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Stellar atmospheres: the link between theory and observation

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Abstract: We review the determinations of the basic parameters of stellar atmospheres and their implications for the stellar evolution models. Particular emphasis is put on the atmospheres of Population II stars and the age determination of globular clusters.

1 Introduction

Stellar atmospheres are the (nearly unavoidable) link between stellar evolution theory and observational quantities, the most notable exception being the solar neutrinos. Most of the observational tests of stellar evolution models thus rely on a proper understanding of the structure of stellar atmospheres.

The basic parameters of a stellar atmosphere are (1) its effective temperature $T_{\rm eff}$, measuring the flux emitted per unit surface, (2) its surface gravity g, or, more correctly, the acceleration of gravity at the stellar surface, and (3) its chemical composition, which may be written as a vector $N_i\,(i = 1, \ldots, K)$, N_i being the fraction by number (the *abundance*) of the chemical species i, and K the total number of different chemical elements present in the stellar atmosphere.

The basic task of the observer is thus to determine these basic parameters as accurately as possible, and the task of the theorist is to devise a model which reproduces all these observational quantities.

However, none of these parameters is directly accessible through observation. All of them must be deduced from raw observational data through the use of a model of the stellar atmosphere. The accuracy of the fundamental parameters will thus depend not only on the accuracy of the observations, but also on the accuracy of the model atmosphere used to interpret these observational data.

The aim of this paper is to discuss the accuracy which can be reached in the determination of these basic atmospheric parameters. It will be illustrated by the case of the Population II stars and, in particular, the globular clusters, whose age determination constitutes a very important test of the cosmological models.

Having these cosmological tests in mind, we shall discuss in turn the determination of the stellar chemical composition, bolometric magnitude and effective temperature.

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2 Chemical composition

The heavy element abundance is generally estimated from the iron abundance alone, assuming that the abundance of all elements heavier than boron scale with the iron abundance. Thus, the heavy element abundance is measured through a single quantity, [Fe/H], which is the logarithmic abundance of iron referred to the solar abundance (thus, $[\mathrm{Fe/H}] = -1$ means that iron is depleted by a factor 10, as compared to the sun). This quantity is often referred to as the *metallicity* of the star.

This is obviously a rough approximation: recent analyses of field Population II stars have shown that there are significant variations in the relative abundances of the heavy elements as a function of the mean metallicity (see, e.g., Wheeler et al., 1989, for a review).

Recently, in view of the growing evidence that some elements do not behave like iron when the stellar metallicity changes, models have also been computed with, e.g., different values of the oxygen abundance.

2.1 Iron abundance

Apart from this problem of the relative abundance changes, the accuracy of [Fe/H] itself can be questioned. In the recent stellar evolution literature, one can find statements that the iron abundance in globular clusters can be determined with a typical uncertainty of 0.15 dex (e.g., Demarque et al., 1990).

In fact, many globular clusters metallicities are still estimated through some global colour index. These colour indices are calibrated by comparing them to metallicities determined from high resolution spectroscopic analyses. 0.15 dex is the typical scatter of such a calibration and, thus, corresponds more or less to the internal precision of the calibration and *not* to the accuracy of the metallicity determination (e.g., Zinn and West, 1984).

The accuracy of the abundance determination ultimately depends, in all cases, on the accuracy of the high resolution spectroscopic analyses. The high resolution observations require a large number of photons : the brightest stars have thus to be used. In a given globular cluster, these brightest stars are the ones located at the top of the giant branch.

Unfortunately, these stars are just the ones we would like to avoid for a number of reasons:
(1) their surface abundances may be different from the original ones, because matter may have been dredged from the interior up to the surface;
(2) their more complex atmospheres are more difficult to model than atmospheres of, e.g., main sequence stars;
(3) the determination of the other atmospheric parameters (T_{eff}, g) is generally of lower accuracy;
(4) because of the lower gas pressure, departures from the local thermodynamic equilibrium (LTE) in the spectral lines are more likely;
(5) the spectra are more crowded and, thus, the equivalent widths of the spectral lines are of lower accuracy.

Indeed, the visible part of the spectrum of these bright globular cluster giants is so crowded that several measurement problems arise.

First, it is generally not possible to measure the weak lines, which are completely masked by the forest of medium and strong lines. However, due to the shape of the line curve of growth and to their greater depth of formation (implying higher pressure and, thus generally smaller departures from LTE), the weak lines are the best suited for abundance determinations. Medium and strong lines, due to their saturated core, are not very sensitive to abundance changes. A small error on their equivalent widths thus implies a larger error on the deduced abundance.

Secondly, it is nearly impossible to determine the position of the continuum with any confidence. A wrong position of the continuum implies a systematic error in the line equivalent widths and, thus, a systematic error in the deduced abundances. This systematic error may even be worse if only medium to strong lines can be measured.

Due to these problems, the abundance determinations in globular cluster giants are much less accurate than those of field halo dwarfs. However, even for the very simple field halo dwarfs, a recent careful analysis (Magain and Zhao, 1995) has shown that the iron abundance depends on the excitation potential of the line used in the analysis. Line-to-line differences may amount to 0.2 dex. The cause of this effect is not really known: it might be due, e.g., to a wrong effective temperature, to departures from LTE or to temperature inhomogeneities in the line-forming region.

If such uncertainties still affect the abundance analyses of field halo dwarfs with top quality spectra, it is certainly unreasonable to expect that the chemical abundances of globular cluster giants can be determined with an accuracy of the order of 0.15 dex.

2.2 Oxygen abundance

Of course, iron is not the only element for which detailed analyses of Population II stars reveal some problems. Other chemical elements display similar effects. As an illustration, we consider the case of oxygen, an important element for the age determination of globular clusters.

The general belief is that oxygen is not as depleted as iron in Population II stars. However, it is not clear whether the oxygen overabundance is roughly constant as a function of metallicity or is increasing with decreasing iron abundance.

The main spectral diagnostics of the oxygen abundance are the infrared triplet O I lines and the ultraviolet molecular OH lines in dwarf stars, the forbidden [O I] resonance line in giant stars. All these lines pose specific problems : the infrared triplet is formed very deep (inside the convection zone) and is subject to departures from LTE; the OH lines are located in a spectral region which is not easily accessible for observation and which is extremely crowded with spectral lines; the [O I] line is too weak to be measured in dwarf stars.

Figure 1 shows the determination of the oxygen abundance in a sample of metal-poor stars, based on the infrared triplet lines (Sneden et al., 1979). For one star, we have been able to obtain a very good spectrum on which the [O I] line could be measured. The arrow in Fig. 1 shows what the oxygen abundance becomes if it is determined from the forbidden line instead of the infrared triplet : no significant overabundance remains (Magain, 1988).

It is by no means our intent to question the reality of the oxygen overabundance in Population II stars. However, it is obvious that some critical problems remain, which must be solved if accurate ages are to be determined for the globular clusters.

Another crucial question is the following : *can the results for field halo dwarfs be extrapolated to globular cluster stars?*. They are all Population II stars, but do not display identical properties : why are the most metal-poor field stars 100 times more metal-poor than the most metal-poor globular clusters?

What should be done? The first task is to solve the problems occuring in the abundance analyses of the field halo dwarfs, to be sure we properly understand the atmospheres of Population II stars. The next step would be to obtain high resolution spectra for main sequence or turnoff stars in globular clusters. This should be possible for the nearest clusters with the new generation of very large telescopes.

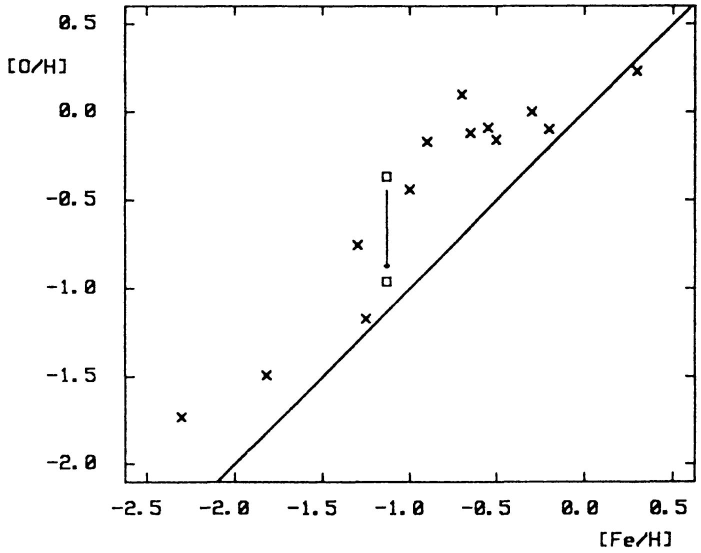

Figure 1: The oxygen abundance in HD76932 as deduced from the infrared triplet (upper square) and from the forbidden line (lower square) is compared to the results of Sneden et al. (1979, crosses).

3 Effective temperature

The usual method of effective temperature determination is to use a photometric colour index. This colour index (e.g., B-V, b-y, R-I, V-K) is transformed into an effective temperature via a calibration curve. These calibration curves can be determined theoretically, by integrating the flux of a model atmosphere through the response curves of the photometric system, and setting the zero point by comparison with a standard star. They can also be built empirically, by comparing the colour indices of a suitable sample of calibrating stars with their effective temperatures determined by another (more direct) method.

Until recently, most calibrations agreed within a few tens of degrees (e.g., Carney, 1983; VandenBerg and Bell, 1985; Magain, 1987). However, in a recent paper, King (1993) argued that these 'classical' calibrations indicate temperatures that are 150 to 200 K too low.

At about the same time, Fuhrmann et al. (1993) obtained effective temperatures from fits of some hydrogen Balmer lines. They claimed that the photometric temperatures are not as accurate as previously believed, and systematically too low by some 200 K.

Moreover, as we have seen in the previous section, Magain and Zhao (1995) find that the Fe abundance deduced from a sample of Fe I lines depends on the excitation potential of the line used in the analysis. Several explanations have been considered but, if due to an effective temperature error, these results would indicate that, on the average, the effective temperatures of the Population II stars would be 150 to 200 K too low.

All these results should be taken with caution. The work of King (1993) contains some misinterpretations of the earlier calibrations. Another recent careful calibration (Edvardsson et al., 1993) agrees with the older ones, not with King. The effective temperatures determined by Fuhrmann et al. (1993) are obviously not as accurate as the authors seem to believe. The effect found by Magain and Zhao (1995) may be explained by another cause.

However, it is suggestive that all three works cited agree not only on the sign of the correction, but also on its magnitude. Obviously, more work is needed to clarify the situation and to provide accurate effective temperature for Population II stars.

4 Bolometric correction

In their determination of the effective temperature from Balmer lines, Fuhrmann et al. (1993) found that, in order to obtain the same effective temperature from different lines in the same star, they had to use model atmospheres computed with a fairly small value of the mixing length parameter of convection: $\alpha = l/H_p = 0.5$. These models, when compared with the usual ones computed with $\alpha \sim 1.5$, have a steeper temperature gradient in the layers where the continuum radiation is formed.

This result confirms our earlier and completely independent finding (Magain, 1985) that the theoretical model atmospheres do not reproduce the accurate spectrophotometric observations of two well-known Population II stars (Oke and Gunn, 1983). We built empirical models designed to reproduce the observed continuous flux, and it turned out that these models also have a steeper temperature gradient in the continuum-forming layers.

The modification of the temperature distribution in the continuum-forming layers implies a change of the emerging flux. It turns out that, for a given flux in the visible region of the spectrum, these steeper models have a larger bolometric flux than the 'classical' theoretical models. Hence, if these empirical models are a better representation of the atmospheres of Population II stars, such stars have, for a given visual magnitude, a higher luminosity than previously thought.

Thus, according to the evidence presented in this and the preceding section, it is possible that the Population II stars near the turnoff have, for given visual magnitude and colour index, a higher effective temperature and a higher luminosity than generally considered. This would imply a reduction of the age of these clusters, the magnitude of which cannot be precisely determined without detailed calculations.

5 Conclusion

I shall conclude this brief review by repeating a rather obvious remark (even obvious statements need to be made from time to time).

As the overwhelming majority of the stellar observations deal with the outer layers, any precise understanding of stellar structure and evolution implies an understanding of the outer layers which is at least as accurate. Otherwise, theory and observation would progressively disconnect and stellar astrophysics might turn into stellar astromathematics.

So, even if the study of these surface layers appears rather boring to many of the astrophysicists, it cannot be neglected. As we have shown, even the most fundamental parameters of the most basic representation of stellar atmospheres suffer from significant uncertainties. The theoretical and observational tools needed to solve these problems are, to a large extent, available. It is therefore mostly a matter of will : there is still a lot to be done in the study of stellar atmospheres, what is needed is researchers who wish to tackle these problems.

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DISCUSSION

D. CALLEBAUT: How much does the age of the population II stars change due to the (estimated) 200 K increase in Teff ?

P. MAGAIN: I have no quantitative estimate yet. Maybe the theoreticians could give the answer. (See comment 3 by B. Dorman, below).

B. DORMAN: I have three comments :

1. The Vandenberg and Bell colours and the Edvardsson calculations are both derived from MARCS model atmosphere calculations, whereas the King colours are from Kurucz; this may be one reason why the former two agree better.
2. The solar spectrum has been quite differently estimated by different authors (Neckel and Labs 1984, Lockwood, Tüg and White 1991). The spectra are very different and lead to different $(B\text{-}V)_\odot$. The Kurucz solar spectrum agrees with the Neckel and Labs Scan, while Bell's spectra agree better with Lockwood et al.
3. Globular cluster ages are probably uncertain by $\sim$ 10 % as a result of uncertainties in the temperature-colour calibration.

I. ROXBURGH: Could you say something about determination of surface gravity ? Observational estimates of g are important for stellar evolution.

P. MAGAIN: The classical method of surface gravity determination is from ionization equilibria. This method should suffer from the same problems as I showed for the excitation equilibrium. It is also possible to use the wings of strong metal lines, but the observations are not obvious.

C. de JAGER: The wings of the H lines are very sensitive to density, hence to gravity. In my experience they are the best g_{eff}-indicators.

P. MAGAIN: In solar-temperature stars, there are also very sensitive to temperature and thus, not direct gravity indicators. The wings of strong metal lines may also be used.

N. GREVESSE: What Pierre has said about the uncertainties effecting the abundances and effective temperatures apply in a peculiar way to the Li problem and the basic diagram showing the Li abundance as a function of effective temperature. The scattering of the points, so difficult to reproduce theoretically, can come from uncertainties in the abundance results but also in effective temperature.

One has to keep in mind that the Li abundance is determined from one single line of LiI whereas Li is essentially once ionized in stars. Furthermore this line is slightly blended; it is also a resonance line. For all these reasons, the abundance result is very sensitive to the temperature structure, to non LTE effects, to heterogeneities...

F. PALLA: How firm is the result that the most metal-poor globular cluster is less metal-deficient than the most metal-poor halo star? And how large is the difference? Are there selection effects that do not allow to measure lower metallicity stars in globular clusters ?

P. MAGAIN: There is a factor 100 in metallicity between the most metal-poor globular cluster and the most metal-poor field halo stars. I cannot imagine any observational error leading to such a large factor, neither any selection effect which would work against the detection of the most metal-poor globular clusters.

A. NOELS: You showed that changing the metallicity in a star is not simply multiplying or dividing the solar metallicity by a constant factor. Could it be possible, in future years, and this is also a question to Forest Rogers, to build opacity tables that could reflect a different distribution of heavy elements in Z, according to the estimation of Z? There is no reason to think that the Sun is representative of the distribution of heavy elements in other stars.

P. MAGAIN: I fully agree. We certainly have firm indications that the detailed composition changes with metallicity.