EXPLORING THE USE OF VO TO DIAGNOSE SPOT PROPERTIES ON M DWARFS

D. O'Neal[1], S. H. Saar[2], and J. E. Neff[3] and M. Cuntz[4]

[1]Allegheny College, 520 North Main Street, Meadville, PA 16335 USA
[2]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
[3]College of Charleston, Charleston, SC, USA
[4]University of Texas, Arlington, TX, USA

Abstract

Spectroscopic observation of molecular features is an effective way to detect starspots on magnetically active cool stars. We have previously used the TiO and OH molecules to study spots on active G and K stars; this technique works because on these stars, these molecules occur primarily or entirely in the spots, not in the warmer photosphere. To extend our technique to cooler active stars, we studied VO absorption features, which first appear in stellar spectra at late-M star temperatures. We find, however, that VO is not an effective diagnostic of cool spots on M dwarfs; we suggest other molecules that might work better, though this needs further study.

Key words: stars: activity – stars: atmospheres – stars: spots – techniques: spectroscopic

1. Introduction

Spectroscopic observation of molecular species, including TiO (O'Neal et al. 2004) and OH (O'Neal et al. 2001) is is an effective way to detect dark, cool starspots on magnetically active G and K stars. These molecules dissociate at photospheric temperatures ≥4300 K, so their presence in the spectra of warmer stars is direct evidence for cool spots. We use spectra of inactive G and K stars as proxies for the non-spot photospheres of the active stars, and spectra of M stars as proxies for the spots. Molecular spectroscopy detects the entire coverage by dark starspots, so long as the temperature of the spots ($T_{\rm S}$) is below the temperature at which strong absorption features of the molecule appear in stellar spectra. Figure 1 illustrates our technique in the region of the TiO bands beginning at 7053 Å; we also show a fit to a spectrum of the active dwarf EQ Vir, for which spot filling factor (fractional area coverage weighted by projection and limb-darkening) $f_{\rm S}$ = 0.39.

Many M dwarfs are highly magnetically active, exhibiting flares, x-ray emission, and spots found by rotational modulation of light curves. TiO and OH are not good diagnostics for spots on these stars, because absorption features from these molecules are strong at M star photospheric temperatures ≤3800 K.

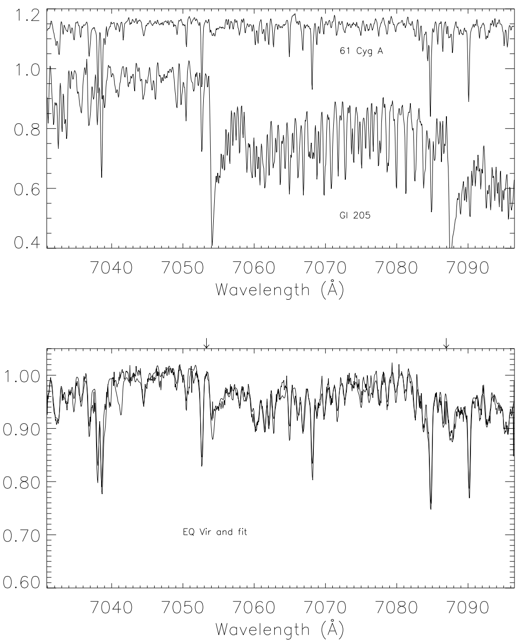

Figure 1. Illustration of TiO-band technique for measuring starspot properties. Top: Spectra of inactive stars 61 Cyg A (K5 V) and Gl 205 (M1.5 V), with a rotational broadening function applied to match EQ Vir's v sin i = 9.5 km/s. Spectra are normalized; 61 Cyg A is vertically offset. Bottom: Spectrum of K5 Ve star EQ Vir (with noise) and fit to it (smooth) using 61 Cyg A and Gl 205 as non-spot and spot proxies. The weak TiO absorption due to starspots is apparent; arrows mark the positions of band heads. In this fit, $f_{\rm S}$ = 0.39. The two plots have different vertical scales.

Bands of vanadium oxide (VO) first appear in late M stars (e.g. Kirkpatrick, Henry, & McCarthy 1991). On a magnetically active early- to mid-M star, VO absorption would be expected only from cool starspots. This molecule thus holds promise for extending our technique to cooler active stars. With this in mind, in 2001 December we obtained R=60,000 spectra of several active M stars (Table 1) using the Cassegrain Echelle Spectrograph (McCarthy et al. 1993) and the 2.1-m telescope at McDonald Observatory of the University of Texas at Austin. We also observed inactive comparison stars on this and pre-

Table 1. Active M Dwarfs Observed

Star	V	I	Spc. Type	P_{rot} (d)
LO Peg = Gl 4199	9.2		K8	
HK Aqr = Gl 890	10.8		M0	0.42
V1005 Ori = Gl 182	10.1		M0	
YY Gem = Gl 278C	9.1	6.7	M0.5+M0.5	0.81
DT Vir	9.7		M0.5	
EV Lac	10.1	7.0	M3.5	4.4
AD Leo	9.4	6.3	M3.5	2.7
YZ CMi = Gl 285	11.1	8.0	M4.5	2.8

vious runs. Our spectra cover from 6500 Å to 9000 Å and include VO band systems near 7400, 7900, and 8600 Å.

2. VO bands in stellar spectra

In a sequence of M dwarf spectra (e.g. Kirkpatrick, Henry, & McCarthy 1991), VO absorption is apparent in the 7400 and 8600 Å bands beginning at approximately M6 V, and for a slightly earlier spectral type in the 7900 Å band. In Figure 2, we compare a CassEchelle spectrum (smoothed to R = $\lambda/\Delta\lambda$ = 8000) of R Hya (listed as M7 III) with one of BY Boo (M4.5 III). The VO bands appear qualitatively different from those of TiO. TiO exhibits sharp band heads at which the flux drops suddenly, while VO manifests as a "scooping out" of flux over a larger wavelength region. To measure VO absorption in the 7400 Å band, Kirkpatrick, Henry, & Simons (1995) define a *VO ratio* as

$$VO_{7400} = \frac{0.5625(F_{7350-7400}) + 0.4375(F_{7510-7560})}{F_{7420-7470}}, \quad (1)$$

where $F_{\lambda_1-\lambda_2}$ is the total flux integrated between the two wavelengths. This is the ratio of flux expected in the absence of VO absorption, as interpolated between pseudo-continuum regions on either side of the band, to the actual flux within the band. The coefficients in the numerator arise because the center of the first wavelength region is closer than the center of the second to the center of the in-band (denominator) wavelength region, by a ratio of 0.4325/0.5625 = 70/90.

For our analysis, we define a similar ratio for the 7900 Å VO band:

$$VO_{7900} = \frac{0.5334(F_{7760-7820}) + 0.4666(F_{8060-8120})}{F_{7900-7960}}, \quad (2)$$

and for the 8600 Å VO band: $VO_{8600} = 1.6\times$

$$\frac{[0.5967(F_{8467-8492} + F_{8505-8530}) + 0.4033(F_{8750-8800})]}{F_{8570-8650}}. (3)$$

The 1.6 coefficient is necessary because the out-of-band (denominator) wavelength regions are 5/8 as long as the in-band (denominator) region. The break in the first region in VO_{8600} avoids the strong 8498 Å Ca II line.

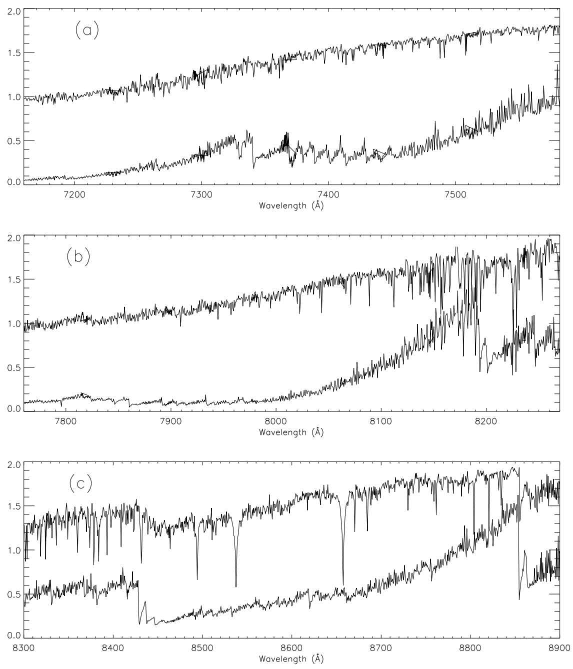

Figure 2. Comparison of BY Boo (M4.5 III, top spectrum in each frame) with R Hya (M7 III). In R Hya, VO bands at (a) 7400 Å, (b) 7900 Å, and (c) 8600 Å are seen as a "scooping out" of flux over a wide wavelength range. In (c), the features near 8432 Å and 8860 Å are TiO band heads. In each panel, intensity scales for the two spectra were matched near the red end of the VO band, then vertically offset.

We measured these VO ratios in inactive M dwarfs and giants. Only VO_{7900} was significantly different from 1 in any of these stars of spectral type M6 or earlier. In Figure 3 we plot VO_{7900} against spectral subclass. The giants and dwarfs have similar dependencies of VO absorption with spectral type. We take σ=0.023 as the uncertainty in each measurement; this is the standard deviation of VO ratio values computed from spectra in which they are expected to be 1.

R Hya shows VO_{7400} = 1.51, VO_{7900} = 2.74, and VO_{8600} = 1.20. We compute its T_{eff} = 3050 K from color-temperature relations (Houdashelt et al. 2000; Bessell, Castelli, & Plez 1998; Strassmeier & Schordan 2000). It is a Mira variable, however, so possibly it was cooler when we observed it. Comparing to a grid of M dwarf spectra (Kirkpatrick, Henry, & McCarthy 1991), our R Hya spectrum most resembles that of an M9 V star. VO absorption strength reaches a maximum among dwarfs at M9 (Martín et al. 1999) and weakens in early L dwarfs (Kirkpatrick et al. 1999). Thus our R Hya spectrum might represent close to the maximum possible strength of the VO features.

3. Search for VO in active stars

Neither VO_{7400} nor VO_{8600} was significantly different from 1 in any of our active star spectra. For VO_{7900} (Figure 3),

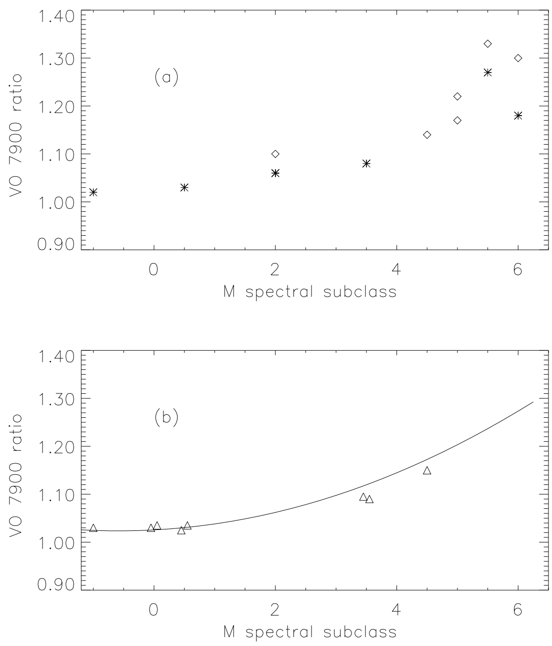

Figure 3. (a) VO_{7900} ratio for inactive M giants (diamonds) and dwarfs (asterisks) plotted against M spectral subclass (-1 = K7-8). (b) A quadratic fit to the VO_{7900} ratio for inactive stars (solid line) and the VO_{7900} ratio for active M stars (triangles), showing the lack of measurable excess absorption.

values for active stars fell very close to the VO_{7900} vs. spectral type relation of inactive stars. Since σ=0.023 a 2σ detection would require the VO ratio to be 0.046 above that for an inactive star of its spectral type.

We thus computed synthetic spectra to set limits for detectable filling factors $f_{\rm S}$ of starspots on these stars; this requires substantial assumptions about the temperature or equivalent spectral type of the spots. Two proxy spectra can be added together to make a model of an active-star spectrum using:

$$F = \frac{f_{\rm S} R_\lambda F_{\rm S} + (1 - f_{\rm S}) F_{\rm Q}}{f_{\rm S} R_\lambda + (1 - f_{\rm S})}. \quad (4)$$

This weighted sum combines the spectrum from a spot proxy $F_{\rm S}$ and a non-spot proxy $F_{\rm Q}$ to simulate the spectrum (F) of a star with dark starspots. The two proxies are normalized to the same arbitrary intensity scale at a chosen wavelength λ; R_λ is the continuum flux ratio (computed using the Phoenix models by Allard, Hauschildt, & Schweitzer 2000) between the spots and photosphere at this wavelength.

A cooler spot does not necessarily lead to stronger molecular absorption in the active star spectrum: if R_λ is small, the spots would have a small effect in the overall spectrum, and even intrinsically very strong molecular features would be difficult to detect by contrast against the photospheric light.

Table 2. Detectability of 7900 Å VO band

$T_{\rm S}$, K	minimum detectable $f_{\rm S}$
2900	0.20
2800	0.25
2700	0.25
2600	0.35
2500	0.40
2400	0.50

Table 3. Detectability of 7400 Å band

$T_{\rm S}$, K	minimum detectable $f_{\rm S}$
2900	0.25
2800	0.30
2700	0.35
2600	0.45
≤2500	>0.50

3.1. Results

As non-spot proxies for the photospheres of the active stars, we used Gl 488 (M0.5 V, $T_{\rm eff}$ = 3700 K) and Gl 273 (M3.5 V, $T_{\rm eff}$ = 3150 K).

The best case for detecting VO in an active star would be if the spot had a spectrum like that of R Hya (Figure 2) but was not much cooler than the photosphere. We use this somewhat unrealistic case [Basri et al. (2000) give $T_{\rm eff}$ ≈2400 K for an M9 V star, whose VO bands are approximately as deep as those in our R Hya spectrum] to explore the detectability of VO from starspots.

The 8600 Å band presents the most difficult case for detection, since in spectra where it is strong, it occurs where the flux is depressed by the strong 8432 Å TiO band; thus VO takes flux out of a spot spectrum already quite dim at that wavelength. We do not consider this band further.

On an M3.5 active star, the 7900 Å band would be detectable (2σ) at or above the values of $f_{\rm S}$ (computed at 0.05 intervals) given in Table 2, for a spot whose spectrum looks like that of R Hya ($T_{\rm S}$ is assumed spot temperature). For an M0.5 active star, each entry in the $f_{\rm S}$ column increases by 0.05.

The 7400 Å band on an M3.5 active star, if the spot looks like R Hya, would be detectable at the $f_{\rm S}$ values in Table 3. On an M0.5 active star, at $T_{\rm S}$=2900 K, $f_{\rm S}$ would have to be 0.40 or greater for this band to be detectable; for $T_{\rm S}$ ≤2700 K, no $f_{\rm S}$ below 0.50 would be detectable.

Zboril (2003) studies photometry of the active M4.5 V star YZ CMi and lists several possible spot models including one with $f_{\rm S}$ = 0.23 and $T_{\rm S}$ = 2700 K. Allard et al. (1997) give $T_{\rm eff} \approx 2700$ K for an M5.5-M6 dwarf; we thus model spots on YZ CMi using our observed spectrum of WX UMa (M6 V, but itself quite active, so possibly exhibiting spots cooler than this). With non-spot temperature $T_Q = 3150$ K and $T_S = 2700$ K, we find that a spot whose spectrum looks like that of WX UMa would not be detectable for $f_S < 0.50$ in any of the three VO bands.

4. Discussion – other molecular indicators

We conclude that VO bands are not a reasonable way to detect starspots with small to moderate filing factors on active M dwarfs. However, because of the intrinsic interest in these stars, it is nonetheless desirable to find a molecular indicator that could be diagnostic of starspots on these stars. In our TiO studies of starspots, we have almost exclusively used the band systems beginning near 7053 Å and 8860 Å. Among other TiO bands, the system beginning at 8432 Å is potentially useful as a diagnostic of spot temperatures on cooler active stars. In giants it becomes strong only at $T_{\rm eff} < 3600$ K ($\approx$ M3 III) and is still increasing in strength at $T_{\rm eff} = 3000$ K (O'Neal, Neff, & Saar 1998). In our M dwarf data, we find possible excess absorption in the TiO 8432 Å band system in the active star LO Peg (K8 V; Figure 4). The utility of this band as a spot diagnostic for all late-type active stars deserves further study.

Another possibility is the FeH band at 9900 Å. This has been used by Valenti, Johns-Krull, & Piskunov (2001) to study magnetic fields in late M stars, and by Kirkpatrick et al. (1999) as a spectral-type diagnostic for late M and L dwarfs. Unfortunately, this feature is difficult to observe due to the low QE of detectors at this wavelength. We plan to explore the utility of this molecule for starspot work in the near future.

Acknowledgements

DO's travel to Hamburg was partially funded by the Academic Support Committee of Allegheny College.

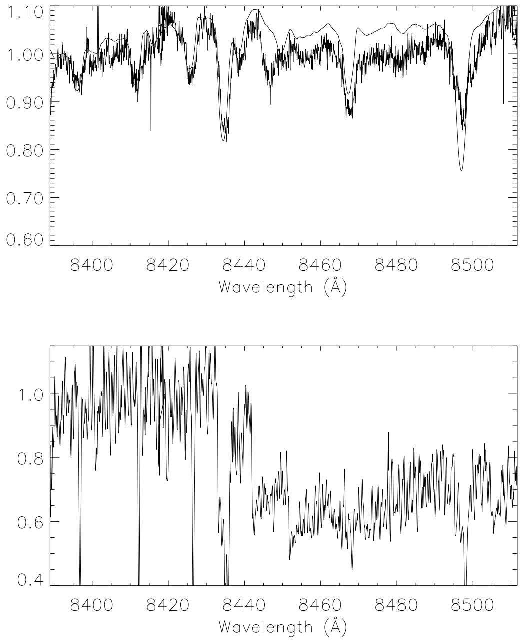

Figure 4. (Top) Spectrum of LO Peg (K8 V, active) in region of 8432 Å TiO band system (with noise), compared with an average of 61 Cyg B (K7 V) and Gl 488 (M0.5 V). This illustrates possible excess TiO absorption in LO Peg due to cool starspots. (Bottom) To illustrate band head positions, a spectrum of S Lep (M6 III); the initial band head is blended with a strong Fe I line.

References

Allard, F., Hauschildt, P. H., Alexander, D. R., Starrfield, S. 1997, Ann. Rev. Astron. Astrophys. 35, 137
Allard, F., Hauschildt, P. H., Schweitzer, A. 2000, ApJ 539, 366
Basri, G., Mohanty, S., Allard, F., Hauschildt, P. H., Delfosse, X., Martín, E. L., Forveille, T., Goldman, B. 2000, ApJ 538, 363
Bessell, M. S., Castelli, F., Plez, B. 1998, A&A 333, 231
Houdashelt, M. L., Bell, R. A., Sweigart, A. V., Wing, R. F. 2000, AJ 119, 1424
Kirkpatrick, J. D., Henry, T. J., McCarthy, D. W. 1991, ApJSS 77, 417
Kirkpatrick, J. D., Henry, T. J., Simons, D. A. 1995, AJ 109, 797
Kirkpatrick, J. D., Reid, I. N., Liebert, J., Cutri, R. M., Nelson, B., Beichman, C. A., Dahn, C. C. Monet, D. G., Gizis, J. E., Skrutskie, M. F. 1999, AJ 519, 802
Marino, G., Rodonò, M., Leto, G., Cutispoto, G. 1999, A&A 352, 189
Martín, E. L., Delfosse, X., Basri, G., Goldman, B., Forveille, T., Zapatero Osorio, M. R. 1999, AJ 118, 2466
McCarthy, J. K., Sandiford, B. A., Boyd, D., Booth, J. 1993, PASP 105, 881
O'Neal, D., Neff, J. E., Saar, S. H. 1998, ApJ 507, 919
O'Neal, D., Neff, J. E., Saar, S. H., Cuntz, M. 2004, AJ in press (Oct. 2004)
O'Neal, D., Neff, J. E., Saar, S. H., Mines, J. K. 2001, AJ 122, 1954
Strassmeier, K. G., Schordan, P. 2000, AN 321, 277
Valenti, J. A., Johns-Krull, C. M., Piskunov, N. E. 2001, in Eleventh Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. R. J. García López, R. Rebolo, & M. R. Zapatero Osorio, ASP Conf. Ser. 223, 1579
Zboril, M. 2003, AN 324, 527