CHEMICAL COMPOSITIONS OF POST-AGB STARS

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ABSTRACT. Objects that may be in a post-AGB evolutionary stage include high-latitude supergiants, UU Her and RV Tau variables, and *IRAS* sources identified with A- to G-type supergiants. Photospheric abundance analyses of such objects typically reveal moderate to extreme iron-group deficiencies, consistent with membership in the thick-disk or halo populations, and with having arisen from low-mass progenitors. The photospheric CNO abundance patterns in such stars are distinctly atypical of normal Population I supergiants, and appear to indicate the presence of helium-burning products at the stellar surface. However, enhancements of *s*-process elements are typically not seen, suggesting that most of the stars have avoided the AGB dredge-up. A subset of the stars, typified by HR 4049, show ultra-low iron-group abundances and extreme enhancements of C, N, O, and S. They appear to constitute a new class of chemically peculiar stars, with severely depleted photospheric metals. Grain formation is proposed as the depletion mechanism.

1. Post-AGB Stars

For purposes of this review, we will define "post-AGB stars" as objects lying in the H-R diagram between the asymptotic giant branch (AGB) and the nuclei of planetary nebulae, for which there is evidence that they are not stars of higher mass undergoing their initial evolution off the zero-age main sequence. More specifically, we will consider only those objects, not completely shrouded in dust, for which an optical photosphere can be observed and an abundance analysis carried out.

Examples of post-AGB candidate objects include:

- High-galactic-latitude supergiants
- UU Herculis and RV Tauri variables
- *IRAS* sources identified with A- to G-type supergiants

2. Discovery Techniques

High-mass Population I stars leaving the main sequence can occupy the same part of the H-R diagram as stars of low to intermediate masses that are in their final evolution off of the AGB. Several discovery methods have been used to distinguish the two classes of objects. The characteristics that can distinguish old post-AGB

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stars from young supergiants include the following:

1. *A galactic location unexpected for young stars.* This technique can be traced back to the work of Bidelman (1951), who pointed out several A- and F-type supergiants that lie at high galactic latitudes ($|b| > 22°$), including 89 Her (F2 Ia) and HD 161796 (F3 Ib). Another example is HR 4912, an F3 Ia supergiant at $b = +36°$ (Bidelman, quoted by Luck, Lambert, and Bond 1983). These objects are located far from star-forming regions, suggesting that they may be low-mass stars masquerading as Population I supergiants.

2. *Presence in an old stellar population, such as globular clusters or metal-deficient field stars.* Examples of candidate post-AGB stars in globular clusters include the A-type supergiant ROA 24 = HD 116745 in ω Centauri (Dickens and Powell 1973) and two similar objects in NGC 5986 (Bond 1977). Among field stars, several examples exist of extremely weak-lined A- or F-type objects, first identified in objective-prism surveys and subsequently found to have very large Balmer jumps indicating luminosities exceeding those of horizontal-branch stars. These include HD 46703 (Bidelman 1966; Bond 1970), BD +39°4926 (Slettebak *et al.* 1961; Kodaira *et al.* 1970), and HD 213985 and BD +14°3061 (Bond, unpublished).

3. *Infrared excesses.* Strong IR excesses are generally atypical of Population I supergiants, but were detected for Bidelman's high-latitude supergiants 89 Her and HD 161796, and for the southern supergiant HD 101584, by Humphreys and Ney (1974). These excesses may be attributed to dust formation in material ejected from the star during its AGB phase.

In recent years, the *IRAS* data base has begun to yield numerous examples of infrared sources optically identified with A- to G-type supergiants, and generally regarded as post-AGB stars. An early discussion of the *IRAS* data for HD 161796 and HD 101584 was given by Parthasarathy and Pottasch (1986). Other objects suggested as post-AGB stars on the basis of *IRAS* observations include HR 4049 (Lamers *et al.* 1986), HD 213985 and HD 52961 (Waelkens *et al.* 1987, 1990*b*), IRAS 18095+2704 (Hrivnak, Kwok, and Volk 1988) and 20056+1834 (Menzies and Whitelock 1988), and several objects listed by Pottasch and Parthasarathy (1988), Hrivnak, Kwok, and Volk (1989), Parthasarathy (1990), and Trams *et al.* (1990*a*).

Jura (1986) has argued that RV Tau variables, which are generally associated with IR excesses, are therefore likely to be post-AGB stars.

Other post-AGB candidates among IR sources include CRL 2688, whose central source was classified F5 Ia by Crampton *et al.* (1975), and HD 44179 (the "Red Rectangle"), for which Greenstein and Oke (1977) discussed the possibility that the central star is similar in nature to +39°4926.

4. *Low mass.* Lambert and Sawyer (1986) have proposed that the mass of the well-known F0 Ia supergiant ϵ Aur is $< 3M_{\odot}$, on the basis of their analysis of radial velocities in the disk surrounding its unseen companion. If this analysis is correct, ϵ Aur is clearly not a massive young supergiant and may instead be an intermediate-mass star in a post-AGB stage.

3. Iron-Group Abundances in Post-AGB Stars

The available abundance analyses have revealed several objects that show metallicities characteristic of halo stars:

Star	[Fe/H]	Reference
BD +39°4926	−2.1	Kodaira *et al.* 1970
HD 46703	−1.6	Luck & Bond 1984
RU Cen	−1.4	Luck & Bond 1989
HR 4912	−1.2	Luck, Lambert & Bond 1983

These low metallicities, along with the high galactic latitudes, high space velocities (at least in the case of HD 46703, whose radial velocity is $-106\ \mathrm{km\,s^{-1}}$ according to Luck and Bond 1984), and the presence of similar stars in globular clusters, are crucial in establishing that objects with low-mass ($\sim 0.8 M_\odot$) progenitors can become A- to G-type supergiants; see Luck, Lambert, and Bond (1983) and Bond, Carney, and Grauer (1984) for details of the argument.

On the other hand, recent work has established the existence of a class of post-AGB candidates with *extraordinarily* low iron-group abundances:

Star	[Fe/H]	Reference
HR 4049	<−3.2	Lambert, Hinkle & Luck 1988
	−4.4	Waelkens, Van Winckel & Trams 1990*a*
HD 52961	−4.5	Waelkens, Van Winckel & Bogaert 1990*b*

Lambert *et al.* (1988) were unable to detect iron lines (nor lines of any other species heavier than Ca) in the spectrum of HR 4049. The translation of this non-detection into an upper limit on the iron abundance depends on the effective temperature of the star. Estimates of T_{eff} have covered a wide range. Lamers *et al.* (1986) and Waters *et al.* (1989) suggested $T_{\mathrm{eff}} \simeq 10,000$ K from the energy distribution and the Balmer profiles (for $\log g \simeq 2$). However, a lower limit imposed by the lack of a detectable [O I] line, and an upper limit provided by the lack of He I and C II features, restrict T_{eff} to a value near 7,600 K (Lambert *et al.* 1988), which is consistent with the Balmer profiles if $\log g \simeq 1$ (Trams *et al.* 1990*b*). The upper limit on [Fe/H] listed in the table above is for this value of T_{eff} on the basis of Lambert *et al.*'s non-detection (they did detect two very weak Ca II lines in the near-IR, from which $[\mathrm{Ca/H}] \simeq -5$ was derived). Subsequently, however, Waelkens *et al.* (1990*a*,*b*) have used very high-S/N spectra to detect very weak iron lines in HR 4049 as well as in HD 52961; the resulting [Fe/H] ratios are also listed above.

The ultra-low iron abundances in these two stars almost certainly cannot be the values they originally had when they were on the main sequence. These are 5th- and 7th-mag stars; their [Fe/H] ratios, if real, would imply that a significant population of ultra-metal-deficient stars exists near the Sun. This population would be represented by numerous red giants with $[\mathrm{Fe/H}] \simeq -4.5$ at about 7th to 10th mag, in severe contradiction with observation (*e.g.*, Bond 1980, 1981). (The first such red giants, like CD −38°245, are only encountered at 12th mag.)

An alternative explanation of the very low [Fe/H] ratios might be that the hydrostatic, LTE models that were used for the abundance analyses are inadequate for these mass-losing, dust-surrounded, variable objects. It seems unlikely, however, that departures from the simplified models could produce iron abundances that are in error by several orders of magnitude.

We are thus led to the conclusion that the ultra-metal-deficient post-AGB stars represent *a new class of chemically peculiar stars*, in which the iron-group elements that were originally present have been selectively removed from the stellar photosphere. The problem is quite similar to that of the main-sequence λ Boötis stars; we will return to this question below.

+39°4926 may also belong to this class; although Kodaira *et al.* (1970) found [Fe/H] $= -2.1$, as quoted above, a rediscussion by Kodaira (1973) reduced the iron abundance to [Fe/H] $= -2.9$.

4. The s-Process Elements

Enhancements of the *s*-process elements might be expected in post-AGB stars, resulting from the dredge-up predicted and observed in thermally pulsing AGB stars (*cf.* Lambert 1990).

Unfortunately, the *s*-process abundances determined in post-AGB candidates are of low accuracy (due to the small number of usable lines, the weakness and blending of the lines in the solar and/or stellar spectra, and the poorly known oscillator strengths). Nevertheless, there is a clear indication, on average, of a *deficiency* of *s*-process elements in post-AGB stars (see Luck and Bond 1989 for a detailed discussion). Typically, the [element/Fe] deficiencies amount to -0.3 to -1.0 dex.

The problem is most acute for post-AGB stars with [Fe/H] $\gtrsim -1$, since galactic-disk dwarfs and red giants in this metallicity range never show a lack of *s*-process elements. The possibility has been raised (Luck 1981; Bond and Luck 1987) that the post-AGB stars with low *s*-process abundances arose from a very metal-deficient population, but have now mixed hydrogen-deficient, processed material to their surfaces. Such mixing would increase the observed [Fe/H] ratio, while leaving unchanged the low [*s*-process/Fe] ratio seen in extreme halo objects (*e.g.*, Luck and Bond 1985). Among the objections to this scenario are the following: (1) the post-AGB stars in question do not typically show halo kinematics; (2) the *s*-process deficiencies are also seen in *pre*-AGB objects such as the Type II (W Virginis) Cepheids, and Raga, Wallerstein, and Oke (1989) have shown that W Vir itself is at best only slightly helium-rich.

Luck and Bond (1989) showed that there is a strong correlation of the element deficiencies observed in post-AGB stars with second ionization potential; specifically, all of the deficient elements have second ionization potentials below the Lyman limit. Although, unfortunately, all of the observable *s*-process elements have such low potentials, there is certainly a strong suggestion of a non-LTE effect (overionization of the relevant species by Lyman-continuum photons). Note that virtually all of the objects in which *s*-process deficiencies have been seen (including the Type II Cepheids) are pulsating variables that exhibit Hα emission over at least part of their pulsation cycles.

Two exceptions to the general deficiency of *s*-process elements are the high-latitude supergiant HR 7671 and the RV Tau variable RU Cen, both of which *do* show modest *s*-process enhancements relative to the bulk of the post-AGB objects (Luck, Bond, and Lambert 1990, and Luck and Bond 1989, respectively). These are accompanied by a strong lithium feature in HR 7671 (implying $\log \epsilon(\mathrm{Li}) = 2.4$), and by strong CH bands in RU Cen, and there is thus a strong case that we *are* seeing evidence of the AGB dredge-up in these two objects. More specifically, Luck *et al.* (1990) suggest that HR 7671 is descended from a Li-rich S-type star.

For the majority of the post-AGB candidates, however, the *s*-process abundances provide no support for the supposition that they have experienced thermal pulses and the third dredge-up.

5. The CNO Abundances: Evidence for an Advanced Evolutionary State

Abundances (relative to iron) of carbon, nitrogen, and oxygen have been determined in several post-AGB candidates, and are listed in the table below. For comparison, the first line lists the mean abundances for a large sample of nearby, Population I supergiants as given by Luck and Lambert (1985).

Star	[Fe/H]	[C/Fe]	[N/Fe]	[O/Fe]	[S/Fe]	Reference
Pop. I supergiants	0.0	−0.6	+0.5	−0.3	0.0	Luck & Lambert 1985
HD 161796	−0.3	+0.3	+1.1	+0.4	+0.7	Luck *et al.* 1990
89 Her	−0.4	+0.3	+0.6	+0.1	+0.1	Luck *et al.* 1990
HR 6144	−0.4	+0.3	+0.9	+0.3	+0.4	Luck *et al.* 1990
HR 7671	−1.1	−0.3	+0.1	−0.3	+0.2	Luck *et al.* 1990
HR 4912	−1.2	+1.0	+0.6	+0.9	+0.2	Luck *et al.* 1983
HD 46703	−1.6	+1.0	+1.8	+1.1	+1.3	Luck & Bond 1984; Bond & Luck 1987
+39°4926	−2.9	+2.5	+3.3:	+2.8	+3.0:	Kodaira 1973
HR 4049	<−3.2	>+3.0	>+3.2	>+2.7	>+2.9	Lambert *et al.* 1988; Takada-Hidai 1990
HD 52961	−4.5	−4.2	+4.1	+4.3	+3.6	Waelkens *et al.* 1990*b*

As the table indicates, normal Population I supergiants show evidence of hydrogen-burning products at their surfaces: nitrogen is overabundant, and carbon (and possibly oxygen) are underabundant. The CNO abundance pattern in the post-AGB stars is strikingly different: C, N, and O are *all* enhanced (with the possible exception of HR 7671).

The elevated C and O abundances provide strong evidence for presence of helium-burning products at the surfaces of the post-AGB stars. The overabundances of nitrogen show that some of the carbon has been converted to nitrogen in an overlying hydrogen-burning zone.

6. Sulfur Overabundances

Also listed in the table above are the abundances of sulfur in several post-AGB candidates. An extraordinary overabundance of sulfur was first noted in HD 46703

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by Bond and Luck (1987); although bizarre, the sulfur enhancement at least seemed unique to this star. Subsequently, however, S overabundances (relative to iron) have been found in HR 4049 and HD 52961. Moreover, a S overabundance had been suspected much earlier in +39°4926, on the basis of several marginally detected S I lines, by Kodaira *et al.* (1970); their approximate abundance result is listed above. It has thus become clear that an anomalously high sulfur abundance is a common feature in post-AGB stars.

A nucleosynthetic origin for the sulfur is difficult to understand. Bond and Luck (1987) considered the possibility that the sulfur could be ^{32}S synthesized by successive α-captures on nuclei starting at ^{12}C. Such a reaction chain would require that a high-temperature episode had occurred in the interior (possibly during a core or shell helium flash), with subsequent mixing or exposure of the processed material at the stellar surface. The suggestion was elaborated in calculations of the nuclear reactions that would occur in a violent helium core flash by Deupree and Wallace (1987). Significant production of ^{32}S was indeed found to be possible, but is accompanied by synthesis of neighboring elements like Mg and Si, in contradiction with the observations.

The large S overabundances are not the result of incorrect stellar parameters, as demonstrated in the case of HR 4049 by the high [S/Ca] ratios found regardless of the adopted $T_{\rm eff}$ (Lambert *et al.* 1988; Takada-Hidai 1990). Nor does it seem likely that departures from LTE could produce orders-of-magnitude effects. We suggest the answer is that ***sulfur is not overabundant***; it is the iron, calcium, and other metals that are anomalously ***underabundant*** in these stars.

7. Post-AGB Stars as Chemically Peculiar Stars

The foregoing discussion forces us to the conclusion that there is a class of post-AGB objects—represented by HR 4049, HD 52961, and probably +39°4926 and HD 46703—in which the photospheric abundances of iron and other heavy metals have been drastically reduced below their original values by some mechanism of chemical-element separation.

The evidence for this conclusion is twofold: (1) the [Fe/H] ratios in HR 4049 and HD 52961 are so low that they are essentially impossible to understand in terms of galactic chemical evolution; (2) the high [S/Fe] ratios in several objects can be understood easily only if it is the iron that is severely underabundant rather than the sulfur overabundant. The second point is strengthened by the strong correlation of the overabundances of S, as well as of the CNO group, with the Fe underabundances, which is apparent in the table above. (In other words, the [CNO/H] and [S/H] ratios remain, roughly speaking, close to solar in these objects, even as their [Fe/H] ratios range over several orders of magnitude.)

Can a gravitational diffusion mechanism account for the low abundances of the heavy metals? This seems unlikely for two reasons: (1) the surface gravities are some three orders of magnitude lower than in the main-sequence, chemically peculiar A-type stars for which diffusion does provide a plausible mechanism; (2) if these objects are in a post-AGB stage, the evolutionary timescale should be orders of magnitude shorter than the diffusion timescale, allowing no time for the chemical peculiarities to be established.

The problem is remarkably similar to that of the λ Boötis stars, a class of metal-deficient, rapidly rotating, Population I A-type dwarfs. Diffusive processes would seem unlikely to be able to operate in the presence of the rapid rotation. Recent abundance analyses of three λ Boo stars by Venn and Lambert (1990) make the parallel with the post-AGB stars even more compelling: C, N, O, and S are precisely the elements that are overabundant (relative to the metals) in these stars! Venn and Lambert note that the underabundant elements in λ Boo stars are those that are also depleted in the gas phase of the interstellar medium, while C, N, O, and S are not depleted.

A plausible scenario to account for the abundance anomalies in HR 4049 and its post-AGB kin might therefore involve selective removal of the metals from the photosphere through grain formation and mass loss. The plausibility of such a scenario is certainly enhanced by the obvious presence of substantial amounts of dust around most of the post-AGB stars. However, it remains unclear why the HR 4049-like stars have undergone extreme selective mass loss, while objects like 89 Her and HR 4912 show no strong evidence for such a process.

8. Are These Stars Really Post-AGB?

As noted above, most of the post-AGB candidates do not show *s*-process enhancements. This observation casts doubt on the hypothesis that these objects have passed through the AGB thermal pulses and third dredge-up.

Further doubts are raised by Fernie and Sasselov's (1989) claim that the rates of pulsational period and color change, dP/dt and $d(B-V)/dt$, are much slower than expected for 89 Her, HD 161796, and UU Her on the basis of the Schönberner (1983) post-AGB tracks. (On the other hand, dP/dt for RV Tau variables appears to be of the right size—Percy *et al.* 1990.) Moreover, post-AGB candidates are surprisingly numerous in globular clusters compared to expectation from the Schönberner timescales.

These points raise the possibility that many of these objects are on evolutionary tracks that leave the AGB before reaching the thermally pulsing stage. (Selection of such objects may be favored by the criteria of high galactic latitudes and/or Population II membership, which strongly favor low-mass stars.) Alternatively, and more speculatively, Iben and Tutukov (1989) suggest that coalesced binaries can occupy locations in the H-R diagram similar to those of our post-AGB candidates.

9. Summary

1. Candidates for objects in a post-AGB evolutionary stage include high-latitude supergiants, UU Her and RV Tau variables, and *IRAS* sources identified with A- to G-type supergiants.

2. The photospheric CNO abundance patterns in such stars are distinctly atypical of normal Population I supergiants, and clearly indicate that these objects have burned helium.

3. The stars typically show moderately to extremely low iron-group abundances, consistent with membership in the thick-disk or halo populations, and with having arisen from low-mass progenitors.

4. Although points 2 and 3 are consistent with a post-AGB evolutionary status, *s*-process enhancements are typically not seen. Alternative scenarios (such as tracks that leave the AGB before the dredge-up, or binary mergers) remain possible.

5. A minority of the candidates, including HR 7671 and RU Cen, *do* show *s*-process enhancements, along with strong Li or CH features, consistent with having passed through a thermally pulsing AGB phase.

6. A few objects, typified by HR 4049, show extraordinary abundance peculiarities, including extremely low [Fe/H] and gross enhancements of C, N, O, and S. These objects appear to constitute a new class of chemically peculiar stars, in which a process of chemical-element separation (possibly formation and ejection of metal-rich grains) has severely depleted the photospheric metals.

References

Bidelman, W.P. 1951, *Ap. J.,* **113**, 304.

______________. 1966, *Vistas in Astronomy,* **8**, 53.

Bond, H.E. 1970, *Ap. J. Suppl.,* **22**, 117.

__________. 1977, *Bull. A.A.S.,* **9**, 601.

__________. 1980, *Ap. J. Suppl.,* **44**, 517.

__________. 1981, *Ap. J.,* **248**, 606.

Bond, H.E., Carney, B.W., and Grauer, A.D. 1984, *Pub. A.S.P.,* **96**, 176.

Bond, H.E., and Luck, R.E. 1987, *Ap. J.,* **312**, 203.

Crampton, D., Cowley, A., and Humphreys, R.M. 1975, *Ap. J. (Letters),* **198**, L135.

Deupree, R.G., and Wallace, R.K. 1987, *Ap. J.,* **317**, 724.

Dickens, R.J., and Powell, A.L.T. 1973, *M.N.R.A.S.,* **161**, 249.

Fernie, J.D., and Sasselov, D.D. 1989, *Pub. A.S.P.,* **101**, 513.

Greenstein, J.L., and Oke, J.B. 1977, *Pub. A.S.P.,* **89**, 131.

Hrivnak, B.J., Kwok, S., and Volk, K.M. 1988, *Ap. J.,* **331**, 832.

______________________________________. 1989, *Ap. J.,* **346**, 265.

Humphreys, R.M., and Ney, E.P. 1974, *Ap. J.,* **190**, 339.

Iben, I., and Tutukov, A.V. 1989, *Ap. J.,* **342**, 430.

Jura, M. 1986, *Ap. J.,* **309**, 732.

Kodaira, K. 1973, *Astr. Ap.,* **22**, 273.

Kodaira, K., Greenstein, J.L., and Oke, J.B. 1970, *Ap. J.,* **159**, 485.

Lambert, D.L. 1990, these proceedings.

Lambert, D.L., Hinkle, K.H., and Luck, R.E. 1988, *Ap. J.,* **333**, 917.

Lambert, D.L., and Sawyer, S.R. 1986, *Pub. A.S.P.,* **98**, 389.

Lamers, H.J.G.L.M., Waters, L.B.F.M., Garmany, C.D., Perez, M., and Waelkens, C. 1986, *Astr. Ap.,* **154**, L20.

Luck, R.E. 1981, *Pub. A.S.P.,* **93**, 211.

Luck, R.E., and Bond, H.E. 1984, *Ap. J.,* **279**, 729.

______________. 1985, *Ap. J.,* **292**, 559.

______________. 1989, *Ap. J.,* **342**, 476.

Luck, R.E., Bond, H.E., and Lambert, D.L. 1990, *Ap. J.,* **357**, 188.

Luck, R.E., and Lambert, D.L. 1985, *Ap. J.,* **298**, 782.

Luck, R.E., Lambert, D.L., and Bond, H.E. 1983, *Pub. A.S.P.,* **95**, 413.

Menzies, J.W., and Whitelock, P.A. 1988, *M.N.R.A.S.,* **233**, 697.

Parthasarathy, M. 1990, these proceedings.

Parthasarathy, M., and Pottasch, S.R. 1986, *Astr. Ap.,* **154**, L16.

Percy, J.R., Sasselov, D.D., Alfred, A., and Scott, G. 1990, preprint.

Pottasch, S.R., and Parthasarathy, M. 1988, *Astr. Ap.,* **192**, 182.

Raga, A., Wallerstein, G., and Oke, J.B. 1989, *Ap. J.,* **347**, 1107.

Schönberner, D. 1983, *Ap. J.,* **272**, 708.

Slettebak, A., Bahner, K., and Stock, J. 1961, *Ap. J.,* **134**, 195.

Takada-Hidai, M. 1990, *Pub. A.S.P.,* **102**, 139.

Trams, N.R., Lamers, H.J.G.L.M., Waelkens, C., and Hubeny, I. 1990*b*, in preparation.

Trams, N.R., Waters, L.B.F.M., Lamers, H.J.G.L.M., Waelkens, C., Geballe, T.R., and The, P.S. 1990*a*, preprint.

Venn, K., and Lambert, D.L. 1990, preprint.

Waelkens, C., Van Winckel, H., and Trams, N.R. 1990*a*, these proceedings.

Waelkens, C., Van Winckel, H., and Bogaert, E. 1990*b*, in *Confrontation Between Stellar Pulsation and Evolution*, ed. C. Cacciari (Chelsea: A.S.P. Conference Series), in press.

Waelkens, C., Waters, L.B.F.M., Cassatella, A., Le Bertre, T., and Lamers, H.J.G.L.M. 1987, *Astr. Ap.,* **181**, L5.

Waters, L.B.F.M. *et al.* 1989, *Astr. Ap.,* **211**, 208.