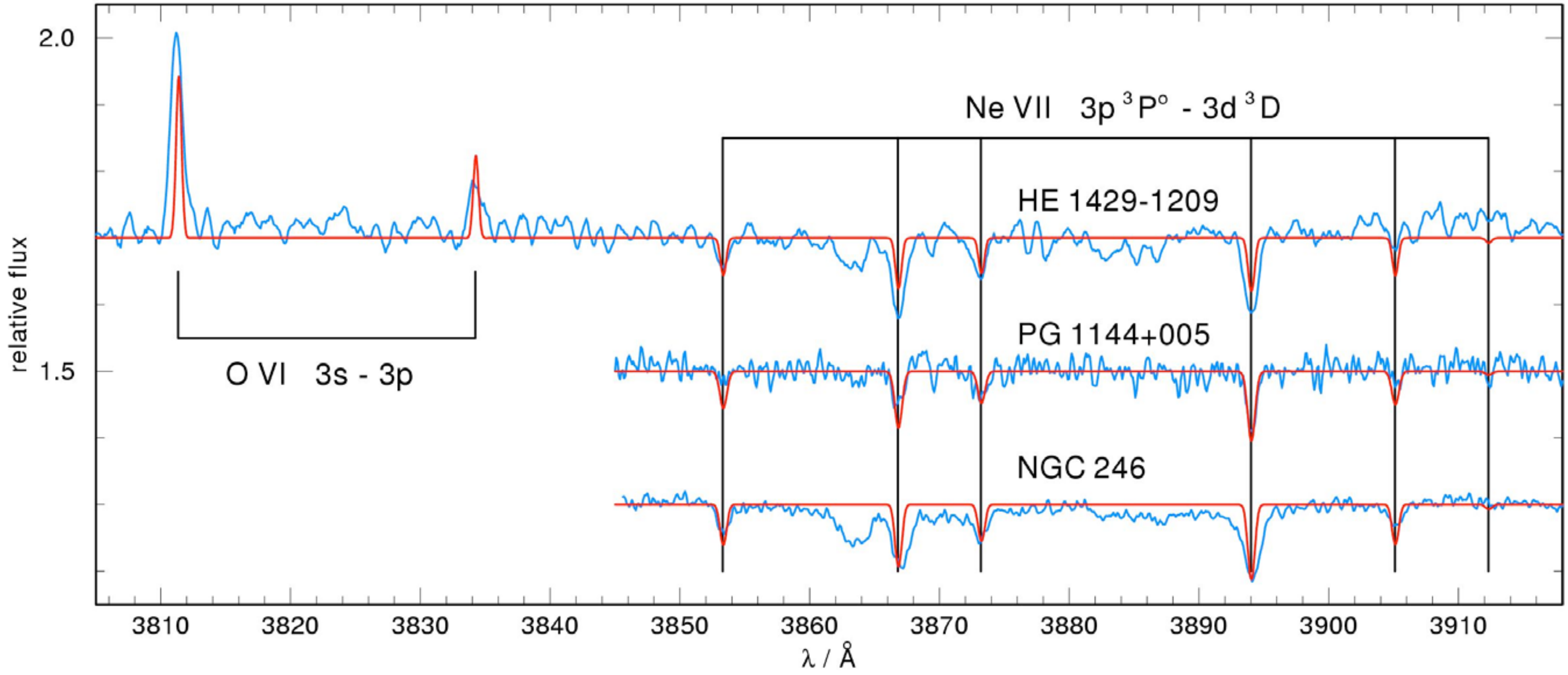


NeVII 973.3Å, one of strongest lines in FUSE spectra, first identified 2004 (Werner et al.)

← NeVII 3644Å first identified 1994 (Werner & Rauch)

Neon

- Newly discovered NeVII multiplet in VLT spectra (Werner et al. 2004):

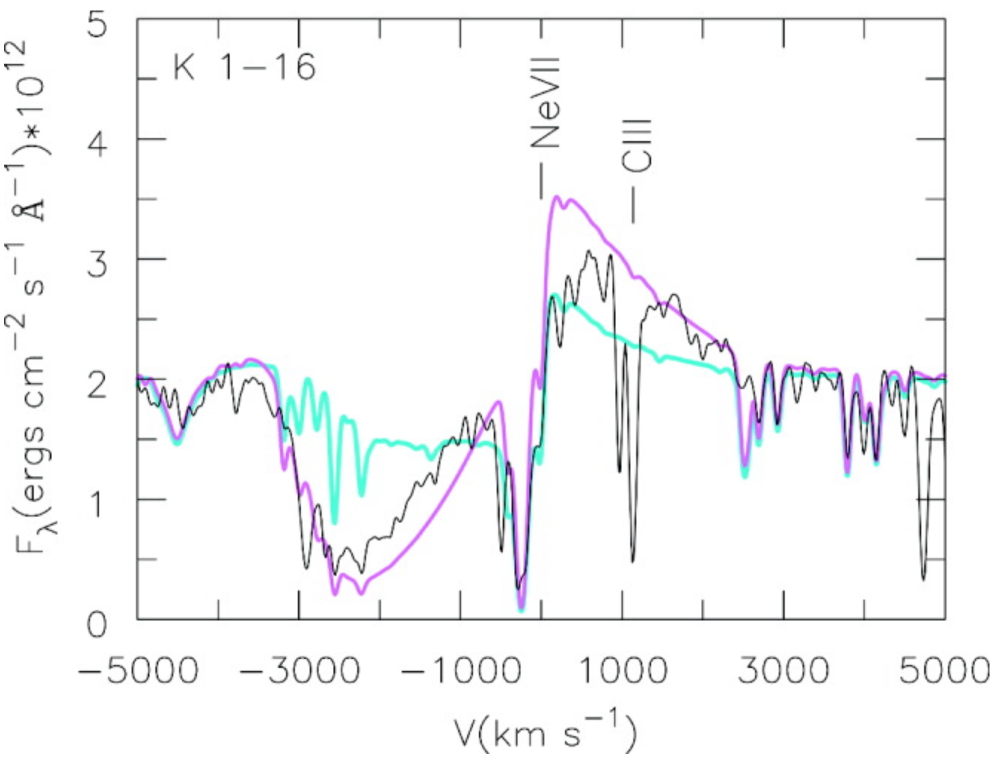


- Allows to improve atomic data of highly excited NeVII lines (line positions, energy levels).

- Was taken over into NIST atomic database (Kramida et al. 2006).

Neon

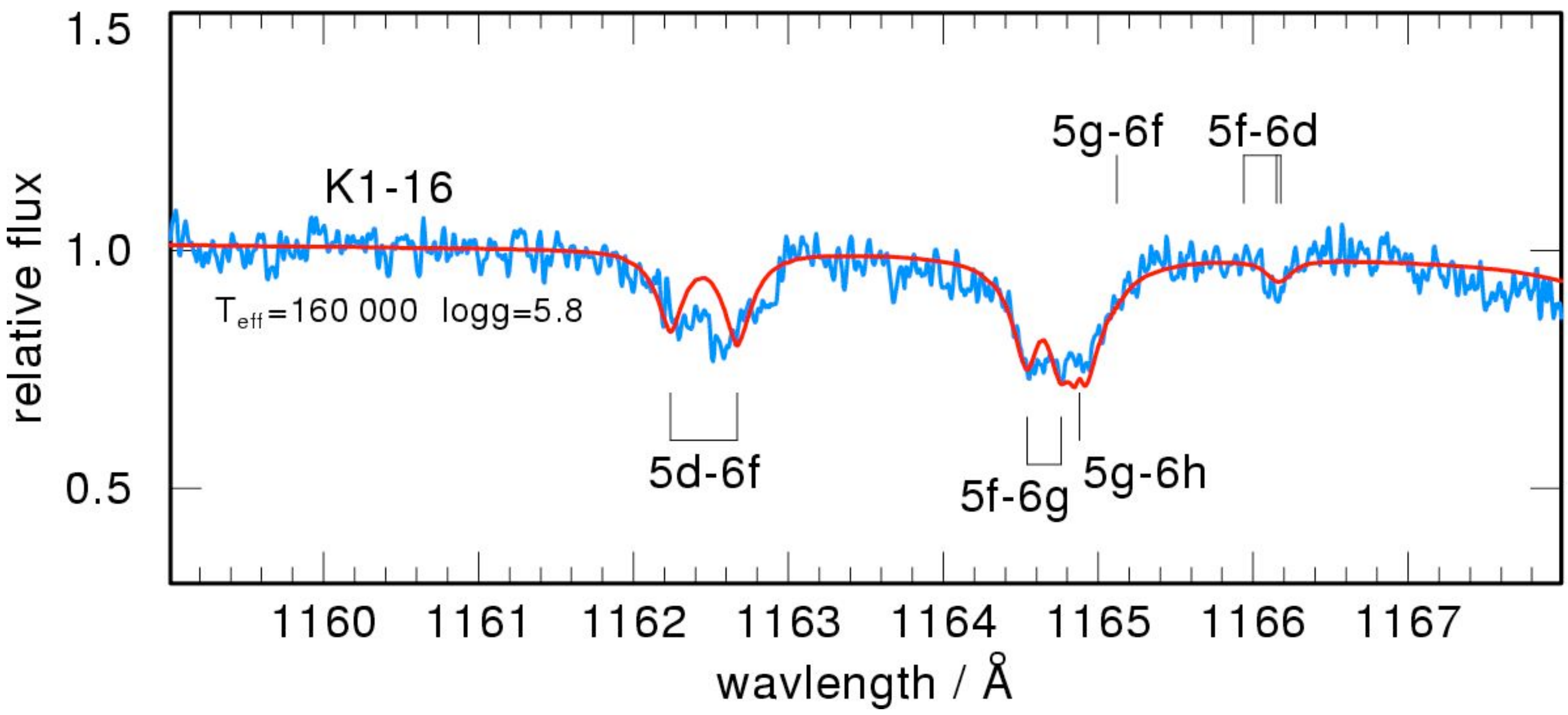
- The NeVII 973Å line has an impressive P Cygni profile in the most luminous PG1159 stars (first realized by Herald & Bianchi 2005):



In conclusion: Neon abundance in PG1159 stars agrees with predictions from late-thermal pulse stellar models.

Neon

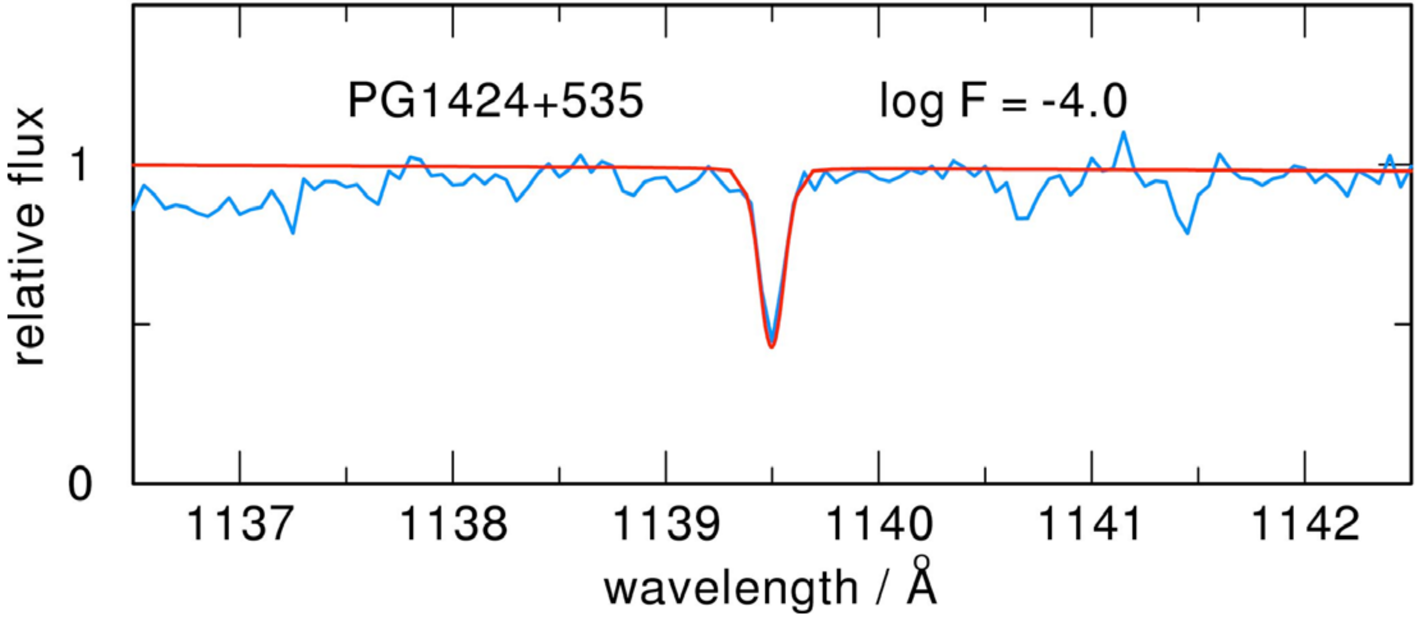
- Recent identification of NeVIII (!) lines in FUSE spectra (Werner et al. 2007) has important consequences



- Allows more precise T_{eff} determination for hottest stars

Fluorine (^{19}F)

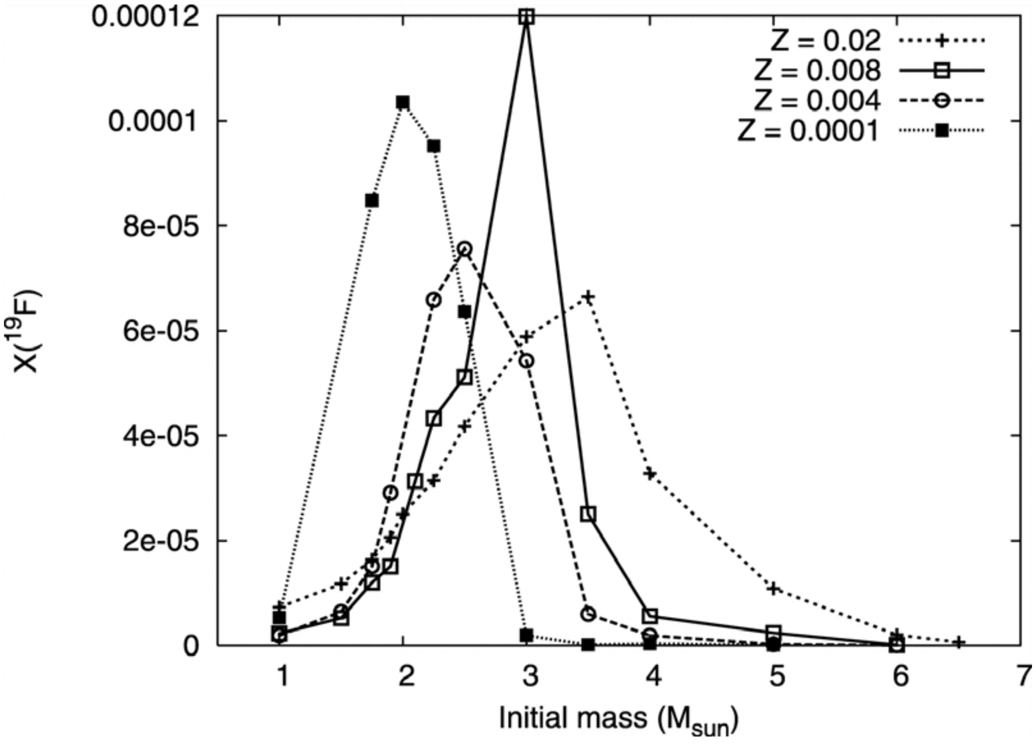
- Interesting element, its origin is unclear: formed by nucleosynthesis in AGB stars or Wolf-Rayet stars? Or by neutrino spallation of ^{20}Ne in type II SNe?
- Up to now F only observed as HF molecule in AGB stars, F overabundant (Jorissen et al. 1992), i.e. AGB stars are F producers
- Would be interesting to know the AGB star intershell abundance of F, use PG1159 stars as “probes”!
- Discovery of F V and F VI lines in a number of PG1159 stars (Werner et al. 2005) is the first identification of fluorine in hot stars at all!



fluorine overabundant by factor 200!

Fluorine (^{19}F)

- Wide spread of F abundances in PG1159 stars, 1-200 solar
- Qualitatively explained by evolutionary models of Lugaro et al. (2004), large F overabundances in intershell, strongly depending on stellar mass:



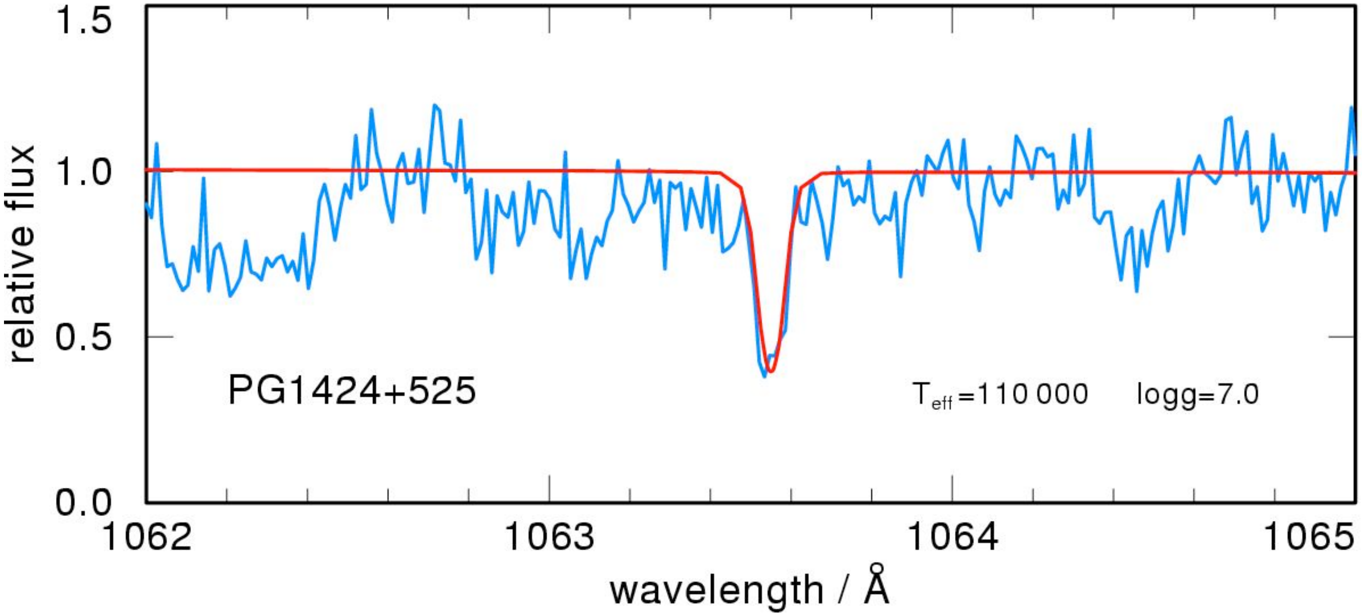
Range of fluorine intershell abundance coincides amazingly well with observations !!!

But: we see no consistent trend of F abundance with stellar mass (our sample has $M_{initial}$=0.8-4 $M_{\odot}$)

Conclusion: fluorine abundances in PG1159 stars are (well) understood

Argon

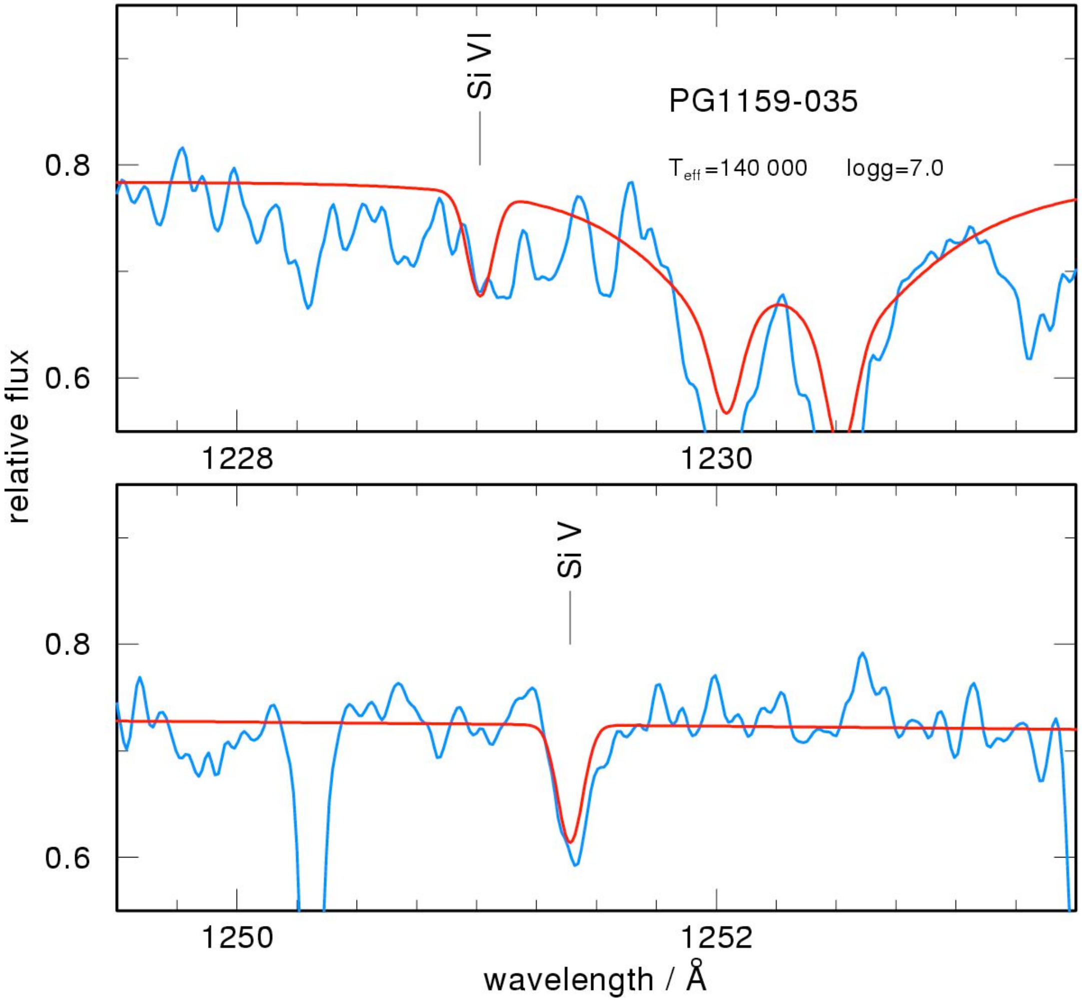
- Up to now, never identified in any hot star
- First identification of an Ar VII line (λ 1063.55 Å) in several hot white dwarfs and one PG1159 star (Werner et al. 2007);
- Argon abundance solar, in agreement with AGB star models, intershell abundance gets hardly reduced (Gallino priv. comm.)



Silicon

- Si abundance in AGB star models remains almost unchanged; solar Si abundances expected in PG1159 stars
- Results for five PG1159s show wide range, from solar down to <0.05 solar

Large Si scatter **cannot** be explained by stellar models.

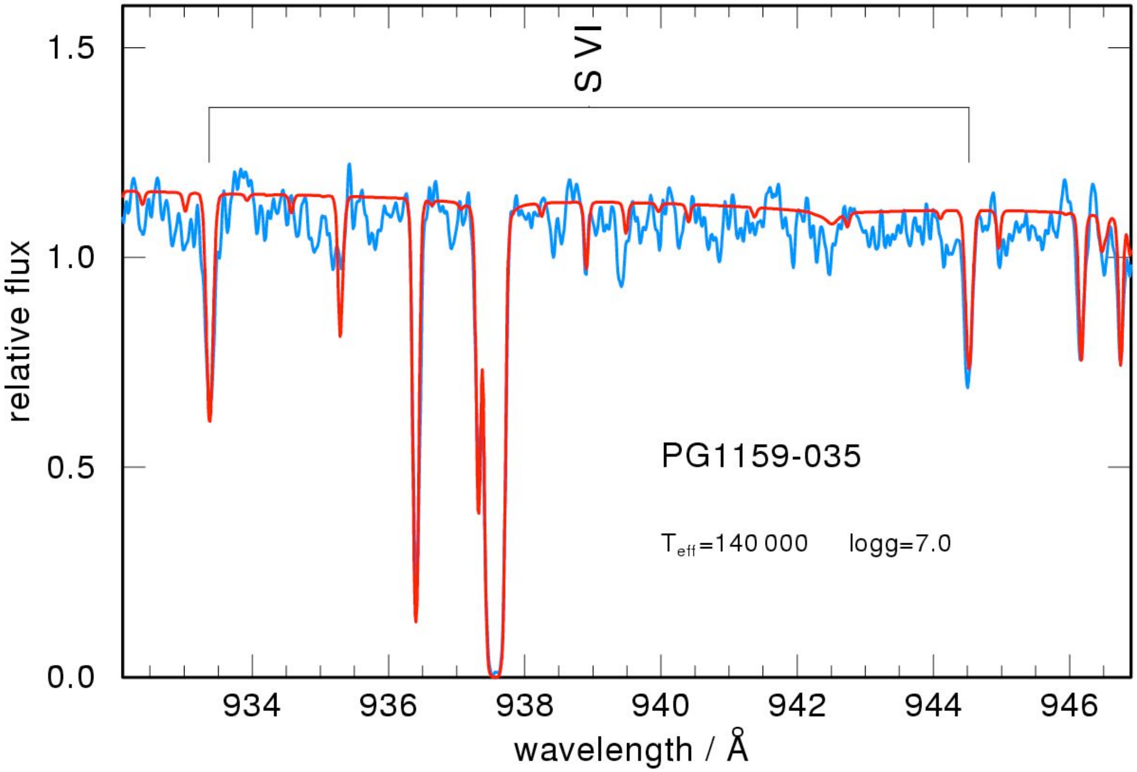


Sulfur

- Discovered in a number of PG1159 stars by identification of S VI resonance doublet λλ 933, 945 Å
- One PG1159 star shows S solar while five others have 0.1 solar
- In contrast, only mild depletion occurs in stellar models: S=0.6 – 0.9 solar.

Conclusion:

Strong S deficiency **not understood**.

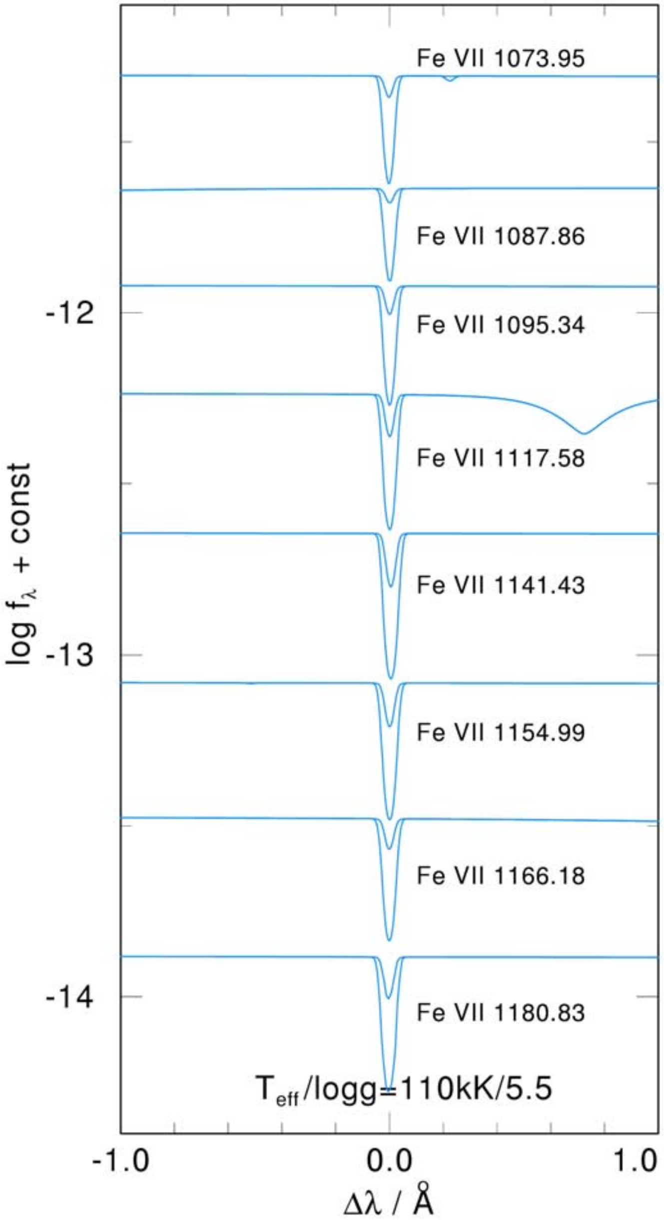


Iron and nickel

- Expectation from stellar models: Slight depletion of Fe, down to ≈90% solar in the AGB star intershell, because of n-captures on ^{56}Fe nuclei (s-process)
- **To great surprise,** significant Fe deficiency was claimed for all PG1159 stars examined so far (1-2 dex subsolar)
- **Where has the iron gone?**
- s-process much more efficient? Was Fe transformed into Ni? Is Ni overabundant? If not, then Fe-deficiency is even harder to explain!

Abell 78 [WC]-PG1159 transition object

Fe abundance variation: 1/10 and 1/100 solar



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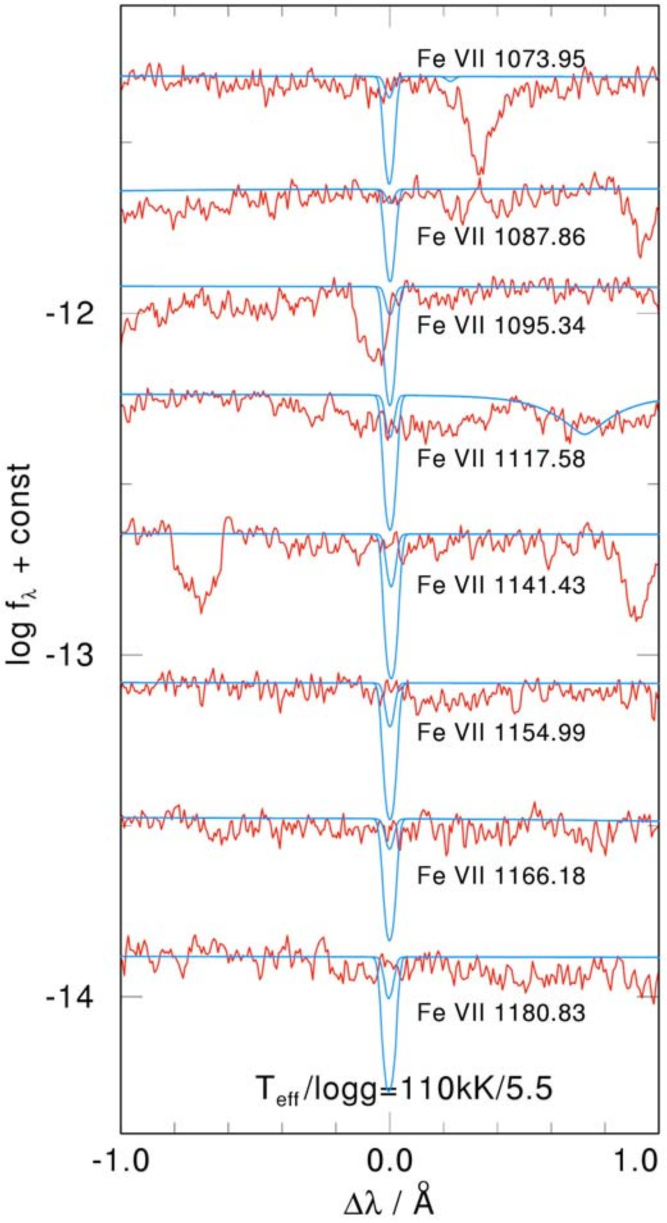
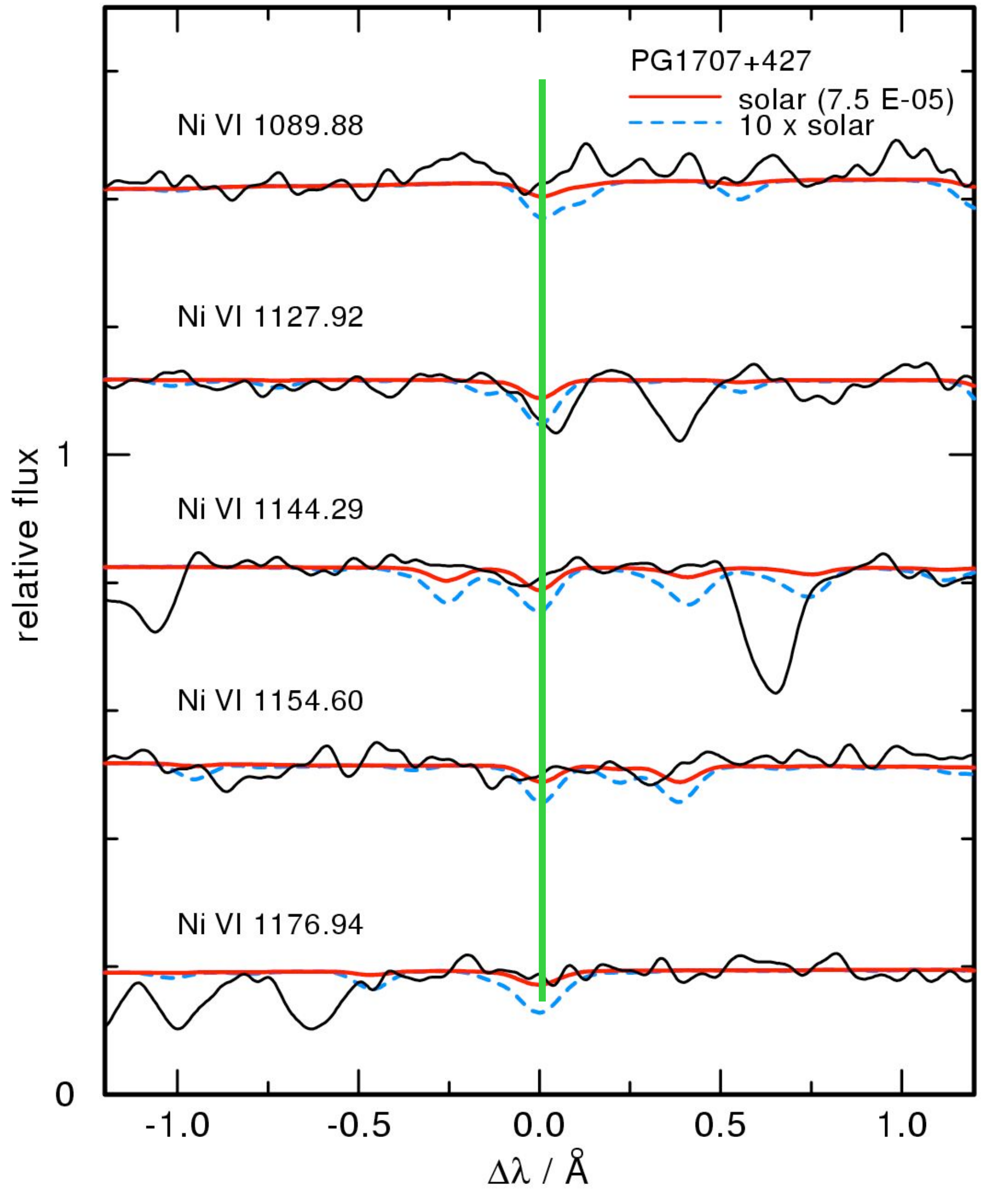


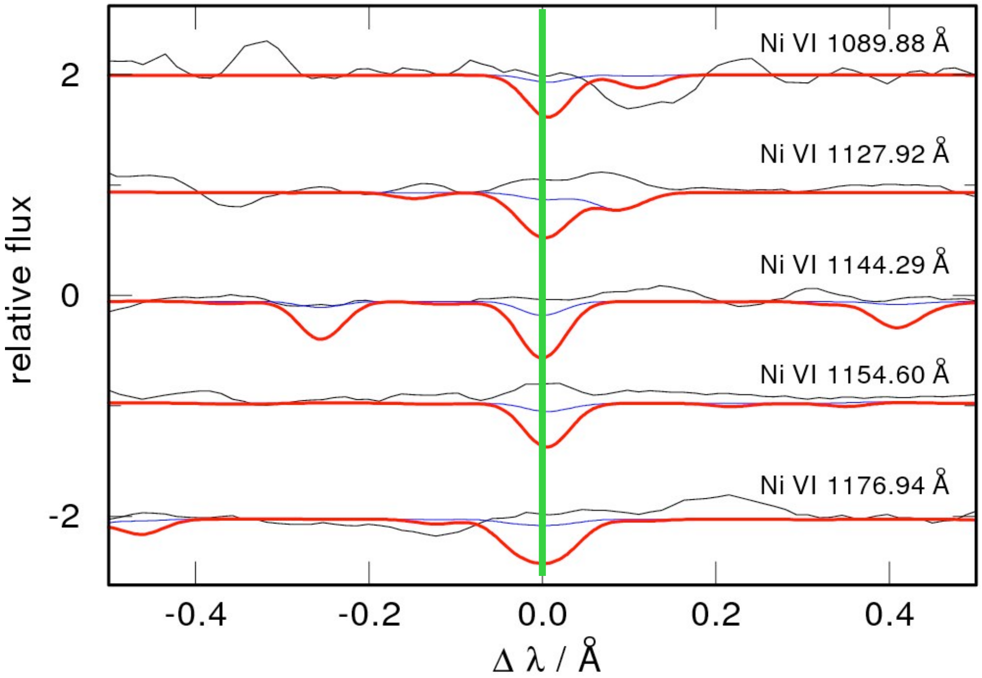
Nickel



- best chance for detection in far-UV range
- Ni VI lines, but very weak in models
- not found in observations
- compatible with solar abundance
- no Ni overabundance

Reiff et al. (2008)

Nickel



Other example:

AFTP central star NGC 7094

Nickel is depleted!

Ziegler et al. (in prep.)

solar and 0.1 solar Ni model; FUSE observation

Dream: Discovery of trans-iron group elements in hottest post-AGB stars

- Strong Ge overabundance (10$*$solar) found in some PNe (Sterling et al. 2002)
- Interpreted as consequence of late TP, but in contrast, other s-process elements like Xe, Kr should also show strongest enrichment, which is **not the case** (Sterling & Dinerstein 2006, Zhang et al. 2006).
- **This is independent evidence that our knowledge about nucleosynthesis and, hence, stellar yields is rather limited**
- It would be highly interesting to discover these (and other) n-capture elements in PG1159 stars
- Atomic data is one problem (almost no UV/optical line data available for high ionisation stages)
- But the main problem is: Lines are very weak, **need much better S/N**

No. 2, 2007 Ge PRODUCTION IN AGB STARS (Karakas et al. 2007) L75

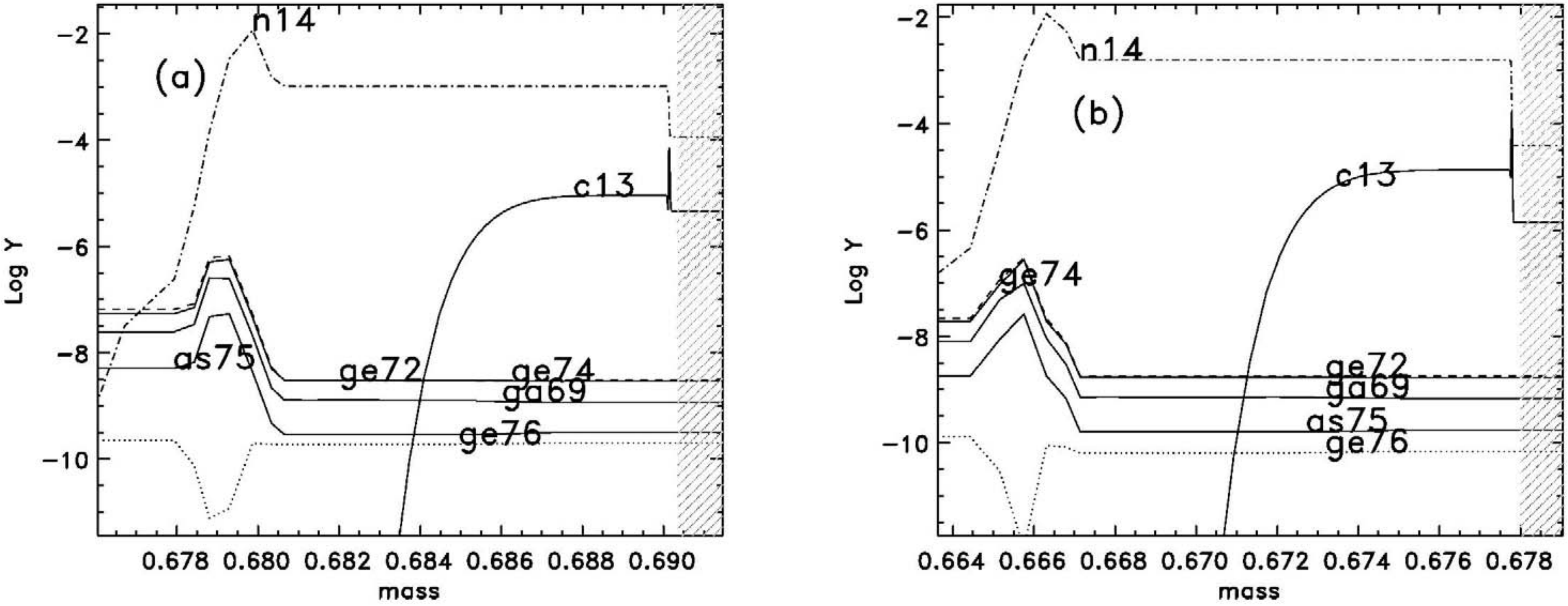


FIG. 1.—Composition profile showing the intershell abundances (in log *Y*, where mass fraction $X = YA$) just before the last computed TP. The shaded region is the inner edge of the convective envelope, and a PMZ of 0.002 $M_\odot$ was used in both models. We show abundances for selected isotopes from (*a*) the 3 $M_\odot$, $Z = 0.012$ model, in which the Ge intershell abundance *after* the last TP is 40 times solar, and (*b*) the 2.5 $M_\odot$, $Z = 0.004$ model, in which the Ge intershell abundance is 63 times solar. The intershell abundances are typically diluted by 1 order of magnitude at the surface by the last TDU episode. [*See the electronic edition of the Journal for a color version of this figure.*]

Composition profile of intershell abundances before last computed TP. Ge abundance near 10^{-6}, could be detectable spectroscopically (we found Ar at that abundance level in a H-rich central star).

Search for these species (Ge, Ga, As, Xe, Kr ….) is not completely hopeless. Future HST/COS spectroscopy might play key role.

Conclusions

- Late He-shell flash phenomenon causes H-deficient post-AGB evolutionary sequence
- Stellar atmospheres are composed of former AGB-star intershell material
- We actually see *directly* the outcome of AGB nucleosynthesis
- Observed abundances represent a strong test for stellar models and predicted metal yields
- Abundances of many atmospheric constituents (He,C,N,O,Ne,F,Ar) are in agreement with stellar models
- But **some elements point out significant flaws:** S and Si
- The extent of the observed iron deficiency is most surprising and lacks an explanation. Efficiently destroyed by n-captures?