Astron. Astrophys. 339, 531–536 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Stellar atmospheric parameters for the giant stars μ Pegasi and λ Pegasi

G. Smith

Department of Physics, Nuclear and Astrophysics Laboratory, Keble Road, Oxford OX1 3RH, UK

Received 3 August 1998 / Accepted 27 August 1998

Abstract. Profiles of the strong lines Ca II 8542 Å and Mg I 8806 Å together with regions containing Ca I, Fe I and Fe II lines in the spectra of the G8 giant stars μ Peg and λ Peg have been recorded at high resolution and with signal/noise ≥ 100. The wings of the strong lines and the full profiles of intermediate strength lines are consistent with an LTE analysis based on the following sets of atmospheric parameters:

	μ Peg	λ Peg
$T_{\rm eff}$ (K)	5000 ± 50	4800 ± 50
$\log g$(g in cm s^{-2})	2.6 ± 0.1	1.7 ± 0.1
[M/H]	-0.1 ± 0.05	-0.1 ± 0.05
Microturbulence, ξ(km s^{-1})	1.4 ± 0.1	1.8 ± 0.2
Macroturbulence, ζ(km s^{-1})	3.00 ± 0.13	7.6 ± 0.5

These results, together with Hipparcos parallaxes and recently published photometry, lead to estimates of luminosity, mass and radius. Inferred angular diameters are consistent with a well established empirical relationship but disagree with direct measurements by an interferometric technique.

Key words: stars: fundamental parameters – stars: individual: μ Peg – stars: individual: λ Peg

1. Introduction

High quality observations of carefully chosen spectral regions in the spectra of F, G, K type stars may be used to place tight constraints on the fundamental atmospheric parameters, effective temperature ($T_{\rm eff}$), surface gravity (g) and overall metallicity (usually denoted by [M/H], the abundance of metallic elements, principally iron, expressed in logarithmic units relative to the Sun). Smith & Ruck (1997) discuss the use of strong-line wings, in particular those of the Ca II 8542 Å line and the Mg I 8806 Å line. More extensive analyses incorporating absorption lines of iron and calcium, for which precise atomic data are available, have been described, for example, by Ruck & Smith (1995), Drake & Smith (1991, 1993).

In the present paper we report analyses of high resolution, high signal/noise spectral observations of the giant stars, μ Pegasi (HR 8684, HD 216131; $V = 3.48$) and λ Pegasi (HR 8667, HD 215665; $V = 3.95$), both of spectral type G8. The Bright Star Catalogue (Hoffleit & Jaschek 1982) assigns both stars to luminosity class III and gives almost identical parallaxes, 0.040 and 0.042 arcsec respectively. Hutter et al. (1989), reporting interferometric measurements of angular diameters, assign λ Peg to luminosity class II. This is supported by the recent Hipparcos satellite observations which place λ Peg about three times more distant than μ Peg, implying a considerably higher luminosity (see Sect. 5). Both stars have formed part of major surveys of the properties of late-type giants undertaken in recent years but have not been subject to individual critical analysis. Table 1 lists the parameters adopted in some recent work and shows a wide spread of values, especially for $\log g$ and [Fe/H]. Clearly, a resolution of these current uncertainties is desirable.

Send offprint requests to: G. Smith

2. Observations and data reduction

Observations of μ Peg and λ Peg were made at the McDonald Observatory on 1–4 November, 1991, by G. Smith and M. Ruck (University of Oxford) and J. Tomkin (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 5858, 6151, 6162, 6170, 6430, 6454 and 8805 Å. These observations made use of an échelle grating giving a dispersion varying between 0.013 Å per diode (15 μm) at 5858 Å and 0.020 Å per diode at 8805 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 to a negligible level. The entrance slit-width of 240 μm projected on to 3.6 diodes in the focal plane which, for the wavelength regions observed, 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

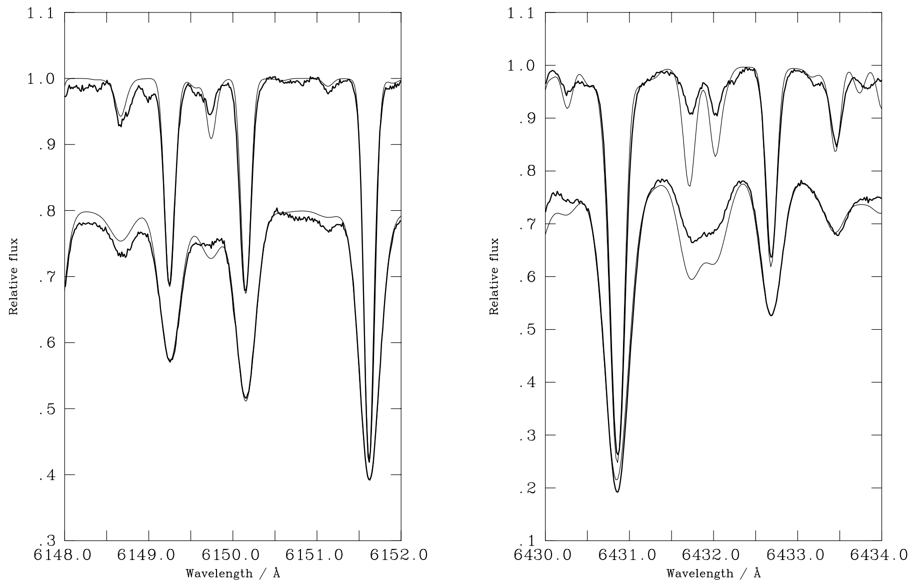

Fig. 1. Observed spectra of μ Peg and λ Peg (ordinates displaced 0.2 lower) together with fitted synthetic spectra for the regions around 6150 Å and 6432 Å. Note particularly the Fe I lines at 6151.62 Å, 6430.86 Å and the Fe II lines at 6149.25 Å, 6432.68 Å.

Table 1. Recent determinations of fundamental parameters for the stars μ Peg and λ Peg

Parameter	μ Peg	λ Peg	Ref.
$T_{\rm eff}$ (K)	4950	4830	1
	5060	4800	2
	4950	4750	3
$\log g$	2.5	1.9	1
(g in cm s^{-2})	3.05	3.20	2
	2.90P	2.35P	3
	2.50S	1.75S	3
[Fe/H]	-0.16	$+0.24$	1
	-0.16	-0.10	2
	$+0.01(+0.18)$P	$-0.03(+0.22)$P	3
	$-0.02(-0.04)$S	$-0.08(-0.11)$S	3

(1) Brown et al. 1989; (2) McWilliam 1990; (3) Luck & Challener 1995: these authors adopt two values for $\log g$; physical (denoted by P) is based on estimates of mass and radius, spectroscopic (denoted by S) is based on the Fe I/Fe II ionisation balance; separate abundances are also determined from lines of Fe I and Fe II (results in brackets).

to allow reliable identification of blends and sufficient spectral range to include all of the line wings. Integration times of 20 min (échelle) and 5 min (conventional grating) yielded spectra with signal/noise $\geq$ 100 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 computed 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 [M/H] than to $T_{\rm eff}$ or g, whereas the wings of the latter line are sensitive to [M/H] and $T_{\rm eff}$ but insensitive to g. Additional constraints on $T_{\rm eff}$ come from spectral regions with adjacent lines of Fe I and Fe II. Atomic data for Ca I lines was taken from the accurate laboratory work of Smith & Raggett (1981) and Smith (1988). 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. We assumed throughout that [Ca/H] = [Fe/H] = [Mg/H] = [M/H], which seems to be well established for stars of metallicity close to that of the Sun (Edvardsson et al. 1993). 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. 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 computed and observed profiles. Turbulence on small scales (microturbulence) broadens the atomic absorption coefficient and may be determined using equivalent widths of relatively unblended lines (see Sect. 4). Turbulence on large scales (macroturbulence) is sufficiently well accounted for by applying a Gaussian smoothing function to the synthe-

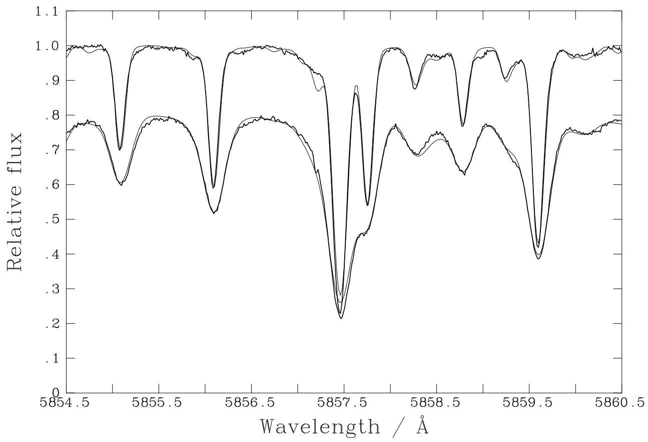

Fig. 2. Spectra of μ Peg and λ Peg (ordinates displaced 0.2 lower) together with fitted synthetic spectra in the 5858 Å region. Note particularly the Fe I lines at 5855.09, 5856.10, 5858.79 and 5859.60 Å; also the Ca I/Ni I blend at 5857.45/.75 Å.

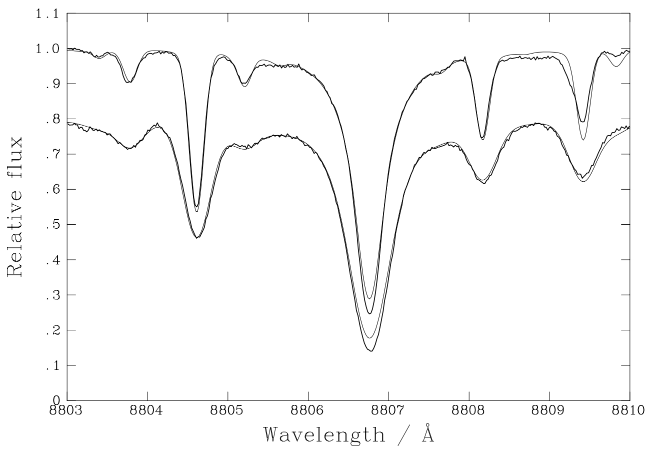

Fig. 3. Spectra of μ Peg and λ Peg (ordinates displaced 0.2 lower) together with fitted synthetic spectra in the 8806 Å region. Note particularly the wings of the strong Mg I line centred at 8806.75 Å. The lines at 8804.62 and 8808.17 Å are from Fe I.

sised spectra. In reality this smoothing function also includes instrumental and rotational broadening but instrumental broadening (equivalent to 1.8 km s^{-1} at 6000 Å) has a small effect compared to macroturbulence ($\simeq 3.5$ km s^{-1}) in lines of μ Peg and an almost negligible effect compared to macroturbulence ($\simeq 8$ km s^{-1}) in λ Peg. We expect rotational broadening to be insignificant in giant stars of spectral type G8.

4. Results

Each spectral region was first independently analysed to discover sets of mutually consistent stellar parameters which gave a good fit to the wings of strong lines and to full profiles of intermediate-strength lines. Our LTE assumption is not adequate to describe the innermost core regions of the strongest lines. Weak features in the spectra of late-type giants are too weak in the solar spectrum for reliable determination of atomic data. When results for all spectral regions were combined, there

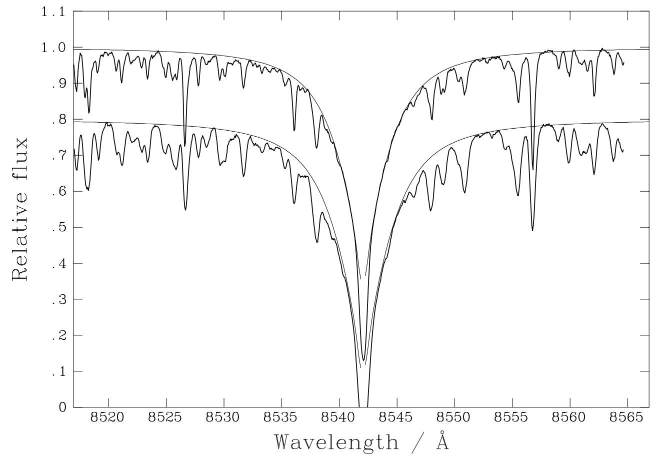

Fig. 4. Spectra of μ Peg and λ Peg (ordinates displaced 0.2 lower) together with profiles fitted to the wings of the extremely strong Ca II line centred at 8542.09 Å.

was clearly only one closely defined set of parameters which gave a good representation of the observed spectrum of each star. These parameters are listed below:

	μ Peg	λ Peg
$T_{\rm eff}$ (K)	5000 ± 50	4800 ± 50
$\log g$(g in cm s^{-2})	2.6 ± 0.1	1.7 ± 0.1
[M/H]	-0.1 ± 0.05	-0.1 ± 0.05
Microturbulence, ξ(km s^{-1})	1.4 ± 0.1	1.8 ± 0.2
Macroturbulence, ζ(km s^{-1})	3.00 ± 0.13	7.6 ± 0.5

Quoted errors on $T_{\rm eff}$, $\log g$ and [M/H] reflect our ability to judge the fit to a wide range of spectral features using MARCS atmospheres. The errors quoted on macroturbulence are the standard deviation of the mean for all the spectral regions investigated (an instrumental contribution equivalent to 1.8 km s^{-1} at 6000 Å has been removed). The determination of microturbulence will be discussed further below.

When comparing the spectra of the two stars, the most striking difference occurs in the width of the line profiles. Fig. 1 shows the region centred on 6151 Å with fitted profiles for our optimum set of parameters. The good fit to the Fe II line at 6149.25 Å and the Fe I line at 6151.62 Å should be noted. These lines respond differently to a change in $T_{\rm eff}$. We obtain an equally good fit to the 6430 Å region (see also Fig. 1) which includes the Fe I line at 6430.86 Å and the Fe II line at 6432.68 Å. Fig. 2 shows the region centred on 5858 Å which contains several Fe I lines and a Ca I line. The difference in line-width between lines in μ Peg and those in λ Peg arises almost wholly from the difference in macroturbulence. Fig. 3 shows the region centred on 8805 Å: the wings of the Mg I 8806 Å line provide a tight constraint on $T_{\rm eff}$ and [M/H] independent of turbulent broadening. Fig. 4 shows the region centred on 8542 Å: the wings of this line constrain $\log g$ once $T_{\rm eff}$ and [M/H] are determined by other spectral regions. For clarity, the fitted profiles shown in the 8542 Å region are those of the 8542 Å line alone. We have also undertaken a full synthesis including atomic and

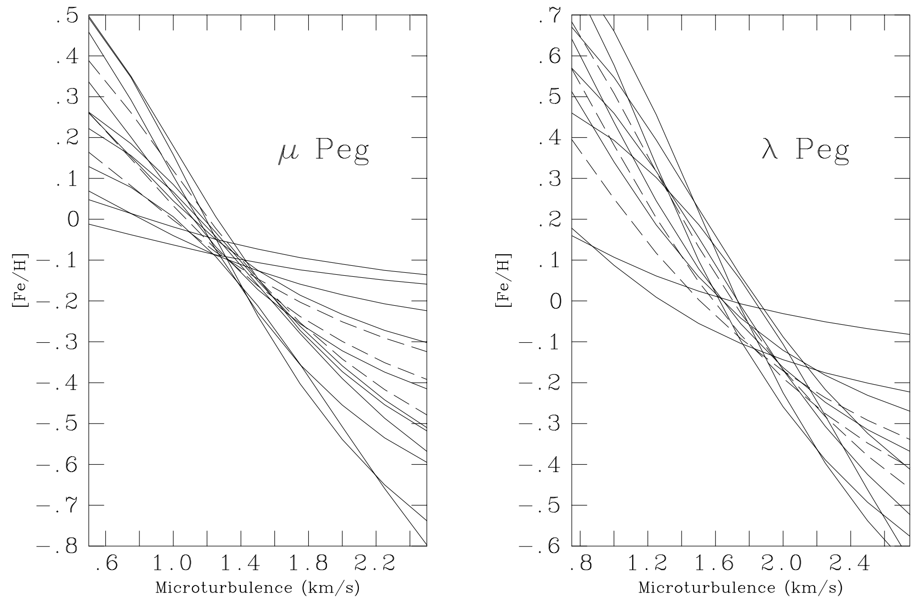

Fig. 5. Logarithmic abundance of iron, relative to the Sun, as a function of microturbulence for the spectral data listed in Table 2. Dashed curves correspond to Fe II lines.

molecular lines to check that the blending in the line wings does not depress the observed wing shape significantly.

The microturbulence parameter, ξ, may be determined, independently of macroturbulence, from equivalent widths of relatively unblended lines. Equivalent widths for Fe I and Fe II lines in μ Peg and λ Peg are shown in Table 2. Weak blends have been removed from the line wings following the method described by Smith et al. (1992). Using model atmospheres corresponding to our optimum parameters, we constructed loci of constant equivalent width on a graph of [Fe/H] against microturbulence for each star. These graphs are shown in Fig. 5. The loci should intersect in a narrow region defining appropriate values of [Fe/H] and ξ. In the case of μ Peg, a well-defined "neck" occurs at [Fe/H] $= -0.12 \pm 0.05$, $\xi = 1.4 \pm 0.1$ km s^{-1}. In the case of λ Peg, the "neck" is less well-defined, as a consequence of the greater blending in the spectrum, but values of [Fe/H] $= -0.08 \pm 0.10$ and $\xi = 1.8 \pm 0.2$ are indicated. Loci arising from lines of Fe II lie well within the regions defined by the more numerous Fe I lines. In both stars the indicated [Fe/H] agrees well with our value of [M/H], determined from strong-line wings, justifying our initial assumption that these quantities are equal in stars of near-solar metallicity. Our microturbulence values are somewhat lower than those often adopted for giant stars by earlier workers in this field, most of which were based on spectra of lower resolution and photometric accuracy. It should be noted, however, that Smith & Drake (1991) obtained $\xi = 1.4 \pm 0.1$ km s^{-1} for the atmosphere of the K0III giant, Pollux (β Gem), using spectra of high resolution and a similar method of analysis to that described here. An analysis of our μ Peg equivalent-width data using an atmosphere with $T_{\rm eff} = 5000$ K, $\log g = 2.5$ from the recent ATLAS9 grid (Kurucz 1992) yields a slightly broader "neck" in the region [Fe/H] $= -0.12 \pm 0.08$, $\xi = 1.35 \pm 0.10$ km s^{-1}. This result does not differ significantly from that obtained using MARCS atmospheres.

Table 2. Atomic data and equivalent widths for lines of Fe I and Fe II in the spectra of μ Peg and λ Peg

Wavelength (Å)	Excitation (eV)	$\log gf^a$	Equivalent width (mÅ)	
Fe I			μ Peg	λ Peg
5855.09	4.61	-1.52	40.6	51.8
5856.10	4.29	-1.55	57.2	75.0
5858.79	4.22	-2.20	31.0	
5859.60	4.55	-0.60	92.8	117
5862.37	4.55	-0.39	104.3	125
6151.62	2.18	-3.30^*	89.9	122
6157.73	4.07	-1.21	86.3	
6159.38	4.61	-1.85	26.3	39.2
6165.36	4.14	-1.47	68.6	90.2
6173.34	2.22	-2.88^*	107.7	146
6430.86	2.18	-2.01^*	163	212
Fe II				
6149.25	3.89	-2.85	46.7	66.4
6432.68	2.89	-3.64	60.9	86.7
6456.39	3.90	-2.21	75.4	101

^{a} $\log gf$ values are derived from the solar spectrum (see text) apart from those marked (*) which are laboratory measurements from Blackwell et al. (1982).

5. Discussion

Our analysis shows that all lines of Ca I, Fe I, Fe II and Mg I in the spectral regions observed are consistent with [M/H] $= -0.1 \pm 0.05$ in both stars. This is in contrast to the wide spread of [Fe/H] values obtained by other workers as shown in Table 1. Similarly, we find no evidence for the anomalous calcium and magnesium abundances found by Luck & Challener (1995) who obtained [Ca I/H] $= -0.46$, [Mg I/H] $= +0.42$ for λ Peg and [Ca I/H] $= -0.09$ and [Mg I/H] $= +0.25$ for μ Peg. An overall metallicity [M/H] $= -0.1$ is close to the mean value for stars in the solar neighbourhood (Edvardsson et al. 1993).

Blackwell & Lynas-Gray (1998) include μ Peg in the list of stars for which they determine $T_{\rm eff}$ using the infrared flux method. Their result, 4981 ± 25 K, is in excellent agreement with our own. This comparison is particularly satisfying since our own result is only the $T_{\rm eff}$ of a model atmosphere which accounts for specific spectral features whereas the infrared flux method determines $T_{\rm eff}$ by reference to the integrated flux from the star. Blackwell & Lynas-Gray (1998) also give an integrated flux above the Earth's atmosphere for μ Peg. Using their value of 1.27×10^{-9} W m^{-2} and the parallax of 27.95 mas recently measured by means of the Hipparcos satellite (see *The Hipparcos Catalogue*, ESA SP-1200, 1997), we determine the luminosity of μ Peg to be $(51 \pm 3) L_\odot$, typical of a star towards the lower end of the Red Giant Branch. From the relations, $L = 4\pi R^2 \sigma T_{\rm eff}^4$, and $g = GM/R^2$, we may eliminate the stellar radius R to obtain:

$$\log(L/L_\odot) = \log(M/M_\odot) - \log(g/g_\odot) + 4\log(T_{\rm eff}/T_{\rm eff}^\odot).$$

Our values for L, g and $T_{\rm eff}$ imply a mass $M \simeq 1.3 M_\odot$ for μ Peg.

There is no integrated flux determination for λ Peg. However, Petford & Blackwell (1989) determine a flux for the wavelength range $3800 - 9000$ Å for both μ Peg and λ Peg, obtaining 6.33×10^{-10} and 4.24×10^{-10} W m^{-2} respectively. We note that the total integrated flux for μ Peg, given by Blackwell & Lynas-Gray (1998) and quoted above, is exactly twice the flux from $3800 - 9000$ Å. If we assume that the same factor of two is applicable to λ Peg and make use of the Hipparcos parallax, 8.26 ± 0.70 mas, we can carry through the same sequence of calculations as carried out above, obtaining, for λ Peg, $L \simeq 390 L_\odot$ and $M \simeq 1.5 M_\odot$. This star is clearly more evolved than μ Peg and can appropriately be assigned to luminosity class II.

Our results imply $R = 9.6 R_\odot$ for μ Peg and $R = 28.5 R_\odot$ for λ Peg and, through the use of the Hipparcos parallaxes, angular diameters of 2.5 and 2.2 mas respectively. These angular diameters are roughly half the values measured interferometrically by Hutter et al. (1989). The interferometric measurements were described as preliminary and, in the case of our two stars, do not appear to have been confirmed. Hutter et al. compare their results with a relationship between the $(V - R)$ colour index, a visual surface brightness parameter, the unreddened V magnitude and the angular diameter developed by Barnes & Evans (1976), Barnes et al. (1978). Fig. 5 of their paper shows that the interferometric angular diameters for μ Peg and λ Peg are roughly twice those predicted by the relationship of Barnes et al. whereas interferometric angular diameters greater than about 6 mas fit the relationship well. Our own angular diameters are a good fit to the relationship and remove this anomaly.

6. Conclusion

Our analysis of high resolution, high signal/noise spectral observations of the stars μ Peg and λ Peg has shown that the profiles of all intermediate strength lines of Ca I, Fe I and Fe II plus the wings of the strong lines of Ca II at 8542 Å and Mg I at 8806 Å are consistent with [Ca/H] = [Fe/H] = [Mg/H] $\simeq -0.1$, which is close to the average metallicity for stars in the solar neighbourhood. Macroturbulent broadening is significantly larger in λ Peg leading to wider and shallower line profiles. The star μ Peg has a luminosity typical of stars at the lower end of the Red Giant Branch whereas λ Peg has a much higher luminosity and is considerably more evolved. The effective temperature of μ Peg, derived from a model-atmospheres analysis of specific spectral features, agrees closely with that determined by means of the infrared flux method (Blackwell & Lynas-Gray 1998). Our results for effective temperature and surface gravity for μ Peg can be combined with the Hipparcos parallax and a determination of the flux incident on the Earth to yield a mass in the region of 1.3 $M_\odot$. Full integrated flux data are not available for λ Peg but an indirect estimate indicates a mass of about 1.5 $M_\odot$. Together with Hipparcos parallaxes, our results imply very similar angular diameters for the two stars which are consistent with the well established empirical relationship of Barnes et al. (1978) but which are smaller by roughly a factor of two than values measured directly using an interferometric method by Hutter et al. (1989).

Acknowledgements. I wish to thank the Director of the McDonald Observatory for granting facilities for our observations. It is a particular pleasure to record my gratitude to Professor D.L. Lambert and Dr. J. Tomkin of the University of Texas for considerable help with observations and data reduction, and for warm hospitality during my visit. Dr. M.J. Ruck gave substantial help with the initial stages of data reduction. I gratefully acknowledge the generosity of Professor B. Gustafsson in making the MARCS suite of programs available to UK astronomers. Data analysis and document preparation at Oxford were undertaken using packages available on the STARLINK network which is supported by the Particle Physics and Astronomy Research Council (PPARC) of the U.K. Dr. A.E. Lynas-Gray deserves special thanks for advice on model atmospheres and use of STARLINK software. I acknowledge support from the Panel for Allocation of Telescope Time of the former Science and Engineering Research Council while carrying out this work.

References

Barnes T.G., Evans D.S., 1976, MNRAS 174, 489
Barnes T.G., Evans D.S., Moffett T.J., 1978, MNRAS 183, 285
Bell R.A., Eriksson K., Gustafsson B., Nordlund Å, 1976, A&AS 23, 37
Blackwell D.E., Lynas-Gray A.E., 1998, A&AS 129, 505
Blackwell D.E., Petford A.D., Shallis M.J., Simmons G.J., 1982, MNRAS 199, 43
Brown J.A., Sneden S., Lambert D.L., Dutchover E., 1989, ApJS 71, 293
Drake J.J., Smith G., 1991, MNRAS 250, 89
Drake J.J., Smith G., 1993, ApJ 412, 797
Edvardsson B., Andersen J., Gustafsson B., et al., 1993, A&A 275, 101

Hoffleit D., Jaschek C., 1982, *The Bright Star Catalogue* (4th edition), Yale Univ. Obs.
Holweger H., Müller E.A., 1974, Solar Phys. 39, 19
Hutter D.J., Johnston K.J., Mozurkewich D., et al., 1989, ApJ, 340, 1103
Kurucz R.L., 1992, In: Barbuy B., Renzini A. (eds.), Proc. IAU Symp. 149, The Stellar Populations of Galaxies, p. 225
Luck R.E., Challener S.L., 1995, AJ 110, 2968
McWilliam A., 1990, ApJS 74, 1075
Petford A.D., Blackwell D.E., 1989, A&AS 78, 511
Ruck M.J., Smith G., 1995, A&A 304, 449
Smith G., 1988, J.Phys.B 21, 2827
Smith G., Lambert D.L., Ruck M.J., 1992, A&A 263, 249
Smith G., Raggett D.St.J., 1981, J.Phys.B 14, 4015
Smith G., Ruck M.J., 1997, A&A 324, 1091