II Peg: Spectroscopic Evidence for Multiple Starspot Temperatures

Douglas O’Neal\textsuperscript{1}, Steven H. Saar\textsuperscript{2}, and James E. Neff\textsuperscript{3}

Abstract:
We present spectroscopic evidence for multiple spot temperatures on the RS CVn star II Pegasi (HD 224085). We fit the strengths of the 7055 Å and 8860 Å TiO absorption bands in the spectrum of an active star using weighted sums of comparison spectra: the spectrum of an inactive K star to represent the non-spotted photosphere and the spectrum of an M star to represent the spots. We can thus independently measure starspot filling factor ($f_S$) and temperature ($T_S$). During 3/4 of a rotation of II Peg in Sept.–Oct. 1996, we measure $f_S$ approximately constant at 55±5%. However, $T_S$ varies from 3350 K to 3500 K. Since our method yields one derived $T_S$ integrated over the visible hemisphere of the star, we present the results of simple models of a star with two distinct spot temperatures and compute the $T_S$ we would derive in those cases. The changing $T_S$ correlates with emission strengths of Hα and the Ca ii infrared triplet, in the sense that cooler $T_S$ accompanies weaker emission. We explore the consequences of these results for the physical properties of the spots on II Peg and for stellar surface structure in general.

1. Introduction

In our previous investigations of starspot coverage on II Pegasi (Neff, O’Neal, & Saar 1995; O’Neal, Saar, & Neff 1996; O’Neal & Neff 1997; hereafter Papers 1, 2, and 3), we measured spot filling factors $f_S$ ranging from ≈30% to 60% and spot temperatures $T_S = 3500\pm100$ K.

We measure spot parameters primarily by fitting the depths of the TiO bands near 7055 Å and 8860 Å. In unsptotted cool stars, the depths of these bands both increase monotonically with temperature, but with different zero points and slopes (Papers 1 and 2). Modeling both simultaneously permits us to constrain independently $T_S$ and $f_S$. On II Peg, these TiO features are produced exclusively in the spotted regions, since the non-spotted photosphere is warm enough to dissociate the molecule. To determine spot parameters, we construct empirical models of a spotted star using observed spectra of inactive G and K stars to represent the unsptotted photosphere and spectra of M stars to represent the spots. Spots on the subgiant II Peg are modeled much better by spectra of M giants than by spectra of M dwarfs (Paper 1).

\textsuperscript{1}JILA/University of Colorado
\textsuperscript{2}Harvard-Smithsonian Center for Astrophysics
\textsuperscript{3}State University of New York at Stony Brook

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System
Here we present evidence that $T_S$ varies as a function of phase on II Peg, i.e., that spots at different longitudes have different temperatures. This result corroborates evidence from photometric studies (e.g. Byrne et al. 1995) and Doppler imaging that all spots on an active star need not have the same temperature.

2. Observations and Analysis

The observations were taken from 28 September to 3 October 1996 with the Sandiford Cassegrain Echelle Spectrograph (McCarthy et al. 1993) at the 2.1 m Struve Telescope at McDonald Observatory. The resolution of our spectra is $R = \lambda/\Delta\lambda \approx 60,000$, and wavelengths from $\approx 6500$ Å to 9000 Å fell on the detector.

Over the six nights of our run, we observed II Peg through 3/4 of a rotation period, obtaining an average of 9 echelle spectra each night. We also observed a grid of inactive comparison stars. The comparison stars observed for this program are a subset of those listed in Papers 1, 2, and 3. For this program, we observed giant and subgiant comparison stars having $T_{\text{eff}}$ within $\approx 250$ K of the expected $T_S$ and non-spot temperature $T_Q$ of II Peg.

To fit spectra of spotted stars in orders containing molecular bands of interest, we use the routine STARMOD (Barden 1985). STARMOD fits an observed spectrum with a linear combination of up to three model spectra. For our purposes, we use two template spectra, one each to represent the spots and unsotted photosphere of II Peg. STARMOD can be used to determine relative brightnesses of stars in systems of multiple components; this function makes it an ideal choice for our problem at hand, finding the relative weights of non-spot and spot components in spectra of active stars. See Paper 3 for more detail on this procedure.

When we fit spectra of II Peg using spot comparison stars with a range of temperatures, we find that the $f_S$ needed to fit the TiO band strength for a given assumed $T_S$ varies in the opposite sense, depending upon whether the 7055 Å or 8860 Å band is being fitted. That is, for a given 8860 Å band strength the spectrum of II Peg, one needs to invoke more spot coverage as $T_S$ increases to match the observed strength of the band. However, one needs a lower $f_S$ as $T_S$ increases (in the range 3200 K $\leq T_S \leq 3700$ K) to match the observed strength of the 7055 Å bands. This counterintuitive result comes about because, over this $T_S$ range, the effect of decreasing intrinsic band strength from warmer starspots is outweighed by the increased flux contribution of the spot to the integrated stellar spectrum. This opposite behavior makes fitting these two TiO bands extremely useful for constraining $f_S$ and $T_S$. This method will be more thoroughly explored by O’Neal, Neff, and Saar (1997; in preparation).

For this paper, we used four different non-spot comparison stars having $4700$ K $\leq T_{\text{eff}} \leq 4825$ K, and averaged the results. Varying $T_Q$ over this small temperature range does not affect the derived $f_S$ and $T_S$ values beyond what is expected from the uncertainty in the technique.
3. Results

In Figure 1 we plot $f_S$ as a function of phase for our observations. $f_S$ for all spectra is 0.55±0.05. This uncertainty, reflected in the spread of the data points for each night’s observations, is also approximately the systematic error for this technique (Paper 2). If we average the $f_S$ measurements for each night’s observations, the difference between the maximum and minimum averaged $f_S$ values is less than half the 0.05 uncertainty. This indicates an approximately longitudinally-uniform fractional area spot coverage on II Peg.

![Graph showing measured spot filling factor as a function of phase for II Peg in 1996 Sept.-Oct.]

Figure 1. Measured spot filling factor as a function of phase for II Peg in 1996 Sept.-Oct. $f_S$ is approximately constant at 55±5%.

In Figure 2a we plot the best-fit $T_S$ against phase. Points are plotted for each observation in which the order containing the 8860 Å band had high enough S/N to permit reliable data analysis. The uncertainty for each point is ±100 K. Averaging the $T_S$ values obtained for all observations on each night, we obtain Figure 2b. A chi-square test yields an 81% probability that $T_S$ is inherently variable, i.e., that the apparent variability is not due to any observational or random effect.
Figure 2. Best-fit spot temperatures for II Peg in 1996 Sept.–Oct as a function of phase. a): $T_S$ measured from the 7055 Å and 8860 Å bands for each spectrum. b): Nightly mean $T_S$ values.

In Figure 3, we plot the emission equivalent widths measured in the II Peg spectra for the Hα line and each of the three lines of the Ca II infrared triplet. To isolate the emission components of the lines, all equivalent widths are measured after the subtraction of the spectrum of an inactive standard star with $T_{\text{eff}}$ similar to that of II Peg (ο Col, K0 IV, $T_{\text{eff}} = 4800$ K). Variation of emission strength with phase is apparent. Trials using other standard stars with slightly different spectral types and $T_{\text{eff}}$ values produced almost identical results.

In Figure 4 we plot $T_S$ against the emission equivalent widths for Hα. The correlation coefficient for these two data sets is 0.55, giving only a 2% probability that the apparent positive correlation between $T_S$ and emission strength has happened at random. For the three infrared triplet lines, correlation coefficients range from 0.58 to 0.67.

4. Interpretation

One might expect a positive correlation between $T_S$ and emission strength because:

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, the spots may be more spread out; there may be more room for plage between them, and hence more chromospheric activity locally associated with the spots.

2. Spots on lower gravity stars may have lower magnetic field strengths $B$ (from pressure balance) and thus may 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 actually 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 towards the turbulent pressure in lower gravity stars. If this
Figure 3. Emission equivalent widths measured, after the subtraction of a standard star spectrum, for the spectra of II Peg from 1996 Sept.–Oct. Emission strengths were measured for Hα and all three lines of the Ca II infrared triplet.

is the case, one might expect that the lower $B$ in warmer, smaller umbrae permit enhanced flux tube “shaking” and perhaps significant MHD energy transfer even in the umbrae themselves.

3. On the Sun, the ratio of the radii of umbrae and penumbrae is independent of spot size (Allen 1976), thus the area ratio $A_{pen}/A_{umb}$ is constant. Spots on II Peg may have variable $A_{pen}/A_{umb}$; if so, they would differ from sunspots in this respect. While possible (II Peg has a lower gravity and is much more active than the Sun, so may differ in many ways), this option is perhaps less likely than (1) or (2).
5. Models with Two Spot Temperatures

If there are two distinct spot temperatures on II Peg, then the $T_s$ we derive from TiO bands will be a weighted sum of the two values. We computed simple models of stars with two spot temperatures. Each model is a weighted sum of three spectra — 50% filling factor of a non-spot comparison spectrum and two spot comparison spectra with a total $f_S = 50\%$. We then fitted these summed spectra using STARMOD, deriving one $T_s$ value for each model (the derived $f_S$ in each case was 50±3\%). As expected, the derived $T_s$ values lie between the two spot temperatures used to generate the model spectra, though slightly weighted towards the warmer spot temperature (since the warmer spot will be brighter and thus produce a greater effect in the overall stellar spectrum). We find, for instance, that a two-spot temperature star with spot temperatures 3200 K and 3550 K can explain our observations, if the filling factor of the 3550 K component varies between approximately 15\% and 45\%. 
This in itself does not discriminate among the possible explanations presented in the previous section. The variable $T_S$ that we calculate could still reflect either a changing balance of penumbral vs. umbral material, or spots of intrinsically different temperatures (and possibly different sizes) at different longitudes on the star. Alternatively, perhaps the polar spot (if any) is at one temperature, while the spot coverage at lower latitude varies in temperature as a function of longitude. We plan to investigate these questions by using the echelle spectra described herein to derive Doppler images of II Peg.

6. Summary

We obtained echelle spectra of II Peg during $3/4$ of a rotation period in 1996 Sept.–Oct. We determined starspot parameters by fitting the spectral orders containing the TiO bands at 7055 Å and 8860 Å. We find that $f_S$ was approximately constant but that $T_S$ varied between $\approx 3350$ K and $3550$ K. The variable $T_S$ is correlated with the strengths of emission in the Hα and Ca ii infrared triplet lines, in the sense that warmer $T_S$ corresponds to stronger emission. We explore some possible reasons for this correlation.

References