PART III

# DERIVATION OF ABUNDANCES THROUGH PHOTOMETRIC AND SPECTROSCOPIC METHODS

# DERIVATION OF ABUNDANCES THROUGH PHOTOMETRIC AND SPECTROSCOPIC METHODS

R. A. BELL

*Astronomy Program, University of Maryland, U.S.A.*

**Abstract.** Several points of detail which affect stellar abundance determinations are discussed. In particular, the importance of including the effects of hyperfine structure and isotopic shifts when considering the lines of some elements is stressed.

The abundance determinations for F dwarfs by Bell and Peytremann, who use theoretical calibrations for intermediate band photometry, and Nissen, who observes very narrow spectral intervals, are intercompared. The agreement between Bell and Nissen, who have 46 stars in common, is quite satisfactory.

Recent work on carbon and nitrogen abundances in cool stars is described. The suggestion of Hearnshaw, that [C/H] = 1.5 [Fe/H] for disc stars with $-0.7 <$ [Fe/H] $< 0.4$, is compared with recent results by Clegg. Whilst Clegg's results are quite precise, they neither confirm nor deny Hearnshaw's suggestion. Work by Branch and Bell on K giants shows that [C/Fe] = 0, or a constant, for the stars in the sample. A value of about 7 for the $C^{12}/C^{13}$ ratio in the atmosphere of Arcturus has now been confirmed by several authors and Lambert and his collaborators have determined this ratio for several K giants.

The suggestion by Spinrad, Taylor and others that the M67 dwarfs are more metal-rich than the Hyades, i.e. that they are super-metal-rich or SMR, seems to be erroneous. However some SMR stars, such as 31 Aql, certainly exist even though there is still some uncertainty in the precise abundance of strong CN stars such as $\mu$ Leo.

Examples of synthetic spectra for metal-deficient giant stars are given and a theoretical colour-colour diagram is compared with observations of globular cluster and Draco stars.

By now, any discussion of the derivation of stellar abundances must cover an enormous amount of ground. In my talk today I will take my lead from the title and primarily discuss the stars whose abundances can be found by both spectroscopic and photometric means. This means that I'll primarily restrict myself to discussing stars of spectral type F and later. In fact, I will be mainly talking about F dwarfs and K giants. Also, I think that all of the results which I will quote, whether my own or those of others, have been obtained by LTE physics. Tremendous progress has been made in studying the spectra of hot stars, with the problem of obtaining self-consistent solutions of the coupled transfer and statistical equilibrium equations having been solved by Auer and Mihalas (1969, 1973). In addition to discussing various abundance and line profile problems, Mihalas (1972) has also published a treatment of non-LTE effects on the continuum and hydrogen line profiles in OB stars and has discussed the *uvby* colours of these models.

My plan, then, is to mention a few points of detail which affect abundance determinations. I'll then discuss the determination of abundances photometrically for F dwarfs. I will make some comparison between different photometric calibrations and with results found spectroscopically. Then I will discuss recent work on K giants, concentrating on CNO abundances and $C^{12}/C^{13}$ work. If time permits, I hope to mention some work on

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Pop II giants which I have been carrying out in collaboration with Dickens (Herstmonceux) and Gustafsson (Uppsala). As you have noted by now, there hasn't been any mention of the effect of stellar abundances on spectral classification. I will show a few slides to illustrate how the spectrum of a star changes with changes in abundance and gravity. Finally, a few requests, comments and complaints.

The standard method of determining abundances by spectroscopic means requires the measurement of the equivalent widths of individual spectral lines. This forces the use of high dispersion spectra, in order to be able to locate the continuum properly and to minimise the problems with line blending. Given the equivalent widths, the actual determination of the abundances can be carried out very quickly. Apart from any problems of line identification, oscillator strengths and so forth, the major criticism of this approach is the amount of telescope time required to obtain the data. We certainly have to use this approach to analyse suitable bright stars in the solar neighbourhood. However, in many interesting cases, such as stars in external galaxies, it is impossible to obtain the relevant data.

And now for the details. In both spectroscopic and photometric work it is necessary to make accurate estimates of stellar temperatures, in order to obtain accurate abundances. The situation here seems to be fairly satisfactory for cool stars, with a large quantity of H$\beta$ photometry for F stars and R – I for G and K stars being available. We obviously haven't heard the last word on how to convert H$\beta$ and $R-I$ to $T_{\rm eff}$ yet, though. We still find it necessary in many cases to include the microturbulent component of the Doppler Broadening Velocity (DBV). Recent solar analyses, however, do indicate that the microturbulent velocity is very small for the Sun. For example, Foy (1972) finds that it is only 0.5 km $s^{-1}$ at the centre of the disc. The larger values found in the past for the Sun seem to have been caused by errors in the oscillator strengths or by damping effects, both of which affect the shape of the curves of growth. The work of Oinas (1974), with the alarming suggestion that the continuous absorption coefficient is being greatly underestimated for K stars, has been challenged by Perrin, Cayrel and Cayrel (1975). These authors argue that the difficulty which Oinas found in reconciling the abundances determined from neutral lines with those found from ionized lines arose from his treatment of the damping. I'm rather relieved that Oinas seems to be wrong, especially after several authors including Gustafsson, Eriksson, Nordlund and I have spent so much time computing flux constant model atmospheres without inventing new opacities. As far as the damping is concerned, only for a few lines do we have a satisfactory treatment and most authors (e.g. Holweger, 1972) are using the Unsöld treatment with an enhancement factor included. This is, typically, of the order of two or three. The use of this treatment in curve-of-growth calculations leads to curves of growth which depend on excitation potential and we can no longer talk about THE solar curve of growth, since there are an infinite number.

In the past, we have generally neglected the effects of hyperfine structure in the calculation of line absorption coefficients, with the exception of the element manganese. We have also generally neglected isotopic shifts. We must be very careful on these two points when determining the abundances of some elements. For example, Hauge (1972) has given a detailed analysis of the 4205 line of Eu II in the solar spectrum. This line is produced by $Eu^{151}$ and $Eu^{153}$ and each of these isotopes produces a line consisting of six hyperfine components. In other words, when analysing the $\lambda$ 4205 line in stellar spectra, we must consider 12 lines and not just 1. The separation of the individual components is very small, being about 0.03 Å for $Eu^{153}$ but this must be compared with the Doppler width, which is about 0.02 Å for the Sun. This means that the equivalent width of an Eu II line will be computed to be much greater when the hyperfine and isotopic effects are included compared to when they are not. Hartoog et al. (1974) have shown that allowance for these effects reduces the Eu abundance obtained by as much as 0.9 dex compared with the abundance obtained when the effects are neglected. Allen and Cowley (1974) have similarly shown that the abundance of Pr in Ba II stars is reduced when the effect of hyperfine structure is included and the resultant Pr abundance becomes in much better accord with the predictions of the s process. Holweger and Muller (1974) have discussed the isotopic and hyperfine effects when considering the strengths of the solar Ba II lines.

Any comparison of abundances determined spectroscopically with those found photometrically must make allowance for the fact that spectroscopic abundance determinations refer to particular elements whereas photometric determinations refer to an average, or overall, abundance. In what follows, I'll use the notation [Fe/H], [Mn/H],... to refer to spectroscopic results and [M/H]: $X$, $Y$ to photometric ones, i.e. the average metal abundance obtained from the colours $X$ and $Y$. Then [A/H] can be used to refer to abundances used in model atmosphere calculations.

The calibration of photometric colours or indices in terms of abundances can be carried out by two completely different methods. Suppose we consider, as an example, the determination of abundances for F dwarfs using $U-B$ and $B-V$.

The original method is to plot the abundance index $(U-B)$ versus the temperature index $(B-V)$, measure the deviation of the abundance index for a particular star from the mean line $(\delta(U-B))$ and plot this deviation vs [Fe/H]. The resultant figure supplies the calibration, usually expressed as an equation. The choice of [Fe/H] as the abundance parameter seems to be the wisest one in the circumstances, since Fe supplies so much of the solar line blocking. Moreover, most of the metal abundances seem to vary pretty well in unison and we do not yet have to cope with a situation where a star is deficient in iron yet overabundant in, say, nickel.

The calibration obtained by this method is very useful and it certainly behoves anyone who has found that a star is metal-deficient to check whether it has an ultra-violet excess. Nevertheless, there are a number of problems with this approach. Firstly, there is the question of the influence of the stellar gravity on the colours. Secondly, the ultra-violet excess is not produced solely by iron and there is the possibility that some particular element may be particularly effective at producing ultra-violet excesses. An example of such an element is carbon, which can produce so many molecular lines. Thirdly, we expect that a given abundance change will produce different ultra-violet excesses in stars of different temperatures. The fourth possibility, frequently mentioned a few years ago, that observed ultra-violet excesses can be produced by differences in microturbulent velocity, need no longer be considered. Whilst all of these problems can be checked observationally, it is a big job to do so, especially since we really need homogeneous results.

The alternative, and more recent, calibration method relies on the use of synthetic stellar spectra. These spectra are computed using model atmospheres and large quantities of atomic and molecular line data and are then convolved with photometric sensitivity functions. A significant number of spectra can be computed with a wavelength resolution of 0.1 Å covering the wavelength interval between 3000 Å and 12 000 Å without requiring the expenditure of excessive computer time. This resolution is sufficient for most colour calculations. By carrying out the calculations for different abundances, a theoretical calibration of the various indices can be obtained.

Usually, an essential point in this work is the determination of the zero points and scale factors for the theoretical colours. For example, if we denote the initially calculated $U-B$ colour as $(U-B)_c$ then the colour which we wish to compare with the observations, $(U-B)_*$, may be given by $(U-B)_* = a\ (U-B)_c + b$. Hopefully, the sensitivity functions used in the convolution closely resemble the actual ones, so that $a = 1$, but there is still the problem of determining $b$. This problem can be solved by identifying a particular star with a particular model. We then say that the colours of the model are the colours of the star. This calibration star is then serving the same purpose as the reference star in differential curve-of-growth analyses. Carrying out the calculations for more than one colour system has advantages here, in that it can point out if inappropriate models are being used. As an example of this, I refer to recent calculations Gustafsson and I made. The colour differences between $\varphi^2$ Ori and the Sun match the computed colour differences much better if we say that $\varphi^2$ Ori has $T_{\text{eff}}$ = 4600 K instead of, say, 4500 K. At the present time, I do not think we can expect that one reference star will be sufficient for all purposes. For example, if we are working on F and G dwarfs then we can use the Sun as the reference star whereas for cooler, lower gravity and more metal-deficient stars we might well use HR 1907 ($\varphi^2$ Ori). One point which I think could well be pursued in more detail at this meeting concerns the establishment of a network of such calibration stars which must be observed by all individuals who are establishing a new system. Even if such a system is intended to refer to K giants, it might be valuable to have observations of B stars to aid in subsequent interpretation. Any network of calibration stars should include a substitute Sun, since the genuine article is so difficult to observe accurately.

Returning to the calibration which is obtained from synthetic spectra, the most serious criticism which can be made is that there is no guarantee that the results will be correct, at least at the present time. As the relevant synthetic spectra become in better and better agreement with the best observed spectra, we can have more and more confidence in the calculations. The results depend heavily on the atomic and molecular line data and, to a lesser amount, on the model atmospheres. For these reasons, the colour predictions must be carefully checked, i.e. if the models do not predict a variation of $\delta(U-B)$ with [M/H] which resembles the observed variation, then one must be sceptical about the ultra-violet fluxes and about other ultra-violet colours. However, one must also be very cautious about the possible influence of particular elements on the colours. For example, one should bear in mind the possible problem with carbon particularly in view of Hearnshaw's (1974a,b, 1975) work.

At this point it is tempting to compare the results which have been obtained by different workers for this problem. Peytremann (1975) has recently published a discussion of the Geneva photometry based upon his flux constant models and synthetic spectra. I will use some of the results which he gives for a sample of G2 V stars. Peytremann's approach is a little different from that outlined above, in that his synthetic spectra are computed with many fewer wavelength points. He also neglects molecular lines. As a foil for this work, I will use my own results for these stars. My calibration is based upon the use of scaled solar model atmospheres and high resolution synthetic spectra (Bell, 1970, 1971) and I have used *uvby* photometry as the observational data. In addition to estimating [M/H], both Peytremann and I have estimated $T_{\text{eff}}$ and $\log g$. I have used H$\beta$ and $R-I$ to get $T_{\text{eff}}$, $c_1$ and $b-y$ to get $\log g$ and $m_1$ and $b-y$ to get [M/H]. Peytremann has tried to find the values of $T_{\text{eff}}$, $\log g$ and [M/H] which give the best agreement between all the observed colours and all the computed ones. The results of the comparison for the stars in common are given in Table I. I'll leave it to the reader to say if he considers the comparison to be encouraging or not. However, to guide the reader, I should point out that Peytremann states that the Geneva system is not particularly good for finding $\log g$ for solar type stars. As far as my results go, H$\beta$ data loses a lot of its precision as a $T_{\text{eff}}$ indicator at about 5800 K and for two of the stars in the Table, 39 Ser and 85 Peg, my calibration of $B-V$ indicates a rather higher value of $T_{\text{eff}}$. There is a rather curious point concerning the results of Table I, [M/H]: $m_1$, $b-y$ – [M/H]: Geneva

TABLE I

Comparison of $T_{\text{eff,}}$ $[M/H]$ and $g$ found from intermediate band photometry

| Star | $T_{\text{eff}}$ | | $[M/H]$ | | $\log g$ | |
|---|---|---|---|---|---|---|
| HR/Name | *B* | *P* | *B* | *P* | *B* | *P* |
| 483/ | 5800 | 5840 | +.26 | +0.2 | 4.0 | 4.3 |
| 3951/20 LMi | 5730 | 5770 | +.57 | +0.6 | 3.5 | 4.2 |
| 5911/39 Ser | 5300 | 5580 | −0.30 | −0.7 | 4.7 | 4.2 |
| 5968/$\rho$ CrB | 5540 | 5680 | −0.10 | −0.4 | 4.0 | 4.1 |
| 6458/72 Her | 5540 | 5500 | −0.22 | −0.6 | 3.9 | 4.0 |
| 7503/16 Cyg | 5650 | 5630 | +0.39 | +0.0 | 3.6 | 4.0 |
| 7569/ | 5600 | 5690 | −0.02 | +0.1 | 3.4 | 4.0 |
| 9088/85 Peg | 5040 | 5180 | −0.78 | −1.2 | 4.9 | 4.1 |

*B* = Derived by Bell (1971) from *u v b y* photometry

*P* = Derived by Peytremann (1975) from Geneva photometry is either small or about 0.4. Whilst this Symposium is devoted to abundance problems, I would also like to quote predictions of gravities as these can be compared with 'observed' gravities deduced from assumed masses and radii, the latter coming from $M_v$ and $T_{\text{eff}}$. If the predicted and observed gravities agree, we can have that much more confidence in the abundances.

Some very interesting studies on the abundances of F dwarfs have been carried out recently by Nissen (1970) and Gustafsson and Nissen (1972). These authors have measured the radiation from stars in very narrow bands, Nissen using 3.5 Å, carefully chosen to contain suitable lines. One of the bands contains weak lines, sensitive to [Fe/H], whilst another, containing very weak lines, serves as a reference. For giants, another band will contain lines on the flat part of the curve of growth, sensitive to the DBV. The measurements are made photoelectrically. It is necessary to allow for the radial velocity of the star at the time of observation when setting up the equipment. I was a little startled to learn that the precision of the latest spectrometer is such that the Danish group could consider observing $C^{13}H$ lines in the spectra of K giants. Synthetic spectra are used to calibrate the relative intensities of the bands in terms of [Fe/H] and, if need be, DBV. The results obtained by this method are probably very reliable, at least for stars which have weaker spectral lines than does the calibrating star. In this context, the calibrating star is the one for which very high dispersion spectra are available and which can be used to check the adequacy of the line list used for the synthetic spectra calculations. If we study stars which are more metal rich or cooler than the calibrating star, then lines may appear in the stellar spectra which are not in the line list. This will yield an erroneous calibration. This is especially true for the cool giants, for which this method has also been used. Gustafsson *et al.* (1974) (hereafter GKA) had to go to a great deal of trouble to ensure that they had included all possible lines in their pass bands. Inclusion of the red system of CN is particularly important owing to the large number of possible bands. For example, Griffin's (1970) Sc index measurements could not be used for Sc abundance determinations owing to the contamination by red CN. Returning to the Nissen work, it seems to me that one of the real advantages of this method is that there is no problem of continuum location, which I think bedevils photographic spectroscopic work. Even if one has spectra of sufficient scale, there still remains the problem of grain noise. The problem of continuum location is especially critical for measuring the equivalent widths of weak lines, which are the ones we really want to use for abundance studies. The photoelectric data is much more readily reproducible.

A comparison of the abundances found by Nissen (1970) and by Bell (1971) (from synthetic spectroscopy and *uvby* photometry) shows quite good agreement. For 46 non-cluster stars in common we find [Fe/H]: N − [M/H]: $m_1$, $b-y$ = +0.09 and the rms deviation is 0.17.

I think that this very narrow band work probably provides the most accurate way of determining [Fe/H] for many kinds of stars and my only reservations concern the possible adequacy of the line list and the relation of the abundances to the Sun. Nissen's abundances depend on the $b-y$ which he used for the Sun and I think his value of 0.424 is about

0.03 mag. too red. This will not affect the scale of his results, only the zero-point. I will return to the GKA results later.

Recent interest in CNO abundances has been, I think, stimulated by work on globular cluster stars such as Zinn's (1973) demonstration that considerable differences exist in the strengths of the G bands in subgiants and asymptotic giant branch stars in M 92. Butler, Carbon and Kraft (1975) have argued that similar differences also exist in the strengths of the NH bands and that the strength of NH is anti-correlated with the strength of the G band. Osborn (1971a) and others have observed a number of globular clusters using the DDO system and Osborn (1971b) pointed out that the anomalous $C(41-42)$ colours of two stars, one in M5 and one in M10, might be caused by differences in CNO from star to star in the cluster. Dickens and Bell (1975) have shown that there is a considerable range in [N/H] in $\omega$Cen giants and Bell and Dickens (1974) analyzed the $\omega$ Cen CH stars. I will show a slide from this latter paper as it indicates a spectral classification point. In the upper panel of Figure 6 of Bell and Dickens (1974) we see the spectra of two $\omega$ Cen Giants, RGO 55 (a CH star) and RGO 84. Note the strength of the Ca I line in the normal giant and its relative weakness in the CH star. In the lower panel we see the synthetic spectra computed for these two objects and it is clear that the enhancement of CH in RGO 55 greatly reduces the contrast in this spectral region and the 4226 line appears much less strong.

Work on CNO abundances in field F, G and K stars has been carried out recently by, amongst others, Sneden (1973, 1974), Hearnshaw (1974a, b) and Clegg (1975). Sneden and Clegg used spectral synthesis to analyse NH, CH and CN whereas Hearnshaw measured equivalent widths of CH lines and analyzed them differentially relative to the Sun, following the treatment in Hearnshaw (1973). It is necessary to be particularly careful when measuring equivalent widths in the neighbourhood of the G band. For the impressively large sample of 50 dwarfs and subgiants between F6 and K0, with $-0.7 <$ [Fe/H] $< +0.4$, Hearnshaw finds [C/H] $\sim$ 1.5 [Fe/H], an extremely interesting result. However in a later paper (Hearnshaw 1975), the result is diluted by the suggestion that it may not be obeyed by high velocity stars. Sneden has considered 11 metal-poor stars and concludes that in metal-poor dwarfs [C/Fe]=0 and, with one exception, [N/Fe]= 0 whereas in giants [C/N] depends on gravity, being $-1$ if log $g < 2.4$ and $> 0$ for higher $g$. However, Sneden's error bars are typically ± 0.6: but at least this indicates that departures from the 'null hypothesis' (i.e. [C/H] = [Fe/H]) for C and N are not large. In a sample of 11 dwarfs, Clegg finds deficiencies in a few of the metal-poor stars, indicating that there may be something in Hearnshaw's result. The star $\alpha$ Tri appears to be quite C deficient, a result also found by Pagel. Clegg also finds some $N$ deficiencies in the metal--poor stars: and whilst these are probably real for 4 high-velocity stars $\mu$ Cas, 171 Pup, HD184499,85 Peg) they are not as large as the suggested relation [N/Fe] = [Fe/H] would predict.

In an attempt to cast more light on this problem of the carbon abundances, Branch and I have tried to determine carbon abundances for G and K giants. If Hearnshaw is correct, we would expect his result for the dwarfs to also hold for giants. The observational data we have used for this purpose is that of Alexander and Branch (1974). This data consists of photometric measurements through three filters, one centred on the (1,0) sequence of the $C_2$ Swan bands and a comparison band on either side. The system is shown in Figure 1 of Branch and Bell (1975) where, for comparison purposes, we show the ratio of the fluxes observed by Willstrop (1965) for $\kappa$ Oph and $\alpha$ Boo. It is clear from this that there is greater absorption centred at 4650 Å in the spectrum of $\kappa$ Oph and we believe that this is $C_2$. The system possesses one major advantage. The $C_2$ bands are composed of many lines each of which is spectroscopically weak and so sensitive to changes in the abundance of $C_2$. The overall feature thus has the advantage of being strong enough to be readily measureable and yet still being very sensitive to abundance. The complication of course is that there are many other lines contaminating the pass bands. Branch and I carried out the relevant synthetic spectrum calculations (we are very grateful to Dr B. Gustafsson for supplying the scaled solar model atmospheres and to the University of Copenhagen for the computer time) and convolved our spectra with the filter transmission profiles. We then took data on the abundances, effective temperatures and gravities of G and K giants from the literature and computed what the $C_2$ indices of these stars would be expected to be under the supposition that [C/H] = [O/H] = [Fe/H]. The results are shown in Figure 4 of Branch and Bell (1975). The abcissa in each of the three plots is the observed $C_2$ index of a star and the ordinate is the predicted index. The data for the left-hand panel comes from Williams (1971, 1972), the centre panel uses GKA [Fe/H] and the right-hand panel uses [Fe/H] from Hansen and Kjaergaard (1971) and $T_{\rm eff}$ and $g$ from Williams. We see a correlation in all three panels but with less scatter in the centre and right-hand ones. We ascribe the smaller scatter to more accurate values of [Fe/H] which allows us to compute more accurate C indices. If we change the carbon abundance by relatively small amounts e.g. say to [C/Fe]=+0.15 then the predicted $C_2$ index changes by about 0.07, a very large amount in these diagrams. We conclude that [C/Fe]=0 for the K giants in this sample.

When carrying out these calculations we used relatively low values for the solar (i.e. reference) C and O abundances. Repeating the calculations with higher values causes the predicted $C_2$ indices to become a little weaker owing to greater depletion of C by CO formation with the $C_2$ electronic oscillator strength being altered to keep the solar $C_2$ line strengths constant. This effect may have produced the zero-point shift.

In this context, I would like to mention some rather curious points concerning the star $\nu$ Indi. Przybylski (1962) obtained a spectrum of this object at Mount Stromlo and pointed out that the CN bands were very weak. Harmer and Pagel analyzed the star and found that the CH lines gave [C/H] =–1.2 and then the CN bands implied [N/H] =–2.0. At Pagel's suggestion, I used my synthetic spectrum programme to compute synthetic spectra for the star and confirmed the C abundance. However, I found an even lower nitrogen abundance, [N/H] =–3.0. Five years, and many synthetic spectra, later, I'm rather sceptical about this result. Firstly, it seems that $\nu$ Indi is rather hotter than was thought earlier, owing to errors in the photometry. Secondly, it also seems very likely that it has a much higher gravity than earlier thought. The point here is that the *uvby*

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photometry of Stokes (1973) shows that $\nu$ Indi has a very low value of $c_1$ for its $b-y$ and, in fact, in Bond's (1971) $c_1$, $b-y$ diagram $\nu$ Indi lies in the same location as the stars BD+66° 268 and BD–0° 4470 which Bond classifies as subdwarfs. The parallax values are 0.046 (Yale) and 0.011 (Cape) and the mean value indicates it is a subgiant. If the star is a subdwarf, as the photometry inplies, then it must have a parallax even greater than the Yale value. We're still a bit uncertain about how good theoretical ultra-violet excesses are, but these calculations certainly support the suggestion of the higher gravity from the *uvby* data. The higher $T$ and $g$ mean that the CN and NH bands can be fitted with a much higher $N$ abundance than found earlier and I think we can no longer argue that $\nu$ Indi definitely has [N/Fe] <0.0. I request that the parallax be re-measured.

Lambert, Dearborn and Sneden (1974) state that their stimulus for the recent work on red giants comes from (i) new observing techniques such as Fourier transform infra-red spectroscopy, (ii) the realization that mixing does occur in stars and can produce changes in surface composition and (iii) developments in model atmosphere calculations. Lambert and his colleague have found $C^{12}/C^{13}$ ratios for numerous stars, using the red CN system, CO bands and the G band (cf. Lambert and Dearborn, 1972; Day *et al.*, 1973; Tomkin and Lambert 1974 and Lambert and Tomkin 1974). This work, and confirming work by other authors (Upson 1973, Krupp 1973 and Griffin 1975) has shown that $\alpha$ Boo has a $C^{12}/C^{13}$ ratio of about 7, compared to the terrestrial/solar ratio of 89. One of the advantages of synthetic spectra calculations is that the observational data can be shown directly and in Figure 1 we see the $p_{1dc}$ (11) line of $C^{13}H$ in the spectrum of $\alpha$ Boo, the data being taken from Krupp (1973). In fact, using Krupp's (1974) precise wavelengths, lines of $C^{13}H$ can be found in the solar spectrum using the Revised Rowland Tables (Moore, Minnaert and Houtgast (1966). However, the solar $C^{12}/C^{13}$ ratio can be more accurately obtained from CO lines (Hall, Noyes and Ayres 1972). In Figure 2 of Lambert and Tomkin we see the observations of $\epsilon$ Peg obtained using the Tull coude scanner at MacDonald and it is clear that, from this superb observational material, it is possible to distinguish between $C^{12}/C^{13}$ ratios of 4,5 and 6. In fact, Lambert and Tomkin give 5.1 ± 0.5 as the $C^{12}/C^{13}$ ratio for $\epsilon$ Peg. With this high precision, it is necessary to include relatively subtle effects such as explicitly considering the satellite lines and, in fact, we are almost near the level of precision where it is necessary to allow for vibration-rotation interaction.

A number of the results obtained by Lambert's group are shown in Figure 1 of Lambert and Tomkin which gives evolutionary tracks from Paczynski (1970) and the $C^{12}/C^{13}$ ratios for various stars. We see that the SMR star $\mu$ Leo doesn't have an especially low ratio. Subgiants have higher $C^{12}/C^{13}$ ratios.

Wing (1974) has described a photometric system for determining $C^{12}/C^{13}$ in K giants, using ~20 Å band passes. We look forward to seeing his results.

What about super-metal-rich (SMR) stars? Even though Spinrad, who introduced this term (Spinrad and Taylor, 1969, hereafter ST), is here I would like to make a few comments since this is one case where the photometric indices appeared to disagree with the spectroscopic ones. To remind you of the situation, ST followed earlier work at

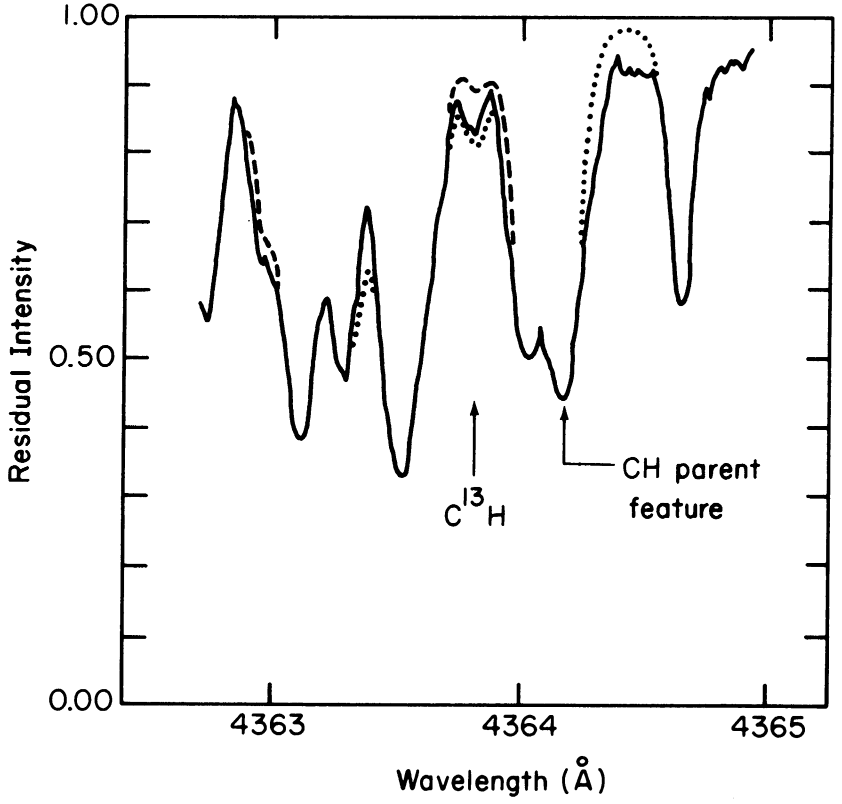


Fig. 1. The observed spectrum of Arcturus (Griffin 1968) is represented by the solid line. The dashed and dotted lines represent synthetic spectra for $C^{12}/^{13}$ = 19 and 9, respectively. The $P_{1dc}$ (11) line of $C^{13}$ H and its parent $C^{12}$ H line are identified.

Cambridge and used band passes of 15 or 30 Å to observe K giants. Some band passes are centred on strong lines or molecular features, others serve as references. On the basis of their observations, ST concluded that 'Evolved K stars with metal abundances greater than those of the Hyades exist in substantial numbers'. This is a controversial result since it is widely felt that, whilst some stars with abundances greater than those of the Hyades do exist, they do not exist in substantial numbers. One of the SMR stars is $\mu$ Leo, previously known to be a strong CN star (e.g. Griffin and Redman 1960). ST found [Ca/H] = [Mg/H] = [Na/H] =0.6 for this object. Since ST also claimed to find a N-Na-Fe correlation, $\mu$ Leo would also be Fe rich. Pursuing the topic vigorously, ST argued that the M67 dwarfs were SMR (Spinrad *et al.*, 1970) both from D line indices and from low dispersion spectra. Subsequent discussion by Abt and Morgan (1973) and Barry and Cromwell (1974) has indicated that the M67 spectra were not as sharply focussed as usual and better spectra do not reveal the abundance anomaly. No explanation has been subsequently offered, to my knowledge, as to why the D line measures give lines which are stronger than those in corresponding Hyades stars.

More recent spectroscopic and photometric work has not confirmed the ST abundances for $\mu$ Leo. Strom, Strom and Carbon (1971) found [Fe/H]=+0.4 (their value is relative to the Hyades which I take to have [Fe/H]=+0.3). Blanc-Vaziaga, Cayrel and Cayrel (1973, hereafter BVCC) obtained [Fe/H]=−0.1 and Pagel (unpublished) states that '$\mu$ Leo and $\alpha$ Ser have very closely similar compositions and their abundance is not greater than that of the Hyades'. Strom *et al.* used 8 Å $mm^{-1}$ spectra, BVCC used 6.8 and 12 Å $mm^{-1}$ whilst Pagel used 2.9 Å $mm^{-1}$. GKA found [Fe/H]= 0.58 or 0.39, depending on DBV, again adopting 0.3 for the Hyades. I give greatest weight to Pagel and GKA in this because of dispersion and because of method, respectively. If we take the lower GKA value we have consistency between the two methods. One problem affecting the GKA work, which will affect much photometric work, is this difficulty of the extraneous lines. In other words, what is the effect of variations in the abundance of other elements relative to Fe in the final value of [Fe/H]? In their discussion, GKA conclude that the abundance of Mg is particularly important for them, owing to the presence of MgH lines in one of their pass bands as well as the importance of Mg as an electron donor. No spectroscopist seems to find $\mu$ Leo to be Mg rich. Lines of CN are equally distributed in both feature and reference bands and thereby the importance of CN variations from star to star is minimised in their case. On the basis of these results we conclude that ST overestimated their Fe abundances. BVCC state that $\mu$ Leo may be overabundant in Ca, Na, Mn, Cu and underabundant in Ba.

Gustafsson, Eriksson, Nordlund and myself have computed a large number of model atmospheres for metal-deficient giant stars. The later set of these models includes the opacity effects of CO and the red system of CN as well as atomic lines, using opacity-distribution functions. The earlier set of models were computed using only atomic line ODFs. We have computed synthetic spectra for both sets of models. The synthetic spectrum programme differs a little in the two cases, with the damping wings of strong lines being followed to only $\pm\ 75\Delta\lambda_D$ from line centre in the earlier case. The later programme allows the damping wings to have any width. The synthetic spectra were also computed using different CNO abundances but the $f_{00}$ for the molecular bands were adjusted so that the solar molecular bands at the centre of the disc were fitted. Examples of curves of growth and synthetic spectra, as well as theoretical colour-colour diagrams are shown elsewhere (Bell and Gustafsson 1975), using the earlier models and their colours. The scatter in the observed FeI and FeII curves of growth for $\varphi^2$ Ori is very small and an excellent fit can be obtained between observation and calculation. However the scatter in the FeI curve of growth, from an 18Å$mm^{-1}$ spectrum, for the M92 star III-13 is very great and the FeII curve of growth is not worth plotting.

In Figure 2, I show the C(42–45), C(45–48) diagram of the DDO system, computed in collaboration with Gustafsson, for the later set of models and using the latest SSG programme and CNO abundances. The lines shown are the ones on which we expect stars in globular clusters with abundances of [M/H] = −3, −2, −1 and −0.5 to lie. The $T_{eff}$ and $g$ values required to construct the lines come from the evolutionary calculations of Rood (1972), being given in Bell and Gustafsson (1975). The observations of cluster stars on

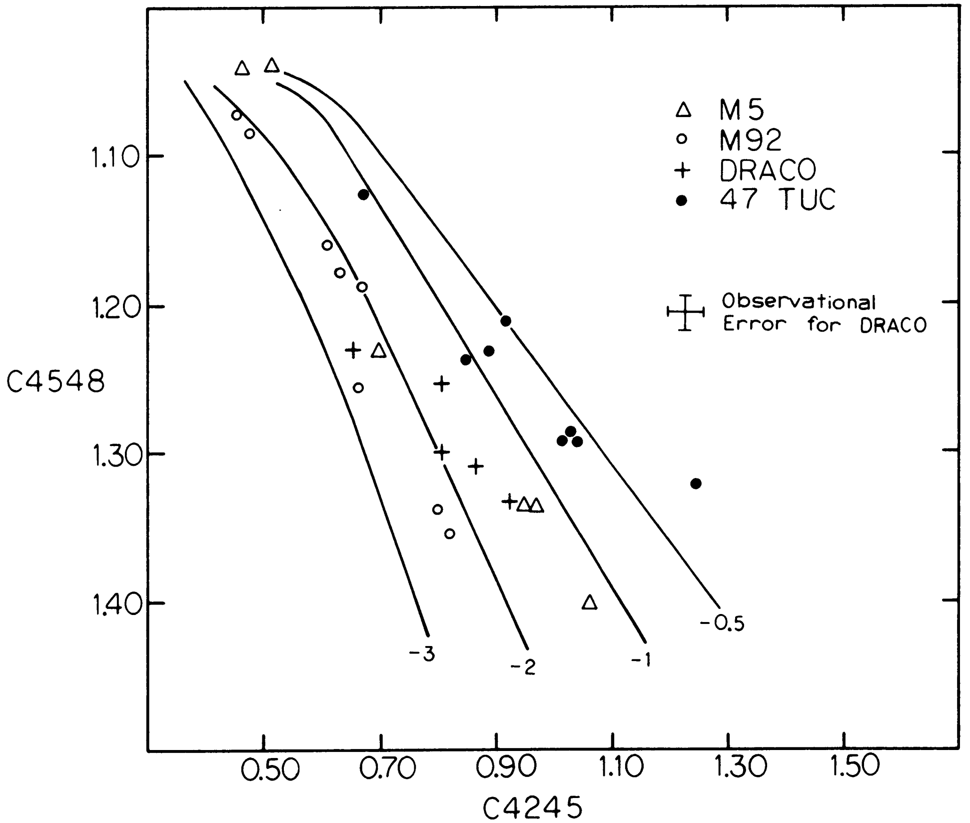


Fig. 2. Using gravities and temperatures found from evolutionary tracks (Rood 1972), theoretical colours on the DDO system are computed for stars in the giant branches of globular clusters with A/H = −3, −2, −1, and −0.5. These are compared with observed C4548, C4245 colours for M5, M92 (Osborn 1973), 47 Tuc, (McClure and Osborn, 1974) and the Draco dwarf spheroidal galaxy (Hartwick and McClure, 1974).

the DDO system (by Osborn, 1971a; McClure and Osborn, 1974; and Hartwick and McClure, 1974) are also plotted in Figure 2. We see that the observations of stars in M92 follow the iso-abundance line for [A/H] = −2 fairly well and, in fact, the average M92 abundance is [M/H] = −2.2. At the present time, with our current equipment, it seems best to try to obtain cluster metal abundances photometrically rather than spectroscopically, in view of the scatter in the curves of growth. This situation may well change in the future as new equipment becomes available.

I will end this talk with a series of requests.

Firstly, I've found it to be enormously helpful to have high dispersion spectra of stars available for study. Many others, for example photometrists who are deciding which wavelength regions to observe, also need this kind of data. But I would request that it be made available in machine readable form, as well as, or even instead of, a printed atlas. In this connection I've found the Delbouille *et al.* (1973) solar atlas to be very helpful when computing solar colours. I can convolve the observed solar spectrum with filter sensitivity functions in the same way that I can convolve synthetic spectra. We can also use computer programmes for identifying lines, we can plot the spectra on any desired scale and we can convolve them with any desired instrumental profile if we have data on magnetic tape. If we are to get a really good match between a computed spectrum for a star and the observed spectrum of that star then I think we will just have to do it using a programme which will automatically optimise the agreement between the two.

Secondly, I'd like spectrograph builders and/or users to measure the instrumental profile of their equipment. This is particularly true for the less common instruments, such as the Image Tube Scanners at Lick and the AAT. Much of the data on faint stars is going to be analyzed using synthetic spectra and anyone doing the calculations will need the instrumental data.

Thirdly, let the laboratory spectroscopists continue their good work on both atoms and molecules, with the reminder that we need damping constants as oscillator strengths. Also let Peytremann and Kurucz continue computing their *gf* values.

Finally, my thanks to all the photometrists and spectroscopists who have obtained all this exciting data on both the mundane and the unusual stars.

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## DISCUSSION

*Hack:* You have shown synthetic spectra at constant $T$ and $g$ and varying chemical composition, and at constant $g$ and composition and varying $T$. Did you compute also the effect of small changes of microturbulence (by 2 or 3 km $s^{-1}$)?

Did it make changes which can be distinguished from changes in $T$ or chemical composition?

*Bell:* We have done such calculations but I have not plotted them. I have not analysed them carefully enough to answer your second question.

*Nissen:* In your calibration of $m_1$ in terms of metal abundance you assume that the atmospheric velocity parameter – the so-called microturbulence – does not change as a function of metal abundance. The fact that the metal abundances you derive agree very well with those that I have determined from a narrow-band index seems to show that this assumption is correct, because the lines in the $v$-band of the $m_1$ index are rather strong and much more sensitive to microturbulence than the weak lines of the narrow-band index.

*Bell:* Yes, at least using my 1970 calibration.

*Foy:* I have measured the microturbulent velocity $\xi$ in the solar photosphere by two ways.

(1) From fitting theoretical curves of growth to the observed one for low excitation potential lines of neutral iron, I have found $\xi \simeq 1.0$ km $s^{-1}$ (Foy, 1972).

(2) I have fitted theoretical line profiles to the observed ones for rather weak lines. I have used the solar spectrum Atlas from Delbouille *et al.* (1974) and, as in (1), the solar photosphere model by Peytremann (1974). Results depend upon the lines considered, because this procedure is more sensitive than the first one to the oscillator strengths and to the iron abundance adopted in the computations. Microturbulent velocities which I have found lie between 0.5 to 0.8 or 1.0 km $s^{-1}$ (Foy, 1975); $\xi$ cannot be larger than 1.0 km $s^{-1}$ to fit the data. The observed profiles cannot be interpreted without involving microturbulent velocity: $\xi$ cannot be decreased under 0.5 km/s.

*McCarthy:* I was interested in the observational data concerning the $^{13}$CH feature in Arcturus as shown in your slide. Who identified this feature and with what spectroscopic equipment?

*Bell:* Lambert and Dearborn initially. Their work was confirmed by Krupp, who re-analyzed the spectrum of $C^{13}$ H to obtain better laboratory wavelengths.

*Maeder:* Would you please make some comments on the evidence concerning systematic differences of observed surface abundances between the bottom and the top of red giants in clusters. Such evidence would reveal what in the peculiar abundances may be considered as a result of interior evolution and what may be considered as a reflection of peculiar initial abundances, which is a problem related to galactic structure.

*Bell:* I can only refer you to my earlier comments and the published literature for clusters other than $\omega$ Cen. In $\omega$ Cen, Dickens and I have spectra of one star with a very strong Ba II $\lambda$ 4554 line, of other stars with very strong blue CN and of the CH stars. The work on CH stars has been published.

*Williams:* Your use of a constant Doppler broadening velocity for all stars implies lower microturbulent velocities in the cooler stars. Do you believe this?

*Bell:* No, but the effect is small. I would really like to know how the microturbulence does vary with $T_{eff}$, $g$ and [M/H] but until then I think it is satisfactory to use a constant DBV, especially since we are working differentially relative to $\phi^2$ Ori when using colours.

*Morgan:* By 'strong CN' in $\omega$ Cen cluster star, do you mean comparable to a Hyades Giant, or stronger?

*Bell:* The comparison is made relative to other $\omega$ Cen giants. Dickens and I haven't compared with spectra of Hyades giants but I guess they would have weaker CN than the strong CN $\omega$ Cen stars.

*Griffin:* I would not trust a quantitative determination of $C^{12}$ / $C^{13}$ based on the $C^{13}$ H spectrum of a K star. Measurements made in the Arcturus Atlas in the region around $\lambda$ 4300 Å cannot be reliable. Contrary to what you said, my result for $C^{12}/C^{13}$ was based upon CN measurements made in the infra-red region of the spectrum.

*Bell:* I know you used the $C^{13}$ N lines for your work, as have several people.

Numerous $C^{13}$H lines can be seen in the spectrum of Arcturus and given a $C^{12}$ / $C^{13}$ ratio consistent with that found from the CN data. This is shown in Krupp's thesis.

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*Griffin:* Have Lambert and Tomkin calibrated their photoelectric technique against high-dispersion photographic spectrophotometry? Their photoelectric equivalent widths published for $C^{12}N$ lines of the (4.0) band in $\beta$ Gem differ systematically from measurements made photographically at 1.5 Å $mm^{-1}$, and this suggests that their results may not be quite as accurate as they claim. (you expressed preference for their method, which yields numerical results *quickly*).

*Bell:* I have not seen their equipment, but the spectra shown by Lambert and Tomkin look very precise and I see no reason to doubt them. I am sure they would be interested in a comparison with your work.

*Griffin:* I would prefer to make measurements slowly and accurately.

*Bell:* I am all for accurate measurements.

*Griffin:* Why did you find it *essential* to adopt a metal abundance in the Hyades giants that is 2 or 3 times (?) the solar abundance? Just because a metal excess would seem desirable to explain broad-band photometry, are you not according undue favour to photometry in the face of spectroscopic evidence?

*Bell:* Some authors have determined the abundance of $\mu$ Leo relative to Hyades giants, others relative to the Sun. A value for the abundances of Hyades giants has to be adopted in order to compare these results. Numerous values exist in the literature and a compromise value of [Fe/H] = 0.3 seems a good one. If the Hyades dwarfs have the same value as the giants then it may be difficult to explain the ultra-violet excess of the Sun relative to the Hyades main sequence with a lower Hyades metal abundance.

*Furenlid:* We have been concerned with the discrepancy in microturbulence between sun and G dwarfs. We find there is no discrepancy; i.e. if a flux spectrum of the Sun is analyzed by stellar analysis methods the Sun too has a large microturbulence (~ 3,0 km $s^{-1}$) if we use the older *gf* values. Microturbulence is a very method-dependent parameter and can normally not be interpreted as a direct measure of physical small scale motions in stellar atmospheres. Care is necessary in choosing the correct value for this parameter in a particular atmosphere analysis, in particular when no weak lines have been measured.

*Bell:* Maybe the microturbulence is really zero.

*Edith Müller:* Sorry! For the solar atmosphere we need microturbulence. We have not shuffled the solar microturbulence under the rug.

*Bell:* You are being very persuasive.

*Müller:* We have now fairly good model atmospheres for the sun which permit to reproduce very well the centre-limb observations of solar spectral line profiles. But we must in all cases introduce a microturbulence in order to keep the abundance unchanged from centre to limb. This is true for calculations both in LTE and in non-LTE. The microturbulence value near the limb (horizontal component) is larger than the value at the centre of the disc (radial component).

*Bell:* You're even more persuasive.

Philosophically, I would like a low solar microturbulence (preferably zero microturbulence in fact). However, as long as the Sun is the same as other G dwarfs we should have no problems. It seems from this discussion that the microturbulence at the centre of the disc differs from that of the disc as a whole. We must allow for this fact when using solar curves of growth.

*Foy:* I have two comments about microturbulent velocity:

(1) The determination of the microturbulent velocity $\xi$ of dwarfs must take into account the splitting of the curve-of-growth (Foy, 1972). I think that large values of $\xi$ in solar type dwarfs are obtained by neglecting this splitting.

(2) I think that the microturbulent velocity is not uniform among G and K giants – I have found (Foy, thesis 1974) that stars near the giant branch have high microturbulent velocities: $\xi \gtrsim$ 1.5 km $s^{-1}$, whereas horizontal branch giants have small microturbulent velocities: $\xi \lesssim 1.0$ km $s^{-1}$.

*Bell:* I quite agree with your first point and appreciate learning about your second point.

*Seitter:* You made a strong point in favour of photometry on the basis of the location of a certain star in a two-colour diagram and compared it to the large scatter in the curve-of-growth of a star in M 92. Looking at the error bars in the two-colour diagram it seems that the uncertainty in metal abundance is rather large – how does it compare to the uncertainty of the abundance derived from the curve-of-growth? I ask this question because it seems that the *single* value obtained in photometry simply *suggests* a higher accuracy as one is inclined to overlook the errors while the curve-of-growth always reveals its scatter.

*Bell:* I think Dr Osborn has a comment on this point. Let me say that the error bars are for Draco, where the stars observed are fainter than in the globular clusters.

*Osborn:* Let me point out that the quoted error of the high dispersion spectroscopy curve of growth analysis was $\sim \pm 0.7$, which is roughly equivalent to the errors for the metal abundance determination from photometry.

*Williams:* First, a question: in your calibration of the DDO photometry, how much of your [M/H] measures are CN abundance and how much metallic abundance?

Secondly, a comment on the comparison of the spectroscopic and photometric methods of abundance determination (I have done both and have no axe to grind). The spectroscopic abundances suffer from the problems of the calibration of photographic plates and the subjective placing of the continuum, which are avoided in photoelectric photometric methods. The latter are more suitable for comparing large numbers of stars and demonstrating abundance differences between them.

*Bell:* In the C (42–45) versus C (45–48) diagram which I showed, the effects of CN line blocking seem quite negligible. This also holds true for changes in the model structure caused by changes in the strengths of the red CN lines. Other DDO indices e.g. C (41–42) are affected by CN, of course.

*Querci:* (1) What HCNO abundances have you used for computing molecular synthetic spectra?

(2) Have you seen the effect of various HCNO abundances on the synthetic spectra and do you think that you do not get similar synthetic spectra from different model atmospheres?

For example, we have seen that two CN synthetic spectra generated by two model atmospheres different by $T_e$, $g$ and HCNO are nearly similar, while the CO and $C_2$ synthetic spectra are never similar for the used parameters.

*Bell:* For our colour calculations in 1974 (Branch and Bell, *Monthly Notices Roy. Astron. Soc.* (in press), Bell and Gustafsson, 1975, *Dudley Observatory Report* **9**, **319**) we used $H = 12.00$, $C = 8.38$, $N = 7.88$ and $O = 8.62$. Before that time, and at the present time, we are using $H = 12.00$, $C = 8.62$, $N = 8.00$ and $O = 8.86$ as the solar values.

Yes, we have run spectra using different CNO abundance ratios. Generally we use spectra in combination with colours (to get temperatures etc.) so hopefully this will minimize the problem of getting similar CN spectra from different models.