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A new abundance analysis of the super-metal-rich K2 giant, μ Leonis

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Abstract. Spectra of the super-metal-rich K2 giant, μ Leonis, have been recorded at high resolution ($\lambda/\Delta\lambda \simeq 10^5$) and with signal/noise $\simeq 200$, in selected regions between 5250 and 8810 Å. An LTE model atmospheres analysis of these spectra, with particular attention to blending by CN molecular lines, suggests that the wings of strong lines and the full profiles of intermediate strength lines are consistent with the following atmospheric parameters and logarithmic abundances, relative to the Sun:
$T_{\rm eff} = 4540 \pm 50$ K,
$\log g = 2.2 \pm 0.1$ dex,
Microturbulence, $\xi = 1.2 \pm 0.1$ km s^{-1},
Macroturbulence/rotation, $\zeta = 2.9 \pm 0.2$ km s^{-1},
[Fe/H] $= +0.29 \pm 0.03$ dex (relative to $\epsilon(\rm Fe)_\odot = 7.50$),
[Ca/H] $= +0.32 \pm 0.05$ dex (relative to $\epsilon(\rm Ca)_\odot = 6.36$),
[Mg/H] $= +0.32 \pm 0.05$ dex (relative to $\epsilon(\rm Mg)_\odot = 7.58$).
In view of the continuing controversy over the extent to which μ Leo is metal rich, we provide a critical review of other recent metallicity determinations and compare the present results with our own analyses, undertaken using essentially identical methods, of the spectra of other late-type giant stars in the solar neighbourhood.

Key words: stars: abundances – stars: fundamental parameters – book reviews – stars: late-type

1. Introduction

Since the discovery by Spinrad & Taylor (1969) of a group of stars having a large apparent overabundance of metals, even when compared with the Hyades, much work has been undertaken in efforts to verify the so-called super-metal-rich (SMR) phenomenon. Confirmation of the existence of SMR stars in the galactic disc would place important constraints on galactic evolution and the abundance gradient in the disc. The nearby K2 giant, μ Leonis ($V = 3.88$), has often been cited as a representative SMR star and, as a result, the study of this star has been closely connected with the SMR phenomenon itself. A paper by Castro et al. (1996), containing results of a new spectroscopic analysis and a revision of three earlier analyses, all published since 1990, provides strikingly consistent evidence for a μ Leo metallicity almost three times the solar value. This paper has been strongly criticised by Taylor (1999) who reviews all results published since 1970 and, following a detailed analysis of likely systematic effects and a discussion of criteria that a trustworthy analysis should satisfy, concludes that there is no convincing evidence for a value of [Fe/H] for μ Leo exceeding 0.2 dex. It is customary to regard [Fe/H], the abundance of iron expressed in logarithmic units relative to the Sun, as representative of the overall metallicity. In the present paper, rather than dwell on previous analyses, we offer new results for μ Leo derived from observational data which we believe to be at least as good, in terms of spectral resolution and photometric accuracy, as any previously obtained for this star. We compare our results with analyses of other late-type giants undertaken using the same observing equipment and analytical methods.

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2. Observations and data reduction

New observations of μ Leo were made at the McDonald Observatory in April, 1990, by G. Smith (University of Oxford) and D.L. Lambert (University of Texas), using the 2.7 m telescope and coudé spectrograph equipped with an 800×800 pixel CCD detector. We observed spectral regions covering approximately 12 Å each centred on 5253, 5261, 5415, 5423, 5855, 5864, 6055, 6079, 6149, 6156, 6162, 6170, 6416, 6430, 6455, 6498, 6508 and 8806 Å. These observations made use of an échelle grating giving a dispersion varying between 0.012 Å per diode (15 μm) at 5253 Å and 0.020 Å per diode at 8806 Å. The required order of the échelle spectrum was isolated before entering the main spectrograph by means of a grating monochromator. This arrangement, in which only about 100 Å of spectrum enters the main spectrograph, is particularly effective in reducing the scattered-light background. As a test for scattered light, recordings were made of the skylight spectrum in the same spectral regions. Subsequent measurements of equivalent widths for representative spectral lines showed that these equivalent widths differed by less than 2% from those measured from the high dispersion spectral atlas of Kurucz et al. (1984). These differences are within the errors of measurement and certainly less than the likely errors arising from blending in the spectra of μ

Leo. Scattered light was therefore assumed to be negligible.The entrance slit-width of 240 μm projected on to 3.6 diodes in the focal plane which at 6000 Å gave a resolution limit of $\simeq 0.05$ Å. A recording of a Th-Ar lamp spectrum showed that the instrumental profile could be well represented by a Gaussian function with a full-width at half-maximum intensity equal to the projected slit width. In addition to the above observations, we also observed the profile of the strongest of the Ca II infrared triplet lines at 8542 Å. A conventional grating was employed in the first order, giving about 50 Å of spectrum on the detector at a dispersion of 0.06 Å per diode. This arrangement gave sufficient resolution to allow reliable identification of blends and sufficient spectral range to include all of the line wings. Integration times of 10-15 min (échelle) and 5 min (conventional grating) yielded spectra with signal/noise $\simeq 200$ in "seeing" of typically 2 arcsec. The spectrum of a tungsten filament lamp, used for subsequent flat-field correction, was recorded at the same grating setting immediately after each stellar integration. Initial data reduction was undertaken at the Department of Astronomy, University of Texas at Austin. Further analysis and measurement were carried out at Oxford using the standard Starlink package DIPSO.

3. Analysis

Our analysis has been carried out by comparing the observed spectra with synthetic spectra calculated in the LTE approximation using model atmospheres. Considerable weight was given to the wings of the strong lines of Ca II at 8542 Å and Mg I at 8806 Å. As explained in detail by Smith & Ruck (1997), the wings of the former line in late-type giant stars are more sensitive to metallicity, [M/H], than to effective temperature, $T_{\rm eff}$, or surface gravity, g, whereas the wings of the latter line are sensitive to [M/H] and $T_{\rm eff}$ but insensitive to g. The spectral regions chosen for observation contain numerous lines of iron and calcium for which accurate atomic data are available. Atomic data for Ca I lines was taken from the laboratory work of Smith & Raggett (1981) and atomic data for low-excitation Fe I lines from the laboratory work of Blackwell et al. (1982). Atomic data for other lines was determined by fitting synthetic spectra, calculated using the Holweger-Müller solar atmosphere (Holweger & Müller 1974), to the corresponding regions of the solar spectrum in the atlas of Kurucz et al. (1984). The laboratory data for calcium lines lead to a logarithmic solar abundance $\epsilon(\rm Ca)_\odot = 6.36$ which is consistent with the meteoritic calcium abundance (Anders & Grevesse 1989). A solution to the long-standing controversy over the solar iron abundance, where analyses of low-excitation Fe I lines indicate $\epsilon(\rm Fe)_\odot \simeq 7.67$ while analyses of Fe II lines and high-excitation Fe I lines indicate $\epsilon(\rm Fe)_\odot \simeq 7.51$ (the meteoritic value), has recently been proposed by Grevesse & Sauval (1999) who have shown that results from both high- and low-excitation lines can be reconciled to an abundance of 7.50 if a small adjustment is made to the temperature structure of the Holweger-Müller atmosphere in the higher photospheric layers. This adjustment has no effect on abundances derived from high-excitation lines. The "solar" gf-values which we have adopted for Fe II and high-excitation Fe I lines have been derived using $\epsilon(\rm Fe)_\odot = 7.50$ and a microturbulence of 1.25 km s^{-1}, which is appropriate for the solar flux spectrum (integrated-disc). Since these lines are fairly weak in the solar spectrum, the resulting gf-values are not particularly sensitive to the choice of microturbulence. A solar iron abundance of 7.50 was also taken as the reference value in construction of the MARCS model atmospheres (see below).

The question of the most appropriate type of model atmosphere for late-type giant stars was considered by Drake & Smith (1991) in a critical analysis of features in the spectrum of the K0 giant, Pollux (β Gem). Using the profile of the Ca II 8542 Å line as a feature to test the temperature structure of the atmosphere, these authors concluded that a model from the MARCS suite of atmospheres (Bell et al. 1976) produced a theoretical line shape in best agreement with the observed profile. These atmospheres have been used successfully in a recent study of the G8 giants, μ Peg and λ Peg (Smith 1998), and to derive the overall metallicity and surface gravity of the Hyades K0 giants, γ Tau and ϵ Tau (Smith & Ruck 1997). Accordingly we adopted MARCS atmospheres for the present analysis. Our stellar spectra are broadened by turbulence which must be included in the synthesis for a realistic comparison between observed and computed profiles. Turbulence on small scales (microturbulence) broadens the atomic absorption coefficient and may be determined from an analysis of equivalent widths (see next section). Turbulence on large scales (macroturbulence) is sufficiently well accounted for in the present case by applying a Gaussian smoothing function to the synthesised spectra. In reality this smoothing function also includes instrumental and rotational broadening but instrumental broadening (equivalent to a Gaussian function with broadening parameter 1.5 km s^{-1} at 6000 Å) has a small effect compared to the combined effect of rotation and macroturbulence ($\simeq 3$ km s^{-1}). Spectral lines of μ Leo are too blended to allow a separation of rotational and macroturbulent broadening using the Fourier techniques described by Gray (1992, chapter 18). However, on p 411 of this reference, Gray states that when rotational and macroturbulent broadening are similar in magnitude the combined effects produce a profile that is close to Gaussian, which seems to be the case encountered here.

The abundance analysis of a relatively cool star which is very rich in metals poses a number of problems. The spectrum is very crowded and true continuum points are seen very rarely, if ever, making the task of continuum location rather hazardous. The same applies to the identification of minimally blended lines and the measurement of equivalent widths: many weak lines that are unobservable in the solar spectrum become prominent in the spectrum of μ Leo. Fig. 1 shows a typical section of the μ Leo spectrum centred on 6055 Å. The continuum is defined by the two highest points on the observed spectrum. These may or may not be true continuum points. The sheer number of lines crowding the spectrum is apparent and particularly noticeable is the strength of the CN features. Gratton & Sneden (1990) in one of the most comprehensive analyses of the μ Leo spectrum published to date, made use of equivalent width measurements only for obtaining an approximate overall metallicity, and to

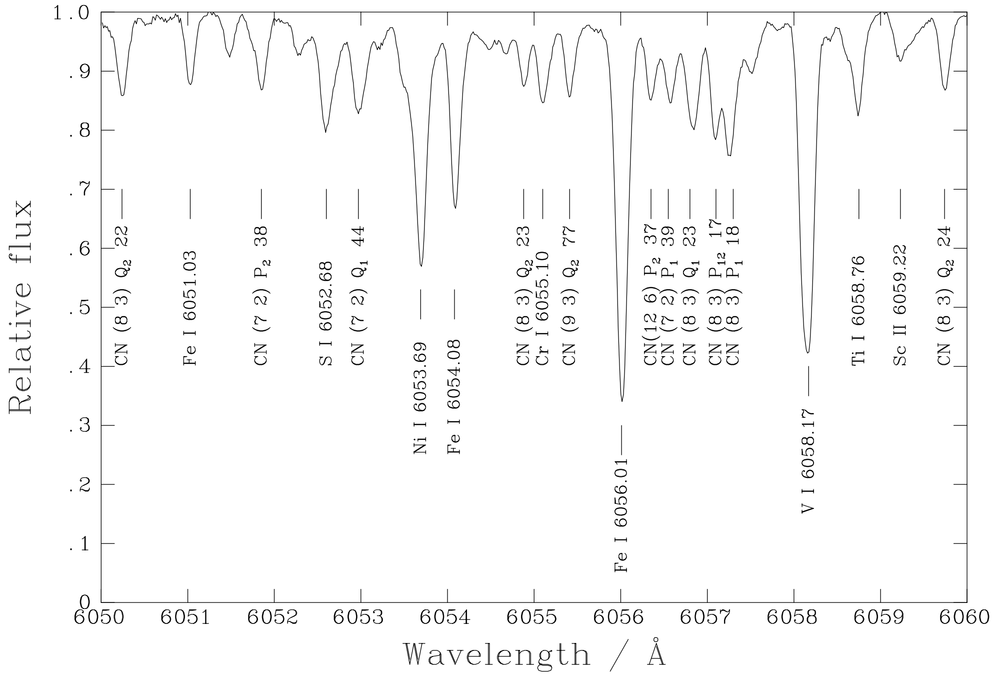

Fig. 1. Spectrum of μ Leo in the region 6050-6060 Å. Note the heavy contamination by CN molecular lines.

constrain the microturbulence. Thereafter they used spectrum synthesis to fit individual lines. In the present study we have used a combination of equivalent widths and spectrum synthesis but, in addition, we have attempted to include as complete a treatment of the blending, in particular the molecular blending, as is currently possible. There are bands of CN and TiO throughout the visible and near infrared regions, and the C_2 Swan system covers our shorter wavelength regions up to about 6800 Å.

For our atomic line list we used the solar line list of Moore et al. (1966), supplemented by additional identifications from Kurucz & Peytremann (1975). In addition we considered lines formed by the molecules CN, C_2 and TiO. For CN we made use of the extremely comprehensive lists of wavelengths and line strengths described by Jørgensen & Larsson (1990): a copy of their SCAN-CN tape was kindly made available to us by the authors. For TiO lines, the most recent calculation of wavelengths and line strengths is that by Plez et al. (1992). For the C_2 Swan system, we used the line lists, identifications and molecular constants from Phillips & Davis (1968), together with Franck-Condon factors from Dwivedi et al. (1978), and Hönl-London factors calculated from the formulae in Kovàcs (1969). An electronic oscillator strength of 0.0329 (Lambert 1978) was adopted. Our calculated $\log gf$ values differ by 0.04 dex or less from those listed in Gratton & Ortolani (1986). CNO abundances and isotopic ratios were taken from the in-depth analysis of Harris et al. (1987), who made use of infrared CN and CO features ($\lambda \sim 2.2\mu$m), together with published equivalent widths of C_2 and O I features. The advantage of using CO features is that, in a star for which C/O < 1, the CO lines can provide a carbon abundance which is virtually independent of the oxygen abundance. The resulting abundances, on the usual scale where $\log \epsilon(\mathrm{H}) = 12$, were $\log \epsilon(\mathrm{C}) = 8.89$, $\log \epsilon(\mathrm{N}) = 8.92, \log \epsilon(\mathrm{O}) = 9.24$ and ^{12}C/^{13}C $= 18$. The isotopic ratio is a clear indication that μ Leo has undergone first dredge-up on the ascent of the Red Giant Branch and that it is a normal core-helium-burning star. Test calculations for a model atmosphere appropriate to μ Leo showed, as expected, that the largest contribution to the molecular line opacity came from ^{12}CN lines with ^{13}CN being far less prominent. C_2 lines are quite prominent in the 5400 Å region, where the Swan system is at its strongest, but weak in most other regions. TiO lines make no appreciable contribution in the visible region, confirming what Gratton & Sneden (1990) inferred from observation, and are minor contributors in the near infrared. A complete description of our molecular line calculations is given in Ruck (1994).

4. Results

4.1. Stellar parameters

The metallicity of μ Leo was first estimated by comparing synthetic and observed profiles of the Mg I 8806 Å line and the Ca II 8542 Å line. As shown by Ruck & Smith (1993), the depth of absorption in the wings of the former line is a good indicator of overall metallicity, [M/H], being independent of surface gravity and only mildly dependent on effective temperature. The wing profiles in this strong line are well developed and the comparison between observed and computed absorption can be made well away from those parts of the line core which are affected by turbulent broadening. We assumed that [Mg/H] = [M/H], which seems to be well established for stars of metallicity close to or greater than that of the Sun (Edvardsson et al. 1993). The effective temperature was initially taken to be 4540 K from Gratton & Sneden (1990): this is discussed further below. Fig. 2 shows a comparison of observed and computed profiles

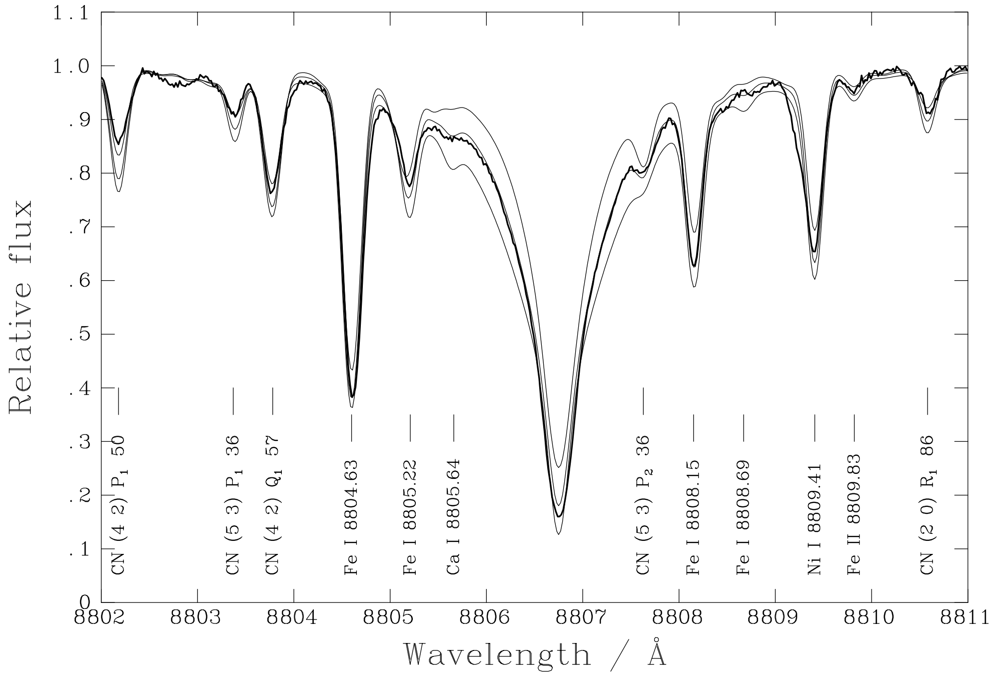

Fig. 2. Observed spectrum of μ Leo in the region of the Mg I 8806 Å line compared to synthetic spectra with $T_{\rm eff} = 4540$ K, $\log g = 2.2$, [M/H] $= 0.0, 0.3$ and 0.6.

for three values of metallicity. The comparison indicates [M/H] $= +0.32 \pm 0.05$ with the uncertainty arising mainly from continuum placement because of the many weak features due to CN. The more prominent CN features are identified on the figure. Note that the calculations were undertaken with fixed CNO abundances as detailed in Sect. 3. These abundances were determined using a MARCS-type atmosphere with $T_{\rm eff} = 4540$ K and $\log g = 2.35$ (Harris et al. 1987), very similar parameters to those adopted here. Variations in strength of the calculated CN features shown in Fig. 2 arise from changes in atmospheric structure with [M/H]. Any discrepancies between the observed CN features and our optimal computed spectrum with [M/H] $\simeq 0.3$ are most likely to arise from our use of theoretical CN line strengths from the SCAN-CN tape of Jørgensen & Larsson (1990), these being the only ones available. Nevertheless, the representation of the CN features in the computed spectrum is sufficiently good to indicate where blending is likely to be signifiicant: this was the main purpose of the molecular synthesis. If $T_{\rm eff}$ were lower by 100 K, the value of [M/H] indicated by the Mg I 8806 Å line wings would be lower by 0.05 dex. A change in $\log g$ by ± 0.3 dex has no effect on the calculated profiles. Contamination of the wing profiles by CN absorption is a more serious problem for the Ca II 8542 Å line. In this case the comparison between observed and calculated profiles yields [M/H] $= 0.3 \pm 0.1$, independent of likely uncertainties in $T_{\rm eff}$ or $\log g$ (Ruck 1994).

Gratton & Sneden (1990) derived an effective temperature of 4540 K for μ Leo using the prescriptions and calibration of Bell & Gustafsson (1989) which were based on the infrared flux method originally described by Blackwell & Shallis (1977). Temperatures derived by this technique are likely to be accurate to about ± 100 K. Taylor (1999) appears to favour $T_{\rm eff} = 4470$ K based on a photometric calibration by McWilliam (1990). As explained in the following subsection, our equivalent width analysis favours the higher value of $T_{\rm eff}$. For surface gravity, Gratton & Sneden (1990) adopted $\log g = 2.30$, the mean of determinations using iron ionization equilibrium, an MgH dissociation equilibrium and the wings of strong lines. The first two methods relied on approximate abundances for Fe and Mg based on a coarse equivalent width analysis: the use of strong-line wings is susceptible to continuum placement errors. Fig. 3 shows the region around the Ca I 6162 Å line whose wing profiles have often been used as a gravity indicator. The comparison indicates $\log g = 2.15 \pm 0.15$ with uncertainty arising from both blending and continuum placement. The equivalent width analysis to be described in the following subsection provides additional support for a surface gravity close to $\log g = 2.2$.

4.2. Equivalent width analysis

It is unlikely that any of the lines in the μ Leo spectrum are completely free from blending, particularly blending from CN lines. However, given our extensive line list prepared for the spectrum synthesis calculations, it was possible to estimate the likely effects of blending on any particular line and prepare a set of equivalent widths corresponding to approximately unblended lines. Most of the lines included in this set are lines where blending does not appear to affect the line core. This exercise was undertaken for lines of Fe I, Fe II and Ca I for which we have good atomic data. In comparing computed and observed spectra in order to eliminate blends, a MARCS model atmosphere with the parameters, $T_{\rm eff} = 4540$ K, $\log g = 2.2$, [M/H] $= 0.3$ was adopted. The measured equivalent widths are shown in Table 1. Our set of iron lines contains three distinct groups: Fe I lines of low excitation (1.0-2.5 eV), Fe I lines of high excitation (4.0-5.0 eV) and Fe II lines. All these lines are

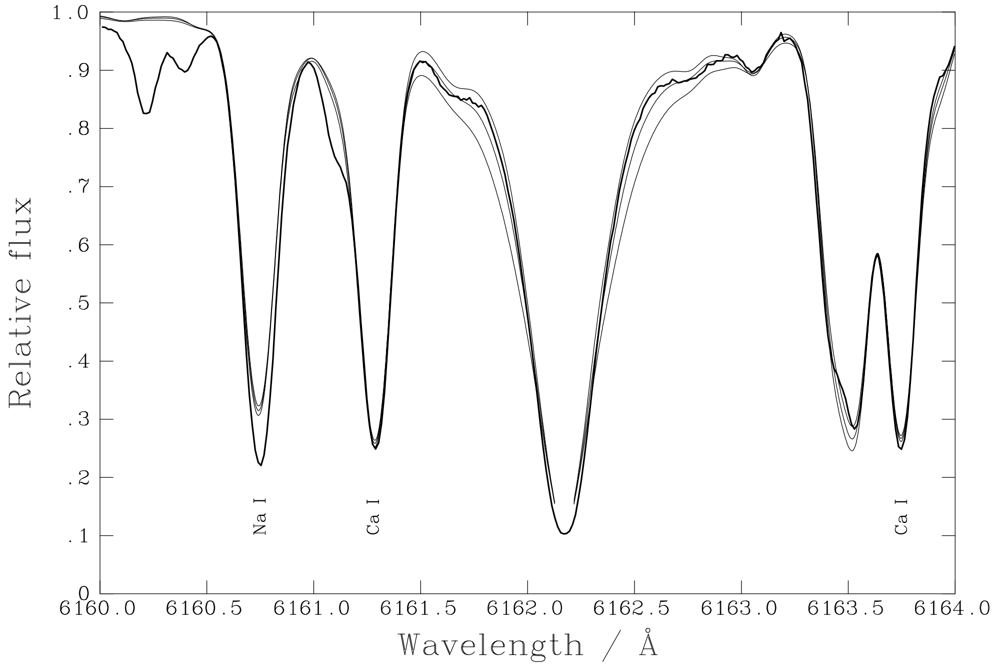

Fig. 3. Spectrum of μ Leo in the region of the Ca I 6162 Å line compared to synthetic spectra with $T_{\rm eff} = 4540$ K, [M/H] $= +0.3$, $\log g = 2.0, 2.3$ and 2.6; note the strengthening of the Na I line at 6160.75 Å relative to the reference metallicity.

of medium strength and sensitive to broadening by microturbulence. Test calculations showed that abundances derived from the first group of lines are sensitive also to $T_{\rm eff}$ but insensitive to $\log g$; abundances derived from the second set of lines are insensitive to both $T_{\rm eff}$ and $\log g$; abundances derived from Fe II lines are sensitive to both $T_{\rm eff}$ and $\log g$. The second set of lines are thus the best indicators of microturbulence. Loci of constant equivalent width on a graph of [Fe/H] against microturbulence, ξ, are shown for these lines in Fig. 4. The loci should intersect in a narrow region defining appropriate values of [Fe/H] and ξ. In order to determine the optimum values of these parameters, we have calculated the mean abundance and standard deviation of the mean as a function of microturbulence. The optimum values are taken to be those corresponding to the minimum standard deviation. This exercise was repeated for the group of low-excitation Fe I lines, for the Fe II lines and for the Ca I lines; also for an alternative value of $T_{\rm eff}$, 4640 K. The results are shown in Table 2.

The high-excitation Fe I lines indicate ϵ(Fe) $= 7.79 \pm 0.02$ and $\xi = 1.22$ km s^{-1} almost independent of temperature in the range 4540-4640 K. A slightly lower $T_{\rm eff} (\simeq 4510$ K) would bring the results for low- and high-excitation lines into coincidence but this must be viewed with caution since other papers (Steenbock 1985, Drake & Smith 1991) have produced evidence for departures from LTE in low-excitation lines of Fe I. High-excitation Fe I lines and Fe II lines are not believed to be sensitive to departures from LTE. If our assumption of $\log g = 2.2$ is correct, then $T_{\rm eff} = 4540$ K would bring results for Fe I (high exc.) and Fe II into coincidence. An increase in $\log g$ of 0.1 dex has a negligible effect on Fe I lines and Ca I lines but results in an abundance higher by about 0.1 dex from Fe II lines. The evidence of our temperature and gravity dependent lines points to an effective temperature of about 4540 K with an uncertainty of about 50 K and a surface gravity, $\log g = 2.2$, with an uncertainty of about 0.1 dex. A weighted average of all results at $T_{\rm eff} = 4540$ K, $\log g = 2.2$ yields [Fe/H] $= +0.29 \pm 0.02$, relative to a solar abundance ϵ(Fe) $= 7.50$ (Grevesse & Sauval 1999) and [Ca/H] $= 0.32 \pm 0.03$, relative to a solar abundance ϵ(Ca) $= 6.36$ (Smith 1981). Allowing for an error of ± 0.1 km s^{-1} in ξ increases the uncertainty in abundance derived from Fe I lines to ± 0.03 dex.

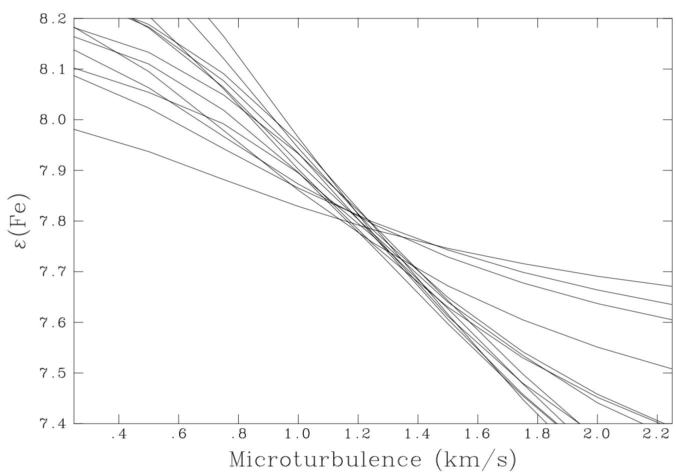

Fig. 4. Logarithmic abundance of iron as a function of microturbulence for high-excitation lines of Fe I listed in Table 1.

4.3. Synthetic spectrum analysis

In addition to the equivalent width analysis described above, we have undertaken a spectrum synthesis analysis of our regions in order to determine abundances for species not so widely represented in our spectra. Adopting the parameters $T_{\rm eff} = 4540$

Table 1. Atomic data and equivalent widths for lines of Fe I, Fe II and Ca I in the spectrum of μ Leo

Wavelength (Å)	Excitation (eV)	$\log gf^a$	Equivalent width (mÅ)
Fe I			
5253.03	2.28	-3.81^*	87
5853.16	1.48	-5.13	80
6082.72	2.22	-3.57^*	110
6151.62	2.18	-3.30^*	122
6173.34	2.22	-2.88^*	138
6498.95	0.96	-4.63	142
5417.04	4.42	-1.42	75
5855.09	4.61	-1.52	62
5856.10	4.29	-1.55	79
5858.79	4.22	-2.20	54
5859.60	4.55	-0.60	111
5862.37	4.55	-0.39	124
6054.08	4.37	-2.33	39
6056.01	4.73	-0.45	105
6078.50	4.80	-0.34	108
6079.02	4.65	-0.99	85
6159.38	4.61	-1.85	49
6165.36	4.14	-1.47	91
6419.96	4.73	-0.20	120
Fe II			
5264.81	3.23	-3.19	60
5425.26	3.20	-3.29	57
6149.25	3.89	-2.85	42
6432.68	2.89	-3.64	57
6456.39	3.90	-2.21	65
Ca I			
5260.39	2.52	-1.72	96
5867.57	2.93	-1.57	87
6156.03	2.52	-2.45	67
6161.29	2.52	-1.27	127
6166.44	2.52	-1.14	134
6169.04	2.52	-0.80	154
6169.56	2.53	-0.48	181
6455.60	2.52	-1.34	124
6499.65	2.52	-0.82	151

[a] Values for Fe lines are derived from the solar spectrum (see text) apart from those marked (*) which are laboratory measurements from Blackwell et al. (1982); values for Ca lines are laboratory measurements from Smith & Raggett (1981).

K, $\log g = 2.2$, [M/H] $= 0.3$, $\xi = 1.2$ km s^{-1}, we synthesised the spectrum around each line, varying the abundance of the element forming the line until a good fit was achieved. In order to bring calculated lines of Fe and Ca into good agreement with their observed profiles, it was necessary to apply a Gaussian smoothing function with Gaussian parameter equivalent to 3.25 km s^{-1}. This smoothing function represented the effects of macroturbulence, rotation and instrumental broadening. Recalling that instrumental broadening could be well represented by a Gaussian with parameter 1.5 km s^{-1}, the combined effects of rotation and macroturbulence are equivalent to a Gaussian of parameter 2.9 km s^{-1}. The results of the spectrum synthesis analysis are summarised in Table 3 and compared with the results of Gratton & Sneden (1990) who conducted a very similar analysis.

Table 2. Optimum values of iron and calcium abundances, ϵ(El), and microturbulence, ξ, in μ Leo for $\log g = 2.2$, $T_{\rm eff} = 4540$ and 4640 K.

	$T_{\rm eff}$(K)	ϵ(El)	ξ(km s^{-1})
Fe I (high exc.)	4540	7.792 ± 0.016	1.22
	4640	7.800 ± 0.017	1.22
Fe I (low exc.)	4540	7.808 ± 0.017	1.20
	4640	7.865 ± 0.023	1.20
Fe II	4540	7.790 ± 0.013	1.21
	4640	7.645 ± 0.015	1.23
Ca I	4540	6.683 ± 0.019	1.18
	4640	6.783 ± 0.024	1.18

Table 3. Mean metal abundances, relative to the Sun, for μ Leo compared to the results of Gratton & Sneden (1990): N is the number of lines measured; σ is the standard deviation of the abundance

Element	N	[El/H] this study	σ	N	[El/H] Gratton&Sneden	σ
Na	2	$+0.73$	–	2	$+0.90$	–
Mg	1	$+0.32$	–	1	$+0.30$	–
Ca	8	$+0.32$	0.05	2	$+0.22$	0.22
Ti	4	$+0.35$	0.07	5	$+0.31$	0.17
Fe I	19	$+0.29$	0.03	36	$+0.34$	0.12
Fe II	5	$+0.29$	0.03	2	$+0.15$	–
Ni	2	$+0.35$	–	5	$+0.44$	0.13

We note that all our values of ϵ(El), apart from that for sodium, where in common with Gratton & Sneden (1990), we find an enhancement, are consistent with a metallicity of about $+0.30$ dex. There is general agreement with the results of Gratton & Sneden though our own results, particularly those for Fe I, Fe II and Ca, have smaller errors and point more convincingly to a common overall metallicity.

5. Discussion

Allowing for possible errors in continuum placement, treatment of blending, choice of stellar parameters, our results may be summarised as:

$T_{\rm eff} = 4540 \pm 50$ K,
$\log g = 2.2 \pm 0.1$,
Microturbulence, $\xi = 1.2 \pm 0.1$ km s^{-1},
Macroturbulence/rotation, $\zeta = 2.9 \pm 0.2$ km s^{-1},
[Fe/H] $= +0.29 \pm 0.03$ (relative to ϵ(Fe)$_\odot = 7.50$),
[Ca/H] $= +0.32 \pm 0.05$ (relative to ϵ(Ca)$_\odot = 6.36$),
[Mg/H] $= +0.32 \pm 0.05$ (relative to ϵ(Mg)$_\odot = 7.58$).

Gratton & Sneden (1990), who used spectra of similar resolution and a spectrum synthesis technique, obtained an average metallicity, based on their result for Fe I lines, of $+0.34 \pm 0.12$ dex. They also obtained a microturbulence of $\xi = 1.2$ km s^{-1} in good agreement with our own result. However, Gratton & Sneden adopted a solar abundance, ϵ(Fe) $= 7.63$, from Simmons & Blackwell (1982), and Castro et al. (1996) have argued that the Gratton & Sneden result for μ Leo should be increased to 0.45 dex to take account of more recent results on the solar iron abundance which tend to favour the meteoritic value, ϵ(Fe) $= 7.51$ (Anders & Grevesse 1989). Castro et al. used similar arguments to bring results from McWilliam & Rich (1994) and from Luck & Challener (1995) into close agreement with their own independent analysis which gave +0.46 dex. Taylor (1999) has strongly criticised these upward revisions pointing out, with good reason, various inconsistencies between the solar and stellar analyses in each case, which are likely to result in serious systematic errors. In particular, the oscillator strengths adopted in the stellar analyses are often gathered from many different sources and it is unlikely that these would produce the solar meteoritic abundance if applied to the solar spectrum. Gratton & Sneden used no less than eight different sources in the case of iron! Although many of these carry the label “solar” in that they are based on fits to the solar spectrum, it is not obvious to what value of the solar iron abundance they are related. There is very little overlap between Gratton & Sneden’s published list of equivalent widths and those we list in Table 1 but, where measurements have been made on the same lines, their equivalent widths tend to be a few mÅ higher: their oscillator strengths are, with one exception, identical to our own. Taken as published, without any upward revision of the metallicity, the result of Gratton & Sneden for Fe I is in good agreement with our own.

In fairness to the papers of McWilliam & Rich (1994), hereafter referred to as MR94, and Luck & Challener (1995), hereafter LC95, it should be pointed out that these papers addressed much wider problems and that μ Leo was just one of many stars subjected to spectral analysis. However, as the results for μ Leo have been used by Castro et al. (1996), hereafter C96, to support their own high value for the metallicity, we wish to examine these results in some detail. Abundances derived for several metallic species are listed in Table 4 together with values for physical parameters and the spectral resolution of the observations.

It should be noted that two of the three papers used $T_{\rm eff}$ and $\log g$ from Gratton & Sneden (1990) but all three papers were based on observations of significantly lower spectral resolution compared to the $R \simeq 80,000$ used by Gratton & Sneden and the $R \simeq 100,000$ used by ourselves. As is usual, the majority of lines analysed were from Fe I and it is this result which defines the metallicity. However, the wildly fluctuating abundances found for other elements and the large errors raise questions about the reliability of the analyses.

LC95 derived values of $T_{\rm eff}$ ranging from 4181 to 4553 K, based on various photometric indices, and adopted a mean of 4375 K. These authors also gave results for two values of surface gravity, a so-called ‘physical’ value (denoted P in Table 4) based on estimated mass and luminosity, and a spectroscopic value (denoted S in Table 4) based on Fe I/Fe II ionisation equilibrium. Their iron abundances are quoted relative to a solar abundance of 7.67 from Grevesse (1984), which they claimed was consistent with their oscillator strength scale. As pointed out by Taylor (1999), the upward revision of the LC95 result by C96 destroyed the differential character of the analysis. A modest upward revision (by $\simeq 0.05$ dex) might be justified on the grounds that LC95 adopted model atmospheres with solar metallicity. The use of a significantly lower $T_{\rm eff}$, compared to other papers, is also likely to have contributed to the lower result for metallicity. A question mark must also be raised over the LC95 turbulent broadening parameters: given the limit of resolution of their observations (~ 10 km s^{-1} FWHM), their values of 2.6 km s^{-1} for microturbulence and 1.0 km s^{-1} for macroturbulence must inevitably be poorly constrained.

MR94 made a careful study of blending by CN lines and identified a set of metallic lines which, they claimed, were free from blending. There is very little overlap with our own list but, where comparison is possible, their equivalent widths are about 10% larger than our deblended values. MR94 also gave equivalent widths for lines likely to be more affected by blending and illustrated the increase in derived abundance (by up to $\simeq 0.3$ dex) when these lines were used. A microturbulence of 1.8 km s^{-1} was determined by requiring weak and strong lines of Fe I to yield the same abundance. Abundances were derived both from an equivalent width analysis and from spectrum synthesis (including CN lines) but no value for macroturbulence is quoted. C96 carried out a very similar analysis to MR94 using new observations of greater spectral resolution. Only one line in their list of supposedly unblended lines, the Fe II line at 6456.39 Å, overlaps our own data set: C96 quote an equivalent width of 70 mÅ compared to our own deblended value of 65 mÅ. This difference of 5 mÅ in equivalent width corresponds to a difference in [Fe/H] of 0.12 dex. C96 used three methods of abundance determination: an equivalent width analysis, a spectrum synthesis method and a curve of growth method. They also investigated two independent sets of model atmospheres: MARCS atmospheres, similar to those used in the present paper, and atmospheres from Kurucz (1992). A curious feature of their results is the widely differing values of microturbulence obtained from different approaches. As usual, microturbulence was determined by forcing strong Fe I lines to yield the same average abundance as weak lines (though none of the lines utilised could be described as genuinely weak). MARCS models gave a microturbulence of 2.2 km s^{-1}, Kurucz models gave a microturbulence of 1.6 km s^{-1} and the curve of growth method gave 1.0 km s^{-1}. Little dependence of the resulting abundances on type of model atmosphere was found and all three methods yielded similar high values of [Fe/H].

Taylor (1999), following Chmielewski et al. (1992), sets out criteria to serve as a benchmark for a consistent abundance analysis, relative to the Sun. Such an analysis should use: (1) the same source of f-values for programme stars and the Sun, (2) the same lines for programme stars and the Sun, (3) equiv-

Table 4. Results for metallicity of μ Leo obtained by McWilliam & Rich (MR94), Luck & Challener (LC95) and Castro et al. (C96): N is the number of lines from which the metallicity is derived; R is the spectral resolving power of the observations; $T_{\rm eff}$ is the adopted effective temperature; $\log g$ is the adopted surface gravity; ϵ(Fe)$_\odot$ is the reference solar abundance

	N	MR94	N	LC95(P)	LC95(S)	N	C96
R		17,000		30,000	30,000		38,000
$T_{\rm eff}$ (K)		4540		4375	4375		4540
$\log g$		2.3		2.35	1.90		2.3
ϵ(Fe)$_\odot$		7.52		7.67	7.67		7.52
[Mg/H]	3	$+0.11 \pm 0.07$	6	$+0.71 \pm 0.24$	$+0.69 \pm 0.26$		–
[Ca/H]	4	-0.26 ± 0.07	2	-0.47 ± 0.11	-0.46 ± 0.13	2	$+0.13 \pm 0.35$
[Ti/H]	8	-0.10 ± 0.16	18	-0.22 ± 0.21	-0.25 ± 0.21	2	$+0.05 \pm 0.11$
[(Fe I)/H]	30	$+0.42 \pm 0.19$	89	$+0.20 \pm 0.20$	$+0.10 \pm 0.20$	22	$+0.48 \pm 0.14$
[(Fe II)/H]	2	$+0.30 \pm 0.14$	1	$+0.40$	$+0.14$	2	$+0.75 \pm 0.15$
[Ni/H]	2	$+0.15 \pm 0.37$	36	$+0.38 \pm 0.24$	$+0.27 \pm 0.24$	3	$+0.44 \pm 0.17$

Table 5. Results of Oxford abundance analyses for various giant stars: ξ is microturbulence; ζ is macroturbulence/rotation

Star	$T_{\rm eff}$ (K)	$\log g$	[M/H]	ξ (km s^{-1})	ζ (km s^{-1})	Ref.
β Gem (K0III)	4865	2.75	-0.04 ± 0.05	1.4	3.5	1
μ Peg (G8III)	5000	2.6	-0.10 ± 0.05	1.4	3.0	2
λ Peg (G8II)	4800	1.7	-0.10 ± 0.05	1.8	7.6	2
γ Tau (K0III)	4965	2.65	$+0.12 \pm 0.03$	1.3	3.3	3,4
ϵ Tau (K0III)	4911	2.45	$+0.15 \pm 0.03$	1.5	3.7	3,4
μ Leo (K2III)	4540	2.2	$+0.30 \pm 0.05$	1.2	2.9	5

1. Drake J.J., Smith G., 1991, MNRAS 250, 89
2. Smith G., 1998, A&A 339, 531
3. Smith G., Ruck M.J., 1997, A&A 324, 1091
4. Smith G., 1999, A&A 350, 859
5. this paper

alent widths derived from a particular telescope/spectrograph combination for all stars (including the Sun), and (4) stellar and solar model atmospheres from a single grid. Whether these are the optimum criteria is a matter for debate, which we do not wish to pursue. As reference solar abundances, we have simply used the best available from critical analyses in the literature. In order to demonstrate the extent to which μ Leo is metal rich, we wish to take a different approach. This is similar to an approach described by Gratton & Sneden (1990) but these authors, in order to pursue their arguments, were forced to draw on the results of observations undertaken by other groups. The present analysis is one of a series where spectra of various giant stars have been analysed. All of these spectra were observed using the same telescope/spectrograph/detector combination. The analyses were undertaken in the same consistent manner using more or less the same spectral regions, the same spectral lines, the same atomic data and the same suite of model atmospheres. As regards the comparisons between different stars, the criteria listed by Taylor (1999) are satisfied. The results are summarised in Table 5.

The first three stars are typical giant stars of the solar neighbourhood and our analysis returns a metallicity, based on iron and calcium lines, close to that of the Sun. Edvardsson et al. (1993), from a very extensive analysis, determined the mean metallicity of stars in the solar neighbourhood to be slightly sub-solar. The stars, γ Tau and ϵ Tau, are two of the four giants in the Hyades cluster and our analysis yields an enhanced metallicity, compared to the Sun, very close to the value, [M/H] $= +0.14$, adopted by Perryman et al. (1998) as typical of recent critical determinations. We also analysed strong-line profiles of several dwarf stars in the Hyades cluster and obtained a similar metallicity to that we obtained for the giants (Smith & Ruck 1997). Taylor (1999) has pointed out that the upward revisions of the results of other workers, which Castro et al. (1996) propose in order to justify their high metallicity for μ Leo, would lead to a metallicity for the Hyades giants which was incompatible with that obtained for the dwarfs. Our own metallicity for μ Leo is significantly higher than that which we obtain for the Hyades, though we find an enhancement, compared to the Sun, by more like a factor of two than the factor of three claimed by Castro et al. We conclude that this enhancement by a factor of two is likely to represent the upper limit of metal enrichment of stars in the solar neighbourhood.

6. Conclusion

We have investigated the metallicity of μ Leo using high resolution, high signal/noise spectra of regions containing lines of iron, calcium and magnesium for which accurate atomic data is available. Our analysis includes a very thorough treatment of blending, particularly that due to CN molecules. A very significant result is obtained from the broad wings of the Mg I 8806 Å line which indicates a metallicity, [M/H] $= +0.32 \pm 0.05$, independent of assumptions about surface gravity and turbulent broadening. If $T_{\rm eff}$ were lower by 100 K than the preferred value of 4540 K, which seems most unlikely, the indicated metallicity would only be lower by 0.05 dex. A fine analysis of high-excitation Fe I lines yields a microturbulence, independent of likely uncertainties in $T_{\rm eff}$ and surface gravity, of 1.2 ± 0.1 km

s^{-1}. At $T_{\rm eff} = 4540$ K, $\log g = 2.2$, all lines of Fe I, Fe II and Ca I yield a consistent metallicity, [M/H] $= +0.30 \pm 0.05$. Similar values are obtained from a spectrum synthesis analysis of small samples of Ti I and Ni I lines. Our

results are in reasonable agreement with the earlier, though less precise, results of Gratton & Sneden (1990) who used spectra of similar resolution. We support the view of Taylor (1999) that the upward revision, by Castro et al. (1996), of results obtained by Gratton & Sneden (1990), McWilliam & Rich (1994) and Luck & Challener (1995), so as to bring these results into near coincidence with their own result, [M/H] $= +0.46$, is misleading and unjustifiable. The high result of Castro et al. most probably arises from inadequate treatment of blending and the significantly lower resolution of their observations. Taylor (1999) concludes, from a survey of analyses stretching back to 1970, that there is no compelling evidence for a metallicity for μ Leo exceeding [M/H] $= 0.2$. By comparison with our own analyses of other giant stars in the solar neighbourhood, all undertaken using very similar methods, we believe we have presented a compelling case for a metallicity of μ Leo close to [M/H] $= 0.3$.

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