Using TiO Spectroscopy To Further Constrain Doppler Imaging

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1. Introduction

We have developed a technique in which the 7055 Å and 8860 Å absorption bands of the titanium oxide molecule are used to measure starspot area and temperature on active stars (Neff, O'Neal, & Saar 1995). We have used this technique to measure the starspot properties of II Pegasi and four other active, evolved, spotted stars (O'Neal, Saar, & Neff 1995). In this poster, we describe how TiO band spectroscopy of active stars could be used in conjunction with Doppler imaging and multi-color photometry to completely determine the photospheric temperature distribution of rapidly rotating, active stars.

2. TiO Band Measurements of Starspots

We model the spectra of active stars using the spectra of M stars as proxies for the spotted regions and spectra of inactive G and K stars as proxies for the unspotted photosphere. For the M stars, we compute relations of band depth versus $T_{\rm eff}$. The 7055 Å and 8860 Å bands of the TiO molecule have different temperature sensitivities, so when they are observed on a spotted star, the ratio of their strengths provides a measure of the spot temperature. The absolute band strengths, on the other hand, are a function only of the total spotted area. Figure 1 illustrates our technique. A weighted sum of the spot spectrum ($F_{\rm S}$) and non-spot spectrum ($F_{\rm Q}$) is compared to the observed spectrum of an active star. The continuum-normalized proxy spectra are added according to

$$F_{observed} = \frac{f_{\rm S} R_\lambda F_{\rm S} + (1 - f_{\rm S}) F_{\rm Q}}{f_{\rm S} R_\lambda + (1 - f_{\rm S})}, \qquad (1)$$

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 continuum surface flux ratio between the spot and quiet photosphere.

This technique can uniquely determine the spot temperature, $T_{\rm S}$, when $T_{\rm S} \leq 3800$ K. Above this temperature, the 8860 Å band is too weak to detect in the spectra of active stars. Combined with contemporaneous photometry, we can determine spot parameters for stars with $T_{\rm S} \leq 4000$ K; above this temperature the 7055 Å band also becomes too weak to detect. With this technique we can measure starspot filling factors independent of the rotation rate of the star, and we can measure spatially uniform starspot distributions as easily as asymmetrical distributions.

3. Summary of TiO Results for Giant Stars

We have analyzed TiO observations of five evolved, single-lined, active stars. We used contemporaneous photometry to compute the unspotted photospheric temperature.

In four epochs of observing EI Eri (HD 26337), we found $T_{\rm S} = 3700 \pm 200$ K and $f_{\rm S}$ ranging from 17% to 38%. For II Peg (HD 224085), in two epochs of observation, we found $T_{\rm S} = 3500 \pm 100$ K and $f_{\rm S}$ between 43% and 56%, correlating with the visual light curve. We observed V1762 Cyg (HR 7275) on only one night, but we computed $T_{\rm S} = 3600$ K and $f_{\rm S} = 31\%$.

V1794 Cyg (HD 199178) and σ Gem (HR 2973) have starspots too warm for us to uniquely determine their temperature, because they do not produce a measurable depth in the 8860 Å band. In both cases, contemporaneous photometry aids in estimating $T_{\rm Q}$ and $T_{\rm S}$. Assuming $T_{\rm S} = 3800$ K for V1794 Cyg, the spot filling factor varied from 16% to 37% in two epochs of observation. For σ Gem, taking $T_{\rm Q} = 4500$ K and $T_{\rm S} = 3850$ K, the maximum filling factor we observed was 33%.

For EI Eri, σ Gem, V1762 Cyg, and II Peg, we found substantially higher starspot filling factors than computed by other investigators using different techniques. Our spectroscopic technique measures the entire starspot distribution, while photometric and Doppler imaging studies rely on an asymmetry in the spot distribution.

4. A New Constraint for Doppler Imaging

As Collier Cameron (1992) notes, Doppler imaging is much better at determining the distributions of inhomogeneities on a stellar surface than their temperatures. He recommends using VRI photometry to determine $T_{\rm S}$. However, photometry is generally better at constraining the mean photospheric temperature, $T_{\rm Q}$, because the unspotted photosphere dominates the light at all wavelengths. Doppler imaging also has difficulties detecting homogeneous distributions of small

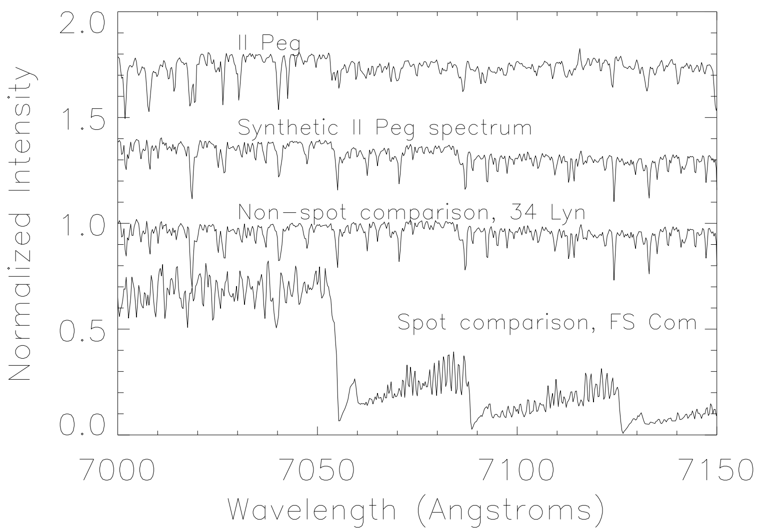

Figure 1: Illustration of how spectra of an M giant (FS Com, M5 III, $T_{\rm eff}$ = 3475 K) and an inactive comparison star (34 Lyn, G8 IV, $T_{\rm eff}$ = 4825 K) are added to produce a synthetic spectrum, which is then compared with the observed spectra of an active star such as II Peg. Observations were made with the stellar spectrograph at the McMath-Pierce Telescope of the National Solar Observatory.

spots; a smooth unspotted surface with $T_{\rm S} < T < T_{\rm Q}$ is typically produced. Our TiO-band spectroscopy, on the other hand, can constrain $T_{\rm S}$ to within $\pm$ 100 K, essentially independent of $T_{\rm Q}$ so long as $f_{\rm S} \gtrsim 7\%$ (O'Neal, Saar, & Neff 1995). It can also detect spots independent of their spatial distribution.

We can combine our TiO spectroscopy with Doppler imaging in several ways. First, a synthetic TiO-band spectrum could be produced from a multi-temperature Doppler map, like those produced by the Doppler imaging method that use maximum-entropy (e.g., Vogt et al. 1987) or Tikhonov-style inversions (e.g., Piskunov et al. 1990). TiO spectroscopy would independently provide an initial estimate for mean $T_{\rm S}$, while echelle spectra or TiO spectroscopy plus photometry could provide a similar estimate for $T_{\rm Q}$. Doppler imaging would proceed in the usual manner, but the modelled temperature distribution must also provide a match to the TiO bands. Our proxy spectra (or a mathematical idealization of them) are available to represent the spectrum generated over a range in $T_{\rm eff}$.

Some methods (e.g. Hatzes & Vogt 1992) require additional constraint to "threshold" the image. This threshold level might be easily derived by matching the total $f_{\rm S}$ provided by TiO spectroscopy.

Thus far in our studies of starspots, we have assumed a two-temperature model of stellar surfaces: a unique $T_{\rm Q}$ and $T_{\rm S}$. With the incorporation of more bands from echelle spectra, we will be sensitive to a larger range of temperatures and will be able to determine whether stars in fact have a unique spot temperature. If this hypothesis is borne out (as it is for the Sun), then there is no need to use temperature as a variable parameter in the Doppler imaging techniques. Methods such as those by Kürster (1993), Strassmeier (1994), and Collier Cameron (1992) could use the temperatures given by TiO spectroscopy and vary the distribution to match the total spotted area.

5. Conclusions

Combining the results of molecular spectroscopy with Doppler imaging will be a powerful tool in constraining the photospheric parameters of active stars. Molecular spectroscopy, especially when combined with multicolor photometry, is effective at determining the starspot temperature and total area of starspots, while Doppler imaging very effectively maps their surface distribution.

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