A Possible Relationship Between Starspot Temperature Deficit and Surface Gravity

S.H. Saar
Smithsonian Astrophysical Observatory, Cambridge, MA, USA

D. O'Neal & J.E. Neff
Dept. of Astronomy and Astrophysics, Penn State Univ., University Park, PA, USA

1. Introduction

Photometric and spectroscopic variability on solar-like stars is often attributed to the presence of starspots, which, by analogy with sunspots, are regions of concentrated magnetic flux. While a quite reasonable hypothesis, there is little *direct* evidence supporting this idea (e.g., actual measurement of fields in dark spots) outside of a few magnetic Doppler imaging results (Donati et al. 1992; Saar et al. 1994), which can be subject to some complex systematic effects (Saar et al. 1994).

Even the temperature deficit between the spot and quiet photosphere, $\Delta T = T_{\rm Q} - T_{\rm S}$, is not always well determined by traditional methods. Photometric models require an assumed pristine spot-free level, which can cause offsets in computed $T_{\rm S}$ and spot area. Doppler imaging determines spot positions more accurately than their physical properties (Collier Cameron 1992). It is thus useful to develop more accurate ways of determining starspot properties, to help eventually establish the truth of the starspot–sunspot association. This paper reports the first results of such a method, molecular band modeling, applied to several stars. By studying molecular bands (which exist only in cool structures) with differing $T_{\rm eff}$ sensitivity, we can determine both the size (from the absolute band strengths) and the temperature (from their ratio) of cool starspots *independent* of spatial distribution. Our observations also fortuitously yield indirect evidence for the presence of magnetic fields in starspots, through an apparent correlation between ΔT and surface gravity.

2. Observations and Analysis

We have observed the 7100 Å and 8860 Å TiO bands in five spotted target stars (EI Eri, σ Gem, HD 179094, HD 199178, and II Peg) and a wide range of inactive comparison stars (G, K, and M dwarfs and giants), which serve as photospheric and starspot proxies. Observations were made at the National Solar Observatory's McMath-Pierce Telescope using the solar-stellar spectrograph with a Milton & Roy grating, 105 mm transfer lens, 5 slice image slicer, and a TI CCD (Smith & Giampapa 1987). The resulting spectra have resolution $\Delta\lambda/\lambda \sim 14,000$ and S/N $\approx$ 200 - 300.

Table 1: Stellar Properties

Star	Sp. type	$P_{\rm rot}$(d)	$\log g$	ΔT(K)
EI Eri	G5 IV	1.945	3.8	1900
σ Gem	K1 III	19.60	2.5	650
HD 179094	K2 IV-III	28.59	3.2	1000
HD 199178	G5 III-IV	3.337	3.3	1550
II Peg	K2-3 IV-V	6.724	3.7	1300

The two TiO bands were selected for their different dependencies on $T_{\rm eff}$: the 7100 Å bands are first clearly visible (> 10% deep) at $T_{\rm eff} \approx 4000$ K, while the 8860 Å band is not as strong until $T_{\rm eff} \approx 3700$ K (Neff, O'Neal, Saar 1995) and grows in strength with decreasing $T_{\rm eff}$ at a different rate (Pettersen & Hawley 1989). Our approach is to model the normalized spectrum from a spotted star ($F_{\rm tot}$) as the weighted sum of $F_{\rm S}$ and $F_{\rm Q}$, the spectra of suitable proxy stars for the spot and quiet photosphere, with $T_{\rm eff} = T_{\rm S}$ and $T_{\rm eff} = T_{\rm Q}$, respectively. The model is given by $F_{\rm tot} = [f_{\rm S} R_\lambda F_{\rm S} + (1 - f_{\rm S}) F_{\rm Q}]/[f_{\rm S} R_\lambda + (1 - f_{\rm S})]$, where $f_{\rm S}$ is the total fractional projected area of spots on the observed hemisphere (weighted by limb-darkening) and R_λ is the surface continuum flux ratio between the spots and the photosphere (taken from Kurucz 1991 models). For these first analyses, we have defined a "band depth index" (the difference between averages in 5 Å segments redward and blueward of the band heads) for target and comparison stars and fit these values rather than the spectra themselves (see Neff, O'Neal, Saar 1995; O'Neal, Neff, Saar, 1994). Some of the results of the analysis are given in Table 1. We have estimated values for stellar gravity using data from several sources including Gray (1992), Schrijver & Zwaan (1991), and Strassmeier et al. (1993).

3. Discussion and Conclusions

When we plot ΔT vs. $\log g$ for our stars and include a point for the Sun at $\Delta T_\odot \approx 1800$ K ($T_{{\rm S},\odot} \approx 4000$ K; *e.g.*, Maltby et al. 1986) and $\log g = 4.44$, there is

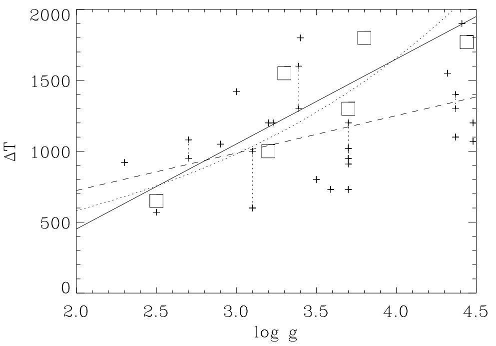

Figure 1: Relation between $\log g$ and $\Delta T = T_\mathrm{Q} - T_\mathrm{S}$. Our TiO band results and the Sun are plotted as squares, with linear (solid line) and power law (dotted line) fits. Photometric results (crosses, with multiple T_S values connected; from Eaton 1992) show a similar, weaker trend (dashed line).

a clear trend of increasing ΔT with $\log g$ (Figure 1; squares). A linear fit yields $\Delta T = 600 \log g - 750$ K ($\sigma = 250$ K); the data can also be fitted reasonably with $\Delta T = 200 \times g^{0.23}$ ($\sigma = 280$ K). A similar trend is found in the photometric ΔT values (compiled by Eaton 1992), but the relation shows more scatter and a shallower slope (Figure 1; best linear fit is $\Delta T = 260 \log g + 200$ K, $\sigma = 340$ K).

If these correlations represent real physical relationships, they imply that the temperature contrast between quiet photosphere and spot is reduced in lower gravity stars. This might be the result of spot pressure balance changing as a function of gravity. For horizontal pressure balance, $\Delta P = P_\mathrm{ext} - P_\mathrm{int} \sim B_\mathrm{S}^2/8\pi$, where P_ext and P_int are the gas pressures external and internal to the spot, and B_S is the spot field strength. If we take the stellar surface layers to be an adiabatic environment, we have $P_\mathrm{gas} \propto T^{5/2}$, so that $\Delta P \propto T^{3/2}\Delta T$. But we also have $P_\mathrm{gas} \propto g^{2/3}$ (*e.g.*, Gray 1992) and expect $P_\mathrm{gas} \propto B_\mathrm{S}^2/8\pi$ (Skumanich 1992), so that $T^{3/2}\Delta T \propto g^{2/3}$, or $\Delta T \propto g^{4/15}$, very close to the $g^{0.23}$ scaling we find in the data. Thus, mean B_S values may be smaller on low gravity stars, reflecting the lower photospheric pressures with which they must be in horizontal pressure equilibrium (*e.g.*, Skumanich 1992). Indirect support of this idea comes from the apparently small plage/network field strengths on evolved stars (there have been few field measurements on *any* evolved star, regardless of activity level; Marcy & Bruning 1984). If *spot* fields on low gravity stars are similarly small, the ΔP and ΔT contrasts between their spots and photospheres may also be reduced. The ΔT values may thus be indirect indicators of the trends of B_S values in stars.

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