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*Research Note*

# Stellar parameters from strong-line profiles: applications to Hyades cluster stars

**G. Smith and M.J. Ruck**

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

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**Abstract.** Profiles of the strong lines Ca II 8542 Å and Mg I 8806 Å in the spectra of the Hyades stars vB 37 (F4 V), vB 52 (G1 V), vB 64 (G6 V), vB 73 (G1 V), $\gamma$ Tau (K0 III) and $\epsilon$ Tau (K0 III) have been recorded at high resolution and with signal/noise $\geq$ 100. The usefulness of these lines as indicators of global metallicity and, in the cases of the late-type giant stars, surface gravity is illustrated. Our results support other recent spectral analyses which conclude that the Hyades cluster has a global metallicity of about +0.13 in logarithmic units relative to the Sun. We confirm that the star vB 52 is anomalous in having near-solar metallicity. We find that both giant stars have log $g$ about 2.5 but the surface gravity of $\epsilon$ Tau is slightly lower than that of $\gamma$ Tau.

**Key words:** stars: fundamental parameters – stars: late-type – stars: abundances

## 1. Introduction

It has been recognised in recent years that the wing profiles of certain strong absorption lines in the spectra of late-type stars place useful constraints on the fundamental stellar 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). In stars of fairly late spectral type (F,G or K) the wing profiles of the strong infrared triplet lines of ionised calcium (Ca II), in particular the wings of the strongest of these lines centred at 8542 Å, are known to be more sensitive to overall metallicity than to effective temperature or surface gravity (Smith & Drake 1987, 1990). In late-type giant stars the wings of the Mg I line at 8806 Å are insensitive to gravity and thus a reliable indicator of metallicity as long as the effective temperature can be determined by other methods (Ruck & Smith 1993). Cayrel et al. (1985) have used the wings of the H$\alpha$ line as a sensitive temperature indicator in an analysis of G-type dwarfs in the Hyades cluster.

In the present paper we analyse new observations of Ca II 8542 Å and Mg I 8806 Å line profiles for selected dwarf and giant stars in the Hyades cluster and discuss their implications for metallicity and gravity determination. Although recent spectroscopic analyses of Hyades stars indicate an overall metallicity [M/H] in the range +0.1 to +0.2, i.e. enhanced compared to the Sun (see Cayrel et al. 1985; Boesgaard & Friel 1990, and references therein), lingering uncertainties remain (Griffin & Holweger 1989).

## 2. Observations and data reduction

In selecting the stars to observe in this programme we took into account the work done by previous groups in order to facilitate some useful comparisons. Thus we observed the K0 giants $\gamma$ Tau and $\epsilon$ Tau, the most studied of the four giants in the cluster, along with a selection of F and G dwarfs, denoted by their van Bueren (1952, vB) numbers. The dwarfs chosen were vB 64 (G6), vB 73 (G1), vB 52 (G1), and vB 37 (F4). All three of our G dwarfs are in the sample observed by Cayrel et al. (1985), while vB 37 was observed as part of the programme by Boesgaard & Friel (1990). The star vB 64 was identified by Hardorp (1980) as a “solar analogue” and vB 52 was noted by Cayrel et al. to show anomalous abundances.

Observations of Hyades stars 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 $800\times800$ pixel CCD detector. For observations of the 8542 Å line profile the spectrograph was fitted with a conventional grating giving a dispersion of 0.06 Å per pixel (15 $\mu$m). Integration times for signal/noise $\simeq$ 100 or better were 60 min for the dwarf stars and 10 min for the giant stars in “seeing” of typically about 2 arcsec. For observations of the 8806 Å line profile in the giant stars the spectrograph was fitted with an échelle grating giving

*Send offprint requests to*: G. Smith

a dispersion of 0.02 Å per pixel. The corresponding integration time was 20 min. 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. Data were reduced at the Department of Astronomy of the University of Texas at Austin. Further analysis and measurement were carried out at Oxford using the standard Starlink package DIPSO.

## 3. Results

Our analysis was carried out by comparing observed wing profiles with profiles computed in the LTE approximation using model atmospheres. Justification for use of the LTE approximation in computations of the 8542 Å line wings has been given by Jørgensen et al. (1992). Several recent papers (see, for example, Drake & Smith 1993, 1991) have shown that departures from LTE only affect the 8542 Å line profile in the line core region within $\pm 2$ Å of the line centre. In the case of the 8806 Å line Ruck & Smith (1993) show several examples where the computed LTE profile fits the observed profile to within $\pm 0.2$ Å of line centre. A summary of the atomic data adopted for the two spectral lines is given in Table 1. A full justification for the choice of damping parameters and oscillator strengths is contained in the cited references. In the case of the 8806 Å line it is important to include the natural damping parameter, $\gamma_{\rm N}$, when calculating the line profile. As explained by Smith & Ruck (1993), it is because of the unusually large value of this parameter that the line wings are insensitive to gravity in the spectra of late-type giants. The hydrogen broadening parameter, $\gamma_{\rm H}/N_{\rm H}$, is the half-width at half-maximum intensity of the Lorentzian component at a temperature of 5000 K. It is determined from the solar spectrum using the abundances shown in the table.

### *3.1. Dwarf stars*

For the dwarf stars it seemed best to use scaled-solar model atmospheres based on the very successful Holweger & Müller (1974) solar atmosphere. Atmospheres were generated for the values of effective temperature, $T_{\rm eff}$, and surface gravity, $g$, listed below and a range of values of overall metallicity, [M/H].

| | vB 37 | vB 52 | vB 64 | vB 73 |
|---|---|---|---|---|
| $T_{\rm eff}$ (K) | 6800 | 5840 | 5780 | 5900 |
| $\log g$ | 4.35 | 4.44 | 4.44 | 4.40 |

For the G dwarfs, effective temperatures and surface gravities were taken from Cayrel et al. (1985) who utilised the wings of the H$\alpha$ line at 6563 Å to determine temperatures relative to the Sun with a claimed accuracy of $\pm 25$ K. In the case of the F dwarf, vB 37, we adopted the temperature derived from photometric calibrations by Boesgaard & Tripiccio (1986) who claimed an accuracy of $\pm 100$ K; our gravity for this star was based on the theoretical ZAMS models of VandenBerg & Bridges (1984) for a star of mass $\simeq 1.5$ M$_\odot$.

**Table 1.** Atomic data for the Ca II 8542 Å and Mg I 8806 Å lines; adopted solar abundances (on the scale $\log A_{\rm H}$ = 12.00)

| Line | $\gamma_{\rm N}$ rad s$^{-1}$ | $\gamma_{\rm H}/N_{\rm H}$(5000K) rad s$^{-1}$ cm$^3$ | $\log gf$ | $\log A$ | Ref. |
|---|---|---|---|---|---|
| Ca II 8542 Å | $1.5\times10^8$ | $1.0\times10^{-8}$ | −0.50 | 6.36 | 1 |
| Mg I 8806 Å | $5.1\times10^8$ | $1.9\times10^{-8}$ | −0.12 | 7.58 | 2 |

References: (1) Ruck & Smith 1993; (2) Smith & Drake 1988.

Line profiles were generated for the 8542 Å line assuming in every case that the calcium abundance relative to the Sun, [Ca/H], followed the overall metallicity. There is now strong evidence that this holds true for stars with metallicity similar to and higher than that of the Sun (Edvardsson et al. 1993). Turbulent, rotational and instrumental broadening were included in the calculations but these had no effect on the comparison between observed and computed profiles which was made at distances from the line centre ($\geq 2$ Å) where these other broadening mechanisms had negligible influence.

Our calculations showed that, at $T_{\rm eff} \simeq 5800$ K, a change in $T_{\rm eff}$ of 100 K has no discernible effect on the computed line profile. Since the effective temperatures of our G dwarfs are believed to be known to better accuracy than this, uncertainty in $T_{\rm eff}$ cannot affect the comparison between observed and calculated profiles. The uncertainty in our adopted values for surface gravity is unlikely to exceed 0.1 dex in $\log g$. Such an uncertainty affects the wing profiles by an amount equivalent to a change in [M/H] of about 0.01 dex. If no other sources of uncertainty were present, the comparison between observed and calculated profiles should thus determine [M/H] to $\pm 0.01$ dex. In fact, uncertainty in continuum placement in the observed profiles adds an additional error so that an uncertainty of $\pm 0.03$ dex is more realistic. At $T_{\rm eff} \simeq 6800$ K, corresponding to the F dwarf vB 37, the calculated profiles are more temperature sensitive. An increase in $T_{\rm eff}$ of 100 K has a similar effect on the line wings to a reduction in [M/H] of 0.07 dex, whereas an increase in $\log g$ of 0.1 dex is equivalent to an increase in [M/H] of only 0.01 dex. Thus, taking into account the likely uncertainties in $T_{\rm eff}$ and $\log g$ for vB 37, the comparison between observed and computed profiles only determines [M/H] to $\pm 0.08$ dex.

Fig. 1 shows comparisons between observed and computed profiles for all four dwarf stars. In the F dwarf vB 37 the red wing of the 8542 Å line is, as expected, depressed quite significantly by the presence of the P15 line of hydrogen (Smith & Drake 1988). The indicated values of overall metallicity are listed below.

| | vB 37 | vB 52 | vB 64 | vB 73 |
|---|---|---|---|---|
| [M/H] | +0.16 | +0.00 | +0.16 | +0.11 |
| | ±0.08 | ±0.03 | ±0.03 | ±0.03 |

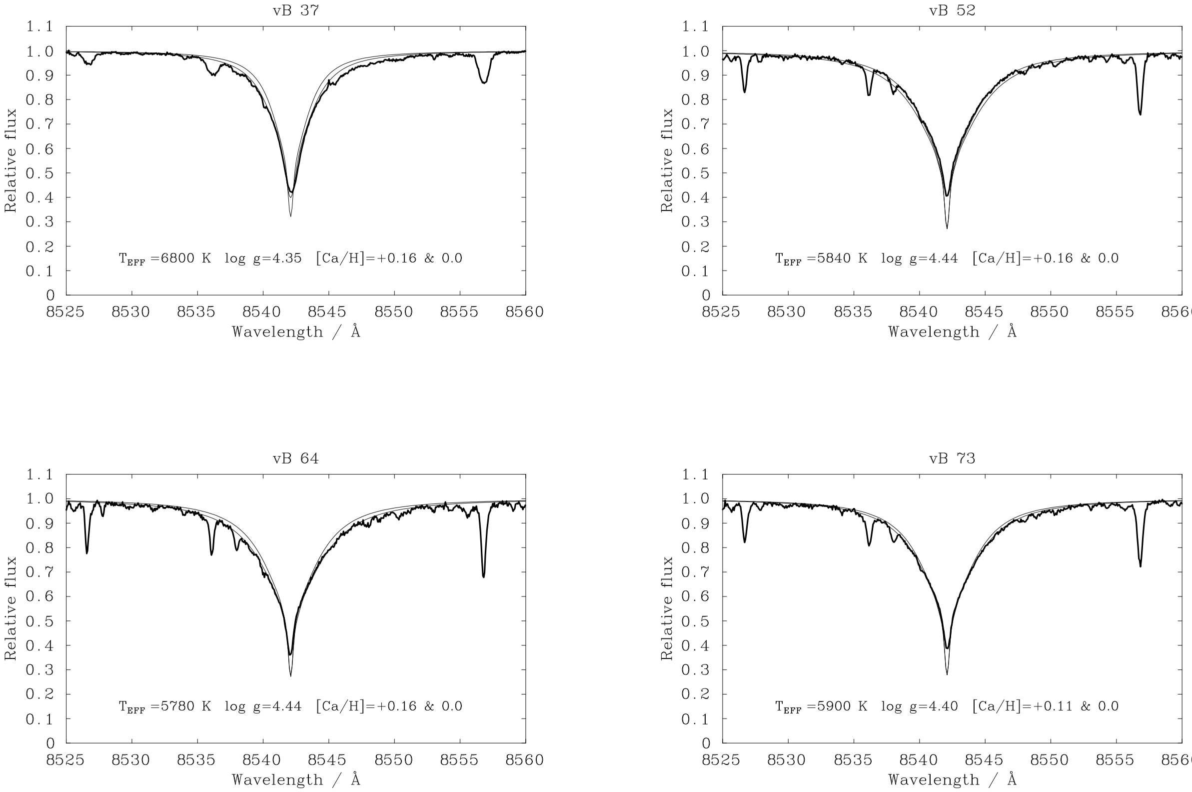


**Fig. 1.** Profiles of the Ca II 8542 Å line in four Hyades dwarfs, compared with synthetic profiles calculated for the parameters shown. In all cases the outer synthetic profile is the one with higher metallicity.

The comparisons for vB 37, vB 64 and vB 73 show clear evidence for enhanced metallicity with respect to the Sun. We find, as did Cayrel et al. (1985), that the star vB 52 is underabundant relative to the other three stars, having a near-solar metallicity. Cayrel at al. noted that vB 52 possessed a larger than average colour anomaly (a photometric index defined by Campbell, 1984, as a function of the colour indices $V-K$ and $B-V$), and a larger than average H$\alpha$ emission signature, both taken as signs of chromospheric activity. However, our profile for the 8542 Å line in vB 52 shows no sign of filling-in which, in any case, should be restricted to the line core as shown by the recent studies of $\epsilon$ Eri (Drake & Smith 1993) and $\xi$ Boo A (Ruck & Smith 1995). It seems likely, therefore, that the metallicity determined for vB 52 is genuine.

### 3.2. Giant stars

Table 2 lists the most recent spectroscopic determinations of the fundamental parameters for $\gamma$ Tau and $\epsilon$ Tau. With the exception of Griffin & Holweger (1989) all the studies listed have formed part of larger surveys of late-type giants. 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 ($\beta$ Gem). Using the profile of the Ca II 8542 Å line as a test feature, it was concluded that a model from the MARCS suite of atmospheres produced a theoretical line shape in best agreement with the observed line profile. We therefore adopted MARCS atmospheres for our analyses of $\gamma$ Tau and $\epsilon$ Tau. Without the anomalously high value from Lambert & Ries (1981), the mean of effective temperature determinations for $\gamma$ Tau listed in Table 2 is 4970 K. This value of the temperature is supported by a recent determination using the infrared flux method (Blackwell & Lynas-Gray 1994) which yields $4965 \pm 40$ K. A comparison of temperature sensitive features in high-resolution spectra of $\gamma$ Tau and $\epsilon$ Tau (G. Smith – unpublished) indicates that $\epsilon$ Tau is cooler than $\gamma$ Tau by about 50 K. This is confirmed by a new determination of the effective temperature of $\epsilon$ Tau, again using the infrared flux method, which yields $4911 \pm 35$ K (Blackwell & Lynas-Gray 1997). The mean value of $\log g$ for $\gamma$ Tau from Table 2 is 2.6. The spread in values, most of which were obtained using the ionisation equilibrium in iron, is much greater than for $T_{\rm eff}$, reflecting the greater uncertainties inherent in the method.

Assuming that the determinations of effective temperature obtained from the infrared flux method are reliable, the observed profiles of the Mg I 8806 Å line provide direct information about the overall metallicity of each star without any need for knowledge of the surface gravity. Fig. 2 of Ruck & Smith (1993) compares the observed 8806 Å line profile in $\gamma$ Tau with calculated profiles for solar and metal-rich compositions. A metal-rich composition is clearly indicated. The 8806 Å line profile

**Table 2.** Recent spectroscopic determinations of the fundamental parameters of the Hyades giants $\gamma$ Tau and $\epsilon$ Tau, together with the regions observed and the reciprocal dispersions used

| $\gamma$ Tau | | | $\epsilon$ Tau | | | Region | Dispersion | Reference |
|---|---|---|---|---|---|---|---|---|
| $T_{\rm eff}$ | $\log g$ | [Fe/H] | $T_{\rm eff}$ | $\log g$ | [Fe/H] | (Å) | (Å $\rm mm^{-1}$) | |
| 5140 | 3.02 | +0.07 | 5050 | 2.79 | +0.15 | 5000–6400 | 1.0 | 1 |
| 5050 | 2.58 | +0.17 | 5075 | 2.60 | +0.46 | 4000–4800 | 3.15 | 2 |
| 4930 | 2.6 | +0.16 | 4790 | 2.5 | +0.16 | 5000–8000 | 2.5 | 3 |
| 4990 | 2.7 | +0.20 | 4950 | 2.7 | +0.23 | 5800–6800 | $\simeq 2$ | 4 |
| 4930 | 2.90 | −0.02 | 4820 | 2.77 | +0.04 | 6550–6800 | $\simeq 2$ | 5 |
| 4990 | 2.80 | +0.20 | | | | 5000–8000 | 2.1 | 6 |
| 4990 | 2.1 | −0.05 | | | | 5200–6300 | 6.7 | 7 |
| 4900 | 2.60 | +0.13 | | | | 5100–7900 | $\simeq 2$ | 8 |

References: (1) Lambert & Ries (1981); (2) Gratton et al. (1981); (3) Kjærgaard et al. (1982); (4) Arimoto & Cayrel de Strobel (1988); (5) McWilliam (1990); (6) Gratton & Ortolani (1986); (7) Griffin & Holweger (1989); (8) Luck & Challener (1995).

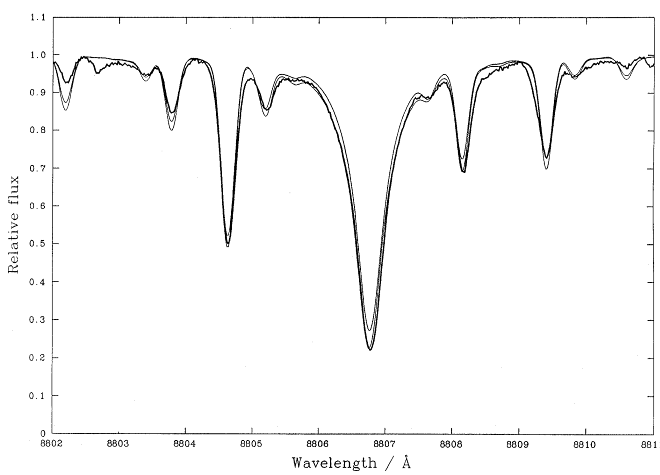


**Fig. 2.** The profile of the Mg I 8806 Å line in $\epsilon$ Tau compared with synthetic spectra calculated for the parameters $T_{\rm eff}$ = 4911 K, $\log g$ = 2.45 and (i) [M/H] = +0.15 (ii) solar metallicity (inner profile).

in $\epsilon$ Tau is slightly wider than that in $\gamma$ Tau mainly as a consequence of the lower effective temperature. Fig. 2 of this paper shows a comparison of observed and calculated profiles for $\epsilon$ Tau again illustrating the metal-rich composition. Our best estimates of [M/H] are $+0.12 \pm 0.03$ dex for $\gamma$ Tau and $+0.15 \pm 0.03$ dex for $\epsilon$ Tau.

Test calculations of the 8542 Å line profile were again made in order to examine the sensitivity of the line wings to changes in the stellar parameters. An increase in $T_{\rm eff}$ by 100 K at 4950 K and [M/H] = +0.15 changes the line depth in the wings by an amount corresponding to an increase of 0.05 dex in [M/H]. An increase in $\log g$ from 2.5 to 2.8 causes the line wings to weaken by an amount which corresponds to a decrease of 0.15 dex in [M/H]. The line wings are clearly sensitive to gravity, given the rather large uncertainty in knowledge of this quantity, but less sensitive to effective temperature. If we adopt the temperature given by the infrared flux method and the metallicity indicated by the 8806 Å line, we can obtain useful information about surface gravity. Fig. 3 shows observed profiles for the 8542 Å line in $\gamma$ Tau and $\epsilon$ Tau with a theoretical profile fitted to the $\gamma$ Tau spectrum. The inner wings in $\epsilon$ Tau are slightly wider most likely as a result of slightly lower surface gravity. The optimum parameters are listed below. Uncertainty in continuum placement is the main cause of error in determination of $\log g$.

| | $\gamma$ Tau | $\epsilon$ Tau |
|---|---|---|
| $T_{\rm eff}$ (K) | $4965 \pm 40$ | $4911 \pm 35$ |
| [M/H] | $+0.12 \pm 0.03$ | $+0.15 \pm 0.03$ |
| $\log g$ | $2.65 \pm 0.20$ | $2.45 \pm 0.20$ |

A possible complication in use of the 8542 Å line profile at the chosen dispersion is the considerable amount of absorption due to weak blending features in the line wings. These are smeared out by the instrumental profile, leading to the possibility that points on the observed profile which appear to represent the unblended depth of the Ca II line may in fact be depressed by blending. In order to check this possibility we have undertaken a complete synthesis of the region 8515 – 8570 Å including atomic lines and lines from the red system of the CN molecule (Jørgensen & Larsson 1990). Details of this synthesis have been given by Ruck (1994). We find that the synthetic spectrum, when convolved with the instrumental profile, still touches the true line profile at several points in the outer wings and is a good fit to the inner wings. Despite the severity of the blending, it is still therefore possible to use the 8542 Å line wings as a constraint on the stellar parameters. Our values for $\log g$ are similar to those obtained by other workers using iron ionization balances (see Table 2) with the exception of the low value found for $\gamma$ Tau by Griffin & Holweger (1989). Values of $\log g$ in the region of 2.5 are compatible with the best available masses of the Hyades giants obtained from structure calculations (Gray & Endal 1982) which assume, on the basis of the observed main-sequence turn-off point, that the present giants must have been main-sequence

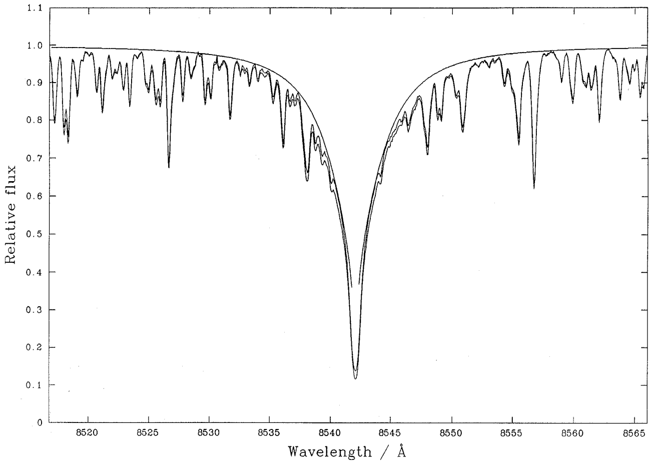


**Fig. 3.** The observed profiles of the Ca II 8542 Å line in $\gamma$ Tau and $\epsilon$ Tau. The more strongly absorbed profile is that of $\epsilon$ Tau. A theoretical profile corresponding to the optimum parameters for $\gamma$ Tau is also shown.

dwarfs with a spectral type of about A2. It should be noted that our method determines the difference in $\log g$ between the two stars more accurately than the individual surface gravities and this result should also be largely independent of choice of model atmosphere.

## 4. Conclusion

We have investigated the fundamental atmospheric parameters of four late-type dwarfs and two giant stars in the Hyades cluster, all of which have been the subjects of previous analyses. Using effective temperatures determined by the infrared flux method and profiles of just two strong lines, we have obtained results for overall metallicity which are consistent with and of comparable precision to recent more extensive analyses. In the case of G-type dwarfs, the wings of the Ca II 8542 Å line alone determine the overall metallicity without need for precise knowledge of temperature or surface gravity. Three of the four dwarfs investigated have metallicity [M/H] enhanced compared to the Sun by 0.11 – 0.16 dex. We confirm the earlier result of Cayrel et al. (1985) that the dwarf vB 52 has near-solar metallicity. In the case of the giant stars, the profile of the Mg I 8806 Å line determines the overall metallicity independent of surface gravity provided the effective temperature is reasonably well known. Again an overall metallicity in the range $0.11 \leq$ [M/H] $\leq 0.16$ is indicated. This result is consistent with other recent determinations (see table 2) apart from those for $\gamma$ Tau by Griffin & Holweger (1989) and McWilliam (1990). The 8542 Å line profiles enable the surface gravities of these stars to be determined once the metallicities and temperatures are known. We find that the surface gravity of $\epsilon$ Tau is less than that of $\gamma$ Tau by about 0.2 dex in $\log g$ but that both stars have surface gravities which are consistent with the presumed mass of these stars as implied from the location of the main sequence turn-off point in the Hyades H-R diagram.

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