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Oxygen Abundances in Old Stars and Implications to Nucleosynthesis and Cosmology

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The Problem of Determining Oxygen Abundances in Old, Metal-Poor Stars

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Abstract. Determination of accurate oxygen abundances in old metal-poor stars is of importance for a variety of astronomical problems ranging from stellar evolution to cosmology. A brief review is given here of the four basic procedures from which values of [O/Fe] can be estimated.

1. Introduction: Motivations

Accurate oxygen abundances ([O/Fe]-ratios) of old, metal-poor stars are required if one is to have a satisfactory resolution of several significant astronomical issues. Chief among these are (1) relative and absolute ages of halo field and globular cluster stars, and the comparison of these with expansion ages based on model cosmologies and the value of H_o; (2) input to abundance ratios found in Type II supernova ejecta and corresponding models of Galactic nucleosynthesis; and (3) tests of atmospheric abundance changes accompanying stars as they evolve from the main sequence to the red giant branch (RGB), and on to the horizontal (HB) and asymptotic giant branches (AGB).

The present situation can be briefly summarized as follows. Over a period of about 30 years, analysis by numerous investigators, almost entirely on giants, has established that <[O/Fe]> rises from 0.0 at [Fe/H] = 0.0 to $\sim +0.3$ at [Fe/H] = -1.0, then levels off reaching $\sim +0.45$ at [Fe/H] = -2.4, the low end of the metallicity range of globular clusters (e.g., reviews by Suntzeff 1993, Kraft 1994, Briley et al. 1994, Wallerstein et al. 1997). This work was based largely on analysis of the [O I] doublet at 6300/6364Å. On the other hand, recent work on subdwarfs, based on the OH bands near 3100Å and the permitted O I triplet near 7770Å, shows that <[O/Fe]> continues to rise below [Fe/H] = -1, reaching $\sim +0.8$ at [Fe/H] = -2.4, and rising to $+1.0$ or even above at [Fe/H] near -3.0 (Abia & Rebolo 1989, Israelian et al. 1998, Boesgaard et al. 1999). One possible explanation is that giants experience internal deep mixing that modifies the surface abundances. Thus <[O/Fe]> obtained from subdwarfs is actually closer to that of the primordial medium out of which these stars were formed. On the other hand, it is possible there is a non-physical systematic difference resulting from inadequate atmospheric modelling either of the subdwarfs, giants, or both.

What effect do these recent changes, if true, have on the issues (1) to (3) raised at the beginning of this paper? First, under (1), the upward "revision" of [O/Fe], if applied to globular clusters, would have the effect of reducing cluster

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ages by ~0.7 to 2.0 Gyr (VandenBerg 1992), a non-trivial result. Under (2), the abundance of oxygen in old metal-poor stars provides a constraint on theories of cosmic ray spallation (Fields and Olive 1999) and the corresponding implications involving Be/O-ratios (Balachandran & Bell 1998, Israelian et al. 2000). It is also required in theories of Galactic chemical evolution (e.g., Chiappini et al. 1999, Pagel & Tautvaisienė 1995) in which the abundance of O is compared with Fe and other so-called "α-elements" and the results used to constrain predicted abundance ratios in the ejecta of massive supernovae (Woosley & Weaver 1995).

Less generally well known are issues raised under (3) above. For example, Gratton et al. (2000) derived the "traditional" pre-1998 values of the C,N,O abundances among old metal-poor halo field dwarfs and giants, and concluded that with advancing evolutionary state, O and Na remained constant, whereas $^{12}C/^{13}C$ approached the equilibrium CNO cycle value near 4, Li and C rapidly declined by three and by half an order of magnitude respectively, and N increased in accordance with CN cycling at the expense of C, essentially in agreement with modern models of stellar evolution. It is also well known that globular cluster giants, otherwise thought to be surrogates for field halo giants, show strong evidence for depletion of O as well as C, enhancement of N at the expense of O as well as C, in some cases enhancement of Al at the expense of Mg, and an anticorrelation of O and Na, especially in M13 (Kraft et al. 1997) and ω Cen (Norris & Da Costa 1995), none of which is in accordance with standard evolutionary theory. If <[O/Fe]> in dwarfs is, in fact, much higher than that deduced for giants among old, metal-poor stars (Israelian et al. 1998, Boesgaard et al. 1999), and if the values deduced for giants are correct, then one must conclude that bright cluster giants are not only more seriously depleted in O than field giants, but that field giants are also depleted in O despite the rather modest enhancement of N. The N enhancements claimed by Gratton et al. are, however, compatible with the observed C depletion and are thus a factor of 2 too small if significant O has in fact been converted to N.

2. The Four Sources of O Abundance in Old, Metal-Poor Stars

1) [O I] doublet at 6300/6364Å

In principle, these features should be the most reliable source of [O/Fe]-ratios since the gf-values are well-known, O is overwhelmingly neutral and in the ground state, and the lines arise from the ground state. In a giant of metallicity [Fe/H] = −2.3 (near the low end of the globular cluster metallicity range), EW(6300) is typically ~ 30 mÅ when [O/Fe] +0.4 (Sneden et al. 1997) and is thus easily and accurately measured. Unfortunately, the [O I] doublet virtually disappears from the spectra of subdwarfs when [Fe/H] drops below −1.4: model synthetic spectra of a subdwarf with solar values of $T_{\rm eff}$ and $\log g$ but with [Fe/H] = −2.3, yield EW(6300) = 1 mÅ (!) even for an [O/Fe]-ratio as large as +1.0. Progress here requires long exposures at high resolution using very large telescopes (see paper by Cayrel later in this JD).

2) The O I Permitted Triplet at 7772/7774/7775Å

These lines arise from levels more than 9 eV above the ground state, and thus we are in a "tail-wags-the-dog" situation: fewer than 10^{-7} O atoms are

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in these levels compared with the ground state. Thus care must be exercised in the choice of temperature and details of the temperature distribution in the model atmospheres also play a role (Tomkin et al. 1992). Generally these lines can be accurately measured, since their EW's lie in the range 5 to 35 mÅ in metal-poor dwarfs. The large values of [O/Fe] found initially by Abia & Rebolo (1989), based on ~30 dwarfs and subgiants, were later revised: independent remeasurement of EWs of these lines, plus re-evaluation of analysis procedures reduced the [O/Fe] ratios in subdwarfs by about 0.2 dex (Tomkin et al. 1992, Cavallo et al. 1997), but these values still remained typically ~0.3 – 0.4 dex higher than the ratios derived from [O I] in giants. King (1993) suggested that the discrepancy could be resolved by adopting a B-V vs. $T_{\rm eff}$ scale for subdwarfs about 200K hotter than the one of Abia and Rebolo, who had used the Carney (1983) calibration. The Carney scale is, however, only about 50K cooler than the later calibration of Alonso et al. (1996), based on the IR flux method (Blackwell & Shallis 1977). Most recently Allende Prieto & Lambert (2000) have modelled the UV flux of a number of subdwarfs and derive $T_{\rm eff}$'s that agree well on the average with those derived from the IR flux method, suggesting that the Alonso et al. scale is to be preferred. Progress in modelling the UV flux distribution of subdwarfs will be outlined in greater detail later in this meeting (Peterson 2000).

Oxygen abundances derived from the near IR triplet also require a correction for NLTE, which according to Gratton et al. (2000) reduces the LTE-derived oxygen abundances by ~0.15 dex on the average. Mishenina et al. (2000) find a reduction of 0.10±0.03 (sdm) based on 9 stars having [Fe/H] < -1.0. Even smaller corrections were found by Tomkin et al. (1992); an uncertain mean suggests a reduction near 0.1 dex.

3) Near-IR OH Vibration-Rotation Bands in the 1.5–1.7 Micron Region

Little work has been done so far using these features in part because the technology is new but more results are expected, some to be reported later in this meeting (Melendez et al., this JD, Balachandran et al. 2001). So far only HD 103095 has been analyzed in a pioneering effort by Balachandran and Carney (1996). EW's of these features are in the 10–20 mÅ range even for this subdwarf of modest metal deficiency ([Fe/H] ~ -1.4) and thus analysis is likely to be confined to stars with $T_{\rm eff} < 5000$K especially for subdwarfs with [Fe/H] below −1.5. Typically only about one in every 300 oxygen atoms is tied up in OH. However, the dissociation potential is low (4.39 eV), and the rotation-vibration lines are typically close to the ground state (~0.5 eV), so the conversion from OH to O is not so sensitive to errors in $T_{\rm eff}$ and its distribution as was the case for the permitted triplet O I lines.

Balachandran and Carney rejected the upward revision of the color-$T_{\rm eff}$ scale proposed by King; the reader is referred to the article for details. In the end, they found rather good agreement among the indicators of [O/Fe] in the case of HD 103095, as follows: [O/Fe] = +0.29±0.05 from rotation-vibration OH lines (14–20 mÅ), [O/Fe] = +0.42±0.11 from O I permitted triplet lines (4–8 mÅ) and [O/Fe] = +0.33±0.12 from [O I] 6300 (2 mÅ).

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4) The near-UV OH Electronic Transition Bands (3080–3300Å)

Following pioneering work (Bessell et al. 1984, Bessell & Norris 1987, Ryan et al. 1991, Bessell et al. 1991, Nissen et al. 1994), these features have been taken up in two important papers in which spectra of more than 20 mostly subdwarfs have been analyzed at high spectral resolution (Israelian et al. 1998 [I98], Boesgaard et al. 1999 [B99]). Although the early investigations concluded that no significant difference existed between values of [O/Fe] derived from UV OH and [O I], the two later papers agreed in finding much higher values of [O/Fe] at a given [Fe/H] from UV OH in subdwarfs than from [O I] either in giants or relatively metal-rich subdwarfs ([Fe/H] > -1.5), as noted in Section I.

Only theoretical gf-values are known for these OH electronic transitions (Goldman & Gillis 1981), and both I98 and B99 checked these by modelling the OH spectral region in the Sun. Herein lies an area of controversy: the belief is widespread that sources of "continuous opacity" have not been fully taken into account in the UV region of the solar spectrum (e.g., Bessell, this conference; Balachandran & Bell 1998). Thus modelling of the solar OH region could lead to gf-values for OH that are too small. Indeed, B99, following the work of Nissen et al. (1994), found it necessary to reduce the theoretically-determined OH gf-values in the region λ/λ 3139–3144Å by –0.16 dex for five (0,0) lines and –0.49 dex for four (1,1) lines in order to achieve the solar oxygen abundance of Anders & Grevesse (1989). An additional puzzle surfaces when one studies the work of I98 who employed a set of 11 mostly (0,0) transitions of OH, which, except for one line, did not overlap with the lines chosen by B99. They found no need for adjustment of the theoretical gf-values when modelling the solar spectrum to achieve the same solar oxygen abundance. Yet their run of [O/Fe] with [Fe/H] closely follows that of I98.

Fulbright & Kraft [FK](1999) noted that two of the stars in the I98 list had surface gravities that placed them in the subgiant domain, and proposed that the [O I] 6300Å line might be marginally detectable. This was borne out when high S/N spectra (R = 45,000) were taken. FK assigned $T_{\rm eff}$ from the traditional Fe I abundance vs excitation plot and $\log g$ from the ionization equilibrium of Fe I and Fe II. From spectral synthesis of [O I], they derived traditional [O/Fe]-values: an upper limit of +0.35 for BD +23 3130 and [O/Fe] = +0.50 for BD +37 1458, whereas I98 had obtained [O/Fe] = +1.17 and +0.97, respectively, from UV-OH. B99 essentially confirmed this result in the case of the latter star (+0.81, Carney $T_{\rm eff}$ vs. color scale; +0.87, King scale).

More recently, Thévenin & Idiart (2000) have criticized the derivation of $T_{\rm eff}$ using the traditional Fe I excitation plot, arguing that since Fe is overionized, Fe-abundances in metal-poor stars should be based on Fe II, not Fe I. Following this admonition, Fulbright (2000) reanalyzed roughly 150 dwarfs with metallicities ranging down to [Fe/H] $\sim$ –2.5, obtaining [Fe/H] exclusively from log eps(Fe II), the surface gravity being estimated from the demand that log eps(Fe I) shall equal log eps(Fe II). The resulting $\log g$'s and [Fe/H]-values agree well on the average with those of Alonso et al. (1996), based on 36 subdwarfs, but are typically cooler by ~50K. Of interest are the revised values of [O/Fe] for BD +37 1458 and BD +23 3130. Compared with I98, for BD +37 1458, Fulbright obtained the same $\log g$ (3.00), a $T_{\rm eff}$ that is 60K cooler, and [Fe/H] that is higher by 0.22 dex. The effect of adjusting I98 parameters to those of Fulbright would

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reduce the former values of [O/Fe], based on OH, from +0.97 to +0.63. Revised synthetic spectra of [O I] 6300Å lead to a new [O/Fe] value of +0.65±0.15. A similar revision of the B99 Carney parameters for this star, although larger, leads to [O/Fe] = +0.64 from the OH features. Although these [O/Fe]-values are now in good agreement, adoption of the Fulbright parameters would still yield a very large value of [O/Fe] if derived from the permitted O I triplet lines (Cavallo et al. 1997).

A corresponding treatment of the remaining star, BD +23 3130, yields a much less happy conclusion, because the adjustments in $T_{\rm eff}$ and especially $\log g$, are quite large. A spectrum of higher S/N than that taken by FK is required, and that is reported later in this meeting by Cayrel.

3. Attempts at Rectification

It seems clear that if the correct values of $T_{\rm eff}$, $\log g$ and [Fe/H] could be unambiguously determined for any given star and if gf-values were reliably known for all atomic and molecular transitions involving oxygen, then an LTE model, coupled with adequate treatment of non-LTE effects where needed, should rectify the values of [O/Fe] derived from each of the four indicators cited in Section II. One attempt at rectification is that by Gratton et al. (2000), who found good agreement in [O/Fe] derived from [O I] and the O I near-IR triplet in the case of halo giants and red HB stars. But this does not relieve the discordance with [O/Fe] determined from the UV OH-bands (I98, B99), and Gratton et al. preferred to attribute this to difficulties with modelling the solar UV and corresponding systematic errors in the adopted gf values of OH.

Changes in the [O/Fe]-ratio resulting from adjustments in $T_{\rm eff}$, $\log g$ and [Fe/H] were considered by B99. As they note, it is not enough to consider oxygen alone: the abundance of Fe also changes as does the continuous opacity. But the result also depends on whether the reference Fe value is taken from Fe I, Fe II, or a mean of the two. [O/Fe] derived from [O I] is relatively insensitive to changes in $T_{\rm eff}$ and $\log g$ if the reference Fe abundance is taken from Fe II. This is because Fe is mostly in the singly ionized state in a typical subdwarf, and O is overwhelmingly in the ground state of the neutral atom. The situation for the abundance of O derived from the other indicators is quite different: with increasing $T_{\rm eff}$, [O/Fe] from the O I triplet falls, whereas [O/Fe] from UV-OH rises. If $\log g$ increases, [O/Fe] from the triplet lines does not change very much, but [O/Fe] derived from OH falls. Indeed, one might turn this to advantage in deriving the correct $T_{\rm eff}$ scale for subdwarfs. If all gf values were well known, if Hipparcos parallaxes were employed to obtain reliable $\log g$'s, and if all departures from LTE were accurately computed, then a forced agreement in [O/Fe] among all the abundance indicators should "manufacture" a reliable $T_{\rm eff}$ scale for subdwarfs. We are, however, still far from such a pleasant outcome and it is to be hoped that the situation will soon improve.

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