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The metallicity of μ Leonis

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Abstract. Castro et al. (1996) have concluded that μ Leo has three times the solar metallicity. That conclusion is based on their own work and on rezeroed values of [Fe/H] from the literature. A review of their paper reveals that there are significant omissions from their list of literature results. In addition, their procedure for establishing zero points for values of [Fe/H] is found to be fallacious. If that zero-point procedure is nonetheless accepted at face value, and if Hyades data available at the time are used, the zero-point procedure yields metallicities for the Hyades giants that appear to differ from those for Hyades dwarfs. The difference is in the opposite sense to that found by Griffin & Holweger (1989). As a first step in resolving these problems, the zero-point procedure is discussed in some detail. Next, the Hyades problem is reconsidered by taking all published data into account. In agreement with a conclusion drawn by Taylor (1998b), no evidence is found for a metallicity difference between Hyades giants and Hyades dwarfs. Published values of [Fe/H] for μ Leo are then analyzed. The technique applied to those data avoids the zero-point problem described above. In addition, it permits the scatter in the μ Leo data to be compared to the scatter in data from about 1000 other stars. In agreement with Taylor (1996), it is found that the value of [Fe/H] for μ Leo does not conclusively exceed $+0.2$ dex. In addition, it is found that the scatter in the μ Leo data is consistent with data scatter for other stars. In contrast, the scatter in the data considered by Castro et al. is found to be unrealistically small. A number of pertinent issues raised by this review are highlighted to encourage future discussion.

Key words: stars: abundances – stars: individual: μ Leo – Galaxy: open clusters and associations: individual:

1. Introduction

The K2 giant μ Leo has now been of special interest for nearly thirty years. Spinrad & Taylor (1969) concluded that μ Leo is SMR ("super-metal-rich"), and a number of authors have since put that conclusion to the test. For some time now, Spinrad & Taylor's conclusion has been accepted–but in a paradoxical way. Judging from published comment about μ Leo, its very high metallicity has been beyond doubt for some two decades. Judging from published analyses, however, spectroscopists believe that the effort to derive and rederive that metallicity should not slacken. When Taylor (1996) reviewed SMR problems, there were 18 published high-dispersion and related values of [Fe/H] for μ Leo. That number is now 21, with two results being added by Luck & Challener (1995) and one by Castro et al. (1996, hereafter C96).

Taylor concluded that the value of [Fe/H] for μ Leo is not known to exceed $+0.2$ dex. That conclusion is a minority view, and it is already somewhat dated as well. Taylor used rms errors from an analysis by Taylor (1991). An improved set of errors is now available (see Taylor 1999a). What happens if those errors are used? In addition, what happens if the three additional results just mentioned are considered? One major aim of this paper is to answer these questions.

Further issues are raised by the analysis used by C96. Those authors conclude that μ Leo has three times the solar metallicity. C96 make no use of any of Taylor's numerical results, and though they mention Taylor (1996), they do not compare their analysis to the one that Taylor performed. The difference between the two analyses is very marked, and it raises fundamental questions about proper numerical techniques and rules of scholarship. The second major aim of this paper is to explore these issues by reviewing C96 and two related papers in detail.

In Sect. 2 of this paper, data selection and rms errors in C96 and related papers are considered. Sect. 3 considers the C96 zero-point procedure. Sect. 4 contains a discussion of Hyades results that are implicit in the C96 analysis. In Sect. 5, the procedure adopted by C96 is revised to produce rules for a contrasting analysis. Using that analysis, the Hyades problem is reconsidered in Sect. 6. In Sect. 7, the alternative analysis is applied to the available μ Leo data. Sect. 8 contains perspectives on issues of general interest that are raised in the preceding sections. Sect. 9 concludes the paper with a review of results and conclusions.

2. C96 and related papers: treatment of literature results

2.1. Data selection

One of the distinctive features of C96 is its citation pattern for previous work. C96 compare their result to those of Gratton & Sneden (1990), McWilliam & Rich (1994), and Luck & Challener (1995). C96 describe those three results as "recent," but they do not explain why their choice of those results is based on epoch of publication. Two of the co-authors of C96 have published a predecessor paper (see McWilliam & Rich 1994).

In that paper also, "recent" results are cited, but no rationale is given.

As noted above, the oldest "recent" paper cited by C96 appeared in 1990. The oldest "recent" paper cited by McWilliam & Rich is that of Branch et al. (1978). Exact beginnings for these time intervals are not given, and neither the way in which they were chosen nor the apparent difference between them is explained. In addition, McWilliam & Rich and C96 do not cite the results of Cayrel de Strobel (1991) and Peterson (1992). Both of those results should be "recent" if either definition of that term is employed.

In his Table 2, Taylor (1996) lists the pertinent values of [Fe/H] for μ Leo that were available to him. The omitted results are those of Luck & Challener and C96. As noted above, C96 cite Taylor (1996), and they also cite Luck & Challener's work. All 21 pertinent μ Leo results were therefore available to C96. Especially for this reason, it is not obvious that some of the results that are not cited by C96 were simply overlooked.

A followup to C96 has been written by McWilliam (1997). There, some differences from C96 appear. Though McWilliam refers to the verdict of "recent" results, he does not choose results from the literature based only or primarily on epoch of publication. Instead, values of [Fe/H] are formally selected for initial discussion on the basis of high spectral resolution and S/N ratio. The best of those values are formally chosen on the basis of high S/N ratio and the amount of detail in abundance analyses. McWilliam does not apply these criteria numerically. Moreover, six results from Taylor's list are omitted from McWilliam's discussion (see Table 4 in Sect. 7.4, below). Necessarily McWilliam does not apply his criteria explicitly to these results.

Peterson's result is one of those that is not cited by McWilliam. Peterson's analysis is based on spectral synthesis and spectra with a resolution exceeding 20,000. Though Peterson does not state a signal-to-noise ratio for her spectra, it seems safe to assume that that ratio had to be high if the spectra were to be matched successfully to synthetic spectra. Based on S/N ratio and especially analysis detail, one would think that Peterson's result would qualify decisively for McWilliam's review. In fact, it does not.

2.2. Accidental errors: assumed size

We now consider C96 again. Another distinctive feature of that paper is a tacit assumption about acceptable rms error size. After adjusting two results published previously, C96 obtain the following list of values of [Fe/H] for μ Leo:

1. $+0.45$ dex for Gratton & Sneden (1990),
2. $+0.42$ dex for McWilliam & Rich (1994),
3. $+0.43$ dex for Luck & Challener (1995), and
4. $+0.46$ dex from their own analysis.[1]

The first and fourth entries are those adjusted by C96.

C96 do not state an rms error per datum (here called $\sigma_{\rm C}$) for these results. However, one readily finds that $\sigma_{\rm C} = 0.018$ dex. This error is small, but it could be supported by showing that it is comparable to the errors for other stars. However, C96 cannot follow this procedure because they set aside Taylor's (1996) results for other stars. In the event, C96 discuss the question of data scatter for only one other star besides μ Leo. They accept the agreement depicted above at face value.

2.3. More on data selection and rms errors

McWilliam & Rich (1994) also give a list of accepted results. That list is as follows:

1. $+0.48$ dex for Branch et al. (1978),
2. $+0.45$ dex for Gratton & Sneden (1990), and
3. $+0.42$ dex for McWilliam & Rich (1994).

The significant entry in this second list is the one for Branch et al. If judged by the C96 standard, that entry agrees well with the four considered by C96. McWilliam & Rich describe the Branch et al. datum as "recent," so C96 could conceivably make the same judgment. Nevertheless, the Branch et al. datum is not listed by C96, though it is considered by McWilliam (1997). No explanation for the disappearance and then reappearance of the Branch et al. datum is given by either C96 or McWilliam.

Peterson's result is also worth noting in this context. Her value of [Fe/H] is $+0.2$ dex. If the C96 standard of judgment is employed, Peterson's result does not agree well with the results cited by C96. While this problem could mean that Peterson's result suffers from a systematic error, it could also mean that the agreement found in C96 and companion papers is fortuitous. This possibility is tacitly underscored by McWilliam (1997), who notes that he does not have a conclusive explanation for another formally discrepant result published by Lambert & Ries (1981). On the whole, it seems fair to say that C96 and the other two papers leave the issue of data agreement unresolved.

3. C96: zero-point procedure

3.1. Some thought experiments

Still another distinctive feature of C96 is its zero-point procedure. That procedure (which may be called "external zeroing") is based on a familiar equation:

$$[{\rm Fe/H}] = \log\epsilon(*) - \log\epsilon_{\odot}, \tag{1}$$

with $\epsilon \equiv ({\rm Fe/H})$. To apply this equation, C96 determine a value of $\log\epsilon(*)$ and adopt a value of $\log\epsilon_{\odot}$ from the literature. They choose the value of $\log\epsilon_{\odot}$ that they deem to be the best available. In a similar way, C96 rezero some published results by using the published values of $\log\epsilon(*)$ and their adopted value of $\log\epsilon_{\odot}$.

[1] All entries in this list except that for Luck & Challener are from Table 7 of C96. An entry in that table from Luck & Challener's paper is from a datum that C96 ultimately set aside. Another entry in that table does not include a correction applied by C96. These points are discussed in Sect. 6 of C96, where their final adopted result from Luck & Challener's paper is given.

To critique this procedure, one may use a paper by Chmielewski et al. (1992) as a benchmark. In the course of their analysis, Chmielewski et al. use

1. the same f-values for program stars and the Sun,
2. the same lines for program stars and the Sun,
3. equivalent widths (EWs) derived from a given spectrograph for all stars (including the Sun), and
4. stellar and solar model atmospheres from a single grid.

Chmielewski et al. say explicitly that this last choice is made because of the differential character of their analysis. Their aim is to allow errors that are introduced by the stellar model to be cancelled by errors introduced by the solar model.

For the sake of argument, let a published analysis that yields a value of $\log\epsilon(*)$ and another published analysis that yields a value of $\log\epsilon_\odot$ be regarded as two parts of a single differential analysis. Using the list given above as a guide, one can identify the following problems that may be introduced by the two contributing analyses.

1. f-values on two different zero-points may be used.
2. Two different line sets are probably used.
3. Almost certainly, EWs from two different sets of spectrographs are used.
4. The stellar atmosphere is almost certainly from a published grid, while the solar atmosphere is dependably that of Holweger & Müller (1974, hereafter HM).

Other differences might also be considered, but these four are adequate for the present purpose. One may now ask how large an error each difference might introduce. Usually the error introduced at point 1 will be no more than 0.02 or 0.03 dex, though it can be as large as 0.08 dex (see Holweger et al. 1995). It seems possible to incur errors as large as 0.1 dex at point 2 (see Luck 1991). For solar EWs measured with stellar spectrographs, Griffin & Holweger (1989) find that the error introduced at point 3 can be as large as 0.08 dex. Solar and stellar EWs can be measured at quite different resolutions, so an additional error could be introduced here by resolution effects on measured EWs (Wright 1951). The error introduced at point 4 can lie between -0.25 and $+0.05$ dex (see Sect. 6 of Taylor 1998a).

C96 cite Bièmont et al. (1991) and Holweger et al. (1991) as sources for their adopted value of $\log\epsilon_\odot$. The first of these papers is based on Fe II lines, while the second is based on Fe I lines. The values of $\log\epsilon_\odot$ from these papers differ by 0.04 dex. In the present context, this difference is small enough to allow the two papers to be considered as two branches of a single solar analysis. By comparing the two papers with the C96 stellar analysis, one finds that the line-set, EW, and model-atmosphere problems listed above are relevant here. There is therefore no guarantee that the C96 zero point is correct.

C96 also use their adopted value of $\log\epsilon_\odot$ to rezero the results of Gratton & Sneden (1990) and Luck & Challener (1995). C96 do not discuss the values of $\log\epsilon_\odot$ that they set aside in the process. According to Luck (1991), the value of $\log\epsilon_\odot$ adopted by Luck & Challener was checked by using

1. the f-values adopted by Luck & Challener,
2. at least a subset of the lines used by those authors,
3. published solar EWs, and
4. the HM solar atmosphere.

By substituting a different value of $\log\epsilon_\odot$, C96 abolish the differential character of the Luck & Challener analysis where points 1 and 2 are concerned. After the substitution, moreover, the HM atmosphere is still being used and solar and stellar EWs are still being secured from different sets of spectrographs. There is therefore a good chance that the corrected value of [Fe/H] has a larger systematic error than the original value. Apparently Gratton & Sneden also use a value of $\log\epsilon_\odot$ that is matched to their f-value system, so similar remarks apply for the result in their paper.

3.2. *An overview and a name for the problem*

The thought experiments described above should probably be supplemented by an overview of the problem they depict. To see what such an overview may be like, let Δ_i be the correction to [Fe/H] required by step i. Then let

$$\log\epsilon'_\odot \equiv \log\epsilon_\odot - (\Delta_1 + \Delta_2 + \Delta_3 + \Delta_4), \qquad (2)$$

so that

$$[\mathrm{Fe/H}] = \log\epsilon(*) - \log\epsilon'_\odot. \qquad (3)$$

Eq. (2) should be regarded as the definition of $\log\epsilon'_\odot$. Eq. (3) is a substitute for Eq. (1).

The fundamental problem here is that there are two different situations in which $\log\epsilon_\odot$ or a datum resembling it may be used. If the solar metallicity itself is of interest, $\log\epsilon_\odot$ is the datum of choice. To compute a value of [Fe/H], however, $\log\epsilon'_\odot$ is required. The two quantities may be similar or identical for a particular choice of f-values, and deliberate attempts to make them identical have been part of some published analyses (see, for example, Luck 1991). Identity is not required, however, and non-identity is actually mandatory if the values of Δ_i listed in Eq. (2) do not sum to zero.[2]

To isolate the fallacy that is central to this issue, one may state it as follows: "A single choice of datum is always required for both $\log\epsilon'_\odot$ and $\log\epsilon_\odot$." The reasoning in this sentence may be referred to as the "single-choice fallacy" in its general form. More restricted forms of the fallacy may be expressed by concentrating on factors that influence $\log\epsilon'_\odot$ instead of $\log\epsilon'_\odot$ itself. One such restricted form reads as follows: "A single choice of solar model is always required to determine both $\log\epsilon'_\odot$ and $\log\epsilon_\odot$." Both forms of the fallacy will play a role in discussion to be given below (see Sect. 8).

4. C96 and the Hyades metallicity

By saying that the C96 zero-point procedure is fallacious, one is saying that it may yield a systematic error. Such an error will not

[2] In addition, $\log\epsilon'_\odot$ need not equal the meteoritic value of $\log\epsilon_\odot$. C96 and a number of other authors cite a result derived from analysis of meteorites in support of their choices of $\log\epsilon_\odot$ (see, for example, Anders & Grevesse 1989.)

Table 1. C96: implied [Fe/H] for the Hyades giants

Sequence Number	Source[a]	Entry[b]	μ Leo (dex)	γ Tau (dex)	δ Tau (dex)
1	GS90	log (Fe/H)(star)	7.97	7.73^{c}	…
2	C96	log $(Fe/H)_{\odot}$	7.52	7.52	…
3	…	[Fe/H] $= [1] - [2]$	0.45	**0.21**	…
4	LC95	[Fe/H]	0.20^{d}	0.14^{d}	0.10^{d}
5	LC95	+log $(Fe/H)_{\odot}$	$+7.67$	$+7.67$	$+7.67$
6	C96	−log $(Fe/H)_{\odot}$	-7.52	-7.52	-7.52
7	…	$[4] + [5] + [6]$	0.35	0.29	0.25
8	C96	Interpolation of [M/H][e]	(0.08)	(0.08)	(0.08)
9	…	Rescaled [8]	0.08	0.05^{f}	0.04^{f}
10	…	[Fe/H] $= [7] + [9]$	0.43	**0.34**	**0.29**

[a] "GS90" is Gratton & Sneden 1990; "LC95" is Luck & Challener 1995; "C96" is Castro et al. 1996.
[b] Numbers in brackets are sequence numbers from column 1.
[c] The entry from group B (weak lines, high excitation potential) is adopted.
[d] For consistency with C96, the Luck & Challener 1995 data for "physical" values of $\log g$ are adopted.
[e] This number is assumed to apply if [M/H] for the adopted model atmosphere is raised from 0.0 dex to $+0.5$ dex.
[f] For γ and δ Tau, this number is entry 8 rescaled by (entry 7)/(0.5 dex).

appear, however, if the sum of the corrections listed in Eq. (2) turns out to be zero. It is worth finding out what happens if this condition holds for the results derived by C96 from previously published work.

Without saying so explicitly, C96 take a fairly definite position about the metallicity of the Hyades giants. Their position is based on results for Hyades giants that are given by Gratton & Sneden and by Luck & Challener. If μ Leo data from those papers are rezeroed, Hyades data from those papers must also be rezeroed. The details of that rezeroing are given in Table 1. The fourth column of Table 1 runs through the C96 rezeroing procedures for μ Leo. The fifth and sixth columns of the table map over those procedures to the Hyades giants. (Readers may verify for themselves that the final μ Leo data in rows 3 and 10 of column 4 correspond to the results quoted in Sect. 2.2.)

The co-authors of C96 include Castro and Rich. Those authors have contributed to a paper in which the Hyades value of [Fe/H] is given as $+0.12$ dex (see Castro et al. 1997, hereafter C97). No source for this datum is given, but it seems reasonable to assume that it is the result given by Cayrel et al. (1985) for Hyades dwarfs. If the value of [Fe/H] is $+0.12$ dex for the dwarfs and $(+0.21, +0.34, +0.29)$ dex for the giants, the dwarfs and the giants appear to have different metallicities. It seems fair to guess that C96 would have had to consider this possibility if they had quoted the data.

A possible difference between Hyades giant and dwarf metallicities will be referred to here as a "Hyades problem." There is a classic version of the Hyades problem that was discussed in some detail by Griffin & Holweger (1989). Those authors found that a Hyades giant has a value of [Fe/H] that is 0.18 dex *lower* than the Cayrel et al. result. If C96 defined their "recent" epoch to start with their first cited μ Leo result (in 1990), they might not have acknowledged the Griffin-Holweger result because it appeared in 1989. However, it is of some interest to consider that result and ask whether it and the C96 Hyades problem can be resolved.

5. Interlude: choosing rules for an alternative analysis

5.1. Listing the rules

The discussion given above will now be reviewed. As this is done, a set of rules will be stated for an alternative approach to the μ Leo problem.

1. The μ Leo results omitted in C96 and its companion papers attract notice. The tacit rules adopted in those papers permit omission of some results without explanation. Moreover, the list of results that are omitted in that way changes from paper to paper. It is therefore not clear that the omissions can be justified. A decisive way to deal with this problem is to cite all pertinent μ Leo data—that is, all published high-dispersion and related results—whether they will ultimately be used or not.
2. If the "recent" criterion is applied in the manner of McWilliam & Rich (1994) and C96, some (but not all) results are cited if those results fall in a time interval which is chosen in an unstated manner and whose beginning is not specified. This is probably not a useful way of gauging results. In addition, criteria such as spectral resolution and S/N ratio are not adequate without numerical demonstrations that they are actually pertinent. A safer way to proceed is to judge data through analyses of numerical evidence whenever possible. If auxiliary assumptions are also required, they should at least be stated. If possible, they should be defended as well.
3. The analyses of numerical evidence should include statistical procedures. This judgment is a response to the problem posed by the size of σ_C.
4. As the σ_C problem also shows, the scatter of values of [Fe/H] for stars other than μ Leo should be consulted.
5. Zero points for the adopted μ Leo results should be established by a procedure that is not fallacious.
6. With the above rules in hand, the Hyades problem should be reconsidered.

Table 2. μ Leo: unused results

Source	Comment[a]
Strom et al. 1971	ϕ Aur [Fe/H] from same spectroscopy is too low by 5σ (see also Bonnell & Branch 1979)
Blanc-Vaziaga et al. 1973	Original value of [Fe/H] is not used (see Cayrel de Strobel 1991 for a result from $\lambda > 6690$ Å only)
Oinas 1974	Original value of [Fe/H] is not used (see Bonnell & Branch 1979 for a revised result)
Peterson 1976	See analyses by Bonnell & Branch 1979, Deming 1980
Foy 1980	A μ Leo result is cited by Luck & Challener 1995, but does not exist
Gratton & Sneden 1990, Cayrel de Strobel 1991	Cayrel de Strobel result from Gratton & Sneden EWs is not used; value of [Fe/H] from complete Gratton & Sneden spectroscopy is used instead

[a] The statistical deductions in Sect. 4.4 of Taylor 1996 do not allow for possible zero-point jitter among values of [Fe/H] from diverse spectrograms (see Sect. 5.3 of Paper III). As a result, those deductions are not quoted here.

5.2. *The zero-point question*

The first five of the rules just listed are a restatement of the procedures of Taylor (1996). The fifth rule requires some further comment. To establish a zero point, Taylor used differential analysis. That procedure will also be applied here.

Taylor's zero-point analysis is based on the work of Taylor (1991). An improved version of the 1991 analysis has since been published by Taylor (1998a, 1998b, 1999a; hereafter Papers I, II, and III, respectively). Though some comments about that "1998 analysis" are given here, full details are given only in those papers. Readers are invited to consult them.

6. The Hyades problem: a revised version

It is convenient to reconsider the Hyades problem before discussing the μ Leo results again. Consider first the data of Gratton & Sneden (1990) and Luck & Challener (1995). In the 1998 analysis, the zero point for the Gratton-Sneden results is based on α Boo and ϵ Vir. Gratton & Sneden give data for those stars, and mean values of [Fe/H] for them are derived in Paper II from a literature survey. The zero point for the Luck & Challener results is obtained when a sizeable zero-point data base has been established. There are about 90 stars with data in that data base that also have results given by Luck & Challener or in two companion papers (Luck 1991, Luck & Wepfer 1995). Precise zero-point adjustments are derived by using the data for those stars. The zero-point adjustments are given in Paper III (see the last two lines of Table 3 of that paper).

The 1998 analysis yields the following values of [Fe/H] for the Hyades giants:

1. 0.09 ± 0.13 dex for Gratton & Sneden (1990),
2. 0.05 ± 0.05 dex for Luck & Challener (1995),
3. 0.04 ± 0.11 dex for Griffin & Holweger (1989), and
4. 0.09 ± 0.02 dex as an overall result.[3]

[3] This is the "analysis D" average from Eq. (8) of Paper II. An alternative "analysis I" average differs from this one by less than 1σ. Here, as for the μ Leo data (see Sect. 7.6), the averages are based on the assumption that the central-limit theorem holds.

It is clear that all four of these results agree.

To establish whether there is a Hyades problem, consider the following two values of [Fe/H] for the Hyades dwarfs:

1. 0.11 ± 0.01 dex (Taylor 1994), and
2. 0.14 ± 0.05 dex (Cayrel de Strobel et al. 1997).

The first of these results was derived by Taylor from the high-dispersion results that were available for Hyades dwarfs in 1994. The second result is from subsequent high-dispersion analyses of Hyades dwarfs. It is clear that for the 1998 analysis, no Hyades problem can be detected. This conclusion was stated in Paper II, and it is worth noting that it can be based only on data that were available when C96 was published.

7. The μ Leo metallicity: an updated version

7.1. *Results that are not used*

The μ Leo metallicity will now be considered. Results that will not be used will be discussed first. A list of those results and the reasons for setting them aside are given in Table 2. A major role is played here by the continuum-placement problems discussed in detail by Bonnell & Branch (1979; see also Gratton & Sneden 1990). Another pertinent issue is the amount of spectroscopy used to derive some of the data. Published results for α Boo suggest that use of small equivalent-width (EW) data sets can lead to systematic errors (see Sect. 5.2 of Paper II). This explains the decision noted in Table 2 to use a value of [Fe/H] derived from all the pertinent Gratton-Sneden spectroscopy instead of a datum derived by Cayrel de Strobel (1991) from a small number of Gratton-Sneden EWs. On the other hand, one can create a small EW data set by setting aside EWs that may be affected by uncertain continuum placement. Here, one must weigh the risk of systematic error from continuum placement against the risk of systematic error from use of a small data set. The (hopefully) educated guess made here is that the continuum-placement risk is the greater of the two. This judgment explains the use of a value of [Fe/H] derived from a subset of the EWs of Blanc-Vaziaga et al. (1973; see Cayrel de Strobel 1991 and the second entry in Table 2).

7.2. An adopted temperature for μ Leo

For a given star, published values of [Fe/H] may have been derived by using a number of different temperatures. In the 1998 analysis, corrections for this problem are made as required. The temperature calibration used in that analysis is from McWilliam (1990). It may be noted that this calibration agrees well with angular-diameter measurements (see Sect. 5.3 of Paper I). For the sake of consistency, a μ Leo temperature from the McWilliam calibration is required here. In addition, it is worthwhile to test the μ Leo temperature adopted by C96. That temperature was derived by Gratton & Sneden by using the infrared flux method (IRFM), and its consistency with the McWilliam calibration is not known. Both of these issues are addressed in Appendix A, where an adjusted IRFM temperature and a color temperature are combined to yield a result that is some 80 K lower than the temperature adopted by C96.

7.3. Pagel's result: a test using numerical reasoning

One of the results that will be accepted below is an upper limit from Pagel (see Bell 1976). Pagel's analysis has not been published in full, and Bell's description of Pagel's work is very brief. One might therefore argue that Pagel's result should not be used. That judgment, however, is not sufficiently numerical. The problem at hand is to gauge Pagel's result by numerical reasoning.

Pagel has also given an upper limit on [Fe/H] for α Ser. That result offers the prospect of a meaningful test. μ Leo and α Ser have quite similar blanketing (see Table 6 of Taylor & Johnson 1987). This is important because Pagel worked at relatively short wavelengths (see the tracing of a Pagel spectrogram in Fig. 2 of Bonnell & Branch 1979). If continuum placement has affected Pagel's μ Leo result, presumably his α Ser result has also been affected and should stand away from other published data for that star.

Values of [Fe/H] for α Ser are given in Table 3. The data (including accidental errors) are from the 1998 analysis. For the moment, no literature sources are given. In addition, no upper-limit label is placed on Pagel's result, since that would identify it at once.

Readers are invited to inspect Table 3 and decide which of its entries is from Pagel's work. When one does this, it seems fair to guess that entry 4 attracts no special attention. Nonetheless, entry 4 is the right choice. Neither continuum placement nor some unknown property of Pagel's analysis appear to have had a detectable effect on Pagel's α Ser datum. Pending a second numerical test (see below), Pagel's μ Leo datum is therefore included.

7.4. The μ Leo data: testing for wild points

Consider now all μ Leo data that are accepted pending statistical tests. Details about those data are given in Appendix B. Literature sources for the α Ser results discussed above are also given in Appendix B. A summary of the μ Leo data from Appendix B is given in Table 4. Entries that were not considered by McWilliam (1997) are flagged in the table.

Table 3. [Fe/H] for α Ser

Sequence number	[Fe/H] (dex)
1	-0.04 ± 0.11
2	0.16 ± 0.10
3	0.12 ± 0.10
4	0.10 ± 0.14
5	0.01 ± 0.07
6	0.33 ± 0.11
7	0.14 ± 0.11
8	0.21 ± 0.09
9	0.10 ± 0.10
10	-0.06 ± 0.11

Table 4. [Fe/H] for μ Leo[a]

Source[b]	[Fe/H] (dex)
Gustafsson et al. 1974	0.39 ± 0.10
Oinas 1974 (Bonnell & Branch 1979)	$\geq 0.38 \pm 0.11$[c]
McWilliam & Rich 1994	0.35 ± 0.11
Gratton & Sneden 1990	0.34 ± 0.11
Branch et al. 1978	0.32 ± 0.11
Cayrel de Strobel 1991	0.30 ± 0.11[c]
Williams 1971	0.26 ± 0.10[c]
McWilliam 1990	0.25 ± 0.12
Peterson 1992	0.20 ± 0.11[c]
Blanc-Vaziaga et al. 1973 (Cayrel de Strobel 1991)	0.20 ± 0.11[c]
Brown et al. 1989	0.18 ± 0.09
Luck & Challener 1995	0.14 ± 0.11
Ries 1981, Lambert & Ries 1981	0.12 ± 0.07
Pagel (Bell 1976)	$\leq 0.10 \pm 0.14$[c]

[a] The values of [Fe/H] quoted here and elsewhere in this paper are from the analysis described in Papers I–III. Usually the analysis has changed the data somewhat from the way they appear in their source papers.
[b] If an earlier source of equivalent widths is analyzed in a later paper, the later paper is cited in parentheses.
[c] This entry is not considered by McWilliam 1997.

Corrections have been applied to almost all of the original data secured from the sources noted in Table 4. The corrections are based on published numerical evidence (see Appendix B and Sects. 4–6 of Paper I).[4] Data appear in the table only if they are based on zero points that are reasonably secure. For this reason, the C96 result does not appear there, though it will be considered below on a tentative basis. Another matter worth noting is that a

[4] Readers who consult the cited discussions of the corrections and conclude that a pertinent correction has been overlooked are invited to publish numerical evidence concerning that correction. Such evidence can then be used in future iterations of this analysis.

larger rms error is assigned to Pagel's datum than to any of the others. The reason for this procedure is explained in Appendix B.

Statistical analysis includes the ability to test for wild points. Pagel's datum is an obvious candidate for such a test. Two other data are also tested: the result of Gustafsson et al. (1974) is considered because it is the highest listed, and the result of Ries (1981; see Lambert & Ries 1981) is considered because it differs from the mean of the Table 4 results by about 1.8σ. McWilliam (1997) tacitly assumes that there is a systematic error in the Ries result, and he expresses uncertainty about the source of that error. In fact, there is no basis for McWilliam's assumption; the Ries datum does not turn out to be a wild point at a net confidence level of 95%. The same result is found for the other two data that are tested.[5] (For details about the tests, see entries 1–3 in Table C1, Appendix C.)

The datum of Gustafsson et al. is a photometric result from a measurement of a cluster of weak lines. The same is true for a result from Williams (1971) that is also quoted in Table 4. The zero points for both of these data are based almost entirely on results for stars with a lower metallicity than that of μ Leo. As a result, the photometric data depend on modest extrapolations. Nevertheless, neither of those data turns out to be a wild point.

The datum of Lambert & Ries (1981) has been corrected for an error whose dependence on temperature suggests that it may be a continuum-placement error (see Sect. 3.3 of Paper III and Sect. 3 of Taylor 1991). Recall that some data have been excluded altogether because of continuum-placement errors (see Sect. 7.1 of this paper). For these reasons, it is felt that the influence of such errors has been reduced to a minimum in this analysis.

7.5. The μ Leo data: testing for excessive scatter

The scatter in the data is of as much concern as the possible presence of wild points. Even if no wild points can be found, the scatter might still be too large to be explained by the quoted errors. To find out whether this is the case, one may employ a χ^2 test. The result of this test may be reported as a value of $R \equiv \chi^2/(N-1)$, with N being the number of data in Table 4. If R does not differ appreciably from unity, the data scatter is consistent with the quoted errors.

For the results considered by Taylor (1996) with the rms errors quoted in that source, $R \sim 0.6$. That number does not differ from unity at 95% confidence. Now, with additional data and somewhat smaller rms errors than before, R has increased to 0.96. However, R still does not differ from unity at 95% confidence. (See entries 4 and 5 in Table C1, Appendix C.)

This result has a special significance. The rms errors in Table 4 have been derived from data scatter for stars other than μ Leo. In other words, *the scatter in the μ Leo results is simply typical of the scatter found for other stars.* Given this result and the unsuccessful search for wild points, it appears that systematic errors that are larger than about 0.2 dex are not to be found in the μ Leo data listed in Table 4. Note also that if one has not analyzed data for a large number of stars, the statement in italics can neither be supported nor rejected. As note above, C96 do not consider a large number of stars and so cannot consider this issue.

[5] At 95% confidence, there is one chance in 20 of a "false alarm." In this case, the false alarm would be an unusually large random fluctuation that would be mistaken for a genuine wild point.

7.6. The μ Leo data: averages

As in previous papers in this series, it will now be assumed that the central-limit theorem applies to corrected values of [Fe/H]. Given this assumption, meaningful averages of the μ Leo data may be obtained. The averages will be compared to a threshold value of [Fe/H] for SMR stars. The adopted threshold value is $+0.2$ dex (see Spinrad & Taylor 1969, Taylor 1982). The reason for this choice will be discussed below.

Readers are invited to look at the first line of Table 5. The boldface entry given there is derived from Table 4 results stated to three decimal places, and is a weighted average of those results.[6] The adopted weights are inverse squares of rms errors. Next to the boldface entry, a value of the t statistic is listed. If $t \geq 1.66$, one may conclude that [Fe/H] $> +0.2$ dex. (See note "c" of Table 5 for further information about t.)

The boldface average does not definitely exceed $+0.2$ dex. One would like to know whether this conclusion still holds if the input data are changed. Reasonable options for modifying the data are as follows.

1) The adopted datum from Luck & Challener (1995) is from analyses done with spectroscopic gravities. Their result based on so-called "physical" gravities may be used instead. Zero-point corrections have been established for both the spectroscopic and "physical" results (see Table 3 of Paper III). The rezeroed μ Leo datum from the "physical" data set is

$$[\mathrm{Fe/H}]_{\mathrm{P}} = +0.153 \pm 0.074 \text{ dex}. \tag{4}$$

2) Two results listed in Table 4 are from Blanc-Vaziaga et al. (1973) and Cayrel de Strobel et al. (1991). The model atmospheres used to produce these data may have been extrapolated appreciably from published grids. In principle, the corrections required for this problem could be deduced from a scale factor given by C96. However, that scale factor is not used here because its exact source is not described by C96. The scale factor adopted instead is a well-documented value from Table 7 of Luck & Challener (1995). The resulting corrections to both of the data in question are $+0.024$ dex. It should be stressed that these corrections (including signs) are conjectural; both of them would be negative if they were drawn from Table 5 of Gratton & Sneden (1990). Nevertheless, the correction of $+0.024$ dex may be applied on a trial basis.

[6] In this paper and companion papers, it is standard procedure to retain an extra decimal place when performing calculations. Source data for the averages in this table are given to three decimal places in Table B2 (see Appendix B).

Table 5. [Fe/H] for μ Leo: averages[a]

C96 included?	Datum from Luck & Challener 1995	Special corrections?[b]	Mean value of [Fe/H] (dex)	t[c]
No	Spectroscopic $\log g$	No	$\mathbf{0.243 \pm 0.028}$	1.52
	Physical $\log g$	No	0.237 ± 0.027	1.44
	Spectroscopic $\log g$	Yes	0.246 ± 0.028	1.63
	Spectroscopic $\log g$[d]	No	0.227 ± 0.031	0.89
Yes	Spectroscopic $\log g$	No	0.256 ± 0.027[e]	2.13
	Spectroscopic $\log g$	No	0.248 ± 0.027[f]	1.85
	Physical $\log g$	No	0.243 ± 0.027[f]	1.63

[a] Weighting is by inverse variances of rms errors. The errors are quoted in Table 4 and (if applicable) in note (d) or note (e) of this table. The rms errors include a temperature contribution (see Sect. 5.3 of Paper I).
[b] These are the uncertain interpolation and extrapolation corrections discussed in the text.
[c] This is the value of $t \equiv \sigma^{-1}\{[\mathrm{Fe/H}] - 0.2\ \mathrm{dex}\}$, with σ and [Fe/H] being from the column just to the left. t is used to test the hypothesis that [Fe/H] ≤ 0.2 dex. The hypothesis is rejected at 95% confidence if $t \geq 1.66$. One-tailed t tests are required for this case.
[d] Photometric data (Williams 1971, Gustafsson et al. 1974) are omitted from this average.
[e] The adopted value of [Fe/H] for C96 is 0.460 ± 0.106 dex.
[f] The adopted value of [Fe/H] for C96 is 0.336 ± 0.106 dex.

3) Photometric results may be excluded and an average based only on high-dispersion data may be calculated.

4) The C96 result may be included with no zero-point correction:

$$[\mathrm{Fe/H}] = +0.460 \pm 0.106\ \mathrm{dex}. \quad (5)$$

The assigned rms error is from stage 2 of the analysis described in Paper III (see Table 1 of that paper). An alternative version of the C96 result is

$$[\mathrm{Fe/H}] = +0.336 \pm 0.106\ \mathrm{dex}. \quad (6)$$

This version is suggested by Fig. 3(a) of C96, which suggests that the EWs of C96 and Gratton & Sneden (1990) have the same zero point. If this is so, a plausible possibility is that the value of [Fe/H] implied by the C96 EWs is the same as that implied by the Gratton-Sneden EWs. The datum quoted in Eq. (6) is in fact the datum of Gratton & Sneden.

Some results derived by combining these modifications are given in Table 5. Some of the derived values of t are above the cutoff value of 1.66, while others are below it. Apparently one cannot say for sure whether the μ Leo value of [Fe/H] exceeds the threshold value of $+0.2$ dex. Note that if some residual CN blending affects some of the input data, those data should be corrected downward (see, for example, Sect. 3.1 of C96). The analysis done here may therefore underestimate the possibility that μ Leo is not SMR.

It should be noted that no uncertainty applies for a different threshold value. Recall that C96 have concluded that μ Leo has three times the solar metallicity. That conclusion is rejected at better than an 8σ level by all the Table 5 averages.

The question of exactly which data to adopt remains to be settled. One obtains approximately the same results by either a) using the "physical" Luck-Challener result and including a C96 datum, or b) using the "spectroscopic" result instead while excluding C96 data. In the second case, the higher-precision "physical" result is not used, but the adopted μ Leo data include only results with well-established zero points. The second option is therefore adopted.

8. Perspectives

Now that a review of C96 is in hand and the averaging of the μ Leo data has been done, some pertinent general questions may be considered. Attention will be focused here on questions for which answers tend to be adopted without discussion.

The definition of supermetallicity. Readers may have noticed that if the SMR threshold value adopted here were to be lowered slightly, one could conclude quite definitely that μ Leo is SMR. This threshold-value problem gains force from the fact that no threshold value is universally accepted.[7] The rationale for using $+0.2$ dex in Sect. 7.6 should therefore be explained. That threshold value is, in fact, the original value from the work of Spinrad & Taylor (1969). Those authors assigned SMR status to stars for which they found that [M/H] > [M/H](Hyades). For the Hyades themselves, Spinrad & Taylor found that the predominant value of [M/H] is $+0.2$ dex (see their Table 14).

After Spinrad & Taylor published their discussion, lower metallicities for the Hyades became current (see especially Cayrel et al. 1985). When a threshold value was required, one could now choose between the updated Hyades metallicity and the original value of $+0.2$ dex. Some authors have used the Hyades metallicity without explanation (see, for example, C97). However, there is a problem with this procedure if [Fe/H]$(*) >$ [Fe/H](Hyades), but [Fe/H]$(*)$ is not definitely greater than $+0.2$ dex. "Borderline" stars of this kind are not distinguished from stars with [Fe/H]$(*) > +0.2$ dex if the Hyades are used to define the threshold value. The problem is enlarged if one

[7] This point is illustrated by the threshold values adopted by three of the co-authors of C96. McWilliam (1997) adopts a threshold value of 0.0 dex and asserts that that value is generally accepted. On the other hand, Castro and Rich adopt a threshold value of $+0.12$ dex (see C97).

follows McWilliam (1997) in lowering the threshold value still farther.

Taylor (1996) adopted the Spinrad-Taylor threshold value. He found that the metallicities of some dwarfs and subgiants exceed that value, but that no metallicity for a giant is known to exceed it. That result suggests that a threshold value of $+0.2$ dex should be retained, as is done in this paper. In addition, "SMR stars" and "borderline SMR stars" can be recognized as two distinct classes. At present, μ Leo would be assigned to the second class. Though the μ Leo metallicity does not decisively exceed the 0.2-dex threshold, it does exceed the high-precision Hyades metallicity derived in Paper II at the 4.7σ level.

Reanalysis. Some entries in the μ Leo data base could be improved by further work. Perhaps the most obvious example is the C96 entry, which could be converted to a differential result if a standard star or (possibly) an asteroid were observed with the spectrograph used for μ Leo. In addition, the McWilliam (1990) data could be reanalyzed (see Appendix B) and the Pagel and Peterson analyses could be described more extensively in the literature. At such time as this work is done or new μ Leo results are published, an updated version of the analysis described in Sect. 7 can be undertaken if necessary.

Differential analysis. For some time now, there has been covert disagreement among high-dispersion spectroscopists about the principles of high-dispersion analysis. Much of the disagreement has been about the model atmospheres that should be used for the Sun. One school of thought has argued persuasively that solar models should be secured from the same source as the models used for program stars. Usually this requirement means that solar and program-star models should be drawn from the same published grid (see, for example, Gustafsson 1980, Trimble & Bell 1981, Drake & Smith 1991, and Chmielewski et al. 1992). A second school of thought has hesitated between this procedure and use of the HM model (see Leep et al. 1987 and remarks by Carretta & Gratton 1997). A third school of thought has simply used the HM model without comment. Presumably the assumption made when using that model is that there is a single solar model that is best for all applications. This fallacy is the single-choice fallacy as applied to solar models (recall Sect. 3.2).

In addition to this "solar-atmosphere" problem, there has been an "EW" problem. As noted in Paper I, it is common practice to measure one's own stellar EWs and then pair them with published solar EWs from a different spectrograph. In effect, C96 and C97 have taken over both the "solar-atmosphere" and "EW" problems and have made "f-value" and "line-set" problems possible as well (recall Sect. 3.1). Behind this step is the general form of the single-choice fallacy, which leads to use of $\log \epsilon_\odot$ instead of $\log \epsilon'_\odot$.

In subsequent discussion, it would be worthwhile to stress the difference between $\log \epsilon_\odot$ and $\log \epsilon'_\odot$. It might also be useful to revive interest in the history of the Cayrel-Jugaku (1963) procedure for doing differential analysis. In its original form, the Cayrel-Jugaku procedure does not include use of $\log \epsilon'_\odot$ as a zero point. This omission can be used to underscore the fact that such a zero point (when used) is simply an analysis artifact, and is not an inherent property of the Sun.

External zeroing. Given the problems with external zeroing that have been described here, it is worth asking whether that kind of analysis should be used. Consider this question first for stars with line strengths that are at least roughly comparable to those of the Sun. For these stars, one option is meticulous differential analysis of the sort done by Cayrel de Strobel and her collaborators (see, for example, Chmielewski et al. 1992). One might argue that the precautions those authors take are unnecessary and that one should instead risk the errors discussed in Sect. 3.1 in the hope that those errors will not be significant relative to accidental error. To the present author, however, that argument seems contrived. Taking the precautions would seem to be the more sensible course.

The scope of differential analysis can be extended by referring some analyses to stars other than the Sun. This practice was once common and would seem to deserve renewed interest. There are several G and K giants with well-known metallicities that could continue to serve in their traditional roles as secondary standards (see Paper II).

Now consider stars with line strengths that differ greatly from those of the Sun. For such stars, the use of external zeroing is probably inescapable. Here, the recommended procedure is to gauge external zeroing by the standards of differential analysis, as was done in Sect. 3.1. As an example of this kind of reasoning, one may consider f-values. Values of $\log \epsilon(*)$ and $\log \epsilon'_\odot$ should be based explicitly on the same parent population of f-values. If it is not certain that this condition is satisfied by using a value of $\log \epsilon'_\odot$ from the literature, $\log \epsilon'_\odot$ should be derived instead.

Accidental errors. Readers may have noticed that the rms errors in Table 4 appear to be quite a bit larger than $\sigma_{\rm C}$, the error adopted tacitly by C96 (recall Sect. 2.3). It should also be noted that the Table 4 errors are quite typical samples from the Paper III analysis. Moreover, that analysis implies that a formal error as small as $\sigma_{\rm C}$ should appear for only about one star in every 125 (see entry 6 in Table C2, Appendix C). One must conclude that there is a genuine difference between the "large-error" scenario of Paper III and the "small-error" scenario of C96 and some other authors (see, for example, Sect. I of Harris et al. 1987).

In the large-error scenario, high-dispersion work on μ Leo has not repeatedly confirmed its very high metallicity (recall Sect. 1). Instead, high-dispersion spectroscopists have been sampling a random variable with a mean value of about $+0.2$ dex and an rms error per sample of about 0.1 dex. If one sets aside results that are affected by continuum-placement problems, the scatter in the remaining results has largely been produced by repeated sampling of that random variable. Inevitably some values of [Fe/H] that are near or below $+0.2$ dex have appeared. No special attention has been drawn to those results in the papers in which they have been published (see Lambert & Ries 1981, McWilliam 1990, Peterson 1992, and Luck & Challener 1995). On the other hand, some data that are more than 1σ above the mean have been published. Those numbers are not inherently more or less significant than data from other parts of the Gaussian. Nevertheless, the "$+1\sigma$" results have sometimes been urged in striking language as proof that μ Leo has a very high metallicity. Interested readers are invited to consult

1. Harris et al. (1987, first sentence on p. 1004);
2. Gratton & Sneden (1990, Sect. 5.2, italics in last sentence); and
3. C96 (last sentence before acknowledgments).

Given this practice, one can see how an unbalanced perspective about the μ Leo metallicity may have been produced.

Hopefully it is now clear that decisions about the metallicity of μ Leo depend critically on judgments about rms errors. Other problems in which such errors play a key role are discussed in Paper II. If valid inferences are to be drawn from values of [Fe/H], the use of accurate rms errors for those data is inescapable.

The issue of explicit discussion of the errors should also receive notice. As noted in Sect. 2.2, C96 set aside Taylor's (1996) error discussion, and they do not depict or discuss the size of the error they adopt instead. McWilliam (1997) follows C96 in both respects. A useful convention that might be adopted for such cases is "not defended, not defensible." The assumption that rms errors are accurate should not be granted unless, at a minimum, those errors have been discussed in print.

Preferred and omitted data. Recall the data selections by C96 and McWilliam (1997) that were discussed in Sect. 2. Their discussions may be contrasted with a review of results by Eggen (1989). For μ Leo, Eggen derived three photometric values of [Fe/H] (see his Table 12). Eggen also cited a high-dispersion value of [Fe/H], but it was not that of Branch et al. (1978), even though that was the most conspicuous μ Leo result of its time. Instead, Eggen cited the result of Ries (1981) published by Lambert & Ries (1981). In its published form, the Ries result is $+0.11$ dex, while that of Branch et al. is $+0.48$ dex. Eggen's photometric results are all $\leq +0.03$ dex. Eggen concluded that μ Leo is not SMR. (Readers are invited to look up the note for HR 3905 in Eggen's Table 13 and compare it to the three passages cited above.)

Explicit citation and discussion. In effect, Eggen declared the Branch et al. result to be erroneous without acknowledging its existence. Both C96 and McWilliam (1997) use the same procedure for the result of Peterson (1992), among others. For another interesting perspective on Eggen's discussion, suppose that some authors were to reproduce it now while noting (without explanation) that their conclusions differ from those of C96. Those authors would then be adopting just the procedure that C96 themselves apply to Taylor (1996).

Hopefully these points are the final steps in a conclusive display of the weakness of tacit judgments. If such judgments continue to be allowed in the literature, there is no reasonable prospect for a meaningful solution to the μ Leo problem. If such a solution is to be gained, choices of data and choices of rms errors should be both explicit and explained. Admittedly this convention would not solve the μ Leo problem by itself, but it would make it more likely for the problem to be argued out on its real merits.

9. Review

C96 and McWilliam (1997) cite some μ Leo results from the literature while omitting others. Neither the omissions nor their reasons for preferring certain literature results are adequately explained. In addition, the procedure used by C96 to establish [Fe/H] zero points is found to be fallacious. If line sets, f-value systems, or spectrographs differ between program stars and the Sun, systematic errors can result from the use of the C96 procedure. Such errors can also occur if the HM atmosphere is used for the Sun and model atmospheres from a published grid are used for program stars.

If the C96 zero-point procedure is accepted at face value, it produces an apparent Hyades problem. If C96 had explored this problem, it is quite possible that they would have concluded that the Hyades giants have a higher metallicity than the Hyades dwarfs. This result contrasts with the classic Hyades problem of Griffin & Holweger (1989), who found that a Hyades giant has a lower metallicity than the Hyades dwarfs. Given the C96 rules of scholarship, it is not possible to decide whether they would have been required to acknowledge the difference between the two Hyades problems. One can show, however, that neither the Hyades problem of C96 nor that of Griffin & Holweger appears if the Paper II analysis is applied.

When a comprehensive analysis of published μ Leo metallicities is performed, one finds that [Fe/H] does not definitely exceed $+0.2$ dex. This result was also obtained by Taylor (1996). The mean value of [Fe/H] for μ Leo does exceed the Hyades metallicity derived by Taylor (1994) at the 4.7σ level. In addition, the μ Leo metallicity falls more than 8σ short of the three-times-solar level quoted by C96. With updated rms errors from Paper III, it is found that the scatter in the contributing μ Leo data is typical of the scatter for other stars. In addition, the rms error per datum that was tacitly adopted by C96 is found to be atypically small.

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Appendix A: a μ Leo temperature from the McWilliam calibration

The μ Leo color temperature used here is derived as follows. Four high-precision measurements of red and near-IR photometric indices are transformed to Cousins $R-I$ (see Table A1 for details). The scatter in these data may be somewhat greater than their accidental errors predict, so the data are averaged without weights and a straightforward error of the mean is obtained. The mean and error are then converted to a value of Johnson $V-K$ by using a transformation from Table IV of Taylor et al. (1987). From the $V-K$ calibration of McWilliam (1990), one then finds that $T_{eff} = 4476 \pm 14$ K.

The Gratton-Sneden temperature for μ Leo is tested in the following way. Gratton & Sneden derived that temperature by

Table A1. μ Leo: photometry for a color temperature

Color Index	Source of datum	Transformation source
74–103	Johnson et al. 1987	Johnson et al. 1987
C(4142)[a]	McClure & Forrester 1981	…
$T_1 - T_2$	Canterna 1976	Taylor 1986
$(R-I)_{\rm C}$	Argue 1967, Jacobsen 1970	…
$U-B$[b]	Mermilliod & Mermilliod 1994	…

[a] This datum is required to transform 74–103 to $(R-I)_{\rm C}$.
[b] This datum is required to transform $(R-I)_{\rm C}$ to $(V-K)_{\rm J}$.

using the IRFM procedure of Bell & Gustafsson (1989). A formal correction to the Gratton-Sneden temperature may therefore be derived by comparing temperatures quoted by Bell & Gustafsson with temperatures derived on the McWilliam scale. The latter are calculated from photometric color indices (see Sect. 5.3 of Paper I). From a two-error least-squares analysis (Madansky 1959), one finds that the correction equation is

$$\theta(\mathrm{McW}) = 1.047\theta(\mathrm{BG}) - 0.026, \quad \text{(A1)}$$

with $\theta \equiv 5040/T_{\rm eff}$. The rms error for the scale factor is 0.016, and a t test shows that the scale factor differs from unity at 99.5% confidence.

The data scatter around Eq. (A1) is readily calculated. Presumably that scatter has two sources: the unknown rms error of Bell-Gustafsson temperatures, and the known rms errors of Paper I temperatures. By allowing for the second of these contributions, one can calculate the first. The data-comparison algorithm described in Sect. 4.3 of Paper III is used. The resulting rms error is applied to the Gratton-Sneden μ Leo temperature. Eq. (A1) is then used to transform that temperature (and its error) to the McWilliam scale. The result is found to be 4435 ± 34 K. An average of this datum with the photometric temperature then yields

$$T(\mathrm{McW}) = 4470 \pm 13 \text{ K} \quad \text{(A2)}$$

if inverse-variance weights are used. (It should be noted that the quoted rms error is from data scatter alone.)

It may be noted that McWilliam (1990) derived a temperature of 4480 K for μ Leo. That result and the one given here are both from the McWilliam calibration, so they may be compared without allowing for systematic offsets in that calibration. Even without knowing the rms errors of McWilliam's temperatures, one can see that his temperature and the one derived here agree to within 1σ.

Appendix B: values of [Fe/H] for α Ser and μ Leo

Values of [Fe/H] for α Ser are given in Table B1. Literature sources are included in that table. In Table B2, a list of accepted μ Leo results is presented. The corrections applied to each datum are listed in the table. Corrections are applied to all data except that of Peterson (1992), so all results except that of Peterson are referred to the Sun through stars with smaller line strengths than those of μ Leo. A more extensive description of the correction process is given in Sect. 3 of Paper III. Details about corrections applied to particular data are given in the notes to the catalog described by Taylor (1999b).

Table B1. [Fe/H] for α Ser (with literature sources)

Sequence number	Source	[Fe/H] (dex)
1	Griffin 1969	-0.04 ± 0.11
2	Williams 1971	0.16 ± 0.10
3	Gustafsson et al. 1974	0.12 ± 0.10
4	Pagel (Bell 1976)	$\leq 0.10 \pm 0.14$
5	Lambert & Ries 1981	0.01 ± 0.07
6	Gratton & Ortolani 1986	0.33 ± 0.11
7	Boyarchuk et al. 1987	0.14 ± 0.11
8	Brown et al. 1989	0.21 ± 0.09
9	McWilliam 1990	0.10 ± 0.10
10	Luck & Challener 1995	-0.06 ± 0.11

One of the entries in Table B2 is from McWilliam (1990). McWilliam (1997) notes that that datum was not derived by using a metal-rich model atmosphere. A correction of $+0.02$ dex has been made for this problem by using a scale factor given by Luck & Challener. Scale factors from C96 and McWilliam (1997) have not been used because their derivation has not been described in any detail.

McWilliam (1997) also points out that the EWs used in his earlier study are affected by CN blanketing. To put this problem in perspective, it should be considered for stars other than μ Leo. In Paper III, a zero-point correction for the McWilliam data was determined by using a sample drawn from the entire McWilliam (1990) data base. For many of the stars in that data base, [Fe/H] ≥ -0.1 dex. In at least some wavelength regions, CN blanketing can be a problem throughout this range of metallicities (Peterson 1992). For this reason, the safest way to allow for the CN problem would be through a reanalysis of all the McWilliam stars with [Fe/H] ≥ -0.1 dex. Pending that reanalysis, the McWilliam data are accepted without a CN correction for the moment. Presumably the CN effect for μ Leo is partially allowed for by the CN effect for a number of the stars that were used in Paper III to determine the zero-point correction. It is also worth noting that in its present state, McWilliam's 1990 datum is well within 1σ of the mean values of [Fe/H] discussed in Sect. 7.6.

The rms error given for Pagel's datum in Table B2 also requires some comment. That error has been assigned by assuming that Pagel performed a differential curve-of-growth (DCOG) analysis. All values of [Fe/H] that Pagel himself has published are from such analyses (see, for example, Pagel 1964). In its basic form, the error assigned to Pagel's results has been derived from the DCOG results of Helfer and Wallerstein (see Sect. 4.6 of Paper III). That basic error is augmented here by allowing for a small contribution from rms temperature error. This is done because the temperatures assigned by Pagel are unknown, so the effects of their rms errors cannot be corrected out of his results.

Table B2. [Fe/H] for μ Leo: detailed list

Source	Zero-point or color correction[a]	Other correction(s)[b]	[Fe/H] (dex)
Gustafsson et al. 1974[c]	Zpt	...	0.394 ± 0.097
Oinas 1974[d]	Zpt	...	$\geq 0.379 \pm 0.112$
McWilliam & Rich 1994	Zpt	θ, nLTE	0.348 ± 0.106
Gratton & Sneden 1990	Zpt	θ	0.336 ± 0.106
Branch et al. 1978	Zpt	θ, nLTE	0.319 ± 0.110
Cayrel de Strobel 1991[e,f]	Zpt	θ, nLTE	0.298 ± 0.106
Williams 1971[c]	Zpt	...	0.261 ± 0.097
McWilliam 1990[g]	Zpt	...	0.251 ± 0.121
Peterson 1992	...	...	0.200 ± 0.106
Blanc-Vaziaga et al. 1973[h]	Zpt	θ, nLTE	0.197 ± 0.106
Brown et al. 1989	$B-V$	...	0.183 ± 0.093
Luck & Challener 1995[f,i]	Zpt	θ	0.142 ± 0.106[j]
			(0.153 ± 0.074)[k]
Ries 1981, Lambert & Ries 1981	$U-B$	...	0.124 ± 0.067
Pagel (Bell 1976)[l]	Zpt	nLTE	$\leq 0.095 \pm 0.135$

[a] "Zpt" denotes a zero-point correction. If a correction of the form "$A + B\times$ (color index)" is made instead, the color index is cited.
[b] "θ" denotes a temperature correction, while "nLTE" denotes a zero-point correction.
[c] Photometric datum (see entry in Table 1 of Paper III).
[d] As revised by Bonnell & Branch 1979. The lower limit is used in averaging.
[e] This datum has been calculated after the Dixon 1951 test has been used to reject results based on the λ6710.3 line.
[f] This datum was derived from EWs at $\lambda > 5600$ Å. In this respect, it is comparable to results that Taylor 1996 has previously analyzed. (See Table 2 of Taylor 1996.)
[g] See Appendix B for comments about this datum.
[h] As revised by Cayrel de Strobel 1991. For editing of the input data, see note "e."
[i] Data from this paper are also corrected for incomplete interpolation in a model-atmosphere grid. See Appendix B of Paper III.
[j] This datum was derived by Luck & Challener using their "spectroscopic" gravities.
[k] This datum was derived by Luck & Challener using their "physical" gravities.
[l] See Appendix B for the procedure used to assign an rms error to this datum. The upper limit is used in averaging.

Pagel's result is assigned a larger rms error than the others, so inverse-variance weighting assigns a smaller weight to Pagel's result than it does to the others. This procedure seems to be a reasonable way to allow for the missing information about Pagel's result.

Appendix C: numbered statistical tests

The results of all numbered statistical tests described in the body of the paper are summarized in Tables C1 and C2. An F test appears in Table C2, while t and χ^2 tests appear in Table C1. The t tests are unequal-variance tests (see the notes to Table 3 of Taylor 1992). The version of the χ^2 test used here is from Eq. (B44) of Taylor (1991).

Values of C_1 listed in Table C1 are threshold confidence levels from Eq. (A2) of Taylor (1996):

$$C_1^N = 0.95. \quad \text{(C1)}$$

Readers who wish to learn more about assigning values of C_1 should first read all but the last paragraph of Appendix A of Taylor (1996). One may then note that for tests 1–3, $N = 14$ because there are 14 entries in Table 4 and each entry must, in principle, be considered as a possible wild point.

Table C1. Statistical tests other than F tests

Test	Statistic	Condition[a]	Value of statistic	C	C_1
1[b]	t	$\nu = 4.2$	1.95	< 0.95	0.996
2[c]	t	...	1.12	< 0.95	0.996
3[d]	t	...	1.63	< 0.95	0.996
4[e]	χ^2	$\nu = 11$	6.23	< 0.95	0.95
5[f]	χ^2	$\nu = 13$	12.46	< 0.95	0.95

[a] ν = number of degrees of freedom.
[b] Test for the datum of Lambert & Ries 1981.
[c] Test for Pagel's datum (see Bell 1976). No value of ν is required to test such a small value of t.
[d] Test for the datum of Gustafsson et al. 1974. No value of ν is required to test such a small value of t.
[e] Test for the data in Table 2 of Taylor 1996.
[f] Test for the Table 5 data.

Table C2. An F (variance-ratio) test

Test	Larger σ	ν[a]	Smaller σ	ν[a]	F	C
6[b]	0.103[c]	73	0.018	3	32.7	0.992

[a] Number of degrees of freedom.
[b] $p \equiv 1 - C$ corresponds to one false alarm per 125 trials.
[c] This is the first result quoted in Sec. 4.2 of Paper III.

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