The Astrophysical Journal, 501:L73–L76, 1998 July 1

SPECTROSCOPIC EVIDENCE FOR NONUNIFORM STARSPOT PROPERTIES ON II PEGASI

Douglas O'Neal[1]
JILA, Campus Box 440, University of Colorado, Boulder, CO 80309-0440; doneal@casa.colorado.edu
Steven H. Saar
Harvard/Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; saar@cfa.harvard.edu
and
James E. Neff
Department of Physics and Astronomy, College of Charleston, Charleston, SC 29424; neffj@cofc.edu
Received 1998 February 17; accepted 1998 April 30; published 1998 June 18

ABSTRACT

We present spectroscopic evidence for multiple spot temperatures on the RS CVn star II Pegasi (HD 224085). We model the strengths of the 7055 and 8860 Å TiO absorption bands in the spectrum of II Peg using weighted sums of inactive comparison spectra: a K star to represent the nonspotted photosphere and an M star to represent the spots. The best fit yields independent measurements of the starspot filling factor (f_S) and mean spot temperature ($\langle T_S \rangle$) averaged over the visible hemisphere of the star. During three-fourths of a rotation of II Peg in late 1996, we measure a constant $f_S \approx 55\% \pm 5\%$. However, $\langle T_S \rangle$ varies from 3350 ± 60 to 3550 ± 70 K. We compute $\langle T_S \rangle$ for two simple models: (1) a star with two distinct spot temperatures, and (2) a star with different umbral/penumbral area ratios. The changing $\langle T_S \rangle$ correlates with emission strengths of Hα and the Ca II infrared triplet in the sense that cooler $\langle T_S \rangle$ accompanies weaker emission. We explore possible implications of these results for the physical properties of the spots on II Peg and for stellar surface structure in general.

Subject headings: stars: activity — stars: atmospheres — stars: late-type — stars: magnetic fields — techniques: spectroscopic

1. INTRODUCTION

In our previous studies of starspots on II Pegasi (Neff, O'Neal, & Saar 1995; O'Neal, Saar, & Neff 1996; O'Neal & Neff 1997; hereafter Papers I, II, and III, respectively), we measured spot filling factors f_S (weighted by projection and limb-darkening effects; see Paper II) ranging from ≈30% to 60% and spot temperatures $\langle T_S \rangle = 3500 \pm 100$ K. Here, we use f_S as the area coverage weighted by projection and limb-darkening effects (see Paper II for how this relates to the true spotted surface area), and $\langle T_S \rangle$ is a similarly weighted mean T_S value over the visible hemisphere; T_S denotes the temperature of a specific starspot or spotted region.

We measure spot parameters primarily by fitting the depths of the TiO bands near 7055 Å [the 7055, 7088, and 7126 Å bands of the $\gamma(0, 0)$ system] and the band at 8860 Å [the strongest of the $\delta(0, 0)$ system]. In unspotted cool stars, the depths of these bands increase monotonically with $T_{\rm eff}$, but with different zero points and slopes (Papers I and II). Modeling both simultaneously permits us to constrain T_S and f_S independently. On II Peg, these TiO features are produced exclusively in the spotted regions. To determine spot parameters, we construct empirical models of a spotted star using spectra of inactive G and K stars to represent the unspotted ("quiet") photosphere (at $T = T_Q$) and M-star spectra to represent spots. These proxy spectra are weighted by their relative continuum fluxes and by f_S to reproduce the active star spectrum. On the subgiant II Peg, the TiO bands are modeled better by spectra of M giants than by spectra of M dwarfs (Paper I). This technique can accurately measure spot parameters in cases where others, such as light-curve modeling or Doppler imaging, have difficulty (e.g., when variability is minimal). In general, we have found f_S values higher than those measured using different techniques, which implies the existence of a significant longitudinally uniform component to the starspot distribution.

For this project, we obtained as many echelle spectra (including the 7055 and 8860 Å TiO bands) of our most active target star (II Peg = HD 224085) as possible during the observing run. We present evidence that $\langle T_S \rangle$ varies as a function of phase (longitude) on II Peg. In addition, $\langle T_S \rangle$ correlates with the strengths of Hα and the Ca II infrared triplet emission lines in the same echelle spectra. Previously, Byrne et al. (1995) presented photometry suggesting multiple T_S on II Peg, and many Doppler imaging methods (e.g., Hatzes & Vogt 1992; Piskunov, Tuominen, & Vilhu 1990; Strassmeier et al. 1991) treat T_S as a variable at each point on the surface. Our result represents the first direct spectroscopic evidence that all spots on a highly active star need not have the same T_S.

2. OBSERVATIONS AND ANALYSIS

The observations were taken from 1996 September 28 to October 3 with the Sandiford Cassegrain Echelle Spectrograph (McCarthy et al. 1993) at the 2.1 m Struve Telescope at McDonald Observatory. The CassEchelle uses a Reticon 1200 × 400 CCD with 27 μm pixels. The spectrograph operates close to true Littrow and uses prism cross-dispersion. The spectra we obtained cover from Hα to ~9000 Å, with no gaps for $\lambda \leq 8500$ Å.

Over the six nights of our run, we observed II Peg through three-fourths of a rotation period, obtaining an average of nine echelle spectra each night. To compute phases (ϕ), we used the ephemeris by Vogt (1981), HJD 2,443,033.47+6.72422E. We also observed a grid of inactive comparison stars (Table 1), including many of the same ones observed for our previous programs. The grid includes two stars (FS Com and VY Leo) observed with the same instrumental setup in 1995 December (O'Neal, Neff, & Saar 1998, hereafter Paper IV). Photometry for the stars comes from Stauffer & Hartmann (1986) and the

[1] Previous affiliation: Department of Astronomy and Astrophysics, The Pennsylvania State University.

TABLE 1
PROPERTIES OF COMPARISON STARS

HR Number	Name	Spectral Type	V	$B-V$	$R-I$	T_{eff} (K)
"Nonspot" Comparison Stars						
1743	o Col	K0 IV	4.8	1.00	0.55	4800
2077	δ Aur	K0 III	3.7	1.00	0.50	4825
7948	γ^2 Del	K1 IV	4.3	1.04	0.48	4700
8538	β Lac	G8.5 III	4.4	1.02	0.57	4775
8974	γ Cep	K1 IV	3.2	1.03	0.51	4725
"Spot" Comparison Stars						
103	TV Psc	M3 III	5.1	1.65	1.54	3575
2286	μ Gem	M3 III	2.9	1.64	1.38	3625
4267	VY Leo	M5.5 III	5.8	1.45	2.09	3325
4949	FS Com	M5 III	5.6	1.59	1.81	3475
5299	BY Boo	M4.5 III	5.3	1.59	1.66	3550
7009	XY Lyr	M4–5 II	6.0	1.65	1.96	3400
7157	R Lyr	M5 III	4.0	1.59	1.91	3425
8775	β Peg	M2 III	2.4	1.67	1.32	3650

Bright Star Catalog (Hoffleit & Jaschek 1982). Effective temperatures were computed using the methods described in Paper II and were rounded to the nearest interval of 25 K.

To fit spectra of spotted stars in orders containing molecular bands of interest, we use the STARMOD spectral synthesis code. STARMOD, which was written (Barden 1985) and later modified (by D. P. Huenemoerder, A. D. Welty, and D. O'Neal) at Penn State, fits an observed spectrum with a linear combination of up to three model spectra. It can be used to determine relative brightnesses of stars in systems of up to three components; we use it to find the relative weights of nonspot and spot components to model spectra of active stars. For our purposes, a K giant or subgiant was used to model the unspotted photosphere, and an M giant was used to model the spotted component. Initial estimates for the radial velocity shift, $v \sin i$ broadening (Gray 1992), and relative weight of each standard spectrum are iterated in succession until the best fit is achieved. In our case, the radial velocity and $v \sin i$ were fixed; before running the program, we extrapolated all spectra onto a common wavelength scale and set $v \sin i = 23$ km s^{-1} for II Peg (Hatzes 1995; Piskunov, Ryabchikova, & Tuominen 1998). See Papers III and IV for more detail.

Over the range 3200 K $\leq T_S \leq$ 3650 K, f_S needed to fit the 7055 Å TiO strength decreases with increasing $\langle T_S \rangle$. This counterintuitive result comes about because the effect of increasing $\langle T_S \rangle$, and therefore increased flux from the spotted regions of the star, is greater than the effect of the intrinsic weakening of the molecular bands in the warmer spots (Paper II). The opposite is true for the 8860 Å band, and their sharply contrasting behavior makes this pair of bands extremely useful for constraining f_S and $\langle T_S \rangle$. This method is explored in detail in Paper IV.

For this study, we used five different nonspot comparison stars having 4700 K $\leq T_{eff} \leq$ 4825 K and averaged the results. Varying T_Q over this small temperature range does not affect the derived f_S and $\langle T_S \rangle$ values beyond what is expected from the uncertainty in the technique; in almost all cases, derived f_S values change by $\leq$0.04 and $\langle T_S \rangle$ values change by $\leq$50 K when a different nonspot template star (with similar T_{eff}) is used for the fits.

3. RESULTS

In Figure 1 we plot $f_S(\phi)$ for our data; we find that f_S shows a range of values of ± 0.05 about an average $\langle f_S \rangle = 0.55 \pm 0.023$ (1 σ). Since the spread of the f_S values is thus about the same as the systematic error of the method ($\pm$0.05; Paper II), our results are consistent with a spot area distribution on II Peg that is approximately uniform in longitude.

In Figure 2 we plot the best-fit $\langle T_S \rangle$ against phase. Our observations began at $\phi \sim 0.8$. Points are plotted for each observation in which the order with the 8860 Å band had a high enough signal-to-noise ratio to permit reliable analysis. The combined random and systematic uncertainty for each point is $\pm$100 K (Paper II). We also show the $\langle T_S \rangle$ values obtained by averaging all observations on each night, plotted with error bars indicating the propagated statistical error assuming the $\pm$100 K uncertainty for each point. A χ^2 test performed on the nightly average values yields an 81% probability that $\langle T_S \rangle$ is inherently variable, i.e., that the apparent variability is not due to random sampling.

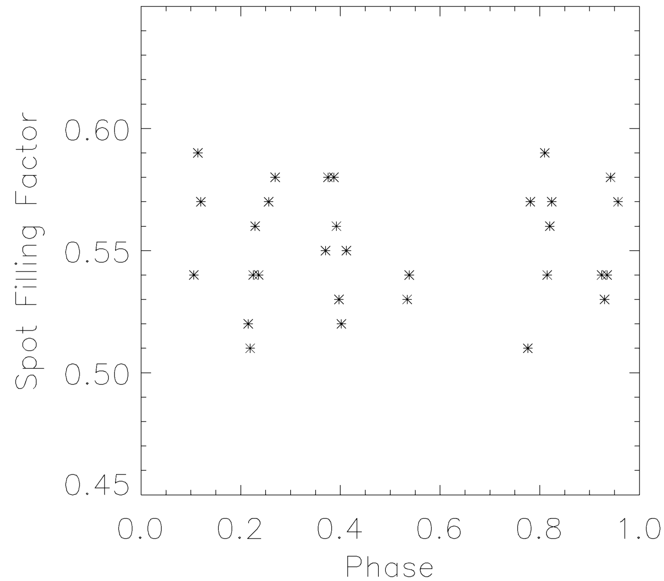

FIG. 1.—Measured spot filling factor f_S as a function of phase for II Peg in 1996 September–October; f_S is approximately constant at 55% $\pm$ 5%.

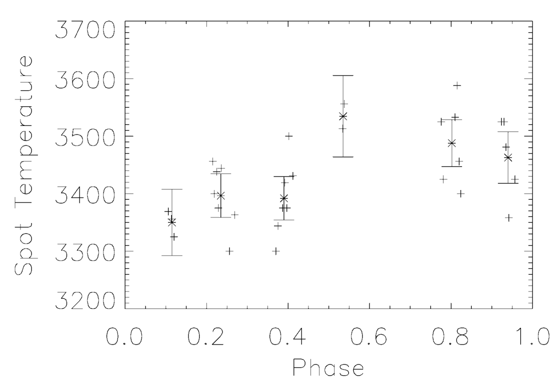

FIG. 2.—Best-fit spot temperatures T_S for II Peg in 1996 September–October as a function of phase. T_S values for each individual echelle spectrum are plotted as plus signs, while the nightly averages are asterisks with error bars. The error bars are propagated statistical uncertainties assuming that all of the measurements within a given night sample the same T_S value and have an experimental error of $\pm$100 K.

Echelle spectroscopy permits the simultaneous monitoring of the strengths of chromospheric emission features and molecular bands. Following Barden (1985), Huenemoerder & Ramsey (1987), and the method of Paper IV, we use the equivalent widths (W_λ) of the emission features to measure levels of activity. All equivalent widths were measured after the subtraction of the (artificially rotationally broadened) spectrum of an inactive standard star with $T_{\rm eff}$ similar to that of II Peg (*o* Col, K0 IV, $T_{\rm eff} = 4800$ K).

The emission strengths of all lines clearly varied with phase. In Figure 3, we plot $\langle T_S \rangle$ against the emission W_λ for Hα. The correlation coefficient for these two data sets is $r = 0.55$, giving only a 2% probability that the parent distributions of $\langle T_S \rangle$ and W_λ are inherently uncorrelated. For the three infrared triplet lines, $0.58 \leq r \leq 0.67$.

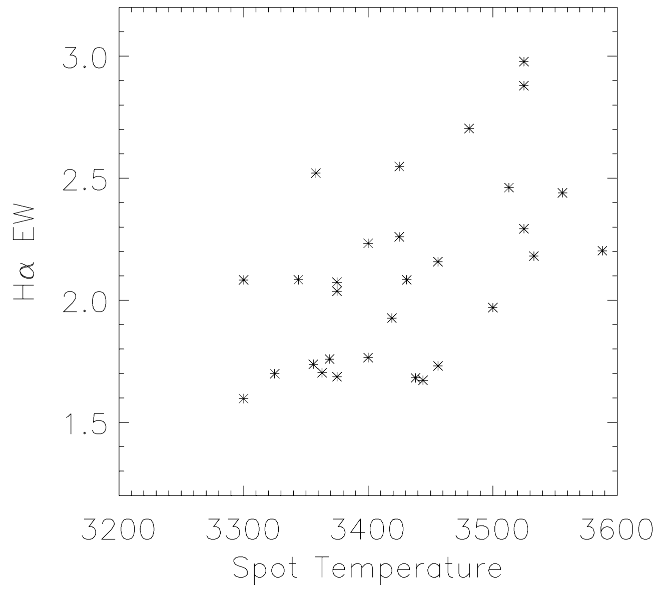

FIG. 3.—Relation between equivalent width for Hα and measured T_S. Increased emission strength correlates with higher spot temperature.

4. DISCUSSION

We caution that since our observations cover slightly less than one rotational cycle of II Peg, we cannot distinguish between asymmetries on the surface of the star and rapid evolution of f_S. However, we are unaware of any previous indications of T_S on II Peg evolving substantially on the timescale of only a few days. Based on our emission-line data, no large flares occurred that could have substantially affected our analysis.

We have considered alternatives to an intrinsically nonuniform T_S that could explain our observations. Any blanketing of the continuum, whether intrinsic to the star or instrumental in origin, can be ruled out by the lack of systematic variations in measured equivalent widths of photospheric absorption lines in the II Peg spectra. Equivalent widths of several lines were measured, and we found variations neither beyond the level expected from noise nor correlated with phase or measured $\langle T_S \rangle$.

If the increased emission strength at certain phases is due to warmer plage appearing on the visible hemisphere, we would also expect a correlation of enhanced emission with *decreased*, rather than increased, $\langle T_S \rangle$, if T_Q is kept fixed. This is because the warmer plage enhances the continuum more at the 7055 Å wavelength and hence decreases the observed ratio of the strength of the 7055 Å band to that of the 8860 Å band, yielding (Papers I and II) a lower derived $\langle T_S \rangle$. To test this, we used STARMOD to fit spectra of artificial spotted stars constructed with 50% spot coverage, 25% coverage with nonspotted photosphere with the effective temperature of II Peg, and 25% coverage with nonspotted photosphere several hundred K warmer. As in our analysis of the observations, we fixed T_Q at the input $T_{\rm eff}$ of the nonspot template (the five nonspot comparison stars used had $T_{\rm eff}$ between 4700 and 4825 K; Table 1). Doing so yielded $\langle T_S \rangle$ values 50–75 K cooler than the T_S input to construct the artificial spectrum, while f_S remained at 50% ± 4%.

One might expect a positive correlation between T_S and emission strength for the follwing reasons.

1. Warmer T_S might correspond to smaller average spot sizes; a similar spot area–T_S correlation is seen on the Sun (Kopp & Rabin 1992). If the mean spot size at a given longitude on II Peg is smaller than average but f_S is the same, there might be a larger total plage area; on the Sun, $A_{\rm spot}/A_{\rm plage}$ increases as a function of $A_{\rm spot}$ (Foukal 1994, 1998). If this is also true on II Peg, areas with smaller spots might have more plage and hence more chromospheric activity locally associated with the spots. A variant of this would have some of the smaller spots as partially decayed remnants of larger spots. Since spots decay much more rapidly than plage (e.g., Howard 1992), small decaying spots naturally have relatively more warm plage in their vicinity.

2. Spots on lower gravity stars such as II Peg might have lower magnetic field strengths B (from pressure balance) and thus might suppress conduction of MHD waves to the upper atmosphere to a lesser extent, especially if B is even lower in warmer spots. Macroturbulent velocities on lower $\log g$ stars are higher than in dwarfs (Gray 1992), and while densities are also lower, the relative balance at the spot boundary between internal, predominantly magnetic pressure ($\propto B^2$) and external gas plus turbulent pressure ($\propto \rho v^2$) may shift more toward the turbulent pressure in lower gravity stars (Solanki 1996). If this is the case, the lower B in warmer, smaller umbrae might permit enhanced flux tube "shaking" and perhaps more significant MHD energy transfer than seen in the Sun from the umbrae themselves (where umbrae are generally *not* the sites of enhanced emission; Sams, Golub, & Weiss 1992).

3. On the Sun, the ratio of the radii of umbrae and penumbrae is approximately independent of spot size (Allen 1973) with small scatter (Solanki & Schmidt 1993; see, however, Kiepenheuer 1953); thus, the area ratio $A_{\rm pen}/A_{\rm umb}$ is roughly constant. Spots on II Peg may have variable $A_{\rm pen}/A_{\rm umb}$; if so, they would differ from sunspots in this respect. Since active loops tend to be rooted more in penumbrae than umbrae (Sams et al. 1992), spots with larger $A_{\rm pen}/A_{\rm umb}$ might then have stronger associated activity and higher T_S (since the larger $A_{\rm pen}$ weights T_S to higher temperatures). While possible (II Peg has a lower gravity and is much more active than the Sun, so it may differ from the Sun in many ways), this option is perhaps less likely than option 1 or 2.

The last possibility is further diminished by tests showing that variations in $A_{\rm pen}$ do not affect $\langle T_S \rangle$ to the degree needed to match observations. We computed two models: one with 60% covered by a $T_Q = 4800$ K photosphere and 40% by a

$T_S = 3500$ K spot, and a second with 30% quiet, 40% spot (at the same T_Q and T_S), and 30% of a $T_{pen} = (T_{pen}/T_Q)_\odot \times T_Q = 4500$ K penumbra [where $(T_{pen}/T_Q)_\odot = 0.94$; Allen 1973]. Analysis of the penumbral model (assuming $T_Q =$ 4800 K) yielded a slightly increased f_S (by 2%–3%) and $\langle T_S \rangle$ (by 25–50 K), which is insufficient to explain the ≈200 K changes in $\langle T_S \rangle$ that we observe. This is primarily because T_{pen} is likely to be closer to T_Q than T_S (as on the Sun).

If there are two distinct T_S regions on II Peg, then the $\langle T_S \rangle$'s we derive from TiO bands will be weighted sums of the two values. We computed simple models of stars with two T_S values. Each model is a weighted sum of three spectra: 50% filling factor of a nonspot comparison spectrum and two spot comparison spectra with a total $f_S = 50\%$. We then fitted these summed spectra using STARMOD, deriving one $\langle T_S \rangle$ value for each model (the derived f_S in each case was 50% ± 3%). As expected, the derived $\langle T_S \rangle$ values lie between the two T_S values used to generate the model spectra, slightly weighted toward the warmer T_S due to the warm spots' greater brightness. When fitting all of the II Peg spectra with two-T_S models, the best overall fits were obtained for T_S values of 3200 K (represented by a spectrum of RZ Ari; see Papers I, II, and III) and 3575 K (represented by TV Psc). A star with these two T_S values can explain our observations if the f_S of the 3575 K component varied between approximately 15% and 45% of the stellar surface.

This in itself does not discriminate among the possible explanations presented in § 4, and there could be a continuous range of T_S rather than only two distinct values. The variable $\langle T_S \rangle$ that we calculate likely reflects intrinsically different T_S's (and possibly different sizes) at different longitudes on the star; a changing balance of penumbral versus umbral material appears less likely to produce the $\langle T_S \rangle$ changes observed. Using Doppler imaging, we plan to address these questions about the spatial distribution of spot components and T_S on the surface of II Peg.

The morphology of starspots on active stars is poorly constrained; the maps generated by Doppler imaging analyses are nonunique. It is not known whether starspots exhibit the penumbral/umbral structure of sunspots or whether larger spots are cooler than smaller spots. The size distribution is highly uncertain, and some studies (e.g., Eaton, Henry, & Fekel 1996) show that a large number of moderately sized spots can produce the same observational consequences as a smaller number of very large spots. In this light, our evidence that all spots on II Peg may not have the same T_S represents a significant result. Alternatively, if our variable $\langle T_S \rangle$ actually indicates a variable A_{pen}/A_{umb}, we have the first evidence that spots on active stars have penumbrae, which is also a significant "first."

5. SUMMARY

We obtained echelle spectra of II Peg during three-fourths of a rotation period in 1996 September–October. We determined starspot parameters by fitting the regions of the TiO bands at 7055 and 8860 Å. We find that f_S was approximately constant but that $\langle T_S \rangle$ varied between ≈3350 and 3550 K. Increased $\langle T_S \rangle$ correlated with the stronger emission in the Hα and Ca II infrared triplet lines. We explore some possible reasons for this correlation, including variation in spot sizes or penumbra-to-umbra area ratios, and the consequences these would have for the magnetic fields and plage associated with the spotted regions. We construct simple models of a star with two T_S's that could explain our observations.

D. O. was supported by grant NGT-51406 from the NASA Graduate Student Researchers Program to The Pennsylvania State University and by grant GO-06072.02-94A to the University of Colorado. S. H. S. was supported by NSF grant AST-9528563 and *HST* G0-06676.01-95A. J. E. N. was supported by grants NAGW-2603 and NAG5-3040 to The Pennsylvania State University and by the College of Charleston. We thank the staff of McDonald Observatory for their allocation of observing time and their assistance with our observations, and the referee for helpful suggestions.

REFERENCES

Allen, C. W. 1973, Astrophysical Quantities (London: Althone)
Barden, S. C. 1985, ApJ, 295, 162
Byrne, P. B., et al. 1995, A&A, 299, 115
Eaton, J. A., Henry, G. W., & Fekel, F. C. 1996, ApJ, 462, 888
Foukal, P. 1994, Science, 264, 238
———. 1998, ApJ, 500, 958
Gray, D. F. 1992, The Observation and Analysis of Stellar Photospheres (2d ed; Cambridge: Cambridge Univ. Press)
Hatzes, A. P. 1995, in IAU Symp. 176, Stellar Surface Structure: Poster Proceedings, ed. K. G. Strassmeier (Vienna: Institut für Astronomie), 87
Hatzes, A. P., & Vogt, S. S. 1992, MNRAS, 258, 387
Hoffleit, D., & Jaschek, C. 1982, The Bright Star Catalogue (4th ed; New Haven: Yale Univ. Obs.)
Howard, R. F. 1992, Sol. Phys., 137, 51
Huenemoerder, D. P., & Ramsey, L. W. 1987, ApJ, 319, 392
Kopp, G., & Rabin, D. 1992, Sol. Phys., 141, 253
Kiepenheuer, K. 1953, in The Sun, ed. G. Kuiper (Chicago: Univ. Chicago Press), 346
McCarthy, J. K., Sandiford, B. A., Boyd, D., & Booth, J. 1993, PASP, 105, 881
Neff, J. E., O'Neal, D., & Saar, S. H. 1995, ApJ, 452, 879 (Paper I)
O'Neal, D., & Neff, J. E. 1997, AJ, 113, 1129 (Paper III)
O'Neal, D., Neff, J. E., & Saar, S. H. 1998, ApJ, in press (Paper IV)
O'Neal, D., Saar, S. H., & Neff, J. E. 1996, ApJ, 463, 766 (Paper II)
Piskunov, N. E., Ryabchikova, T. A., & Tuominen, I. 1998, A&A, in press
Piskunov, N. E., Tuominen, I., & Vilhu, O. 1990, A&A, 230, 363
Sams, B. J., Golub, L., & Weiss, N. O. 1992, ApJ, 399, 313
Solanki, S. K. 1996, in IAU Symp. 176, Stellar Surface Structure, ed. K. G. Strassmeier & J. L. Linsky (Dordrecht: Kluwer), 201
Solanki, S. K., & Schmidt, H. U. 1993, A&A, 267, 287
Stauffer, J. R., & Hartmann, L. W. 1986, ApJS, 61, 531
Strassmeier, K. G., et al. 1991, A&A, 2477, 130
Vogt, S. S. 1981, ApJ, 247, 975