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# Solar-type stars with planetary companions: 51 Pegasi and 47 Ursae Majoris ⋆

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**Abstract.** Accurate stellar parameters are presented for the solar-type stars 51 Peg and 47 UMa. The announcement of the detection of jovian planets around these objects has recently caused much attention to extrasolar planet research. From the analysis of high resolution spectrograms we obtain for 51 Peg: $T_{eff}$ = 5793 ± 70 K, log $g$ = 4.33 ± 0.1, [Fe/H]= +0.20 ± 0.07 and for 47 UMa: $T_{eff}$ = 5892 ± 70 K, log $g$ = 4.27 ± 0.1, [Fe/H]= +0.00 ± 0.07. Evolutionary tracks computed individually for both stars and with detailed model atmospheres as upper boundary condition, come up with stellar masses of $1.12 \pm 0.06$ $M_\odot$ and $1.03 \pm 0.05$ $M_\odot$ for 51 Peg and 47 UMa, respectively. The stellar ages inferred are 4.0±2.5 Gyr for 51 Peg, not significantly different from the age of the Sun, and 7.3±1.9 Gyr for 47 UMa. A comparison of the spectroscopic parallaxes with accurate distances available from the Hipparcos satellite shows good agreement, a result that primarily gives confidence in the values for the surface gravity parameter, which is derived here from the wings of the strong Mg Ib lines.

**Key words:** Techniques: spectroscopic – stars: distances – stars: evolution – stars: fundamental parameters – stars: late-type – stars: planetary systems

## 1. Introduction

The study of extrasolar planetary systems is appealing for a number of reasons. Fundamental questions such as the formation of our own Solar System and the possible existence of habitable Earth-like planets can be addressed, as well as the question of star formation in general. The very small separation (∼0.05 AU) of the companion of 51 Peg (Mayor & Queloz 1995), placing it even closer than Mercury to the Sun, but with a mass comparable to Jupiter, certainly came as a surprise to contemporary predictions. One consequence, for instance, is that the planet's effective temperature due to the stellar insolation is well in excess of 1000 K, which contradicts an *in situ* formation out of icy planetesimals and may give rise to evaporation processes as possible loss mechanisms. Mayor & Queloz suggest two scenarios, where the planet might have either undergone orbital migration to its actual location, or could have been a brown dwarf, but stripped by radiation. The 47 UMa system (Butler & Marcy 1996) is different in that it qualitatively resembles our own Solar System. The separation of the planet is ∼2.1 AU, the period is 2.98 yr and its mass at least 2.4 $M_{\rm J}$ (where $M_{\rm J}$ is the mass of Jupiter), but otherwise well below the 0.08 $M_\odot$ hydrogen-burning limit (Perryman et al. 1996).

Spectroscopically, the orbital periods are read from the radial velocity curve. The separation and mass of a putative candidate, however, depend on the mass of the host star. Information of its spectral type is normally sufficient, since in most cases the orbital inclination of the system is not known, and planetary masses are then only lower limits. But if one asks for the *evolutionary stage* or *age* of the star, accurate stellar parameters are a necessary condition.

This request is reinforced by the very recent claim of Gray (1997) that – based on the analysis of high resolution spectra with $\lambda/\Delta\lambda$ ∼100000 – the 4-day period spectroscopic variations of 51 Peg are *intrinsic to the star* and the chance of their being caused by a planet vanishingly small. But if the star itself is varying periodically, what kind of oscillations can we expect? Radial pulsations, for instance, are most probably excluded by the absence of any significant photometric brightness variations (Mayor & Queloz 1995, Burki et al. 1995, Guinan et al. 1995, Perryman et al. 1996, Henry et al. 1997) and to date the line variations have been found to be sinusoidal and perfectly stable for more than 300 cycles, which is another constraint to pulsation scenarios. Nevertheless, according to Hatzes et al. (1997), the presence of low-order nonradial pulsations cannot be excluded with certainty. Evidently, the focus is now back on the nature of the star and its position in the H-R diagram, and the same holds true for the other recent planet detections around $\rho^1$ Cnc, $\tau$ Boo and $\upsilon$ And (Butler et al. 1997), with orbital periods comparable to 51 Peg.

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⋆ Based on observations collected at the German Spanish Astronomical Center, Calar Alto, Spain

For deriving reliable stellar parameters it is, however, important to realize that effective temperatures, surface gravities and metallicities are not found without reference to other quantities, such as microturbulence, for metallicity gets its fine tuning from this non-thermal velocity component. Even more, one has to specify the metal abundance pattern, if significant deviations from solar values should occur, as is the case with e.g. metal-poor stars. In addition it often happens that straightforward equivalent width measurements do not suffice, but instead, detailed line profile analyses are required. High resolution, high signal-to-noise spectroscopy is then the prerequisite to take care of broadening effects such as macroturbulence, rotation, hyperfine structure, isotopic shifts or Zeeman splitting.

From analyses found in the literature 51 Peg and 47 UMa are deemed to be solar-type G dwarfs, although 51 Peg has also been claimed to be somewhat evolved towards the subgiant stage. The resemblance of both stars to the Sun is attractive, because it provides a well defined *reference point* in the model atmosphere calculations and stellar evolutionary tracks. The reverse of the medal, however, is that age estimates may lack the desired accuracy. Hipparcos data for three stars with planetary candidates – including 51 Peg and 47 UMa – have recently been published by Perryman et al. (1996) prior to the general catalogue release. The third star, 70 Vir, has a companion of at least 6.6 $M_{\rm J}$ (Marcy & Butler 1996), which is already close to the brown dwarf limit ($\sim$10 $M_{\rm J}$). In fact, the eccentric orbit of this object intimates it was not born in a disk, but instead as a separate cloud fragment during the initial collapse (Boss 1996, Beckwith & Sargent 1996, Gehman et al. 1996, Mazeh et al. 1997). The prepublication of Hipparcos data enables a direct comparison of the accurate (1%) astrometric distances with our spectroscopic parallaxes, the uncertainties of which are inferior by at least one order of magnitude, but otherwise rather *independent* of distance. This in turn provides a good estimate of the stellar surface gravity, for uncertainties in the spectroscopic distance scale are dominated by this parameter.

In Section 2 we give a short description of the observations. The stellar parameters are discussed in Sect. 3, followed by mass and age estimates in Sect. 4 and a comparison of the spectroscopic parallaxes to the Hipparcos astrometry in Sect. 5. The last section summarizes the results.

## 2. Observations

We obtained redundant spectra of 51 Peg and 47 UMa on two consecutive observing runs (Sep./Oct. 1996) at the Calar Alto 2.2m telescope equipped with the fiber optics Cassegrain échelle spectrograph FOCES (Pfeiffer et al. 1997).

51 Peg (=HR 8729, HD 217014) has a visual magnitude of $V$=5.47, 47 UMa (=HR 4277, HD 95128) is even brighter with $V$=5.05. Typical exposure times were therefore only a few minutes with nominal signal-to-noise values of 200-350 at $\lambda$=5500Å. The actual data, however, show an unexpected residual noise as a result of moving the fibre position with the telescope. For this reason the real quality of the data is not exceeding S/N$\sim$150. The September 1996 spectra were exposed to a $1024^2$ $24\mu$ CCD and have a wavelength coverage from 4200Å to 8800Å with a resolution of $\lambda/\Delta\lambda \sim 35000$. In October 1996 we employed a $2048^2$ $15\mu$ CCD, with $\lambda/\Delta\lambda \sim 60000$ from 4000Å to 10000Å. The data reduction follows the common path as outlined by e.g. Horne (1986). Details with respect to the FOCES spectrograph and the data reduction will be found in Pfeiffer et al. (1997).

## 3. Stellar parameters

The stellar parameters are obtained following the prescriptions in Fuhrmann et al. (1997): in short, Balmer lines are used to determine the effective temperature, the surface gravity is deduced from Mg Ib lines and with reference to other weak Mg I lines. The iron abundance and microturbulence parameter are derived from Fe II lines. For the line profile analyses the instrumental profile results from additional spectra of the Moon in combination with the Kitt Peak Solar Flux Atlas (Kurucz et al. 1984). Our values for neither macroturbulence $\zeta_{RT}$ nor rotation $v\sin i$ are individually very precise since these quantities are hardly separable from each other in both stars. This compensatory characteristic has however no influence on other parameters such as metallicity.

### *51 Pegasi*

From inspection of the Balmer lines in Fig. 1 it becomes immediately clear that 51 Peg must be very close to the solar effective temperature. With H$\alpha$ and H$\beta$ from the redundant observations we get $T_{eff}$ = 5793 $\pm$ 70 K. The absorption line spectrum suggests a metallicity higher than solar, but this also depends on the microturbulence parameter $\xi_t$ and – since only Fe II lines are taken into account – on the gravity parameter, as well. Therefore, as usual, the final set of the stellar parameters is the result of an iterative procedure with even macroturbulence, rotation and the instrumental profile as additional ingredients.

Figure 2 displays one of our October 1996 exposures in the range of the Mg Ib triplet $\lambda\lambda$5167–5183 and theoretical line computations for these three lines. Convolution with a Gaussian of 4.1 km s$^{-1}$ for the instrumental profile (derived from a Moon spectrum taken in the same night), a macroturbulence $\zeta_{RT}$ = 3.8 km s$^{-1}$ and $v\sin i$=2.0 km s$^{-1}$ (from the analysis of weak lines) is included for the sake of completeness, but has only a small effect here. The magnesium abundance is fixed from line profile fitting of weak Mg I lines. The only free parameter in Figure 2 is therefore the atmospheric pressure, that is, the gravity dependance of the Mg Ib damping wings. Our final choice – the dot-dashed curve – suggests log $g$ = $4.33 \pm 0.1$. For comparison, the shaded area indicates changes in log $g$ by $\pm 0.2$ dex, i.e. twice the uncertainties.

The iron abundance and microturbulence parameter of 51 Peg are simultaneously determined by forcing all Fe II lines to produce results independent from equivalent widths. The mean abundance is found to be [Fe/H]= +0.23 $\pm$ 0.03 (rms). The rms error is however not very significant, instead, an external error of $\sim$0.07 dex has to be assumed. The microturbulence

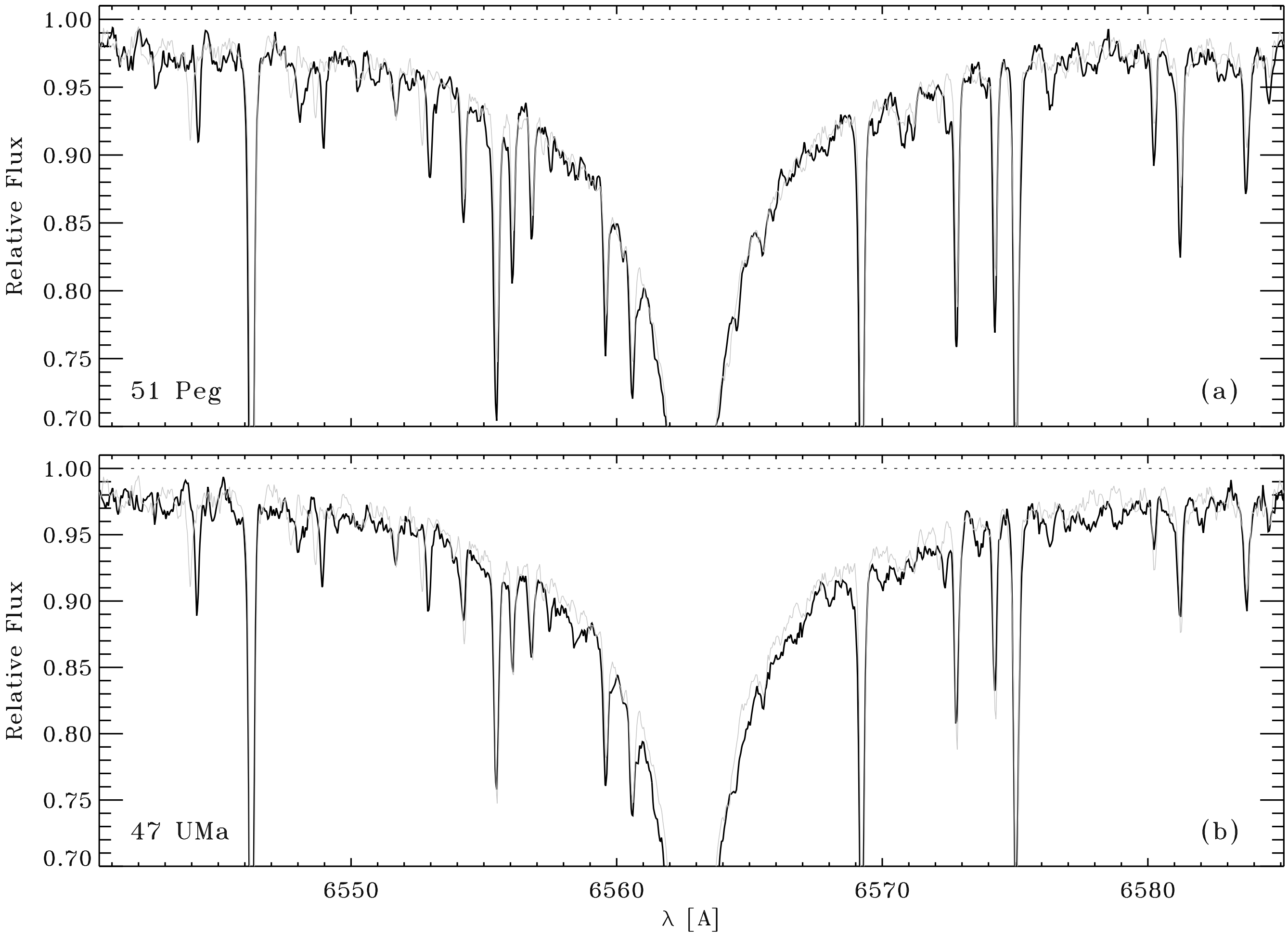


**Fig. 1.** H$\alpha$ line profiles of 51 Peg (thick curve, top panel), 47 UMa (thick curve, bottom panel) and the Moon (=reflected sunlight, dotted curve). Top: There is no perceptible difference in the location of the Balmer line wings of 51 Peg and the Sun. The effective temperature of 51 Peg is very close to the solar value: $T_{eff}$ = 5793 $\pm$ 70 K. Below: For 47 UMa we derive $T_{eff}$ = 5892 $\pm$ 70 K. The $\sim$100 K higher effective temperature of this star is also directly indicated from a peek at the tracings in both panels ($\Delta T$=100 K corresponds to $\sim$1% flux depression in the line wings)

associated with the iron abundance is $\xi_t$ = 0.95 km s$^{-1}$ and should be accurate to $\sim$0.20 km s$^{-1}$.

In complete analogy to 51 Peg, we also reduced several Moon spectra taken in the same nights to verify whether the solar abundance is reproducible by means of our differential method. But, as with earlier spectra taken in 1995, we do not escape the complication of a systematically higher metallicity, although the effect is relaxed to $\sim$0.03 dex with the higher resolved ($\lambda/\Delta\lambda \sim$ 60000) October 1996 spectra. Consequently, we adopt [Fe/H]=+0.20, instead of +0.23, for the metallicity of 51 Peg. Table 1 summarizes the final set of parameters.

Compared to analyses in the literature we find no contradicting values for the rotational velocity, which is reported to be in the range $v\sin i$ = 1.4...2.8 km s$^{-1}$ (Soderblom 1982, Benz & Mayor 1984, Mayor & Queloz 1995, François et al. 1996, Hatzes et al. 1997, Gonzalez 1997b). Measurements of the rotation period from the modulation of Ca II HK emission fluxes may arguably be the most precise data, since they are free of any aspect dependence. From the Ca II activity - Rossby number relation of Noyes et al. (1984) 51 Peg should rotate with $P_{calc}$ $\sim$29.6 days. Recently, Henry et al. (1997) mention two weak rotation modulations measured in 1987 and 1989, from which they infer $P_{obs}$ $\sim$37.1 days. With $R_\star$ = 1.20 $R_\odot$, as de-

**Table 1.** The stellar parameters of 51 Peg and 47 UMa derived from Balmer lines ($T_{eff}$), Mg Ib lines ($\log g$) and singly ionized iron lines ([Fe/H], $\xi_t$)

| Object | $T_{eff}$ [K] | $\log g$ | [Fe/H] | $\xi_t$ [km/s] | $v\sin i$ [km/s] | $\zeta_{RT}$ [km/s] |
|---|---|---|---|---|---|---|
| 51 Peg | 5793 | 4.33 | +0.20 | 0.95 | 2.0 | 3.8 |
| 47 UMa | 5892 | 4.27 | +0.00 | 1.01 | 2.0 | 3.7 |

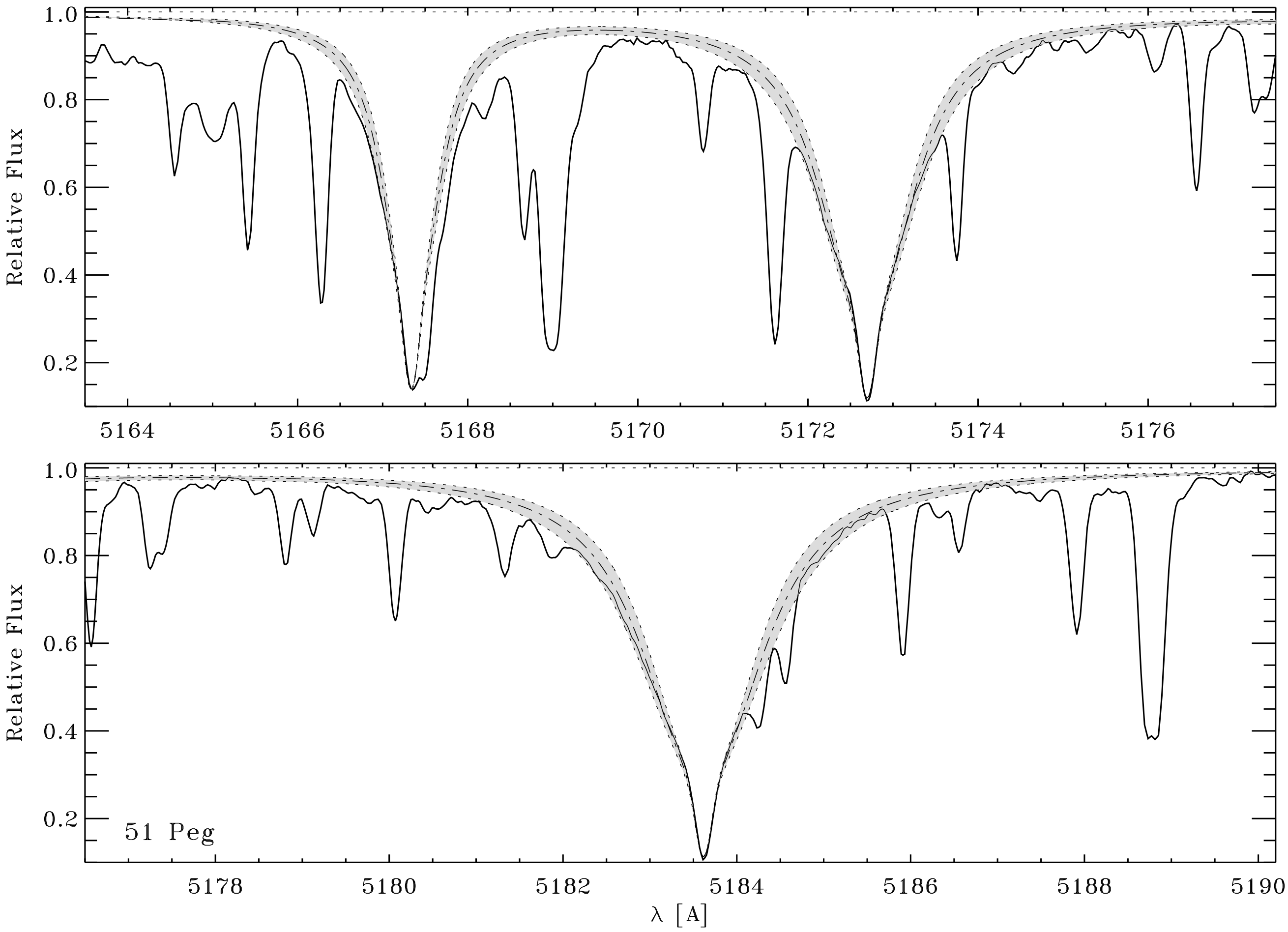


**Fig. 2.** The spectroscopic surface gravity determination of 51 Peg from the analysis of the Mg Ib triplet lines. $\lambda$5167 – being heavily masked by iron – can only be used in a complete spectrum synthesis approach, not done here. $\lambda$5183 on the contrary has broad damping wings and therefore receives higher weight compared to $\lambda$5172 in estimating the gravity parameter. The dot-dashed curve represents our final choice log $g$ = 4.33, the shaded area displays changes from this value by $\pm 0.2$ dex

duced below from log $g$ and the mass of 51 Peg, the equatorial velocities result in $v$ = 2.1 km s$^{-1}$ and $v$ = 1.6 km s$^{-1}$ for the calculated and observed periods, respectively. Our own measurement $v\sin i$ = 2 km s$^{-1}$ is erroneous by $\sim$1 km s$^{-1}$, but, as stated above, this poses no problems to the line profile analyses, for a too small $v\sin i$ value is compensated by a somewhat higher macroturbulence parameter $\zeta_{RT}$, and vice versa.

The determination of the effective temperature compares to other analyses as follows: Hearnshaw (1972), $T_{eff}$ = 5727 K; McWilliam (1990), $T_{eff}$ = 5740 K; Edvardsson et al. (1993), $T_{eff}$ = 5755 K; M. Grenon, $T_{eff}$ = 5773 K, and J. Valenti, $T_{eff}$ = 5724 K (both cited in Mayor & Queloz 1995); Gratton et al. (1996), $T_{eff}$ = 5669 K; Gonzalez (1997b), $T_{eff}$ = 5779 K; and Gray (1995), who estimates 51 Peg to be 61 K cooler compared to the Sun. The overall metal content of 51 Peg is consistently proposed to be higher than solar within the limits +0.05$\leq$[Fe/H]$\leq$+0.24. Our value is at the high end of this range, thereby suggesting that 51 Peg is in fact a super-metal-rich star.

Substantial discrepancies, however, arise from the determination of the surface gravity. The very low value log $g$ = 3.76 given by McWilliam (1990) is the result of an erroneous absolute visual magnitude $M_V$, which in turn was derived from its revised spectral classification that misidentifies the star as a subgiant (G2.5 IVa). Xu (1991) derives log $g$ = 4.13 from low resolution spectra of Na I and Ca II lines in the near infrared; the Strömgren $c_1$ index employed by Edvardsson et al. (1993) suggests log $g$ = 4.18. Both values are not supported from inspection of Fig. 2. The even lower surface gravity value given by Gratton et al. (1996), log $g$ = 4.06, is based on the iron ionization equilibrium and is therefore the direct result of their somewhat low effective temperature 5669 K. The only analyses that agree with ours is Hearnshaw's (1972) log $g$ = 4.27, M. Grenon's log $g$ = 4.32 from Geneva photometry, and the spectroscopic work of J. Valenti, that comes up with log $g$ = 4.30. There is only marginal agreement with the very recent analysis of Gonzalez (1997b), who advocates the highest of all surface gravity values, log $g$ = 4.44.

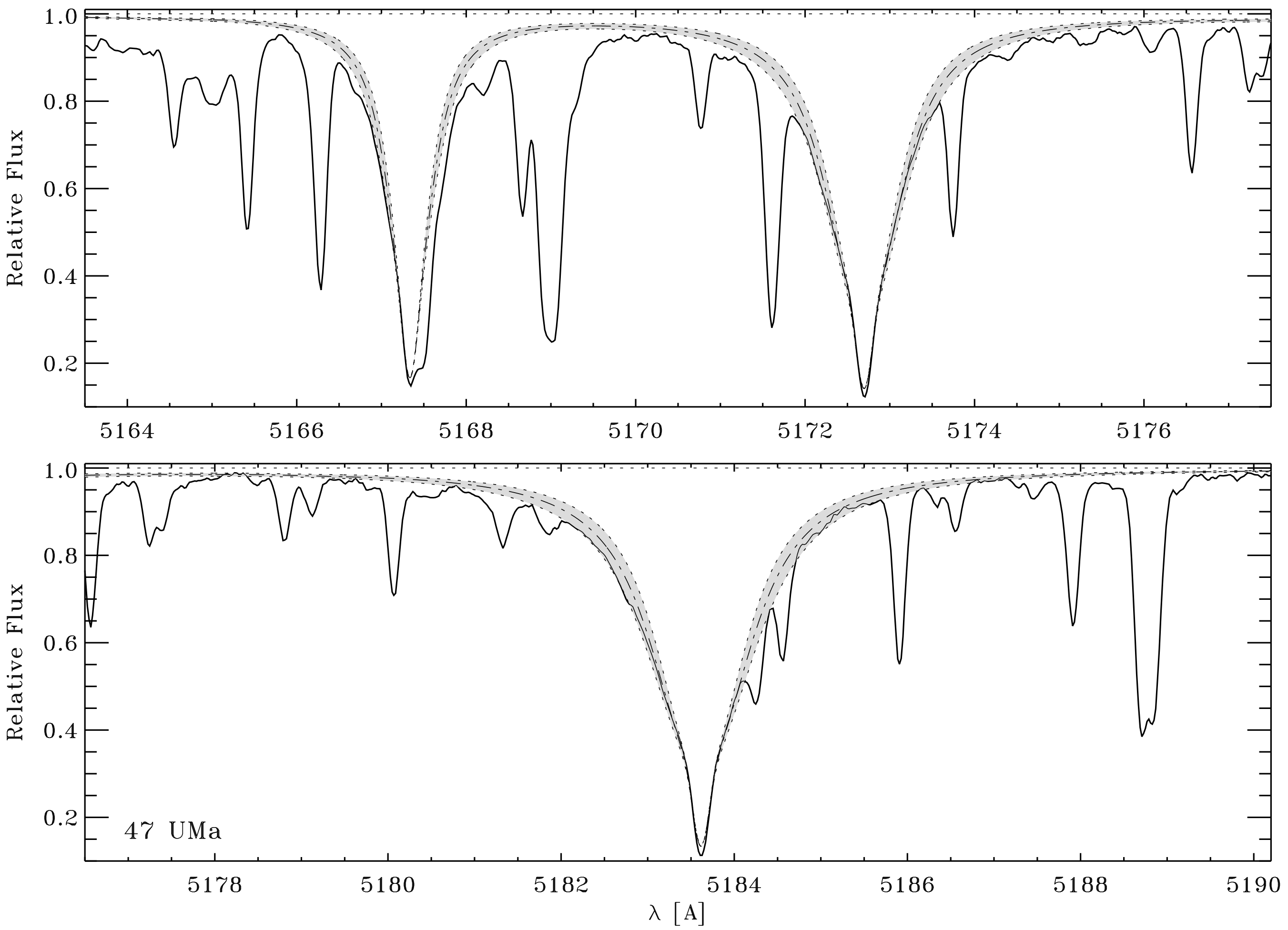


**Fig. 3.** Same as Fig. 2, but for 47 UMa. The surface gravity is found to be log $g$ = 4.27 (dot-dashed curve), the shaded area displays changes from this value by $\pm 0.2$ dex

An ill-determined surface gravity parameter has of course consequences on quantities such as metallicity, mass, radius, luminosity, age and distance (and therefore kinematics and orbital parameters) of a star. The Hipparcos data definitely improve the setting in that spectroscopic distance estimates, which mainly depend on log $g$, can now be tested. We come back to this point in Sect. 5, after having derived the stellar masses of 51 Peg and 47 UMa.

*47 Ursae Majoris*

In analogy to 51 Peg we compare in Fig. 1 the H$\alpha$ Balmer line of 47 UMa to a spectrum of the Moon. The mean effective temperature derived from H$\alpha$ and H$\beta$ is found to be $T_{eff}$ = $5892 \pm 70$ K. The surface gravity determination is displayed in Fig. 3: we infer log $g = 4.27 \pm 0.1$ from the wings of $\lambda$5172 and especially $\lambda$5183. The iron abundance, derived from Fe II lines, results in [Fe/H]= +0.03 $\pm$ 0.02 (rms). Again, an external error of $\sim$0.07 dex is more significant and we decrease the absolute value by –0.03 dex to [Fe/H]=+0.00, in analogy as explained above for 51 Peg. All stellar parameters along with $\xi_t$, $\zeta_{RT}$ and $v\sin i$ are summarized in Table 1.

The comparison with analyses from the literature leads to a similar picture as for 51 Peg: little scatter for the effective temperature and metallicity, but no consensus with respect to log $g$.

Hearnshaw (1974) derives $T_{eff}$ = 5860 K, very close to the value of Edvardsson et al. (1993), $T_{eff}$ = 5882 K. Gratton et al. (1996) and Gonzalez (1997b) get $T_{eff}$ = 5811 K and $T_{eff}$ = 5943 K, respectively. Gray (1994, 1995) determines an effective temperature 100 K higher than the Sun. Metallicities are derived to be in the range –0.02$\leq$[Fe/H]$\leq$+0.09, i.e. approximately solar.

There are also consistent results with respect to the projected rotational velocity $v\sin i$ = 1.9...3.0 km s$^{-1}$ (Soderblom 1982, Benz & Mayor 1984, Henry et al. 1997, Gonzalez 1997b). From the above mentioned Ca II HK activity relation, Henry et al. (1997) give $P_{calc}$ $\sim$21.5 days for the rotation period. If confirmed, and with $R_\star$ = 1.23 $R_\odot$, our preferred value for the stellar radius of 47 UMa, the equatorial velocity would then become $v$ = 2.9 km s$^{-1}$.

Although the investigations of 47 UMa consistently lend support to a star close to solar effective temperature and metallicity (Edvardsson et al. even call 47 UMa to be *the closest equivalent to the Sun* in their sample of some 200 field F and G disk dwarfs), we are left with a "continuum" of proposed values for the surface gravity: Gratton et al. (1996), log $g$ = 4.09; this work, log $g$ = 4.27; Hearnshaw (1974), log $g$ = 4.31; Edvardsson et al. (1993), log $g$ = 4.34; and Gonzalez (1997b), log $g$ = 4.45, from photometric and spectroscopic data, and log $g$ = 4.55, from the analysis of iron lines.

## 4. Evolutionary tracks

Knowing that 51 Peg and 47 UMa should have masses close to the Sun, we restrict the stellar evolutionary calculations to 0.95...1.20 $M_\odot$, with solar metallicity for 47 UMa and [Fe/H]=+0.20, being representative for the metallicity of 51 Peg (cf. Table 1).

The absolute magnitudes follow immediately from the Hipparcos parallaxes given in Perryman et al. (1996). Bolometric corrections are taken from VandenBerg & Bell (1985) and VandenBerg (1992) and are on the scale $BC_{V,\odot} = -0.12$ mag. For 51 Peg and 47 UMa the bolometric corrections are $-0.12$ mag and $-0.10$ mag, respectively. Uncertainties, mainly due to zero-point shifts, are estimated to be $\Delta BC_V \simeq$ 0.05 mag. Along with the small distance scale error from the Hipparcos data, we consider the bolometric magnitudes to be accurate to 0.06 mag for both stars, that is, $M_{bol}$ is remarkably fixed in the H-R diagrams displayed in Figs. 4 and 5. A major concern is still the uncertainty in $T_{eff}$, which we estimate to ~70 K, although this may be somewhat conservative in view of the fact that both stars are not very distinct from the Sun.

As a consequence of detailed investigations concerning unified stellar models and convection in cool stars (Bernkopf 1997), the evolutionary tracks are calculated by means of a stellar evolution code that makes allowance for line-blanketed model atmospheres as upper boundary condition. Furthermore, the convection model of Canuto and Mazzitelli (1991, 1992) is applied to the calculations and the OPAL opacities of Rogers and Iglesias (1992) are used. The helium abundance $Y = 0.273$ and the convection parameter $\alpha_{\rm CM} = 0.82$ are the results of fitting an evolutionary track for solar mass to the position of the Sun in the H-R diagram at its present age. The solar metal abundance is adopted to be $Z = 0.0174$. A more detailed description and references to the stellar evolution program are given in Bernkopf (1997). The evolutionary tracks for different stellar masses and solar metallicity as well as [Fe/H]=+0.20 are presented in Figs. 4 and 5.

According to Fig. 4 the stellar mass of 47 UMa is situated between 1.00 and 1.05 $M_\odot$ due to the error in the effective temperature. The effect of the ~0.07 dex uncertainty in the spectroscopic metallicity determination can be studied in Fig. 5, where the position and error bars of 47 UMa are marked by dotted lines. The shift of 0.2 dex in metallicity results in a stellar mass that is about 0.13 $M_\odot$ higher compared to Fig. 4. Therefore rescaling this mass error to $\Delta$[Fe/H]=0.07 dex and with $\Delta T$ = 70 K a quite accurate mass of $1.03 \pm 0.05$ $M_\odot$ is found. In the same way the stellar mass of 51 Peg results in $1.12 \pm 0.06$ $M_\odot$ from Fig. 5 for the temperature error and Fig. 4 for an estimate of the metallicity error.

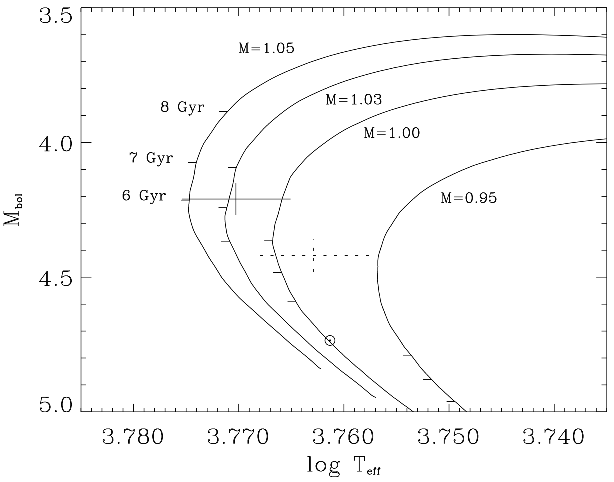


**Fig. 4.** Evolutionary tracks for 0.95, 1.00, 1.03 and 1.05 $M_\odot$ with solar abundance for 47 UMa. Tick marks are given for 6, 7 and 8 Gyr. The stellar mass is found to be $1.03 \pm 0.05$ $M_\odot$ and an age 7.3±1.9 Gyr is indicated. The open circle denotes the position of the Sun and the dotted cross the position of 51 Peg

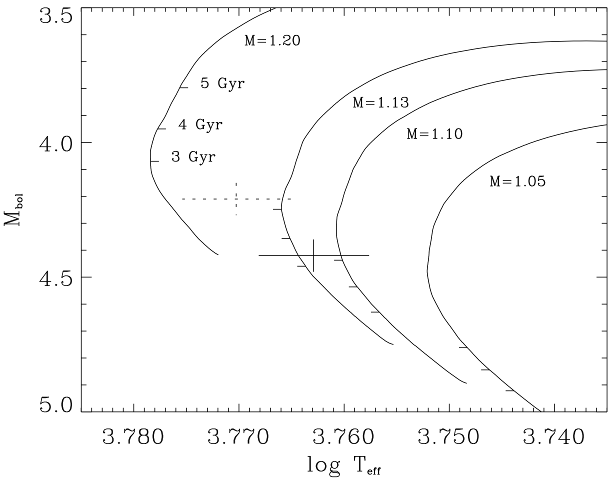


**Fig. 5.** Same as Fig. 4, but for 51 Peg. The evolutionary tracks are calculated for 1.05, 1.10, 1.13 and 1.20 $M_\odot$ and [Fe/H]=+0.20, the metallicity of 51 Peg. From this diagram a stellar mass 1.12±0.06 $M_\odot$ and an age of 4.0±2.5 Gyr are inferred. For comparison the position of 47 UMa is also given by the dotted cross

The stellar ages remain however somewhat more uncertain. From Fig. 4 an age of 7.3 Gyr is derived for 47 UMa which is situated in the turnoff region. The error in the bolometric magnitude is translated to an age error of about 0.5 Gyr. The uncertainty in the effective temperature results in a further age error of ∼1.6 Gyr as can also be read from the diagram. Finally, uncertainties due to the metallicity effect are again deduced from Fig. 5. There the age for the dotted marked position of 47 UMa is only 4 Gyr. Thus assuming 47 UMa to be enriched by 0.2 dex in metallicity an age error of 3.3 Gyr would be the result; rescaling to the 0.07 dex metallicity error leads to ∼1 Gyr. Hence, the age of 47 UMa is found to be 7.3 ± 1.9 Gyr. In Fig. 5 the age of 51 Peg is determined to 4.0 Gyr. The errors in bolometric magnitude, effective temperature and metallicity correspond to 0.6, 2.1 and 1.2 Gyr, respectively. We are therefore left with an uncertainty of 2.5 Gyr, which is the direct consequence of 51 Peg's unevolved evolutionary stage. Of course, further inaccuracies might be introduced from the stellar evolutionary calculations, but this concern is considerably relaxed from the fact that the Sun is taken as the reference point.

**Table 2.** Age and mass estimates of 51 Peg and 47 UMa from the evolutionary tracks in Figs. 4 and 5

| Object | $M_V$ | $M_{bol}$ | $BC_V$ | Mass $[M_\odot]$ | Age [Gyr] |
|---|---|---|---|---|---|
| 51 Peg | 4.54 | 4.42±0.06 | –0.12 | 1.12±0.06 | 4.0±2.5 |
| 47 UMa | 4.31 | 4.21±0.06 | –0.10 | 1.03±0.05 | 7.3±1.9 |

It is therefore highly unlikely that 51 Peg has an age of about 10 Gyr, as has been deduced from stellar evolutionary tracks and isochrones by Perrin et al. (1977) and from activity-age relations in Barry (1988) and Henry et al. (1997). The 8.5 Gyr proposed by Edvardsson et al. (1993) – again from isochrone fitting – may also be too high by several Gyr. On the other hand, Gonzalez (1997b) advocates an age of only $3^{+2}_{-1}$ Gyr for 51 Peg. This result is also based on evolutionary tracks and makes use of the recent Hipparcos data. Interestingly, Hearnshaw's (1972) early estimate also results in 3.3 Gyr, although this was considered to be only a lower limit.

The spread in the proposed ages of 47 UMa is not much less. The calculations of Perrin et al. (1977) result in 10 Gyr. Edvardsson et al. (1993) get 6.9 Gyr in agreement with Henry et al. (1997), who favour 7 Gyr. Barry (1988) finds 5.9 Gyr, whereas Gonzalez (1997b) derives 5 ± 1 Gyr.

As a cautionary remark, we note that the large ranges in the age determinations of 51 Peg and 47 UMa are certainly not atypical and we should be prepared that a good deal of the scatter in published age-metallicity relations (AMR) may *not* be intrinsic.

## 5. Spectroscopic parallaxes

With the advent of the Hipparcos parallax data we are in the pleasant situation to scrutinize the significance of spectroscopic parallaxes. Knowing the effective temperature, surface gravity and mass of a star, its apparent visual magnitude and bolometric correction, the spectroscopic parallax is found from

$$\log \pi = 0.5([g] - [M]) - 2[T_{\rm eff}] - 0.2(V + BC_V + 0.26)$$

with $M_{bol,\odot}$=4.74 and the usual logarithmic notation $[X] = \log(X/X_\odot)$. In this formula $V$ is well-known for 51 Peg and 47 UMa and the bolometric corrections ($BC_V$) are small.

The comparison of the astrometric Hipparcos distance and our spectroscopic evaluation is illustrated in Fig. 6 (the numbers are given in Table 3). The vertical dashed line in both panels of Fig. 6 is the Hipparcos distance as given by Perryman et al. (1996), with the shaded area indicating the uncertainties. Our spectroscopic measurement is depicted by the filled circles with detailed error bars for (top to bottom) $T_{eff}$, log $g$, mass, bolometric correction and the total distance scale error from all four quantities (cf. Table 3). From these data we immediately derive two results: first, there is good agreement with the astrometric distance scale and our spectroscopic distance scale and, second, the primary limitation of the spectroscopic parallaxes, is the accuracy achievable in log $g$ for both stars. Inferences of these results follow up in the final section.

For comparison, Fig. 6 also displays some spectroscopic distances calculated for different atmospheric parameters ($T_{eff}$, log $g$) and stellar masses found in the literature. We combine these data with our values for the bolometric corrections and – if not available from the literature – our mass estimates of Table 2 to compute the spectroscopic parallaxes (illustrated by open circles). Note, that it is Hearnshaw's (1972, 1974) seemingly out-dated analyses that show the best results.

## 6. Discussion

We have analyzed two stars of the solar neighborhood, for which the detection of periodic Doppler shifts has been announced in recent investigations. These observations have been interpreted in terms of tiny wobbles in the positions of the stars caused by planetary jovian-type companions. But since these discoveries are *indirect* in nature, and actually 51 Peg has subsequently been questioned to be accompanied by a planet, the focus is partly back on the characteristics of the parent stars.

In this respect, our differential model atmosphere analysis reveals two solar-type stars, one 0.2 dex enriched in metallicity, but otherwise solar effective temperature (51 Peg); the other only ∼100 K hotter and actually of solar metallicity (47 UMa).

If stellar pulsations should account for the observed periodicity of the spectral lines, the evolutionary stage of the stars is of course one of the most intriguing questions. Here, our analysis advocates that both stars are only slightly evolved. In fact, 51 Peg turns out to be younger than has been claimed in most analyses: an age close to the Sun seems more appropriate. Following the suggestion of Gonzalez (1997a, 1997b), the super-metal-rich status of 51 Peg may however be the mere result of atmospheric self-pollution from circumstellar disk material, induced by orbital migration of the planetary companion to its present ∼0.05 AU location (cf. Lin et al. 1996). In this case evolutionary tracks of decreased opacity would apply. As

**Table 3.** Comparison of the astrometric and spectroscopic distances of 51 Peg and 47 UMa. Individual errors as a function of temperature, gravity, mass and bolometric correction are given and also expressed in terms of distance errors

| Object | Hipparcos distance | Spectroscopic distance | $\Delta T_{eff}$ | $\Delta$ log $g$ | $\Delta$ Mass | $\Delta BC_V$ |
|---|---|---|---|---|---|---|
| 51 Peg | 15.36±0.18 pc (1.1%) | $15.97^{+2.12}_{-1.91}$ pc ($^{+13.3}_{-12.0}$%) | 70 K (0.48 pc) | 0.1 dex ($^{+1.99}_{-1.76}$ pc) | 0.06 $M_\odot$ (0.43 pc) | 0.05 mag (0.37 pc) |
| 47 UMa | 14.08±0.13 pc (0.9%) | $14.11^{+1.87}_{-1.68}$ pc ($^{+13.3}_{-11.9}$%) | 70 K (0.42 pc) | 0.1 dex ($^{+1.76}_{-1.56}$ pc) | 0.05 $M_\odot$ (0.34 pc) | 0.05 mag (0.33 pc) |

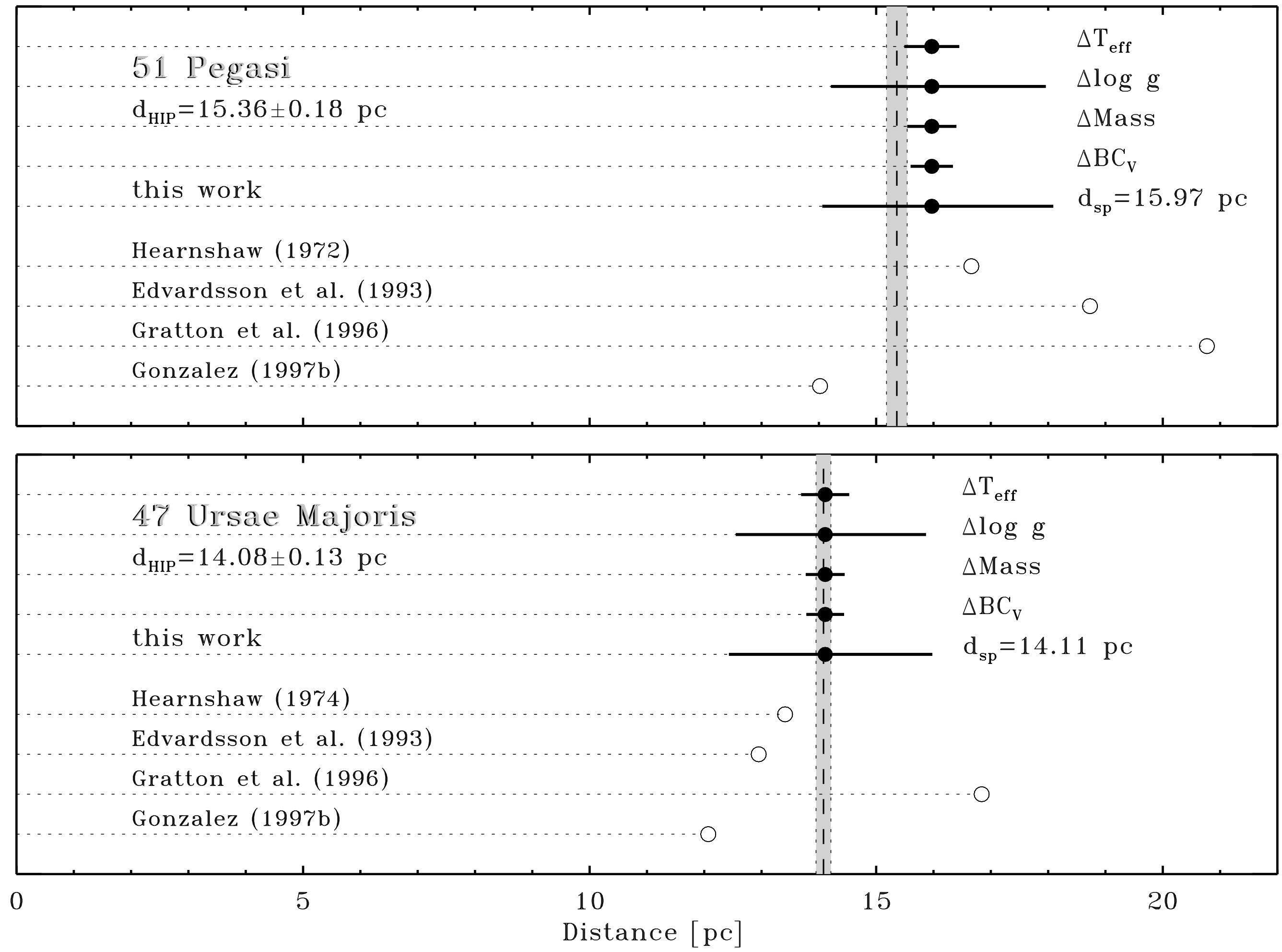


**Fig. 6.** The spectroscopic distance of 51 Peg and 47 UMa (filled circles) compared to the accurate astrometric data (vertical dashed lines) from the Hipparcos satellite (Perryman et al. 1996). Estimates of the individual spectroscopic uncertainties are indicated by horizontal bars. Astrometric errors are displayed by the shaded area. For both stars the spectroscopic distance scale is dominated by the accuracy achievable in log $g$. For comparison, open circles indicate spectroscopic distances for different sets of stellar parameters found in the literature

a result, 51 Peg would become older by 2–4 Gyr and an age close to the one we derive for 47 UMa would be indicated (cf. Fig. 4).

Nevertheless we confirm that both stars are by no means in portions of the H-R diagram where simple explanations for the observed radial velocity curves, other than a planetary signature, are conceivable. We are therefore inclined to the view that pulsational scenarios have a hard time at present, though only on-going high resolution bisector analyses and long-term monitoring of both stars may settle this question beyond doubt. According to Pan et al. (1997) there is also the possibility that *direct* interferometric observations may “resolve” the controversy.

The other aspect of our work is to exemplify for both stars the impact of the Hipparcos parallax data on the stellar surface gravity. This notoriously conflicting quantity can now be assessed more accurately, at least for those objects that are not in advanced stages of evolution, where mass estimates become increasingly uncertain.

We have demonstrated this especially for 51 Peg: contemporary investigations of this star agree in that the effective temperature is close to the Sun and the metallicity higher than solar. Contrary, the log $g$ determinations show a considerable spread. Knowing however that the mass of 51 Peg must be close to $1.1\ M_{\odot}$, the Hipparcos distance confines the gravity to log $g\ \sim$ 4.3...4.4. As a consequence, the stellar radius is $1.10...1.25\ R_{\odot}$; a value of $1.7\ R_{\odot}$, as suggested by Hatzes et al. (1997), can be ruled out.

In other words, by virtue of the small astrometric parallax errors, the Hipparcos data can give support to validate the reliability of methods for surface gravity determinations. The use of strong line wings of neutral species, as proposed by Blackwell & Willis (1977) and Edvardsson (1988) and also favoured in our recent work, is encouraging in this respect: for both stars, 51 Peg and 47 UMa, the log $g$ derived from the Mg Ib lines agrees with the Hipparcos distance scale.

This result certainly has to be put on a sound base as soon as the Hipparcos catalogue will be available. But in case of further confirmation for a much larger sample, we may realize that the strong line method for gravity determinations applied to spectroscopic parallaxes has the *potential* to establish a distance scale for F and G dwarf stars on a $80-90\%$ confidence level, almost independent of distance itself. If we take $V\ \sim$17 mag as a limit to high resolution spectroscopy for the class of giant telescopes currently put into operation, then one may reach up to 6 kpc for turnoff stars with $M_V\ \sim$3 mag. The scope of this scale would emcompass the thick disk as well as the globular clusters and would even meet the Galactic bulge.

Finally, very reliable $\log T_{eff}$-$\log g$ *Kiel Diagrams* could then be established for globular cluster turnoff- and main-sequences stars. Neither color-$T_{eff}$ transformations would be required nor any assumptions about reddening or distance. As a consequence, cluster age dating would certainly experience yet unkown accuracies.

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