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
  • similar surface chemistry (He-C-O dominated)
  → PG1159-type (pre-) white dwarfs
  • pure-He surface (gravitational settling)
  → non-DA white dwarfs
• 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 correctly 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_☉ star. Born-again track offset for clarity.
(Werner & Herwig 2006)
AGB star structure

Initial composition: modified by first dredge-up

CO core
$^{12}\text{C}, ^{16}\text{O} (^{22}\text{Ne})$
$^4\text{He} (^{14}\text{N})$
$+$CO core material (dredged up)

He burning shell
$^4\text{He} \rightarrow ^{12}\text{C}$

H burning shell
$^1\text{H} \rightarrow ^4\text{He}$

Convective Envelope

from Lattanzio (2003)
s-process in AGB stars

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

$$^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta^+\nu)^{13}\text{C}(\alpha,n)^{16}\text{O}$$

protons mixed down from H envelope

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**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
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)
Evolutionary tracks for a 2 M$_\odot$ star. Born-again track offset for clarity.
(Werner & Herwig 2006)
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%.

(from Lattanzio 2003)
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: $N<3 \cdot 10^{-5}$

- Nitrogen is a reliable indicator of a LTP or VLTP event: $N<0.001 \Rightarrow \text{LTP}$, $N \approx 0.01 \Rightarrow \text{VLTP}$ (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 $^{14}\text{N}$ (from previous CNO cycling) via $^{14}\text{N}(\alpha,n)^{18}\text{F}(e^+\nu)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$
- Evolutionary models predict $\text{Ne} \approx 0.02$
- 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.
Recent identification of NeVIII (!) lines in FUSE spectra (Werner et al. 2007) has important consequences.

- Allows more precise $T_{\text{eff}}$ determination for hottest stars.

![Graph showing relative flux vs. wavelength for a star with NeVIII lines.](image)
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 spectrum]

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:
  
  \[
  X(^{19}\text{F}) \text{ vs. Initial mass (M}_\odot\text{)}
  \]

  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 $M_{\text{initial}} = 0.8-4\ M_\odot$)

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 ($\lambda$ 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 \( \lambda \lambda 933, 945 \text{ Å} \)
- 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 $^{56}\text{Fe}$ 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

$T_{\text{eff}}/\log g = 110 \text{kK}/5.5$
Fe abundance variation: 1/10 and 1/100 solar

\[ T_{\text{eff}} / \log g = 110 \text{kK} / 5.5 \]
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
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?