CHEMICAL COMPOSITIONS OF POPULATION II MID- AND LATE-TYPE STARS

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ABSTRACT. The abundance patterns in Population II red giants provide information about galactic chemical evolution and nucleosynthesis sites for various chemical elements. These patterns were first revealed by moderate-S/N photographic spectra and are now being refined and extended to additional chemical elements and fainter stars with high-S/N data. The well-established features include overabundances of O and Ca, underabundances of *s*-process elements, and solar ratios of heavy *r*-process elements. An excess of nickel found by us on moderate-S/N spectra is less certain, and should be checked with high-S/N data. New information on oxygen abundances in Population II red giants is becoming available from high-S/N observations of weak [O I] lines, and consistently indicates an oxygen overabundance due to the preferential sampling in Population II stars of ejecta from massive stars of previous generations. Recent studies of highly evolved, post-AGB Population II stars are revealing remarkable overabundances of light elements (C, N, O, and S) and deficiencies of the heaviest elements; these are probably signatures of internal nucleosynthesis followed by mixing up to, or exposure by mass loss at, the stellar surface.

1. WHY DETERMINE CHEMICAL ABUNDANCES IN POPULATION II STARS?

The chemical compositions of the oldest stars in our galaxy are of interest for several reasons:

(1). The wide range of metallicities ($-4.5 < [Fe/H] < -1$) that is observed among halo stars provides "snapshots" of the process of chemical enrichment during the early stages of formation of our galaxy.

(2). Population II stars sample material ejected by stars with short lifetimes (*i.e.*, high masses), and thus provide information on the sites of nucleosynthesis of various chemical elements. Thus, for instance, chemical elements that are preferentially produced by high-mass stars would be expected to show posi-

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tive [element/Fe] ratios at low [Fe/H]; examples to be discussed below are O, Ca, and possibly Ni. Secondary elements should have [element/Fe] < 0; *e.g.*, the *s*-process elements such as Sr, Y, Zr, and Ba, which require pre-existing Fe for their synthesis. On the other hand, primary elements should have [element/Fe] $= 0$; an example would be heavy *r*-process elements, if they are directly synthesized in Type II supernovae without the need for pre-existing iron-group seeds.

(3). Population II stars with peculiar abundances can provide information on internal nucleosynthesis and the exposure of processed material at the stellar surfaces via mixing and/or mass loss, and thus provide constraints on the evolution of low-mass stars. For example, the CN cycle depletes C and enhances N, but helium burning makes C and O, so that very distinct abundance signatures are produced.

General discussions of this subject have been given by several recent authors, including Luck and Bond (1985*a*), Spite and Spite (1985), Truran and Thielemann (1986), Lambert (1987), and Truran (1988). This brief paper will concentrate on the importance of high-S/N spectroscopy to current and future developments. Moreover, we will concentrate on abundance analyses of *field* Population II stars, for which the highest-S/N data can be obtained, leaving discussion of the fainter globular-cluster stars to other speakers at this Symposium.

2. ABUNDANCE PATTERNS IN METAL-DEFICIENT FIELD RED GIANTS

2.1. Population II Abundances from Moderate-S/N Data

The capabilities and limitations of classical photographic spectroscopy for abundance analyses of 8th- to 11th-magnitude stars are typified by our results for field metal-deficient red giants (Luck and Bond 1985*a*). We used photographic (IIIa-J) echelle image-tube spectrograms obtained with the KPNO and CTIO 4-m telescopes, and carried out LTE model-atmosphere analyses. The spectra had S/N $\simeq$ 35, leading to measured equivalent widths that were uncertain by about a factor of 2 at $\sim 25\,\mathrm{m\AA}$ (*cf.* Luck and Bond 1985*a*, Fig. 1). From such material it is possible to determine abundances for species like Fe, which are represented by numerous absorption lines of moderate strength, to an accuracy of about ± 0.2 dex; most of this error is actually contributed by uncertainties in the atmospheric parameters, T_{eff} and $\log g$. For species represented by fewer or weaker lines, the contribution from equivalent-width errors becomes more important, and systematic errors due to continuum placement and line blending (both in the program star and in our reference star, the Sun) could also be significant.

The chief results of this and similar studies are the following:

(1). Oxygen shows a general overabundance of [O/Fe] $\simeq +0.4$ for all stars with [Fe/H] < 1 (see below), and the [Ca/Fe] ratio behaves similarly. These results suggest that both oxygen and calcium are preferentially synthesized in massive Type II supernovae, in agreement with theoretical expectation.

(2). Sr, Y, Zr, and Ba are underabundant at low [Fe/H]; this supports the conclusion that these elements have, at least in part, a secondary (*s*-process) origin in Population II stars.

(3). However, the elements heavier than barium do *not* appear to be secondary elements. For example, we found that [Nd/Fe] $\simeq 0$ at all [Fe/H]. This indicates that these are primary *r*-process elements, possibly synthesized in Type II supernovae as suggested by Truran (1981). The heavy-element patterns in individual Population II stars have been analyzed by Sneden and Parthasarathy

(1983) and Sneden and Pilachowski (1985), and these patterns also support an *r*-process origin for the heaviest elements. The lines of the *s*- and *r*-process elements are often very weak in Population II stars, and it is clear that the high S/N now available from modern detectors will provide much new information (*cf.* Sneden, Pilachowski, and Krishnaswami 1988).

(4). Our most unexpected result was that nickel is overabundant in field red giants with [Fe/H] < -1.8 (Luck and Bond 1983, 1985*a*). The nickel overabundance rises to [Ni/Fe] $\simeq +0.5$-0.8 at [Fe/H] $= -3$. We suggested that this effect could indicate that the mass cut (between ejected and retained material) may have been deeper in massive Population III Type II supernovae, leading to ejection of more highly neutronized matter. Some support for this view comes from our observation that the Ni abundance appears to be anticorrelated with the Ti abundance for Population II red giants, as would be expected from the mass-cut argument. In the next subsection, we discuss the reality of the nickel overabundances in more detail.

2.2. Is Nickel Overabundant at Low [Fe/H]?

There are reasons for doubting the high [Ni/Fe] ratios in Population II red giants that were just mentioned. First of all, our studies were the first in which a significant number of Ni I lines were measured in extremely metal-poor stars (because there are numerous Ni I lines around 5100 Å, a region covered by our echellograms but not by conventional direct IIa-O plates); nevertheless, these Ni I lines are still quite weak. Fig. 1 shows histograms of the Ni I equivalent-width distributions in four of our metal-poor red giants covering a wide range of [Fe/H]; the equivalent widths have been published by Luck and Bond (1985*b*).

At moderate iron deficiency, *e.g.*, in HD 26297 ([Fe/H] $= -1.4$), the strengths of the Ni I lines are such that a rather accurate Ni abundance can be derived (comparable in accuracy to Fe, in fact). However, as we move below [Fe/H] $\simeq -2$, the Ni I lines become quite weak, and for [Fe/H] ≤ -2.6 virtually all of the Ni I lines are below the equivalent width at which the uncertainty is at least a factor of two. At such low metallicities, it thus becomes possible that we are preferentially retaining only the Ni I lines for which the noise, line blending, or continuum placement has created a spuriously large equivalent width.

A further argument against the reality of our nickel overabundances is that several other authors have not confirmed it. Bessell and Norris (see discussion after this paper) found normal [Ni/Fe] in several of our stars, on the basis of low-excitation Ni I lines near 3400 Å. Peterson (1988), working in the same spectral region as we did, also did not find Ni overabundances in several of our stars.

On the other hand, we can mention several reasons for believing that the Luck and Bond nickel results are correct. (1) Other elements with weak lines (*e.g.*, Cr I) did not show overabundances in the Luck and Bond (1985*a*) analyses; (2) our observed anticorrelation of Ni and Ti (over the whole range $-3 <$ [Fe/H] < -1) is as expected from the mass-cut argument given above; (3) the change in slope of the [element/Fe] *vs.* [Fe/H] ratios occurs at the same [Fe/H] for Ni and the *s*-process elements, suggesting a common and real cause for both.

This is clearly an issue that will be resolved only with high-S/N spectra obtained in the region near 5100 Å; we, as well as several other groups, are now obtaining such data. Meanwhile, we warn that a nucleosynthetic explanation can probably be found for any abundance trend, even if the trend does not really exist!

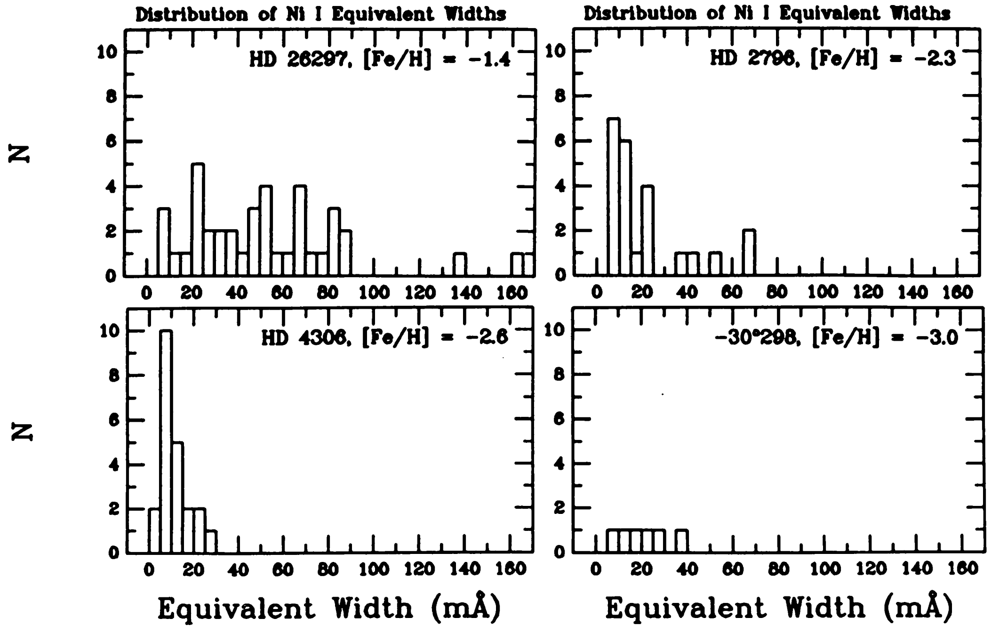

Figure 1. Ni I equivalent-width distributions in four metal-deficient red giants. Note that in the most metal-poor stars, nearly all of the Ni I lines are very weak.

2.3. Oxygen Overabundances in Metal-Poor Field Stars

As discussed above, a clear prediction of chemical-evolution theory is that [O/Fe] > 0 is expected in Population II stars because they preferentially sample the ejecta of massive objects.

In fact, an overabundance of oxygen now appears to be a well-established feature in Population II stars. In Fig. 2, we plot [O/Fe] *vs.* [Fe/H] for field (sub)dwarfs and giants. All oxygen determinations of which we are aware for stars with [Fe/H] < −1 are included. Most of the measurements for [Fe/H] < −1 refer to the [O I] line at 6300 Å, which is extremely weak in the most metal-deficient stars.

Different symbols are used in Fig. 2 to distinguish measurements made with photographic (moderate-S/N) or electronic (high-S/N) detectors. The figure clearly shows that the scatter in [O/Fe] is smaller for the high-S/N data. Whether or not any residual cosmic scatter remains is a significant question, since a scatter in [O/Fe] among globular clusters might be related to horizontal-branch anomalies. Pilachowski, Sneden, and Wallerstein (1983) did report a larger scatter in oxygen abundances among globular clusters than is seen in our Fig. 2, but since that work was based on photographic spectra it would be important to obtain higher-S/N data. So far, the high-S/N observations for field red giants have failed to reveal any analogs of the oxygen-*deficient* globular-cluster stars claimed by Pilachowski *et al.*

The high [O/Fe], if it is as pervasive among globular-cluster stars as it is

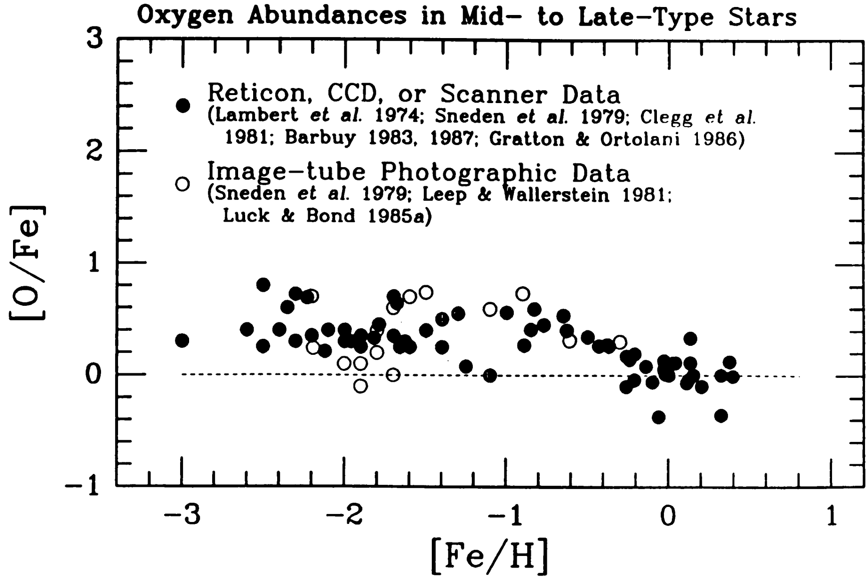

Figure 2. [O/Fe] *vs.* [Fe/H] for field stars, taken from the sources noted in the legend. Stars with [Fe/H] < −1 show a scatter around a constant [O/Fe] ≃ +0.4. *Open circles* refer to data obtained with photographic techniques, while *filled circles* plot higher-S/N data obtained with digital detectors.

among the field stars in Fig. 2, is also of fundamental significance because it acts to decrease the ages of globular clusters as derived from color-magnitude diagrams (*e.g.*, Fahlman, Richer, and VandenBerg 1985).

The availability of high-S/N detectors on large telescopes is making possible significant advances in this area; for example, the authors are now determining oxygen abundances in an additional three dozen field Population II giants on the basis of excellent CCD spectra obtained with the 4-m reflector at CTIO (Luck and Bond, in preparation).

3. PECULIAR CNO, S, AND *s*-PROCESS ABUNDANCES IN POST-AGB STARS

We will conclude this article by discussing some recent findings of remarkable abundance patterns in stars that are in their final evolution off the asymptotic giant branch (AGB) toward the realm of the nuclei of planetary nebulae.

3.1. The Population II Supergiant HD 46703

HD 46703 is a 9th-magnitude F-type star that appears to be a post-AGB object of the type just described. Our initial study of its chemical composition (Luck and Bond 1984) showed a halo metallicity ([Fe/H] = −1.6) and overabundances of both carbon and oxygen by factors of more than ten. More recently, we used a CCD detector at the 2.1-m KPNO reflector in a follow-up high-S/N study of the

N I lines near 8700 Å, and got a double surprise (Bond and Luck 1987).

Nitrogen is overabundant in HD 46703 by more than a factor of 50; the excesses of C, N, *and* O point to substantial mixing to the stellar surface (or exposure there by extreme mass loss) of CN-cycled material, along with additional material from the CO core. Our second surprise was serendipitous; by chance, several lines of S I happen to lie near 8700 Å, and their extraordinary strengths imply that sulfur is overabundant by nearly a factor of 20. We suggested that this is ^{32}S, synthesized by successive α-captures on ^{12}C during a transitory high-temperature episode in the stellar core and subsequently exposed at the surface. If so, an unexpected new feature of the evolution of low-mass stars is indicated.

BD +39°4926 is an A-type field star that is in a very similar evolutionary stage to that of HD 46703. On the basis of photographic spectra, Kodaira, Greenstein, and Oke (1970) reported pronounced overabundances of C, O, and, tentatively, S. It would be extremely interesting to repeat this analysis using high-S/N digital spectra to see whether the extraordinary abundance pattern of HD 46703 exists in a second object.

3.2. The *s*-Process Elements in Post-AGB Stars

A further remarkable property of HD 46703 is that the *s*-process elements are underabundant by ~ 0.7 dex (Luck and Bond 1984). Underabundances of this amount are encountered in Population II red giants, but only at [Fe/H] $\simeq -2.5$ (Luck and Bond 1985*a*); in HD 46703, the iron abundance is nearly an order of magnitude higher.

In fact, there are several studies that indicate that unusually low *s*-process abundances may be a pervasive phenomenon among low-mass post-AGB stars. These include abundance analyses of high-latitude A- and F-type supergiants (Luck, Lambert, and Bond 1983, and in preparation), W Virginis stars (Barker *et al.* 1971; Anderson and Kraft 1971), and RV Tauri variables (Luck 1981; Luck and Bond, in preparation).

One tentative explanation for this phenomenon would be to suppose that the stars were initially of very low iron content, and that they had the low *s*-process abundances typical of such objects. Exposure of processed, hydrogen-deficient layers has now produced higher observed [Fe/H] ratios, while leaving the [*s*/Fe] ratios at their original low values. Alternatively, one will have to conclude that plane-parallel, LTE model-atmosphere analyses are inadequate for highly evolved objects that have extended atmospheres and may even be surrounded by cool proto-planetary nebulae. In any event, the heavy-element abundances are based on very few, and often very weak, absorption lines. High-S/N data would help place this phenomenon on a firmer basis.

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DISCUSSION

BESSELL The Ni I lines that Bessell and Norris have measured use low-excitation lines near λ3400 Å. These lines indicate no deficiencies relative to Fe in the stars with [Fe/H] < −2.5, but Dr. Holweger's paper this morning showed large difference for Fe I between abundances for low and high excitation.

BOND The NiI lines we used are near 5100 Å and have excitation of ≈ 1.6–3.6 eV.

HOLWEGER It is difficult to assess the non-LTE effects for low-and-high excitation lines without detailed calculations. Empirical evidence indicates that low-excitation lines give larger abundances than those of high excitation in Pollux (T_{eff} ≈ 4840K, [M/H] ≈ 0) but that the situation is reversed in the halo giant HD 122563. In any case I would strongly discourage anybody to use excitation temperatures in the analysis of red giants.

SNEDEN Why do you recommend 5100 Å for followup Ni I observations ?

BOND Simply because Ni I lines are particularly numerous in this region.

PETERSON The N I and S I in HD 46703 are very high-excitation lines and are sensitive to the temperature gradient at large optical depths. The abundances derived from such lines should be checked, by deriving abundances for species represented by both very high-excitation lines and normal (i.e. Fe I like) lines, e.g. Mg II and Mg I.

BOND It is not sufficient to change just the overall effective temperature –the dependance of [S/Fe] on the assumed T_{eff} is too weak to remove the huge sulfur overabundance. We have not checked Mg I-II, but both low-excitation [C I] and high-excitation C I give virtually the same carbon abundance.

R. CAYREL You convinced us that no Pop.III has been seen, already six years ago.
Is it not true that we have not even seen a second generation star, because s-process elements are always present at some level, even in the most iron-poor stars ?

BOND If Sr, Y, Zr, and Ba are s-process elements (or have an s-process component) in our extreme Pop.II stars, then there must have been at least 2 previous unseen generations.

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