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# ABSOLUTE MEASUREMENTS OF STARSPOT AREA AND TEMPERATURE

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## INTRODUCTION

Photometric and spectroscopic variability of late-type stars frequently has been interpreted as evidence of magnetic activity. The standard picture of stellar activity – inherited from solar observations – includes cool, dark "spots" in the photosphere and hot, dense regions in the chromosphere and coronae. The immediate cause of each of these phenomena is a closed topology of the local magnetic field. Because stars appear as mere points of light, these localized phenomena have not been directly resolvable on stars other than the Sun. Most observed effects are produced by an *asymmetric* distribution of starspots. If the distribution is symmetric, it would escape detection by most current techniques of light-curve and line-profile modeling. Even more troubling, the stellar properties measured with these techniques describe only a *difference* between contrasting hemispheres, not an absolute measure.

In order to devise an absolute measure, we searched the solar spectrum for spectroscopic features that would be produced <u>only</u> in starspots. The spectrum of sunspots in the region of the molecular bands of TiO near 7100 and near 8860 Å is radically different from that of the non-spotted photosphere. The presence of these features in the globally-averaged spectrum of a warmer star would be incontrovertible evidence for a cool (i.e., starspot) component of the photosphere.

We are using spectra of the TiO bands to *independently* measure the <u>area</u> and the <u>temperature</u> of starspots. The absolute strength of all the absorption bands is primarily a function of the total area of spots, while the relative absorption strength in different bands provides an independent constraint on the spot temperature.

## OBSERVATIONS AND TARGET SELECTION

Our target stars consist of rapidly-rotating, late-type stars, primarily of BY Dra and RS CVn-type. Our method requires that we also obtain high-quality spectra of several categories of "inactive" stars. Spectra of inactive G and K dwarfs and subgiants represent unspotted photosphere at a variety of effective temperatures.



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Spectra of M giants and M dwarfs represent spectra of starspots with various effective temperatures in stars with various gravities.

Our data were obtained during 9 observing runs at the National Solar Observatory's McMath telescope. They consist of 569 medium-resolution ($\Delta\lambda/\lambda \sim 20,000$), high-S/N (200–300) spectra with a range of approximately 200 Å centered on the TiO bands clustered near 7100 Å and on the band at 8860 Å. We observed 9 dwarf and 7 giant target stars, 13 inactive G and K stars, and 30 M dwarf and giant comparison stars.

## ANALYSIS & MEASUREMENT TECHNIQUES

The two wavelength regions we selected contain TiO absorption bands with different temperature sensitivities: the 7100 Å bands first become visible for an immaculate star at spectral type about K5, while the 8860 Å band is not evident until M1 (Huenemoerder 1988; Ramsey and Nations 1980). Modeling the two bands simultaneously thus permits an estimate of both the size (from the absolute band strengths) and the temperature (from the ratio of the band strengths) of cool spots on the stellar surface. Our approach (patterned after Huenemoerder and Ramsey 1987 and Vogt 1981) is to model the normalized spectrum from a spotted star ($F_{total}$) as the weighted sum of $F_{spot}$ and $F_{phot}$, the spectra of suitable standard stars with $\mathrm{T}_{eff}$=$\mathrm{T}_{spot}$ and $\mathrm{T}_{eff}$=$\mathrm{T}_{phot}$, respectively. The model is given by $F_{total} = [AR_\lambda F_{spot} + (1-A)F_{phot}]/[AR_\lambda + (1-A)]$, where $A$ is the total fractional projected area of spots on the observed hemisphere (weighted by limb-darkening) and $R_\lambda$ is the surface flux ratio between the spots and the photosphere. We assume that $R_\lambda = B_\lambda(\mathrm{T}_{spot})/B_\lambda(\mathrm{T}_{phot})$, the ratio of the respective Planck functions. We use simultaneous least-squares fits in both wavelength regions, with various standards to simulate $F_{spot}$ and $F_{phot}$, until the best fit is achieved.

## EXAMPLE: II PEG IN OCTOBER 1989

To illustrate our method, we have analyzed a series of spectra of the single-lined spectroscopic binary system II Pegasi (HD 224085) (see Saar and Neff 1990 for results for the dwarf star Gl 171.2A). We observed II Peg in both wavelength bands on each of five nights between 9 and 14 October 1989.

Because these spectra are being used to debug and develop our new fitting algorithm, the results are still uncertain. In particular, our current constraint on the net effective temperature is still quite primitive, and we have not yet codified the uncertainties in the derived properties.

Our preliminary results for II Peg yield $\mathrm{T}_{quiet} = 5050 \pm 100$ K and $\mathrm{T}_{spot} \sim 3250$ K. The fractional area coverage of such spots is 55 to 65% of the visible hemisphere. Both bands vary visibly in strength from night to night. The rotational period of this star is about 6.6 days, so we likely are witnessing rotational modulation of the spectrum from a star that is asymmetrically spotted. Huenemoerder, Ramsey, and Buzasi (1989) also saw variability in the 8860 Å band strength, but without observations at 7100 Å, they were unable to uniquely model the starspot properties.

## WORK PLANNED AND IN PROGRESS

Thanks to the telescope allocation policy of the solar-stellar program at the U.S. National Solar Observatory, we were able to accumulate—over 45 nights spread over 2 years—a sufficient number of observations of comparison stars to piece together an appropriate "grid". This is the foremost requirement for our procedure to work. With the comparison grid in hand, we plan to continue monitoring our target stars to measure variability over rotational and cycle timescales.

There are still some difficulties in the analysis procedure that we must overcome: (1) The biggest problem is normalizing the 7100 Å continuum for the coolest M-type comparison stars. There are other TiO bands shortward of our ≈200 Å bandpass that could affect our normalization. (2) Our comparison grid is empirical, non-continuous, and non-evenly sampled. Our fitting procedure must account for this. (3) There is no evidence of spots on any of our comparison stars (though surely they have some small fraction of spottedness), but we must be wary of any anomalies in their spectra.

In March 1992 we began a new phase of our observational program using the Penn State fiber-optic echelle spectrograph at Kitt Peak. This instrument allows us to observe the entire spectrum simultaneously with the same sensitivity as our existing observations. We will have thousands of Angstroms of spectrum to constrain the synthesis, many more bands of differing temperature sensitivity, and a well-constrained continuum. The echelle data will produce superior results and will permit us to re-analyze our McMath data, solving any problems with normalization. These spectra also will simultaneously provide a measure of the chromospheric activity level.

## REFERENCES

Huenemoerder, D. P. 1988, in *Cool Stars, Stellar Systems, and the Sun*, eds. J. Linsky and R. Stencel (Dordrecht: Reidel), p. 512.

Huenemoerder, D. P., Ramsey, L. W. 1987, *ApJ*, **319**, 392.

Huenemoerder, D. P., Ramsey, L. W., Buzasi, D.L. 1989, *AJ*, **98**, 2264.

Ramsey, L. W., Nations, H. L. 1980, *ApJ*, **239**, L121.

Saar, S.H., Neff, J.E. 1990, in *Cool Stars, Stellar Systems, and the Sun*, ed. G. Wallerstein, (ASP Conf. Series), p. 171.

Vogt, S.S. 1981, *ApJ*, **247**, 975.