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Molecular Band Proxies, Model Atmospheres, and Line Depth Ratios: Comparing three methods of measuring starspot parameters on highly active stars

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Abstract. In a series of papers, we have used absorption bands of titanium oxide to study dark, cool starspots on magnetically active stars. In this contribution, we compare the results (spot filling factor and temperature) obtained using TiO-bands to those obtained using a new technique (Catalano et al. 2002) using the ratios of the depths of atomic lines. We find that the line-depth ratio technique encounters serious difficulties when applied to stars with spot temperature $T_{\rm S} < 4000$ K. We also present the first results in our efforts to fit active star TiO-band spectra using model atmospheres.

1. Background

In a series of papers (Papers 1 through 4) we have used absorption bands of titanium oxide to study dark, cool starspots on magnetically active stars. TiO has long been used as a spectral-type indicator for M stars. We have principally used the TiO band systems at 7055 Å and 8860 Å. On active stars where the photospheric (non-spot) temperature is greater than (4200 K, TiO exists only in the spotted regions. These bands both increase in strength as Teff decreases from 4000 K to 3000 K, but with different zero points and slopes. By observing both of these bands in the spectra of an active star, we simultaneously measure both the filling factor of starspots (area coverage weighted by limb-darkening and projection), $f_{\rm S}$, and their temperature, $T_{\rm S}$. When we began our investigations, we often found higher $f_{\rm S}$ values than found by other techniques; more recently, some studies (e.g. Marino et al. 1999) using photometric light-curve modeling or Doppler imaging confirm our high values of $f_{\rm S}$, even at photometric light maximum.

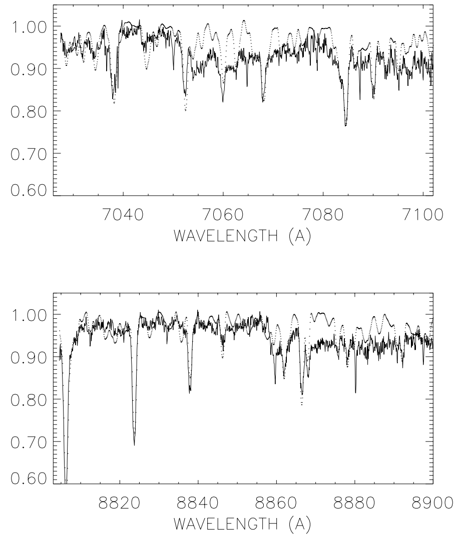

Figure 1. Spectrum of γ^2 Del (K1 IV, $T_{\rm eff}$ = 4700 K), artificially rotationally broadened (dotted), compared to a spectrum of the highly active (and heavily spotted) RS CVn star II Peg (solid line). Top: region of 7055 Å and 7088 Å bands; bottom: region of 8860 Å band. The excess absorption due to TiO in the starspots of II Peg is apparent.

Figure 1 shows these TiO bands in the heavily-spotted RS CVn star II Pegasi (HD 224085), compared to an artificially-rotationally-broadened spectrum of γ^2 Del, an inactive star with a similar spectral type.

This technique is not without limitations. We have thus far used spectra of inactive stars as proxies to model the spot and non-spot components of active stars. Spectra of M stars are not perfect models for starspot atmospheres, mostly due to differing log g values. With model atmospheres, we can exactly match log g, $T_{\rm eff}$, and [Fe/H] of spot and non-spot components of the active star. As a first step towards using these, we fit spectra of the active dwarf EQ Virginis (HD 118100) using the Phoenix models (e.g. Hauschildt & Baron 1999, Aufdenberg 2001) as proxies for the spot and non-spot regions of the star.

Recently Catalano et al. (2002; hereafter C02) introduced a technique that uses ratios of depths of atomic lines to measure average surface temperatures of active stars. If the temperature of the non-spotted regions ($T_{\rm Q}$) is known, $T_{\rm S}$ and $f_{\rm S}$ can be calculated. We observed a set of active and comparison stars in order to reproduce this technique and compare the results to those obtained with the same data set from TiO bands. Our goal was to search for any systematic differences between spot parameters computed using the two techniques, and to constrain the temperature regions of applicability of both.

2. Data

Spectra (R=$\lambda/\Delta\lambda$ = 60,000) were obtained in December 2002 with the Cassegrain Echelle Spectrograph (McCarthy et al. 1993) on the 2.1-m Otto Struve Telescope at McDonald Observatory in Texas. We used two spectrograph settings to cover different wavelength regions: one included the TiO bands at 7055 Å and 8860 Å, while the other was centered near 6200 Å and included the atomic lines used by C02. Spectra of active stars in the two wavelength regions were generally taken within two hours of each other. Details of data reduction are similar to those described in Papers 3 and 4.

We obtained four pairs of spectra of II Peg, and individual pairs (i.e. one spectrum each at the TiO and 6200 Å settings) of spectra of six other active stars. In addition, we observed a grid of inactive comparison stars of a range of $T_{\rm eff}$ and luminosity class.

The EQ Vir spectra were obtained in May 2000 using the Cassegrain Echelle and Struve Telescope. Only the 'TiO' wavelength setting was used.

3. Line Depth Ratio Technique

We measured the depths and equivalent widths of sixteen lines of Fe I, Fe II, Sc I, and V I between 6199 Å and 6275 Å, as marked in Figure 2 in a spectrum of δ Ari (K2 III, $T_{\rm eff}$ =4800 K). C02 use ten ratios of the depths of these lines to determine average stellar surface temperatures. Many of these ratios are highly temperature-sensitive, and have been used (e.g. Gray & Johanson 1991) to determine $T_{\rm eff}$ of stars that are not heavily spotted.

For blended lines, we measured equivalent widths by reflecting the unaffected half of the line profile about the line center. Some of the lines (e.g. V I 6243 Å) were blended to such a great extent that we could not reliably measure equivalent widths.

Calibrations of line depth ratios (LDR) and equivalent width ratios (EWR) with temperature were done as described by C02, using spectra of inactive stars. In Figure 3, for instance, we show the corrected (for gravity effects) LDR of V I 6275 Å to Fe I 6270 Å for luminosity class III stars. $T_{\rm eff}$ values were calculated by averaging recently-published color-temperature relations, i.e. those by Strassmeier & Schordan (2000), Houdashelt et al. (2000), and Bessell, Castelli, & Plez (1998) for G and K giants.

From this plot, one can read the average surface temperature (weighted by projection and limb-darkening) of an active star in whose spectrum the LDR has been measured. The mean of average surface temperatures read from each LDR gives $T_{\rm m}$, an apparent flux-weighted mean temperature of the stellar disk at the time of observation.

Once $T_{\rm m}$ is determined, $T_{\rm Q}$ can be assumed, and a relation between $T_{\rm S}$ and $f_{\rm S}$ calculated:

$$T_{\rm m} = \frac{f_{\rm S} R_\lambda T_{\rm S} + (1 - f_{\rm S}) T_{\rm Q}}{f_{\rm S} R_\lambda + (1 - f_{\rm S})} \qquad (1)$$

This is equivalent to eqs. 11-12 in C02. R_λ is the continuum flux ratio between the spotted and non-spotted regions of the star, computed using the

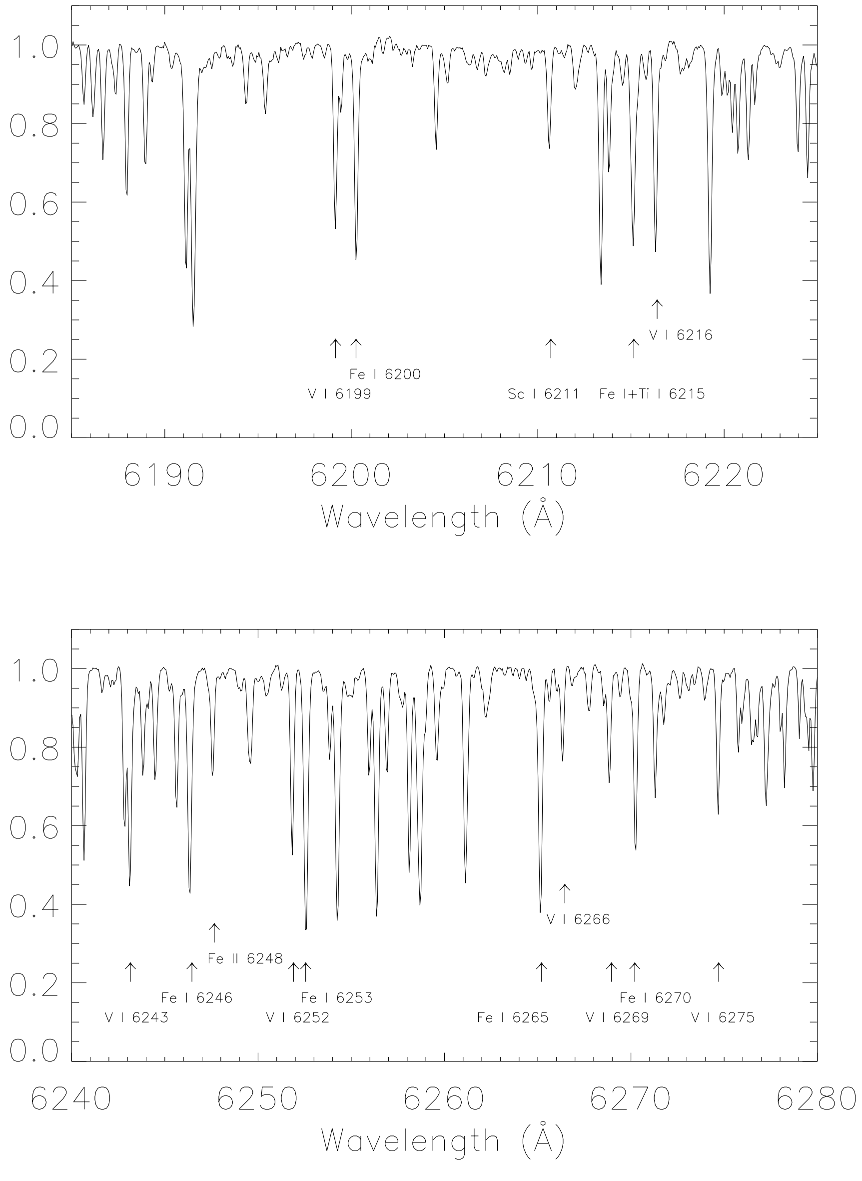

Figure 2. Spectrum of inactive K2 III star δ Ari (K2 III, $T_{\rm eff}$ = 4800 K), with lines used by C02 in the line depth ratio technique marked.

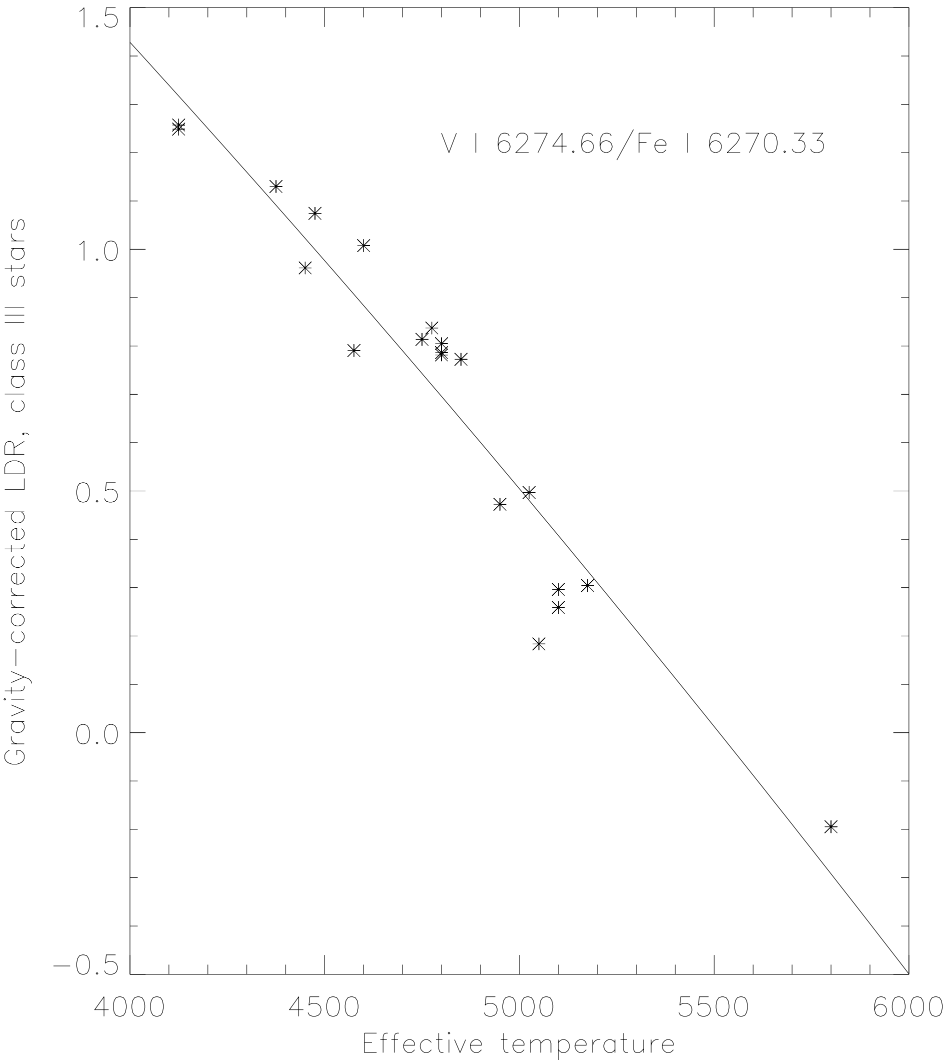

Figure 3. One LDR, with data points – corrected for gravity effects using the C02 method – as asterisks, and the best quadratic fit as a line.

Kurucz (1992) models. A curve (e.g. Figure 4) of $\frac{T_{\rm S}}{T_{\rm Q}}$ is then plotted. C02 chose the lowest $f_{\rm S}$ ($A_{\rm rel}$ in their terminology) consistent with a star's $T_{\rm m}$.

4. Difficulties with LDR Technique

LDR values vary with a star's v sin i. For instance, the LDR 6211 Å (Sc I) / [6215.15 Å (Fe I) + 6215.22 Å (Ti I)] varies from 0.486 to 0.360 in the spectrum of δ Ari when rotational broadening of v sin i = 28 km/s is applied. Tm of a star with this v sin i would be judged as 130 K higher than reality. This dependence of LDR on rotation motivated us to carry out the same measurements using EWR, which (other than through measurement uncertainties) do not vary with a star's v sin i. For our II Peg spectra, EWR yielded smaller $T_{\rm m}$ values than LDR by an average of 150 K. In addition, EWR produced smaller standard deviations (σ) in average temperatures measured from different line pairs.

The most serious difficulty in using these particular lines is illustrated in Figure 5. In spectra of the M4.5 III star BY Boo ($T_{\rm eff}$ =3500 K) and the M1.5 III star 82 Vir ($T_{\rm eff}$ =3700 K), we see that the atomic lines near 6200 Å are mired within the strong 6140 Å TiO band. If an active star has spots with $T_{\rm S}$ in this range, the contribution to the atomic lines from the spots will be strongly blended with many TiO lines. Thus, in cool starspots, the LDR and EWR at the positions of two atomic lines will change very little as temperature decreases below the "turn-on" temperature of this TiO band (4000 K).

We thus find that the LDR and EWR techniques have trouble measuring $T_{\rm S}$ below about 4000 K. For II Peg, from TiO bands we measure $T_{\rm S}$ = 3425±75 K, consistent with our earlier findings. From LDR, we find $T_{\rm S}$ = 3800 to 3900 K, and from EWR, $T_{\rm S}$ = 3700 to 3850 K. We believe that this difference is due to the contamination of the atomic lines by TiO in the star's spotted regions; thus the spotted regions do not appear in the combined spectrum of the star as representing their "true" temperature from an LDR standpoint. For other giant and dwarf active stars, LDR and EWR overestimate $T_{\rm S}$ by 300-500 K compared to values measured from TiO bands.

Additionally, $f_{\rm S}$ (computed using Equation 1) depends extremely sensitively on assumed $T_{\rm Q}$. For the RS CVn star λ And (G8 III), LDR yielded $T_{\rm m}$ = 4672 K. Changing assumed $T_{\rm Q}$ from 4900 K to 4700 K alters computed $f_{\rm S}$ from 0.52 to 0.10; $f_{\rm S}$ approaches 0 as $T_{\rm Q}$ approaches $T_{\rm m}$. For the TiO band technique, altering $T_{\rm Q}$ over a 200 K range changes computed $f_{\rm S}$ by no more than ±0.05.

LDR and EWR measurements were unable to reproduce inputs used to generate test spectra. We constructed an artificial active star spectrum using δ Ari to represent the unspotted regions and BY Boo to represent the spots, with $f_{\rm S} = 0.35$. From LDR and EWR, respectively, this artificial spectrum yielded $T_{\rm S}$ = 4051 K and $f_{\rm S}$ = 0.24; and $T_{\rm S}$ = 4084 K and $f_{\rm S}$ = 0.14. The point on the graph of $\frac{T_{\rm S}}{T_{\rm Q}}$ vs. $f_{\rm S}$ (as in Figure 5) where $f_{\rm S}$ = 0.35 yielded $T_{\rm S}$ = 3168 K. Constructing the artificial star with 82 Vir as spot proxy gave values closer to the inputs (computed $T_{\rm S}$ = 3996 K for both LDR and EWR, $f_{\rm S}$ = 0.32 and 0.31), illustrating that the technique has less difficulty for higher $T_{\rm S}$. The $T_{\rm m}$ values of these two artificial stars differed by only 13 K, for a 200 K change in

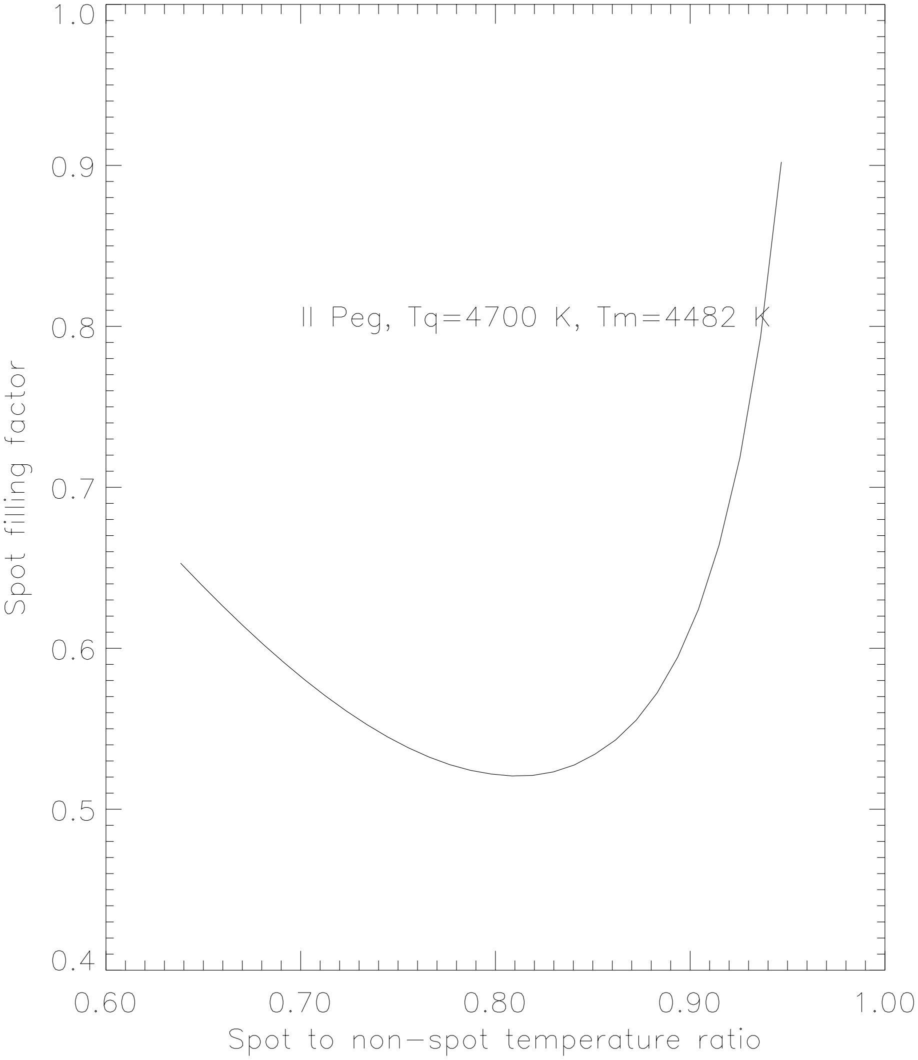

Figure 4. The relation between $\frac{T_\mathrm{S}}{T_\mathrm{Q}}$ and f_S for one December 2002 spectrum of II Peg; T_m was measured using the LDR technique. In this technique, the values of T_S and f_S at the bottom of the curve are assumed to apply to the active star spectrum.

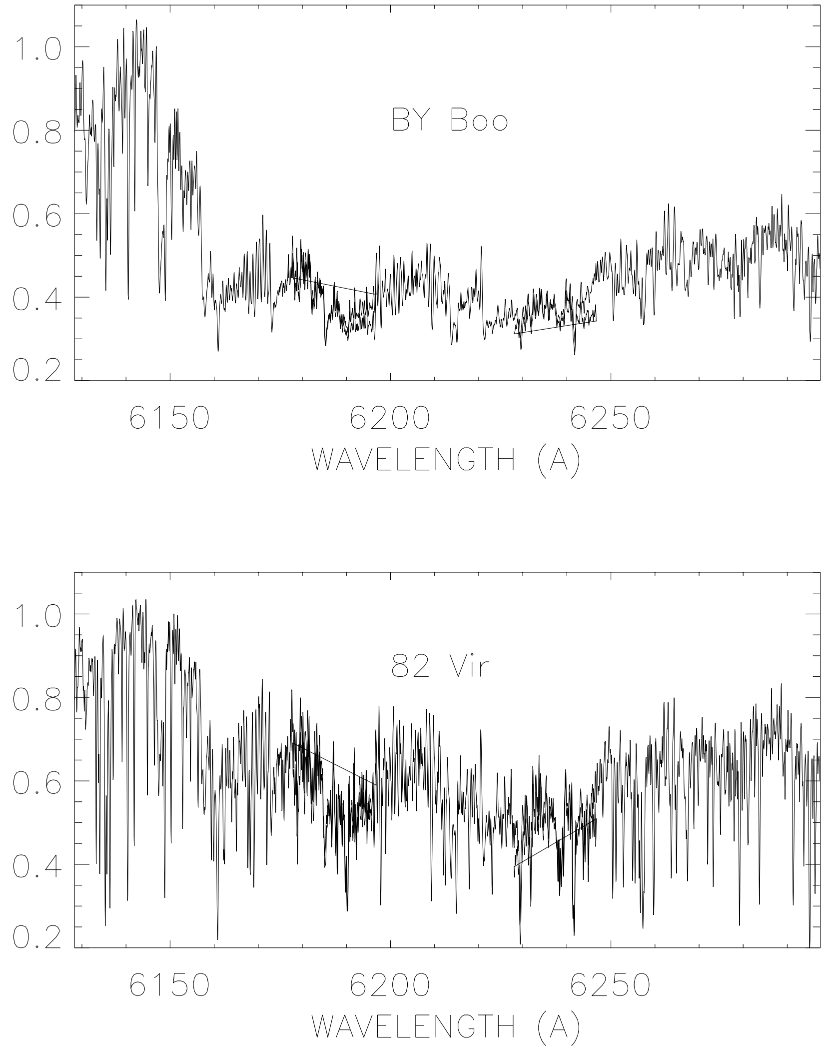

Figure 5. Spectra of M giants BY Boo (M4.5 III, 3500 K) and 82 Vir (M1.5 III, 3700 K) in the region of the 6140 Å band of TiO. Intensity is normalized to the pseudo-continuum blueward of the band. The presence of this band in cool stellar atmospheres (therefore, apparently, in starspots) introduces severe blending problems into the LDR and EWR techniques. Straight lines are overlaps between echelle spectral orders.

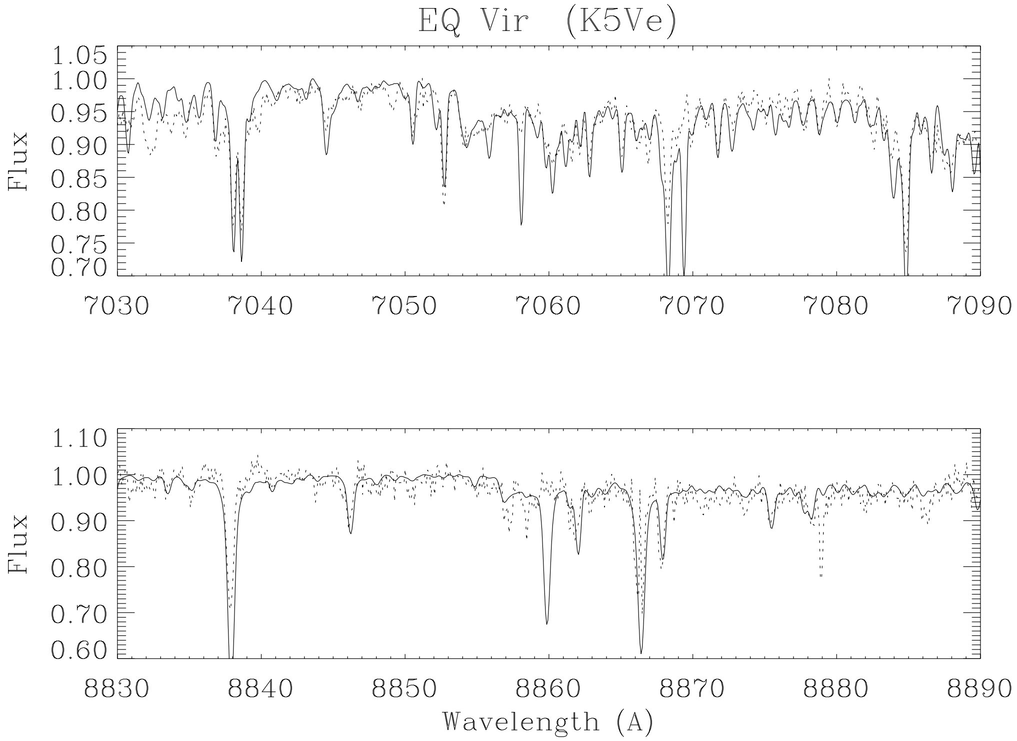

Figure 6. Spectrum of EQ Vir together with the best fit, computed using Phoenix models: $T_{\rm Q}$ = 4535 K, $T_{\rm S}$ = 3050 K, $f_{\rm S}$ = 0.32.

$T_{\rm S}$. This (13 K) is approximately the size of the uncertainties in $T_{\rm m}$ stated by C02.

5. Use of Phoenix Models

At present, the models are a “work in progress”: oscillator strengths for many atomic lines have not been optimized to best fit cool star atmospheres. Still, initial results are promising. Figure 6 shows a spectrum of EQ Vir together with the best fitting model: $T_{\rm Q}$= 4535 K, $T_{\rm S}$ = 3050 K, $f_{\rm S}$ = 0.32. This differs from Saar et al. (2000) who used stellar proxies to fit, and found $T_{\rm Q}$ = 4380 K, $T_{\rm S}$ = 3550 K, $f_{\rm S}$ = 0.43. The lower (correct!) gravity of the models, compared to the proxy stars, makes the bands deeper at fixed temperature, explaining some of the differences. We are continuing to refine this modeling method.

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