THE EFFECT OF NON-LTE AND ATMOSPHERIC PERTURBATIONS ON RELATIVE ABUNDANCE DETERMINATIONS IN METAL-POOR GIANTS

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ABSTRACT. This paper reports an abundance analysis of spectra of 10 extremely metal-poor giants, including two in the globular cluster M92, in collaboration with Robert Kurucz and Eugene Avrett of the Center for Astrophysics and Bruce Carney of the University of North Carolina. An intercomparison of equivalent widths indicates that Luck and Bond have seriously overestimated the strengths of very weak lines and so deduced a spuriously high nickel abundance in the most metal-poor stars. A review of line-formation effects in the Sun strongly suggests that the rather high metallicities found for some extremely metal-poor stars by Pilachowski and coworkers is due to errors in their solar gf values, which unfortunately are unpublished. In our own analyses, stars with asymmetric H-alpha line profiles tend to have an excitation temperature at odds with the effective temperature found from infrared photometry. The discrepancy is removed by lowering the surface temperature by 100 K or by increasing the microturbulent velocity, either by a constant 0.5 km/s or by an amount which increases toward the surface. These changes have the most impact on those abundances deduced from strong lines or low-excitation lines of the neutral species; this includes sodium and barium as well as all the Fe I lines with very accurate gf values. Despite these difficulties, our findings reveal a low abundance for M92, and intrinsic scatter in the relationship between the relative abundances of sodium and oxygen and the overall iron abundance. In one field star, oxygen is apparently overabundant by an order of magnitude or more, while in the two M92 giants, the sodium abundance appears to differ by nearly this much.

1. INTRODUCTION

One of the major motivations for spectroscopic determinations of elemental abundances in metal-poor stars is to establish or constrain the mechanism(s) of nucleosynthesis during the early history of the Galaxy from trends in relative abundances (reviewed by Spite and Spite 1985). To establish a consistent set of analyses from which such trends may be reevaluated, my colleagues and I have undertaken a series

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of abundance analyses of metal-deficient giants. The following results are extracted from a series of papers to be submitted to the Astrophysical Journal.

2. OBSERVATIONAL DATA, EQUIVALENT WIDTHS, AND THE NICKEL ABUNDANCE

At Kitt Peak and Cerro Tololo Interamerican Observatories, we obtained 4m echelle spectra (resolution 15 km/s) with the long-focus camera and Carnegie image tube and baked IIIaJ plates. All stars were observed in the red, from 4860 to 6750 A, and four in the blue also. Two spectra were obtained for several stars, with a combined S/N of ~50. Spectra were digitized on the Lockheed PDS microdensitometer with a 6 micron slit and the curve-following procedures of Peterson and Title (1976).

A detailed intercomparison of our equivalent widths (EW) with modern ones published for the same stars is generally encouraging. Below 100 mA there is excellent agreement with the CCD values of Sneden and Parthasarathy (1983): the mutual error is ±10 mA, which translates into an abundance error of ±0.17 dex throughout this range. The strongest line detected by them that we missed was 12 mA. Above 100 mA, our values are larger and the scatter increases; this might be due to subjective differences in the measurement of line wings, or to scattered light in the CCD spectra. It has no effect the abundance determinations, however, because it is absorbed in the determination of the microturbulence, discussed below.

At all EW values, our measurements are on the same scale as those of Luck and Bond (1985b), though the scatter is much larger. However, these authors often list EW values of 25 mA for lines which are not detectable in our spectra. This assumes critical importance given their result (Luck and Bond 1985a) that nickel is overabundant with respect to iron in the most metal-poor stars. Unfortunately, the element nickel is represented only by rather weak lines in the spectral region redward of 4000 A. The overabundance was detected only where virtually all the Ni I lines they measured have EW < 25 mA. Since our analysis does not show an overabundance of nickel in these stars, we attribute their result to the overestimation of very weak features.

3. METHOD AND ASSUMPTIONS OF ABUNDANCE DETERMINATIONS

We determine abundances by computing a theoretical strength for every line individually using Kurucz's program WIDTH. A model stellar photosphere is provided as input, along with the line transition probability (gf value) and a trial abundance.

Unfortunately the theoretical EW depends on assumptions of the model. The stellar effective temperature is a critical parameter for most of the elements under study here (see Pilachowski, Sneden, and Wallerstein 1983). A higher temperature tends to ionize more atoms, which produces more continuous opacity and depopulates lower ionization and excitation states. The gradient of temperature towards surface layers also affects the strongest lines of such species: a steeper gradient can dramatically enhance lines by increasing level populations, especially for the neutral species of an element which is predominantly once-ionized.

Strong lines of all types are subject to the choice of microturbulent velocity v_t and its variation with depth, for this desaturates moderately strong lines by inducing an artificial Doppler velocity over and above thermal. In K giants such as these, gas densities are so low that broadening by van der Waals damping mechanisms is ineffective below 100 mA, so v_t is very influential for EW ~ 50 - 100 mA (referred to 5000 A). In the Sun, though, the higher gas density produces damping effects at EW ~ 50 mA.

Since an error in the line transition probability translates directly into an error in the abundance of the opposite sign, it is important to use values without systematic errors. Very accurate gf values are now available for certain Fe I lines from the Oxford group, as summarized by Blackwell, Petford, and Simmons (1982). Their comparisons with Fe I gf-value determinations of other groups frequently show sizable errors in the latter, often dependent on transition strength or excitation level.

Because the Oxford furnace measurements are limited to rather strong, low-excitation lines, the analysis of the iron abundance in the Sun depends on both the solar model and on the choice of v_t and damping constants. Blackwell and Shallis (1979) show that log(Fe/H) from Fe I lines with Oxford gf values decreases by 0.2 dex in going from the solar model of Holweger and Müller (1974) to that of Vernazza, Avrett, and Loeser (1976). We would expect this given the steeper temperature gradient of the latter model. Their analysis also demonstrates that a smaller value of v_t is deduced when using a model with a steeper temperature gradient. Note also that the best-fit v_t value also depends on the source of solar EW values. Those from the solar intensity spectrum at the center of the solar disk (e.g. Delbouille, Roland, and Neven 1973) require smaller v_t values that those from the integrated light of the solar disk (e.g. by Beckers, Bridges, and Gilliam 1979).

It appears that inappropriate solar parameters may be largely responsible for rather high abundances found for the most metal-poor stars by Pilachowski and coworkers. Table 1 of Buonanno, Corsi, and Fusi Pecci (1985) illustrates the problem: for the three extremely metal-poor clusters M15, M92, and NGC 5466, the Pilachowski results are consistently the highest of the dozens listed, 0.2 - 0.4 dex above the mean. Most (but not all) analyses by Pilachowski and Sneden and their coworkers rely on somewhat dubious solar gf values. Pilachowski, Wallerstein, and Leep (1980) chose v_t for the disk of the Sun but used solar intensity EW values; Sneden and Parthasarathy (1983) used Fe I damping constants that are about four times too large for the low-excitation lines (see Simmons and Blackwell 1982, Table 3). Because the strongest solar lines are the most affected, the systematic errors introduced are largest for the most extremely metal-poor stars. Unfortunately, none of the papers lists the gf values, so this potential source of error cannot be checked.

Our own Fe I analysis is based primarily on lines with Oxford gf values. In stars with low interstellar reddening, or in clusters such as M92 where reddening is well determined, the model effective temperature T_{eff} is established to 100 K from the infrared color V-K (Cohen, Frogel, and Persson 1978). Yet in several such stars, the dependence on lower excitation potential of the iron abundance deduced solely with Oxford gf values indicated a lower T_{eff} unless v_t was made artificially large. This applied equally to models from the Kurucz (1979) and the Gustafsson et al. (1975) grids. The discrepancy appeared only for stars with a blueshifted H-alpha core.

We have begun to explicitly calculate non-LTE effects as a possible cause. The sodium calculation is straightforward, and suggests that only the very core of the NaD lines are enhanced, so the abundance effect is small. The Fe I calculation is much more difficult because many transitions are involved. In particular, the non-LTE excitation of the lower levels of various transitions in the visible is strongly influenced by which ultraviolet excitations are included, and what is assumed for the stellar UV flux.

The discussion above suggests a steeper surface temperature gradient or an increase in v_t could also remove the discrepancy. WIDTH calculations show that a model with the surface temperature lowered by 100 K does so, as do models with v_t increased by a constant 0.5 km/s or progressively enhanced by up to 2 km/s at shallow levels. There is no physical basis for these alterations, however. The Fe I abundance deduced from Oxford lines does depend rather sensitively on whether such a change is invoked, but not on which prescription is followed. So the overall iron abundances in our work should be considered uncertain by at least 0.2 dex, the amount of change when v_t is raised by 0.5 km/s. The abundances of species such as oxygen and nickel that are represented only by weak lines are independent of v_t, so a comparable uncertainty pertains to their relative abundance. And no matter what approach is taken, the strongest Ti I lines can give abundances differing by about 0.3 dex from those of the Ti II lines; the sodium abundances deduced from the NaD lines should be considered uncertain by this amount in those cases.

4. CONCLUSIONS

Despite these difficulties, we feel that our iron abundances are an improvement over previous values. In general our results are lower; for M92, for example, we find [Fe/H] = -2.5 ±0.3, which is within 0.2 dex of the abundances of the extremely metal-poor field stars.

It seems to us that genuine cases exist of radical overabundances of oxygen and sodium. In most stars the oxygen line at 6300.3 A, the strongest accessible, is too weak to be detected. In star XII-8 in M92, for example, our upper limit of 14 mA places an upper limit of -2.0 ±0.2 on the oxygen abundance relative to the Sun. However, in one field star, HD 184711, this line appears at a strength of 63 mA, and the weaker member of the doublet is also detected at 15 mA. The implied oxygen-to-iron ratio is nearly thirty times solar. Also, the NaD lines are extremely strong in M92 III-13, and a weaker line is also detected; their analysis yields a sodium-to-iron ratio 0.5 dex above solar. This is significantly larger than the remainder of our sodium-abundance ratios, notably that in XII-8. Thus we find evidence for intrinsic scatter in whatever relationship may exist for the relative abundances of these elements versus overall stellar metallicity.

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REFERENCES

Beckers, J. M., Bridges, C. A., and Gilliam, L B. 1976, A High Resolution Spectral Atlas of the Solar Irradiance From 380 to 700 Nanometers, AFGL-TR-76-0126.

Blackwell, D. E., Petford, A. D., and Simmons, G. J. 1982, M.N.R.A.S., 201, 595.

Blackwell, D. E., and Shallis, M. J. 1979, M.N.R.A.S., 186, 673.

Buonanno, R., Corsi, C. E., and Fusi Pecci, F. 1985, Astron. Astrophys., 145, 97.

Cohen, J. G., Frogel, J. A., and Persson, S. E. 1978, Ap. J., 222, 165.

Delbouille, L., Roland, G., and Neven, L. 1973, Photometric Atlas of the Solar Spectrum from λ3000 to λ10000 (Liège: Institut d'Astrophysique).

Gustafsson, B., Bell, R. A., Eriksson, K., and Nordlund, A. 1975, Astron. Astrophys., 42, 407.

Holweger, H., and Müller, E. A. 1974, Solar Phys., 39, 19.

Kurucz, R. L. 1979, Ap. J. Suppl., 40, 1.

Luck, R. E., and Bond, H. E. 1985a, Ap. J., 292, 559.

Luck, R. E., and Bond, H. E. 1985b, Ap. J. Suppl., 49, 249.

Peterson, R. C., and Title, A. M. 1976, Appl. Opt., 14, 2527.

Pilachowski, C. A., Sneden, C., and Wallerstein, G. 1983, Ap. J. Suppl., 52, 541.

Pilachowski, C. A., Wallerstein, G., and Leep, E. M. 1980, Ap. J., 236, 508.

Simmons, G. J., and Blackwell, D. E. 1982, Astron. Astrophys., 112, 209.

Sneden, C., and Parthasarathy, M. 1983, Ap. J., 267, 757.

Spite, M., and Spite, F. 1985, Ann. Rev. Astron. Astrophys., 23, 225.

Vernazza, J. E., Avrett, E. H., and Loeser, R. 1976, Ap. J. Suppl., 30, 1.

DISCUSSION

JUDGE With respect to your third suggestion for the solution of the colour vs. excitation temperature discrepancy by the desaturation of photospheric lines by velocity fields associated with mass flow, I get the feeling that you would need very large mass loss rates indeed to produce the effect in your photospheric lines. Significant mass flows indicated by asymmetry in Hα almost certainly occur in the chromospheres at much lower column masses than where your photospheric lines are formed, if are taken recent theoretical work (e.g. of Cram and Mullan, Mallick) and observations (e.g. Zarro and Rodgers) of population I giants into account. Current estimates of mass loss in K III population I stars are ≈ 10^{-10} – 10^{-9} $M_{\odot}$ yr^{-1}. If I am wrong, here we have a potential diagnostic of mass loss rates !

PETERSON The mass loss rate depends on the column density and thus on the radius at which the flow becomes strong. This is presently unknown but some constraints may be established from calculations such as those of Dupree, Hartmann and Avrett (Ap J. Lett, 1984). However, Hα is less suitable than Ca II K, but that is a very difficult line to observe.

The desaturation mechanism I am suggesting is a crude representation since the dependence of flow velocity on optical depth is virtually unknown. I will model it only as a dependence of microturbulent velocity on optical depth. A small increase in microturbulent velocity is probably all that is needed.

BUDGE You mention that you could solve some of yours problems if you could find a reason to lower the temperature of the outer photospheres of your models. As I recall, ATLAS assumes plane-parallel geometry. Since these are giant stars, and especially since you find evidence at mass outflow in these stars, I wonder it perhaps the effects of spherical geometry might not be important and result in such a lowering of the boundary temperature ?

PETERSON Plane-parallel atmospheres are probably valid since the extent of the photosphere is small with respect to the stellar radius. Recall that these are giants, not supergiants, and the brightest have $M_{bol} \approx -3$ and $T_{eff} = 4000K$. Furthermore, several stars analyzed, e.g. the fainter one in M92, lie rather far from the red-giant-branch tip. This star has very nearly the same T_{eff} and log g and [Fe/H] as HD 122563, for which T_{exc} and T(V-K) are in excellent agreement.

G. CAYREL Are you calibrating *gf* values also in the near infrared ≈ 6750 region ?

PETERSON Our data end at approximately this wavelength, as the S/N becomes low. There is no reason that this could not be done in the future from additional data.

GRATTON The derivation of accurate *gf*'s for high excitation lines, where we have to rely on solar *gf*'s, is a potential hazard for metal poor stars. In fact in this case we have to use lines which are rather strong in the Sun. The derivation of solar *gf*'s for quite strong Fe lines depends very much in the way we handle damping. Therefore, we must be careful when considering trends with line strength or line excitation in metal poor stars.

PETERSON Important guidelines are available from intercomparaisons of laboratory oscillator strengths, especially by the Oxford group. Our T_{exc} is based solely on Fe I lines with Oxford *gf* values. The high-excitation Fe I lines are run separately to check the consistency of the scale. Since the high-excitation Fe I lines have strengths which change more slowly with temperature, we hope to bootstrap *gf* values over ranges of stellar metallicities by including hot, rather metal-rich stars as well as cool, very metal-poor ones. Thus we are trying to ensure that iron abundances are on a consistent scale over the range $-2.5 \leq [Fe/H] \leq -1.0$.