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Metallicity calibration of a DDO CN index and other low-resolution indices for G and K stars

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Abstract. Metallicity calibrations of low-resolution parameters are potentially useful for (at least) two problems: the properties of moving groups, and the supermetallicity problem in K giants. In this paper, metallicity calibrations are derived for six sets of parameters. One of these parameters is the DDO CN index δCN. This parameter and three others are calibrated for use with evolved G and K stars. Two additional sets of low-resolution parameters are calibrated for use with G and K dwarfs. The calibrations are derived by comparing the input data with two catalogs of homogenized high-dispersion results from diverse authors (see Taylor 1995, 1999a). Using rms errors that are given in the catalogs, intrinsic rms errors are derived for metallicities deduced from the calibrations. The errors turn out to be comparable to those that apply for averaged high-dispersion results.

Key words: stars: abundances — stars: fundamental parameters

1. Introduction

The problem of deriving metallicities for large numbers of cool stars continues to deserve attention. Many such stars have not been analyzed at high dispersion, while others have high-dispersion (H-D) results whose precision is low or whose accuracy may be questioned. Because low-resolution (L-R) data are often available, they are an obvious choice to fill these gaps. To make use of these data, accurate calibrations are required.

This paper presents new L-R calibrations that will be used to study the supermetallicity problem in K giants (see Taylor 1999c) and the metallicities of moving groups. The calibrations are based on two catalogs of mean H-D values of [Fe/H] for evolved stars. Each catalog is based on results published by diverse authors, and its entries are on a uniform zero point and include rms errors. One of the catalogs is for dwarfs, and is given by Taylor (1995). The other catalog is for evolved stars, and is described by Taylor (1999a). Derivations of the catalogs are described by Taylor (1994) and Taylor (1999b), respectively.

In Sect. 2 of this paper, there is a discussion of the L-R indices that are considered for calibration. The derivation of the new calibrations is considered in Sect. 3. The calibrations themselves are presented and discussed in Sect. 4. A brief summary in Sect. 5 concludes the paper.

2. Choosing indices

The first task at hand is to choose the indices to be calibrated. The indices that have been considered for this problem are listed in Table 1. At the head of the list is the DDO CN index δCN, for which a number of calibrations have been published. Calibrations of interest here have been derived by Taylor (1991) and Twarog & Anthony-Twarog (1996). The first of the previous calibrations is based on an earlier version of the Taylor (1999a) catalog (see Taylor 1991). The second previous calibration is based on an expanded version of the 1991 catalog.

The DDO CN index, $\langle\mathrm{Fe}\rangle$, and G were all considered in a previous review of supermetallicity (Taylor 1996). M_1 and $(R-I)_{\mathrm{E}}$ are included specifically to retrace the steps of Eggen (1989c), who used these parameters to derive a photometric metallicity for the SMR candidate star μ Leo. As noted in Table 1, Copenhagen photometry (Dickow et al. 1970) is not used in its published form, but some of it is accepted after being converted to δCN. The $(38-42)$ and m_2 indices are noted in Table 1 because, like M_1, they have been calibrated by Eggen (1989b, 1989c). They are not calibrated here because their spectral information duplicates that in δCN, G, and M_1.

For dwarfs, the D parameter discussed by Taylor & Johnson (Table 1) is calibrated. In addition, formal metallicities are obtained by using a theoretical grid (Buser & Kurucz (1992), with $U-B$ and Cousins $R-I$ chosen as

Table 1. Kinds of data considered for calibration

Kind of data	Luminosity classes	Paper(s)	Features measured
DDO [δCN]	II-IV	See Table 2	CN[a]
$\langle$Fe$\rangle$	III-IV	Faber et al. 1985	Primarily Fe
G	III-IV	Taylor & Johnson 1987	Ca, Mg, Na, CN, blanketing[b]
$M_1, (R-I)_{\mathrm{E}}$	III	Eggen 1989a	Blanketing
Copenhagen[c]	II-IV	Dickow et al. 1970	Same information as δCN[d]
DDO [$(38-42)$][c]	II-IV	Eggen 1989b,c	Blanketing, CN[e]
m_2 (Geneva)[c]	III	Eggen 1989b,c	Similar to M_1^{f}
D	V	Taylor & Johnson 1987	CN, Ca, Fe, Mg, Na[g]
$[M/H]$	V	Buser & Kurucz 1992	Blanketing[h]

[a] Relations given by Janes (1975) are used to obtain δCN from DDO photometry.
[b] G is a weighted mean of feature-strength residuals for the strong features named (see Sect. V and Table 5 of Taylor & Johnson 1987). "G" is short for "giant," and does not refer to the G band. The data calibrated here include the original measurements of Spinrad & Taylor (1969).
[c] No calibration is derived. See notes "d," "e," and "f."
[d] Metallicities derived from these data by Hansen & Kjaergaard (1971) are not used. Instead, the data are transformed to δCN (see Table 2, note "a"). This is done only for stars that lack direct measurements of the DDO indices.
[e] See Fig. 1 of McClure (1976).
[f] See Eq. (12) of Eggen (1989b).
[g] D is a weighted mean of feature-strength residuals for the strong features named (see Sect. V and Table 5 of Taylor & Johnson 1987). "D" is short for "dwarf," and does not refer to the D lines. The data calibrated here are from Taylor (1970).
[h] Measured values of $U-B$ and $[(R-I)_{\mathrm{C}} - 0.007$ mag$]$ are compared with a grid derived from model atmospheres. The $(R-I)_{\mathrm{C}}$ correction allows for the difference between the Buser-Kurucz solar value of $(R-I)_{\mathrm{C}}$ and the solar value deduced by Taylor (1997).

arguments. The values of $[M/H]$ from the grid are then calibrated.

For $\langle$Fe$\rangle$, G, M_1, $(R-I)_{\mathrm{E}}$, and D, source papers for the adopted calibration data are listed in Table 1. The sources used for DDO data are listed in Table 2.

3. Deriving calibrations

3.1. Reviewing isoabundance relations

All indices that are calibrated here are derived from relations between metallicity parameters and temperature parameters. These relations are intended to be isoabundance relations. In practice, however, they may not quite satisfy this condition. One would therefore like to test the isoabundance relation for (say) index q by using it to calculate

$$[\mathrm{Fe/H}] = f(q) = Sq + Z \qquad (1)$$

while allowing S and Z to vary with color if necessary.

This test is feasible for δCN and $[M/H]$. No variation of S and Z with color can be detected for $[M/H]$, so a single relation that is applicable for all pertinent colors is obtained for this index. For δCN, variation in both S and Z is detected and allowed for (see Sect. 4).

Table 2. Sources of DDO photometry

Literature source	Literature source
Boyle & McClure 1975	Lu & Upgren 1979
Cottrell & Norris 1978	Lu et al. 1983
Dawson 1979	McClure 1970
Dean 1981	McClure & Forrester 1981[b]
Deming et al. 1977	Mermilliod et al. 1997[c]
Dickow et al. 1970[a]	Norris et al. 1985
Eggen 1989c, 1993, 1994	Schmidt 1984
Goodenough 1970	Yoss 1977
Janes 1972, 1979	Yoss & Hartkopf 1979
Janes & McClure 1971	Yoss et al. 1991
Johnson et al. 1987	

[a] This source contains Copenhagen photometry, and is used only if no directly-measured DDO data are available. The data are converted to DDO color indices by using the transformations of Janes 1975 (see his Table 5).
[b] Data from this source are preferred, as McClure & Forrester recommend.
[c] This valuable secondary source contains data from almost all the primary sources in a readily accessible form.

For ⟨Fe⟩, G, and D, there are not enough data to carry out the test. The formal isoabundance relations for these indices are therefore assumed to be correct. For ⟨Fe⟩ and G, the results of the analyses offer some support to this assumption (again, see Sect. 4).

The isoabundance relations given for M_1 by Eggen are not adequately documented[1]. A relation was therefore derived by assuming that the mean metallicity of stars in a large sample measured by Eggen (1989a) is independent of temperature. Eggen did not base the selection of his sample on a metallicity parameter, so this assumption is at least plausible.

The data used to derive an isoabundance relation should have some scatter around the relation. The character of the scatter must be understood if the relation is to be derived correctly. In this case, the scatter turns out to be quite a bit larger than one would predict from plausible measurement error. Presumably the "excess" scatter is caused by star-to-star metallicity differences. Those differences should have relatively large effects on a blanketed index like M_1, but should have small effects on $(R-I)_{\rm E}$ (see the entry for the similar index $(R-I)_{\rm K}$ in Table III of Taylor et al. 1987). $(R-I)_{\rm E}$ was therefore treated as an error-free parameter, and a one-error least-squares regression of M_1 on $(R-I)_{\rm E}$ was obtained. The result of this calculation will be given below (see Sect. 4, Table 3, footnote "h").

3.2. Choosing a least-squares algorithm for the [Fe/H] relation

The derivation of Eq. (1) may now be considered. Again one must consider the scatter around a calculated relation. This time, three sources of such scatter may be important:

1. the rms errors of the catalog values of [Fe/H],
2. measurement error in q, and
3. intrinsic scatter around $f(q)$.

The nature of the intrinsic scatter is most easily visualized for δCN. Here, one expects CNO/Fe variations to yield a range of values of δCN for any given choice of temperature, surface gravity, and [Fe/H]. In the same way, G should be influenced by Ca/Fe variations and their counterparts for other metals. Variations in Fe-line strength should be closely correlated with variations in [Fe/H], but nonetheless there is also intrinsic scatter in the relation between these two parameters. The same is true for blanketing and [Fe/H].

[1] The source of the relation in Eggen (1989c) is given as Eggen (1989a). The latter paper contains no algebraic relations. The next paper in the literature after Eggen (1989a) is by Eggen (1989b), and it does contain an isoabundance relation. However, that relation differs from the one in Eggen (1989c; compare Eq. (1) in Eggen 1989c with Eq. (14) in Eggen 1989b). Eggen does not describe the way in which either relation was obtained.

It might be argued that a "structural" least-squares technique is required here because of the intrinsic scatter. However, since the sources of the scatter affect only q and not [Fe/H], one can presumably regard the net scatter from items (2) and (3) as if it were an additional measurement error in q. This viewpoint permits the use of one of the better-known "functional" least-squares techniques[2]. The technique used here is a linear, two-error algorithm based on the following parameter:

$$\lambda = v([\mathrm{Fe/H}])/v(q), \tag{2}$$

with v denoting variance per datum (the square of the rms error per datum). (See Sect. 1.2 of Madansky 1959 and Eq. (7.7) of Babu & Feigelson 1996.)

For single determinations of [Fe/H], the rms errors that yield $v([\mathrm{Fe/H}])$ are in the range $0.10 - 0.13$ dex (see Table 2 of Taylor 1999b). The errors are smaller, of course, for stars with multiple determinations. This range of errors poses a problem, since the adopted algorithm requires $v([\mathrm{Fe/H}])$ to be the same for all contributing stars. To deal with this problem, the data are analyzed in groups with similar rms errors. The values of S from all the groups are then averaged using inverse-variance weights, with the same procedure being applied to Z.

3.3. Calculating $v(q)$

Though $v(q)$ is required by the algorithm described above, its value is not known in advance. However, one can derive $v(q)$ by assuming that the net scatter around Eq. (1) is produced by $v(q)$ and a known contribution from $v([\mathrm{Fe/H}])$. A "data-comparsion" algorithm for deriving $v(q)$ in this way is summarized in Sect. 4 of Appendix B of Taylor (1991).

In practice, an initial guess for $v(q)$ is made. An initial version of Eq. (1) is then calculated, and the data-comparison algorithm is applied to the scatter around this equation to obtain an improved estimate for $v(q)$. This procedure is iterated to convergence.

4. The new calibrations

Calibrations obtained from the procedure described above are given in Table 3. These calibrations supersede all counterparts that have previously been derived from Taylor's [Fe/H] catalogs. The notation "[Fe/H](q)" is used in Table 3 to designate metallicities derived from the calibrations. The metallicity limits within which the calibrations apply are given (with other information) in Table 3's footnotes.

[2] The distinction between structural and functional models is discussed on pp. 123 and 125 of Babu & Feigelson (1996). This book is an indispensable source of information about statistical analysis for problems in astronomy.

Table 3. Calibrations: [Fe/H](q) = $Sq + Z$[a]

Input datum	$(45-48)$: limits	S	Z	[Fe/H](q): intrinsic σ	Number of stars used
δCN[b,c]	1.100, 1.185	3.75 ± 0.13	-0.156 ± 0.006	0.067 ± 0.009	309
δCN[b]	1.195, 1.245	3.09 ± 0.13	-0.115 ± 0.005	0.055 ± 0.007	281
δCN[b,d]	1.255, 1.300	4.11 ± 0.19	-0.073 ± 0.008	0.123 ± 0.013	338
δCN[b,e]	1.186, 1.194	3.42	-0.136	0.061	...
δCN[b,f]	1.246, 1.254	3.60	-0.094	0.086	...
G[g]	...	0.77 ± 0.07	-0.125 ± 0.009	0.043 ± 0.009	115
⟨Fe⟩[h]	...	0.37 ± 0.04	-0.059 ± 0.012	0.058 ± 0.014	58
δM_1[j]	...	2.90 ± 0.19	-0.076 ± 0.008	0.114 ± 0.014	240
D[k]	...	2.62 ± 0.24	-0.101 ± 0.019	0.090 ± 0.023	43
$[M/H]$[m]	...	0.87 ± 0.03	-0.170 ± 0.012	0.118 ± 0.016	126

[a] Units are magnitudes for δCN and δM_1. Values of [Fe/H](q) are in dex.
[b] Limits in [Fe/H](q) are -0.8 dex and $+0.2$ dex.
[c] Data for HD 13530 were not used to derive this equation.
[d] Values of [Fe/H] with $\sigma \geq 0.11$ dex yield a value of S that is anomalous at better than 99.5% confidence. That value of S is rejected, but the corresponding value of Z is retained, and the large-σ values of [Fe/H] help to determine the error quoted in Col. 5. Data for HD 116713 and HD 198700 were not used to derive this equation.
[e] This relation is an average of the first and second relations given above, and is intended for the transition region in $(45-48)$ between the two.
[f] This relation is an average of the second and third relations given above, and is intended for the transition region in $(45-48)$ between the two.
[g] Limits in [Fe/H](q) are -0.25 dex and $+0.2$ dex.
[h] Limits in [Fe/H](q) are -0.35 dex and $+0.2$ dex.
[j] $\delta M_1 = M_1 + 0.695 - 4.336(R-I)_{\rm E} + 3.120(R-I)^2_{\rm E}$. This calibration was derived only from data in Eggen (1989a). Data for HR 2574, HR 4308, and reddened stars are not used to calculate S and Z from [Fe/H] and δM_1 (see Appendix B of Taylor 1996, and Sect. 5.2 of Taylor 1998). Limits in [Fe/H](q) are -0.6 dex and $+0.2$ dex.
[k] Data for HD 41593 were not used. Limits in [Fe/H](q) are -0.6 dex and $+0.45$ dex.
[m] The Buser-Kurucz grid is read within the following limits: $-2.0 \leq [M/H] \leq +0.5$, 4000 K $\leq T_{\rm eff} \leq$ 6000 K. At $T_{\rm eff} = 6000$ K, the grid is read at $\log g = 4.25$ to allow for some evolution in program stars. Values for $\log g = 4.5$ are read at other effective temperatures. Stellar values of $U-B$ and $[(R-I)_{\rm C} - 0.007$ mag$]$ are compared to the numbers from the grid (see note "h" of Table 1).

4.1. The DDO calibration

The values of S in the δCN calibration require comment. Taylor (1991) presented a calibration in which S depends on color. By contrast, Twarog & Anthony-Twarog (1996) found no evidence for a color dependence that is statistically significant. As part of the new analysis, preliminary solutions were performed to investigate this problem. The results of the solutions revealed three intervals in the color $(45-48)$, with S and Z being essentially constant within each interval but differing between intervals. For the final results given in Table 3, t tests show that the values of S and Z differ between the first and second intervals with confidence levels of at least 99.9%. The same is true for the second and third intervals.

The first three lines of Table 3 contain results for the three color intervals. The fourth line contains averages for use near the boundary between the first and second color intervals. In the same way, the fifth line applies for the boundary between the second and third intervals. These latter relations are based on a guess that relatively smooth transitions between color intervals are more likely than abrupt changes between them.

Somewhat to the author's surprise, S decreases as one goes from the first color interval to the second, but then increases again as one goes from the second interval to the third. The reason for this kind of variation is not known. Given the results of the statistical tests quoted above, however, the existence of the variation seems to be reasonably well established.

4.2. Accidental errors for [Fe/H](q)

Values of the following rms error are given in the fifth column of Table 3:

$$\sigma_{Fq} = S[v(q)]^{0.5}. \quad (3)$$

These are the errors that apply to values of [Fe/H](q). Equation (3) is derived from Eq. (10.14) of Kendall & Stuart (1977).

One would like to know how well the errors listed in Table 3 compare to the errors given for values of [Fe/H] in Taylor's catalogs. The largest of the Table 3 errors are for δM_1 and $[M/H]$, and are quite comparable to the rms error range for a single determination of [Fe/H] (Taylor 1994, 1999b). The smallest of the Table 3 errors are for G and $\langle\mathrm{Fe}\rangle$, and would be typical for stars with values of [Fe/H] that have been determined several times. The small sizes of the latter errors suggest that the isoabundance relations for G and $\langle\mathrm{Fe}\rangle$ are correct.

It is also of interest to find out whether net values of σ_{Fq} can be decreased by averaging results from two (or more) calibrations. This is possible only if the datum from each calibration is an independent sample of underlying random effects. That condition is not met if there are internal correlations in the data; if (say) $F(Q) - $[Fe/H] and $f(q) - $[Fe/H] are correlated, $f(q)$ and $F(Q)$ are effectively identical samples of underlying random effects, and their average conveys no more information than $f(q)$ or $F(Q)$ alone. To check for correlations of this sort, the two-error least-squares algorithm described in Sect. 3.2 was applied to residuals from the Table 3 relations. For the following parameter pairs, correlations with a confidence level of 3.5σ or better were found:

1. D and $[M/H]$,
2. δCN and $\langle\mathrm{Fe}\rangle$, and
3. δCN and G.

No corresponding correlation was obtained for G and $\langle\mathrm{Fe}\rangle$. However, the number of stars for which both parameters are available is relatively small. Larger numbers of data could be used to test these parameters against δCN. Since correlations were found when both G and $\langle\mathrm{Fe}\rangle$ were tested in this way, it appears safest to assume that the G and $\langle\mathrm{Fe}\rangle$ residuals are correlated.

Recall now that the M_1 calibration is intended only to answer a question about μ Leo (see Sect. 2). In the present context, that calibration may be set aside. Apparently results for the other three evolved-star calibrations cannot be meaningfully averaged. The same appears to be true for results for the two calibrations for dwarfs. To avoid misleading appearances, it is probably best not to average results from two or more calibrations at any point in an analysis.

5. Summary

For evolved G and K stars, metallicity calibrations have been derived for δCN and three other L-R parameters. For G and K dwarfs, two calibrations have been obtained. For metallicities obtained from the calibrations, rms errors turn out to be comparable to those for averaged H-D results. No pair of calibrations is found for which averaging of results definitely yields improved rms errors.

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