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Original Publication Citation
Astronomy and Astrophysics 398 2 (23) 731-738

A&A 398, 731–738 (2003)
DOI: 10.1051/0004-6361:20021675

Astronomy & Astrophysics

Statistical cataloging of archival data for luminosity class IV–V stars

II. The epoch 2001 [Fe/H] catalog*

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Received 2 July 2002 / Accepted 14 November 2002

Abstract. This paper describes the derivation of an updated statistical catalog of metallicities. The stars for which those metallicities apply are of spectral types F, G, and K, and are on or near the main sequence. The input data for the catalog are values of [Fe/H] published before 2002 February and derived from lines of weak and moderate strength. The analyses used to derive the data have been based on one-dimensional LTE model atmospheres. Initial adjustments which are applied to the data include corrections to a uniform temperature scale which is given in a companion paper (see Taylor 2003). After correction, the data are subjected to a statistical analysis. For each of 941 stars considered, the results of that analysis include a mean value of [Fe/H], an rms error, an associated number of degrees of freedom, and one or more identification numbers for source papers. The catalog of these results supersedes an earlier version given by Taylor (1994b).

Key words. catalogs – stars: abundances

1. Introduction

Some years ago, Taylor (1994b) published an [Fe/H] catalog for about 400 class IV–V stars. The input data for the catalog consisted of published values of [Fe/H] derived from weak lines, usually by means of high-dispersion analysis. Those data were corrected to a common temperature scale and (as far as possible) to a common zero point. They were then used to calculate mean values of [Fe/H] and rms errors, with the latter being derived from a statistical analysis.

A second iteration of the catalog appeared in 1995 (see Taylor 1995, hereafter Paper II). For that version, the cutoff date for published values of [Fe/H] was the end of 1993. Numerous high-dispersion metallicities have been published since that time, so an updated version of the catalog is now desirable. The production of that version is described here.

The plan for this paper is as follows. In Sect. 2, the zero-point reliability of the input data for the catalog is considered. The production of the catalog is described in Sect. 3. In Sect. 4, there is a discussion of possible systematic errors which may affect the catalog data and whose status will require clarification in the future. The paper concludes in Sect. 5 with a brief review of the derivation of the catalog and a description of its contents.

* Catalog is only available in electronic form at the CDS via anonymous ftp `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/398/731`

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2. The zero-point issue

2.1. Drawing an extended sample

The zero-point issue is considered here for two reasons: *a*) the reliability of extant zero-point techniques does not seem to have been discussed comprehensively in the literature, and *b*) there appears to be a common misconception about which of those techniques is most often used. It is sometimes maintained that the predominant zero-point technique is "external zeroing," in which a published solar value of (Fe/H) is subtracted from a derived stellar value of (Fe/H) (see especially Kurucz 2002a, 2002b). In fact, that technique does not yield rigorous results, and its prevalence would almost certainly rule out the possibility of assembling a catalog with a reliable zero point. This is established in Appendix A, in which the zero-point reliability of techniques found in the literature is discussed at some length.

To establish a reliable picture of zero-point practice, an "extended sample" of published papers is compiled. All papers included in this sample were published before the end of 2002 January. The stars whose spectra are analyzed in those papers

- are on or near the main sequence,
- have spectral types earlier than K5, and
- have effective temperatures $T_e < 6833$ K.

Table 1. Percentages for various kinds of high-dispersion analysis.

ID[a]	Description	Percentage
1[b]	Differential analysis (own solar EWs)[c]	41
3[b]	Differential analysis (solar EWs from atlas)[c]	41
1, 3[b]	Differential analysis (all comparisons to Sun)	82
5, 6	External zeroing	7
7	Pseudo-absolute analysis	3
4	Star other than Sun used as a standard star	4
–	Zero-point procedure not adequately described	4

[a] Number of example in Appendix A.
[b] Analyses with and without the Holweger-Müller (1974) solar model are both counted. "EWs" are equivalent widths.

In addition, the following relation applies for one or more of the stars considered:

$$[Fe/H] > 3.43 - 5\theta, \quad (1)$$

with $\theta \equiv 5040/T_e$. Note that Eq. (1) admits only metal-rich and modestly metal-poor stars. HD 103095 and similar cool stars are included, but HD 140283 and stars with similar metallicity and temperature are not considered.

Restrictions are applied to the selection of analyses as well as the selection of stars. If two reports of an identical analysis appear in the literature, only one of those reports is included. In addition, there are restrictions based on the number of lines N_L that are used in the analyses. N_L is ≥9 for analyses based on photographic spectra and is usually ≥6 for analyses based on Reticon and CCD spectra. This rule will be required when a limited version of the extended sample is used to derive the catalog (see below). The rule reflects the fact that zero-point problems may arise when values of [Fe/H] are derived from small numbers of lines (see Sect. 5.2 of Taylor 1998b). Exceptions to the rule are allowed if the zero points of the pertinent values of [Fe/H] can be established extrinsically (see Sect. 3.2). (For further discussion of all but the last of these rules, Sect. 3.3 of Taylor (1994a, hereafter T94) should be consulted.)

2.2. Surveying the extended sample

The 182 papers in the extended sample are now sorted according to zero-point procedure. For each kind of analysis considered, the frequency of use may be expressed as a percentage. These percentages are listed in Table 1. As the entries in that table show, external zeroing is in fact a minority technique for the kinds of stars considered here. The majority technique is differential analysis relative to the Sun, with 82% of the papers in the extended sample being included in this class.

3. Producing the catalog

3.1. Choosing analyses

The prevalence of differential analysis is a first indication that a reliable zero point may be found for the catalog data. The first step in calculating those data may now be taken by sorting the extended sample in a somewhat different way. Two classes of accepted results are established, with one class including results from all analyses for which extrinsic zero points can be calculated (again see Sect. 3.2). Some results in this class have small values of N_L, while others contribute to the fourth through the seventh lines in Table 1. The other class considered here includes only results from differential analyses relative to the Sun for which the N_L limits given above are always satisfied. No distinctions among these results are made which are based on their input solar equivalent widths (EWs) This procedure will be justified in Sect. 3.4[1].

Table 2. Reasons for deleting analyses from the extended sample.

Reason
DCOG result–not used for certain metal-poor stars
EWs from a blanketed wavelength region
[Fe/H] zero point cannot be determined adequately
Few or no lines on linear part of curve of growth
Further analysis of program stars may not take place[a]
Noisy EWs
Only one result in catalog [Fe/H] range
Only previously published stellar EWs used
Results superseded by improved analysis
Subsequent analysis indicates systematic error
Values of [Fe/H] not given numerically

[a] Cunha et al. (1995) have derived metallicities for stars in the Orion association. The cautious assumption made here is that those stars are less likely than field stars to be the objects of further analysis. This issue is deemed to be important because rms errors are determined from the scatter in multiple data for given stars. It is not clear that errors derived in that way should be applied if there is a minimal prospect for further analyses.

The second step is to edit the extended sample. Papers are deleted from that sample for reasons given in Table 2. After the deletions are performed, the remaining sample is augmented by adding data from Nissen (1981). Nissen's results are from photometry of one cluster of weak lines and a second cluster of moderately-saturated lines.

3.2. Initial corrections

The third step in the analysis is to apply an initial set of corrections to the data. These corrections are made only if they can be based on published numerical results. When necessary, solar values of [Fe/H] are corrected to the Liège EW system (see Delbouille et al. 1973; Rutten & van der Zalm 1984a, 1984b). Corrections are also applied if incompatible solar and stellar model atmospheres have been used (see examples (5) and (6) in Appendix A). The entire data base is also corrected to a temperature scale which is described in a companion paper (see Taylor 2003). This part of the correction procedure is described in more detail in Sects. 3.4 through 3.6 of T94.

[1] It should be noted that a similar procedure has been used for earlier versions of the catalog.

For each data set which requires an extrinsic zero point, a special reduction procedure is adopted. One or more stars with data in the set are designated as ad hoc standard stars. Averaged values of [Fe/H] for those stars are then calculated from data sets with reliable zero points. Finally, corrections for the problem data sets are derived, with a "comparison algorithm" being applied if necessary (see Taylor 1999a, Sect. 4.3).

3.3. Data averaging and input rms errors

The fourth step in the analysis is to calculate overall averages from the data. For each star considered, this averaging yields a mean value of [Fe/H], an rms error of the mean, and a number of effective degrees of freedom[2]. Each input datum is weighted by the inverse square of an input rms error. The integrity of the resulting mean values of [Fe/H] must be checked by performing a zero-point analysis, and that test will be described in the next section. For the moment, attention is focused on the input rms errors.

Each block of input data is assigned to rms error class S, N, or W. Class N contains data which are quoted in the literature without errors from EW scatter, while class W data are quoted with such errors. For the most part, older papers are in class N, while more recent papers are in class W. Data are assigned to class S if there are reliable rms errors for them in the literature. They are also assigned to this class if special rms errors have been derived for them by using the comparison algorithm. Further discussion of class S data is given in Sect. 4.1 of T94.

For all data without reliable published rms errors, those errors are derived from scatter in residuals from averaged values of [Fe/H]. A sample of such scatter is given in Fig. 1, where residuals for part of the Edvardsson et al. (1993) data are depicted. The procedure for deriving class N errors is adopted unchanged from Sect. 3.8 of T94. An improved procedure for deriving the counterpart class W error is described in Appendix B of this paper. The resulting values of the two errors are as follows:

$$\sigma(N) = 0.128 \text{ dex}, \;\; \nu(N) = 98, \qquad (2)$$

and

$$\sigma(W) \equiv (V_w)^{0.5} = 0.051 \text{ dex}, \;\; \nu(W) = 299, \qquad (3)$$

with V_w being defined in Appendix B. V_w is added to a contribution from EW scatter to obtain errors for class W data (again see Appendix B).

The rms errors in Eqs. (2) and (3) contribute to useful insights about the input catalog data. An F test shows that $\sigma_N > \sigma_W$ at a confidence level $C > 99.9\%$. One might think this to be an expected result, since it implies that more recent values of [Fe/H] are more precise than their older counterparts. However, no comparable trend can be found for evolved stars (see Sect. 4.6 of Taylor 1999a). In addition, if $N_{\rm L}$ is about 10 or greater, $\sigma_{\rm W}$ is substantially larger than the error contribution from EW scatter. Again, a similar result holds for evolved stars (see Sect. 5.3 of Taylor 1999a). Apparently most of the scatter in the input data is from one or more sources other than EW scatter.

[2] For a pertinent discussion of the importance of the rms errors, see Sect. 2 of T94.

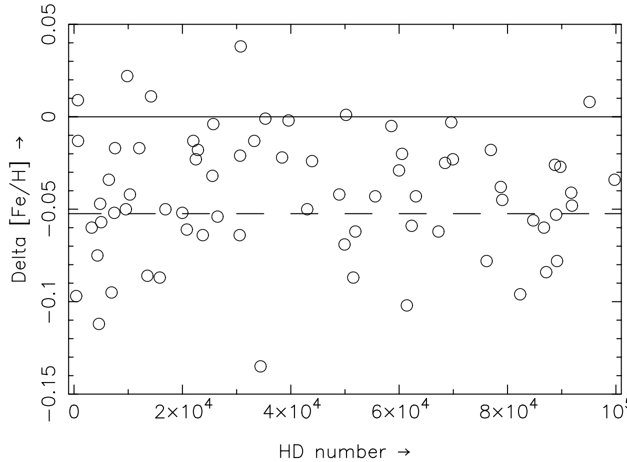

Fig. 1. For the data of Edvardsson et al. (1993), residuals from averaged values of [Fe/H] (in dex) are plotted against HD number. Only data for HD numbers which equal 99 999 or less are plotted. The solid line applies for a residual of zero, while the dashed line is the mean residual. The adopted reduction of the Edvardsson et al. data is that of the authors themselves, not the subsequent reduction by Gratton et al. (Table 3).

3.4. Statistical testing for systematic offsets

The zero-point assessment referred to above is performed by searching for papers whose data yield precise average residuals. These averages are calculated by using an interim solution in which no corrections have yet been made for the non-zero mean residuals which will ultimately be found. To estimate the statistical significance of each averaged residual, a t test is used to derive a value of

$$P \equiv -\log_{10}(1 - C), \qquad (4)$$

with C being the confidence level for rejecting the null hypothesis that the true average is zero. The resulting values of P are given with the averaged residuals in Tables 3–5.

Table 3 contains the most encouraging results found. For the last two entries in the table, $P \geq 1.3$ ($C > 0.95$). However, the listed mean residuals are small, and it seems probable that their nonzero status would not have been recognized if unusually large numbers of contributing data had not been available. For the remaining entries, $P < 1.3$. In these cases, the null hypothesis stating that the averages are zero is maintained[3]. Note that each of the first four entries in Table 3 is from a series of six or more papers produced by a given author and collaborators.

In Table 4, results with $P > 1.3$ are listed if they can be attributed plausibly to a known source of possible zero-point error. The following sources are considered.

– Solar and stellar EWs are from different spectrographs.

[3] To see why the null hypothesis is "maintained" instead of being accepted, the reader is invited to consult footnote 7 of Miller et al. (2001).

Table 3. Acceptable mean residuals from interim [Fe/H] solution.

Source	No. of papers	No. of stars	Mean residual[a]	P^{b}
Boesgaard[c]	6	62	+14 ± 13	–
Cayrel de Strobel[d]	13	33	+ 7 ± 14	–
Gratton (group 1)[e]	6	83	+ 2 ± 9	–
da Silva[f]	6	18	−22 ± 19	–
Chen et al. (2000)	1	43	−18 ± 14	–
Favata et al. (1997)	1	30	−10 ± 14	–
Feltzing; Neuforge-Verheecke & Magain[g]	3	15	+10 ± 18	–
Fuhrmann (1998)	1	46	+ 3 ± 10	–
Santos et al. (2001)	1	42	−10 ± 11	–
Edvardsson et al. (1993)[h]	1	137	−20 ± 6	2.94
Nissen (1981)[j]	1	111	−34 ± 12	2.24

[a] The listed numbers are mean residuals multiplied by 1000. Units are dex.
[b] $P \equiv -\log_{10}(1 - C)$, with C being the confidence level.
[c] Included papers: Boesgaard (1987, 1989), Boesgaard et al. (1988), Boesgaard & Friel (1990), Friel & Boesgaard (1992), Deliyannis et al. (2000).
[d] Included papers: Cayrel de Strobel (1968), Cayrel et al. (1977), Cayrel de Strobel et al. (1981), Cayrel et al. (1985, 1988), Perrin et al. (1988), Cayrel de Strobel & Bentolila (1989), Cayrel de Strobel & Cayrel (1989), Cayrel de Strobel et al. (1989), Chmielewski et al. (1992), Friel et al. (1993), Cayrel de Strobel et al. (1994), Chmielewski et al. (1995).
[e] Included papers: Gratton & Ortolani (1986), Gratton & Sneden (1987), Gratton et al. (1989), Gratton et al. (1996), Clementini et al. (1999), Randich et al. (1999).
[f] Included papers: da Silva (1975), da Silva & Foy (1987), Porto de Mello & da Silva (1997a, b), Castro et al. (1999), del Peloso et al. (2000).
[g] Included papers: Neuforge-Verheecke & Magain (1997), Thoren & Feltzing (2000), Feltzing & Gonzalez (2001). The zero points for the first and third papers should be similar (see Sect. 4.2 of Feltzing & Gonzalez 2001).
[h] Data source: reduction by Gratton et al. (1996).
[j] Nissen's metallicites have been derived from photomultiplier measurements of clusters of weak lines.

Table 4. Probably acceptable mean residuals from interim [Fe/H] solution.

Source	No. of papers	No. of stars	Mean residual[a]	P^{b}
Balachandran (1990)[c]	1	63	−81 ± 15	> 6
Boesgaard & Lavery (1986)[d]	1	11	+98 ± 20	3.28
Clegg (1977)[e]	1	11	−162 ± 25	4.15
Gratton (group 2)[f]	2	16	+42 ± 18	1.46
Pasquini et al. (1994)[g]	1	26	−146 ± 16	> 6
Thévenin et al. (1986)[h]	1	10	−173 ± 33	3.27
Varenne & Monier (1999)[j]	1	19	−262 ± 25	> 6

[a] The listed numbers are mean residuals multiplied by 1000. Units are dex.
[b] $P \equiv -\log_{10}(1 - C)$, with C being the confidence level.
[c] Only results with N_L = 6 are used. Stellar and solar EWs are from different spectrographs.
[d] Only results with N_L = 9 are used. Stellar and solar EWs are from the same spectrograph.
[e] The source of solar EWs is unknown. For stellar EWs, 4200 Å $\leq \lambda \leq$ 4700 Å.
[f] Included papers: Gratton (1989), Sneden et al. (1991). For each paper, stellar and solar EWs are from different spectrographs.
[g] N_L = 2 for all results. The description of the zero-point procedure in this paper is incomplete.
[h] For stellar EWs, 4200 Å $\leq \lambda \leq$ 4700 Å. The description of the zero-point procedure in this paper is incomplete.
[j] The zero point for this paper is from external zeroing.

– The source of solar EWs is not stated.
– The description of the zero-point procedure in the paper is incomplete.
– N_L is small.
– The zero point is from external zeroing.
– Stellar EWs have been measured at short wavelengths where blanketing may be a concern.

For two papers in the last of these categories, the signs obtained for the mean residuals turn out to be consistent with a possible blanketing effect (see the entries for Clegg 1977 and Thévenin et al. 1986). Special attention should also be paid to the entry in Table 4 for the data of Varenne & Monier (1999). The absolute value of that entry is about 0.26 dex, and its size can presumably be attributed to the fact that Varenne & Monier used external zeroing. This result underscores the need for cautious use of externally-zeroed data (recall Sect. 2.1).

Like Table 4, Table 5 contains entries with $P \geq 1.3$. However, none of the explanations listed above will work for those entries. They show that even when zero-point procedures with every appearance of rigor are applied, the resulting values of [Fe/H] can sometimes have appreciable offsets.

Overall, one can say that Tables 3 through 5 do not support extreme conclusions. Tables 4 and 5 show that there is more zero-point diversity than might have been hoped. On the other hand, Table 3 suggests that a meaningful zero point may nevertheless be found in the data. To see whether this is the case, corrections are first made by subtracting the listed offsets from the data to which the offsets apply. This is done if $P > 1.3$. Corrections $|\Delta F| < 0.06$ dex are applied to 18% of the input data. For an additional 18% of the data, $|\Delta F| > 0.06$ dex.

A revised version of the catalog is now produced, and check statistics are calculated. Numerical values for those statistics are listed in Table 6. One set of tests is applied to data of classes N and W which were not obtained by using solar EWs derived from stellar spectrographs. No detectable offset is found. In the fourth row of the table, the overall zero points for data of classes N and W are compared. Again no detectable offset is found, suggesting that the older data are on the same zero point as their more recently derived counterparts. It seems fair to assume that such results are obtainable only because the data are on a common zero point.

Table 5. Problem mean residuals from interim [Fe/H] solution.

Source	No. of papers	No. of stars	Mean residual[a]	P^{b}
Bikmaev et al. (1990)	1	15	−132 ± 36	3.77
Edvardsson et al. (1993)[c]	1	186	−52 ± 6	> 6
Fulbright (2000)	1	38	−95 ± 12	> 6
Gonzalez[d]	6	21	+59 ± 14	3.31
Hartmann & Gehren (1988)[e]	1	4	−330 ± 34	> 6

[a] The listed numbers are mean residuals multiplied by 1000. Units are dex.
[b] $P \equiv -\log_{10}(1 - C)$, with C being the confidence level.
[c] Data source: Edvardsson et al. reduction.
[d] Included papers: Gonzalez (1998), Gonzalez & Vanture (1998), Gonzalez et al. (1999), Gonzalez & Laws (2000), Gonzalez et al. (2001), Laws & Gonzalez (2001). Data from Feltzing & Gonzalez (2001) may be on a different zero point, and that paper is therefore included in a separate entry (see Table 3).
[e] The authors give a datum for HD 59984 which yields a discrepant residual and has therefore been omitted.

Table 6. Test statistics for accepted [Fe/H] solution.

Statistic[a]	ν^{b}	Mean residual[c]
N(no) − W(yes)	42	+9 ± 19
W(no) − W(yes)	91	−8 ± 7
Net correction[d]	113	−5 ± 6
N(all) − W(all)	135	−5 ± 9

[a] "N" and "W" designate rms error classes (see Sect. 4.4). "No" denotes data whose zero points may be uncertain because solar EWs were not measured with stellar spectrographs. "Yes" denotes data with zero points that are deemed to be reliable, and "all" denotes a combination of data of both kinds.
[b] ν is the number of degrees of freedom that would be used in a t test of the listed mean residual.
[c] The listed numbers are mean residuals multiplied by 1000. Units are dex.
[d] This is the net correction for data with uncertain zero points, and has been averaged from the two entries just above.

4. Notes about possible systematic errors with uncertain status

When high-dispersion analyses are performed, it is necessary to assume (often tacitly) that no corrections are required for some possible sources of systematic error for which inadequate information is available. In some papers, potential error sources of this kind are discussed explicitly (see Norris et al. 2001 and especially Carretta & Gratton 1997). That procedure also seems appropriate for the cataloging described here, and it was in fact adopted by T94. The review of uncorrected systematic effects given in that paper will be updated here.

In T94, there is a brief discussion of possible effects of chromospheric activity. Since that discussion was published, an extensive analysis of this problem has been produced by Valenti (1994). Judging from Valenti's work, there is good reason to suspect that chromospheric activity can affect some of the numerical results of high-dispersion analysis. However, if one asks about derived values of [Fe/H] in particular, the situation remains unclear. It is for this reason that possible chromospheric effects have not been considered above.

The widespread use of plane-parallel model atmospheres which are horizontally homogeneous is a possible problem which was not considered in T94. Here, a paper by Allende Prieto et al. (2001) is consulted for guidance. Those authors find that if a particular model atmosphere with structure like that described above is used, derived solar abundances are within 10% of the correct abundances. Admittedly it would be premature to generalize this result to all dwarfs and all model atmospheres that have been used to analyze them. However, it does seem fair to regard the work of Allende Prieto et al. as a reason for setting aside the issue at present.

A third possible problem is from nLTE effects, which have arguably attracted more concern than any other systematic effect considered in high-dispersion analysis. In this case, contradictory theoretical results have been published. On the one hand, Thévenin & Idiart (1999) find that nLTE effects on derived values of [Fe/H] can be appreciable for metal-poor dwarfs, but not for metal-rich dwarfs. On the other hand, Gratton et al. (1999) find that nLTE effects are not important for either metal-poor or metal-rich dwarfs. Norris et al. (2001) cite these studies as part of their reason for omitting nLTE effects from their analysis. The same reasoning is applied here.

5. A review and a description of the catalog

The catalog discussed here has been derived by choosing suitable input data (mostly from the literature), applying initial corrections to those data, and then subjecting them to a statistical analysis. Improvements in the published data include 1) correction to a common temperature scale, 2) correction of the output averages to a zero point which is presumably uniform, and 3) derivation of rms errors for those averages. The final version of the catalog is available from the Strasbourg Astronomical Data Center (CDS) and has entries for 941 stars. A sample of the catalog is given in Table 7.

Acknowledgements. Dr. G. Basri alerted me to the existence of Dr. Valenti's Ph.D. Thesis, and Drs. Basri and Valenti then made a copy of that thesis available to me. Phil Warner set up for my use the plot package used to produce Fig. 1. Mike and Lisa Joner proofread the paper carefully, and two anonymous referees made a number of constructive suggestions for improving the paper. I cheerfully thank all these individuals while noting that page charges for this paper have been generously underwritten by the College of Physical and Mathematical Sciences and the Physics and Astronomy Department of Brigham Young University.

Appendix A: Zero-point procedures for [Fe/H] analysis

Let f be an unknown true value of log (Fe/H), and let E be a generally nonzero systematic error in f which results from

Table 7. A sample of the [Fe/H] catalog[a].

Catalog number[b]	[Fe/H]	σ	ν[c]	No. of sources	Sources[d]
400	−0.274	0.058	99.0	3	565, 2055, 2072
693	−0.414	0.045	99.0	3	565, 624, 2003
739	−0.122	0.054	99.0	2	624, 2003
1461	0.138	0.079	99.0	3	166, 2001, 2004
1671	−0.130	0.100	17.2	1	2003

[a] This sample reproduces catalog entries, but differs from the catalog in format. For [Fe/H] and σ, units are dex.

[b] The numbers listed are HD numbers. In the catalog, prefixes designate other star catalogs, while "A" and "B" suffixes designate components of binaries (when required).

[c] This is the number of degrees of freedom.

[d] The numbers correspond to the following literature sources: *166*, Branch & Bell (1971); *565*, Balachandran (1990); *624*, Edvardsson et al. (1993); *2001*, Raff (1976); *2003*, Nissen (1981); *2004*, Clegg et al. (1981); *2055*, Fuhrmann (1998); *2072*, Chen et al. (2000). In the catalog, a complete list of numbers and references appears in a supplementary list.

a high-dispersion analysis. The derived value of log (Fe/H) is then $f+E$. Let $f_\odot$ and $E_\odot$ apply for the Sun, and let f_s and E_s apply for a program star. Finally, to focus attention on the simplest case of interest, let E_s be the same for all program stars. With these constraints in mind, seven zero-point procedures will be discussed.

1) Differential analysis (relative to the Sun). When this case is satisfied in practice,

$$[\mathrm{Fe/H}] = (f_s + E) - (f_\odot + E) = f_s - f_\odot. \quad (A.1)$$

No subscript is attached to E because it is presumably the same for program stars and the Sun. Note that since E is generally nonzero, there is no constraint of any kind on the quantity $f_\odot+E$ to equal a published solar metallicity. To perform this kind of differential analysis, one must measure and analyze the Sun and program stars as identically as possible. In particular, solar and stellar model atmospheres must both be empirical or must both be from the same grid (see Sect. 6.1 of Drake & Smith 1991 for a more extensive discussion of this essential point). For instructive examples of differential analysis, the work of Cayrel de Strobel and her associates may be consulted (see, for example, Chmielewski et al. 1992).

2) Differential analysis with model-atmosphere mismatch. Here,

$$\begin{aligned}[\mathrm{Fe/H}] &= (f_s + E_G) - (f_\odot + E_{HM}) \\ &= (f_s - f_\odot) + (E_G - E_{HM}), \end{aligned} \quad (A.2)$$

with [Fe/H] now being the derived metallicity instead of the true metallicity. In this case, a model atmosphere from a grid is used to calculate $E_G \equiv E_s$, while the Holweger-Müller (1974) model is used to calculate $E_{HM} \equiv E_\odot$. As a result, the absolute difference $|\Delta E|$ between them is commonly nonzero (see, for example, Gustafsson 1980; Trimble & Bell 1981, Sect. 5; Cayrel de Strobel 1983; Taylor 1998a, Sect. 6). Examples of this kind of analysis have been given by McWilliam & Geisler (1990) and Gratton & Sneden (1991).

3) Differential analysis with equivalent-width mismatch. In this case,

$$[\mathrm{Fe/H}] = (f_s + E_s) - (f_\odot + E_\odot) = (f_s - f_\odot) + (E_s - E_\odot). \quad (A.3)$$

Solar equivalent widths (EWs) from a published solar atlas are used instead of EWs from the spectrograph used to observe the program stars. It is known that $|\Delta E| \equiv |(E_s - E_\odot)|$ can be as large as 0.08 dex in this case (see Griffin & Holweger 1989, Sect. 3.2). Larger values of $|\Delta E|$ are conceivable. As noted in Sect. 3.2 of the text, this kind of differential analysis is commonplace.

4) Differential analysis relative to a star other than the Sun. The equation for example (1) applies here, but with a star such as Procyon substituted for the Sun. Model-atmosphere and EW mismatch do not occur here in practice because the standard star and the program stars are observed and analyzed in the same way. However, the zero-point process is incomplete. If it is to be completed, the value of [Fe/H] for the standard star relative to the Sun must be known. An example of this kind of analysis is given by Kyrolainen et al. (1986).

5) External zeroing to meteoritic abundances. Here,

$$[\mathrm{Fe/H}] = (f_s + E_s) - f_\odot = (f_s - f_\odot) + E_s. \quad (A.4)$$

For the sake of argument, it is assumed that $E_\odot = 0$ in this case (see, for example, Grevesse et al. 1996). The nature of this technique becomes clear if example (1) is used as a benchmark. To frame example (1), one reasons that since E_s is not zero except by rare happenstance, $E_\odot$ must be chosen to compensate for E_s. Here, one reasons that since E_s is not zero except by rare happenstance, its *uncompensated* value will almost always affect derived values of [Fe/H]. For this reason, metallicities zeroed in this way should not be accepted unless their zero points can be checked (and revised if necessary). Note that this problem is caused by a plausible-looking mistake: an accurate value of $f_\odot$ is adopted instead of a datum that will cancel the effect of E_s. Examples of this procedure are given by Liu et al. (1999) and Russell (1995). In an instructive comment, Balachandran & Carney (1996, Sect. 3.3) pinpoint the zero-point problem which is common to this example and the one discussed just below.

6) External zeroing to photospheric solar abundances. Here,

$$[\mathrm{Fe/H}] = (f_s + E_s) - (f_\odot + E_\odot) = (f_s - f_\odot) + (E_s - E_\odot). \quad (A.5)$$

The value of $f_\odot + E_\odot$ is now an absolute solar metallicity from a published analysis. In contrast to example (5), $E_\odot$ is cautiously regarded as nonzero because of the history of absolute solar analyses (for example, compare the results of Holweger et al. 1995 and Blackwell et al. 1995 and note the title of Kostik et al. 1996). A good way to gauge external zeroing is to look for differences between parallel procedures used in the stellar and published solar analyses. One such difference is the model-atmosphere mismatch that applies to example (2). An extensive discussion of these and other pertinent problems appears in Taylor (1999b, Sect. 3.1). Examples of this kind of external zeroing are given by Beveridge & Sneden (1994) and Castro et al. (1996).

7) Pseudo-absolute analysis. In this case, only values of $f_s + E_s$ are given. The reasoning applied to E_s is the same here as it is for example (5). In a procedure that is intermediate between this example and example (5), values of $f_s + E_s$ and $f_\odot$ are compared without subtraction (see, for example, Adelman et al. 2000). Examples of this kind of analysis are given by Klochkova & Panchuk (1987, 1990).

Appendix B: An improved derivation of rms errors for class W values of [Fe/H]

In the first two iterations of the catalog, rms errors for class W data were derived by comparing them with class N data (see Appendix B of T94). This process is far from optimal because the class N rms errors are substantially larger than their class W counterparts. As a result, the noise introduced by the former yields an indeterminate result for the latter (see Sect. 3.8 of T94). When T94 was published, there was no apparent way around this problem. Now, however, there are more class W data than previously, so an improved way of deriving their errors may be applied.

Suppose that for star i of N stars in total, there are M class W data, with $M \geq 2$. Let the weight for datum F_j be given by

$$w_j = (V_w + v_j)^{-1} \tag{B.1}$$

(see Eq. (10.16) of Kendall & Stuart 1977). In this equation, v_j is a variance produced by EW error, while V_w is a "frame-to-frame variance" for which an initial guess is made. The calculated values of w_j are used to obtain a weighted average F_M of the values of F_j. A statistic Q is then calculated:

$$Q_i = \sum_{j=1}^{M} w_j (F_j - F_M)^2. \tag{B.2}$$

Q is χ^2 distributed with $\nu \equiv M - 1$ degrees of freedom (see Lampton et al. 1976, Appendix, Sect. III). ν is the associated number of degrees of freedom.

The values of Q_i and ν_i are summed over the data for all N stars. This procedure is repeated with a number of trial values of V_w. The correct value of V_w is the one for which

$$\sum_{i=1}^{N} Q_i = \sum_{i=1}^{N} \nu_i. \tag{B.3}$$

The χ^2 distribution may be used to calculate an rms error U_W for V_w. An equivalent number of degrees of freedom ν_W is then obtained from the following definition:

$$U_W^2 = V_w^2 (2/\nu_W) \tag{B.4}$$

(see Eq. (A.4) of T94).

As Eq. (B.1) shows, this algorithm requires knowledge of values of v_j. Those variances are calculated as follows:

$$v_j = v_{j0} n_j^{-1}, \tag{B.5}$$

with n_j being the number of contributing lines. Values of v_{j0} are sometimes given in contributing papers, but a default value of $(0.072\ \mathrm{dex})^2$ (from Favata et al. 1997) is commonly used instead. The results of the calculation are not at all sensitive to this choice because V is substantially larger than v_j in almost all cases.

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