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THE INCLINATION DEPENDENCE OF THE MEAN SPECTRAL LINE SHAPES OF RS CVn STARS: FURTHER EVIDENCE FOR POLAR SPOTS

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ABSTRACT

The mean spectral line shape of the Ca I 6439 Å line profile is examined in four RS CVn–type stars having different stellar inclinations. It is found that the low-inclination stars (HR 1099 and EI Eri) have a calcium line with a more pronounced flat-bottomed shape compared to the two high-inclination stars (AR Lac and V471 Tau) whose line shapes are close to those of rotationally broadened profiles. If the flat-bottomed line shape seen in many RS CVn stars arises purely from the atmosphere of the star and is not due to the surface temperature distribution, then one should expect to see flat-bottomed profiles in high-inclination stars as well, and this is not the case. Four models are considered as an explanation for the line shapes seen in the low-inclination RS CVn stars: (1) gravity darkening, (2) a bright band at the equator of the star, (3) surface differential rotation, and (4) a cool polar spot that is viewed with different projected areas. It is shown that gravity darkening cannot produce a flat-bottomed profile even when taking into consideration the temperature sensitivity of the Ca I 6439 Å line. A bright equatorial band is capable of producing a flat-bottomed profile, but the change in line shape with stellar inclination is not as dramatic as is observed with actual stars. Likewise, differential rotation with the poles of the star rotating faster than the equatorial regions can also produce a box-shaped line profile, but an unreasonable amount of differential rotation is required (the poles must rotate with an angular velocity at least twice that of the equator). The polar spot model is the only one of the four considered that is capable of producing a flat-bottomed profile whose shape changes significantly with stellar inclination. This model is also consistent with the presence of cool spots on RS CVn stars that have been established via photometry and the presence of persistent TiO molecular features in the spectra of these stars and provides further support to the presence of polar spots on RS CVn stars.

Subject headings: binaries: eclipsing — line: profiles — stars: activity

1. INTRODUCTION

Most Doppler images of rapidly rotating RS CVn and FK Comae–type stars reveal a spot distribution dominated by a polar spot with several appendages extending to lower latitudes. Such morphology has been seen on HR 1099 (Vogt & Penrod 1983), UX Ari (Vogt & Hatzes 1991), EI Eri (Strassmeier 1990; Strassmeier et al. 1991; Hatzes & Vogt 1992), HD 106225 (Strassmeier 1994), DM UMa Hatzes 1995a), and the FK Comae stars HD 199178 (Vogt 1988) and YY Men (Kürster et al. 1992). In spite of the numerous Doppler images that have been derived using a variety of techniques, and all showing polar spots, the presence of these features on RS CVn–type stars is still somewhat controversial (Byrne 1991). One argument for their appearance in Doppler images of RS CVn stars is that it is an artifact due to an error in the atmospheric physics of these stars. Gross errors, however, in the shape of the local line profile cannot account for the mean shape of the observed spectral line profiles in rapidly rotating spotted stars. In such a case the observed line shape is completely dominated by the rotational broadening profile which is insensitive to the assumed shape of the local line profile. In fact, one can replace the local line profile by a square-shaped function with the appropriate equivalent width and the integrated spectral line profile would not depart markedly from a rotationally broadened profile generated from specific intensity profiles from a real model atmosphere (Ramseyer, Hatzes, & Jablonski 1995). To produce the persistent flat-bottomed shape seen in several RS CVn stars requires a more global variation in the local spectral line profile across the star. For instance, a high degree of limb brightening (Hatzes & Vogt 1992) can result in a flat-bottomed spectral line profile. Alternatively this shape can be due to filling-in of the core from chromospheric emission or from some unkown mechanism. A time-invariant, flat-bottomed spectral line profile can be modeled with cool spots only by placing these features on a region of the stellar surface that is always in view—i.e., the rotation pole of the star.

It is important to establish that the reality of such polar spots as this can impact theoretical interpretations of the spot distribution on these stars. For instance, Schüssler & Solanki (1992) have argued that the presence of polar spots in rapidly rotating stars is due to the Coriolis force dominating over the buoyancy force acting on magnetic flux tubes that causes magnetic flux to emerge predominantly at the rotation pole of the star. This hypothesis would be in error if polar spots, in fact, did not exist on these stars.

In this paper, the mean spectral line shape of the Ca I 6439 Å line is examined for two high- and two low-inclination RS CVn–type stars, and this is compared to a synthetic, rotationally broadened profile. It is shown that there are systematic differences in the mean spectral line

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shape between stars of different inclinations. It is argued that these differences most likely arise from a dark polar spot present on all stars but seen with different projected areas.

2. THE SPECTRAL LINE SHAPES

2.1. *Data Acquisition and Stellar Parameters*

The mean spectral line shape for the Ca I 6439 Å line was examined in four RS CVn stars: HR 1099, EI Eri (=HD 26337), V471 Tau, and AR Lac. The last two stars are eclipsing systems with well-determined inclinations of 90° (Nelson & Young 1970) and 87° (Chambliss 1976), respectively. The double-lined spectroscopic binary HR 1099 is believed to have an inclination of 33° (Fekel 1983). EI Eri is a single-lined spectroscopic binary whose inclination of 46° was determined by Strassmeier (1990).

For each star the mean profile was calculated by summing spectra covering a complete rotation period. The spectral observations for HR 1099, EI Eri, and AR Lac were acquired using the coudé spectrograph of the Lick 3 m Shane telescope. The details of the spectrograph setup and data acquisition can be found in Hatzes & Vogt (1992). Data for V471 Tau were taken using the Sandiford Echelle at the McDonald 2.1 m telescope. A description of this instrument can be found in McCarthy et al. (1993) and the details of the observational data are in Ramseyer et al. (1995).

The mean Ca I profile for EI Eri was computed using 11 observations taken in late 1987. The Doppler image derived from these profiles can be found in Hatzes & Vogt (1992). Eighty-one observations of V471 Tau taken in 1992 October were averaged to produce the mean profile for that star. The Doppler image derived from that data set can be found in Ramseyer et al. (1995), and it is characterized by a polar spot and a persistent equatorial spot in the direction of the white dwarf companion to V471 Tau.

Ten observations taken in late 1987 were used in producing the mean Ca I profile for HR 1099 and 12 spectra taken in the latter part of 1990 were used for the mean profile of AR Lac. The Doppler images from these data sets are currently in preparation and will be presented in forthcoming papers (see Vogt 1988 or Donati et al. 1992 for a typical spot distribution on HR 1099). Both Doppler images of HR 1099 and AR Lac show the characteristic polar spot, or high-latitude spot activity seen on many RS CVn stars.

Table 1 summarizes the list of stars, their spectral types, projected rotational velocities ($v \sin i$), inclinations, gravities, metallicities, effective temperatures, and spot temperatures. The values of the surface gravity come from Fekel (1983) [HR 1099], Lacy (1979) [AR Lac], Randich, Gratton, & Pallavicini (1993) [EI Eri], and Young & Nelson (1972) [V471 Tau]. Metallicities are from the list of Randich et al. (1993) or Cayrel de Strobel et al. (1992). No metallicities have been published for V471 Tau. However, it is a main-sequence star that is suspected to be a member of the Hyades group, so its metallicity was assumed to be solar. The photospheric and spot temperatures for AR Lac and HR 1099 were taken from Rodonò et al. (1987) and for EI Eri from Strassmeier (1990). No spot temperature has been derived for V471 Tau.

All stars with the exception of EI Eri show a high degree of stellar activity with variable Hα emission and strong Ca II *h* and *k* emission according to Strassmeier et al.'s (1993) catalog and Hα is predominantly in absorption although it shows a line profile shape that is presumably "filled-in" with emission.

2.2. *Results*

The crosses in Figure 1 represent the mean spectral line profile for the four stars. Each solid line represents the rotationally broadened profile (from an unspotted star) that best fits the observed profile. These rotationally broadened profiles were calculated by integrating a stellar disk consisting of 120 × 120 cells. Local line profiles were computed using model atmospheres from Bell et al. (1976) and a macroturbulent velocity of 4 km s^{-1} was also employed in the simulation. The resulting values of $v \sin i$ are listed in Table 1.

It is evident from Figure 1 that the highest degree of distortion in the line core (i.e., flat-bottomed) is exhibited by the two stars having the lowest inclination (HR 1099 and EI Eri). In fact, these profiles are not so much flat-bottomed as they have a slight central "hump." The mean spectral line shapes for the two stars seen nearly equator-on show only a slight departure from a rotationally broadened profile. The stellar parameters between the various stars are not all that dissimilar, and, with the possible exception of V471 Tau, these stars are in comparable stages of stellar evolution. Ostensibly, if the mean spectral line shapes were not produced by the cool spot distribution, one would expect the four stars to have similar atmospheres and thus produce nearly identical line shapes. If the filling-in of the line cores of RS CVn stars is due primarily to some global atmospheric effect such as limb brightening, then the degree to which this effect modifies the shape of the spectral line profile depends on the stellar inclination.

There may be some concern that averaging the observed spectral line profiles may not completely remove time variable distortions in the profiles. For instance, is it possible that averaging the distortions of a low-latitude spot can produce a flat-bottomed profile? We believe that this is not the case. The weak T Tauri star V410 Tau has a spot distribution consisting of a decentered polar spot and several low-latitude spots, yet the mean shape of the Ca I 6439 Å line is almost that of a rotationally broadened line profile without distortions (Hatzes 1995b). Further evidence that distortions from low-latitude spots cannot produce flat-bottomed profiles can be seen in Figure 2. The top panel

TABLE 1

STARS AND STELLAR PARAMETERS

Star	Spectral Type	$v \sin i$ (km s^{-1})	i (deg)	log g	[Fe/H]	T_{eff} (K)	T_{spot} (K)
HR 1099.......	K1 IV	40	33	3.4	−0.65	4700	3500
EI Eri..........	G5 IV–III	50	46	4.1	−0.30	5500	3600
AR Lac........	K0 IV	75	87	3.7	−0.70	4700	3500
V471 Tau......	K2 V	90	90	4.3	0.00	5000	?

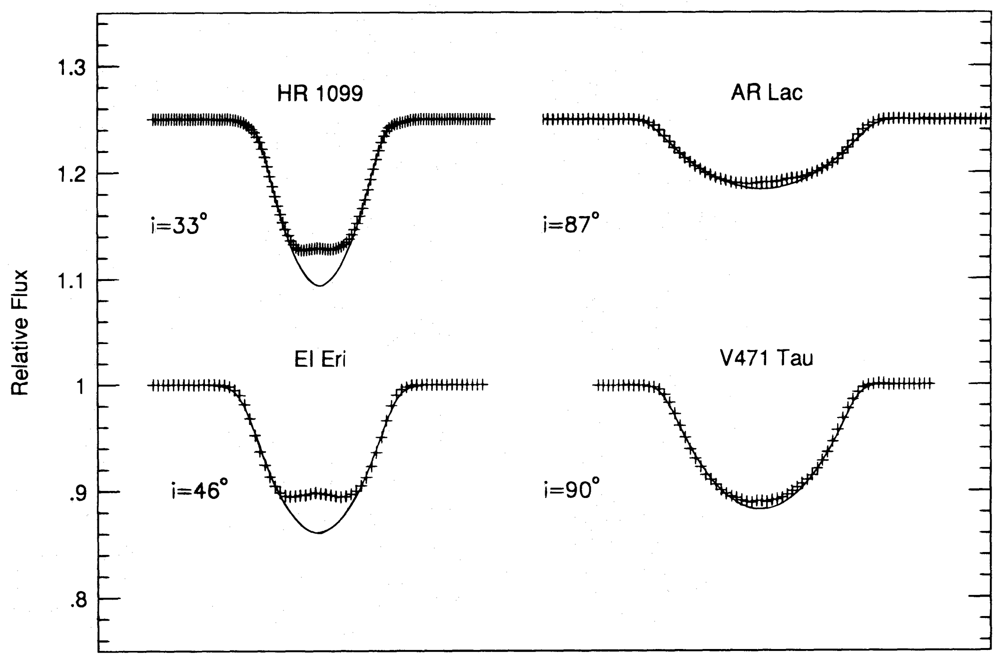

FIG. 1.—The mean shape of the observed Ca I 6439 Å line (*crosses*) for HR 1099, EI Eri, AR Lac, ad V471 Tau. The lines represent the best fit using a pure rotationally broadened line profile from an unspotted star.

shows the Ca I 6439 Å line at five rotation phases for a star having a spot of radius 15° located at latitude +20°. (A stellar inclination of 60° and a $v \sin i$ of 50 km s^{-1} were used in this simulation.) This sequence of profiles is centered on the phase when the spot is at disk center. The line in the lower panel is the mean profile of the five "spotted" phases. The crosses represent a rotationally broadened profile from an unspotted star. This simulation indicates that low-latitude features are not effective in producing a distortion in the mean profile.

Clearly, there are limitations to the analysis that follows. First, and foremost, the noted "trend" in the line shapes is based on a small sample of stars and there are differences in stellar properties such as spot coverage, plage filling factor, level of activity, etc., which can affect the spectral line shapes to one degree or another. There are also uncertainties in the estimate of the stellar inclination for the noneclipsing stars. Although Figure 1 is highly suggestive, true trends can be discerned only by looking at a larger sample of spotted stars and thus averaging out uncertainties and star-to-star differences. However, even if the trend is not real, much of the analysis that follows is valid and useful for eliminating possible hypotheses for the appearance of polar spots in Doppler images.

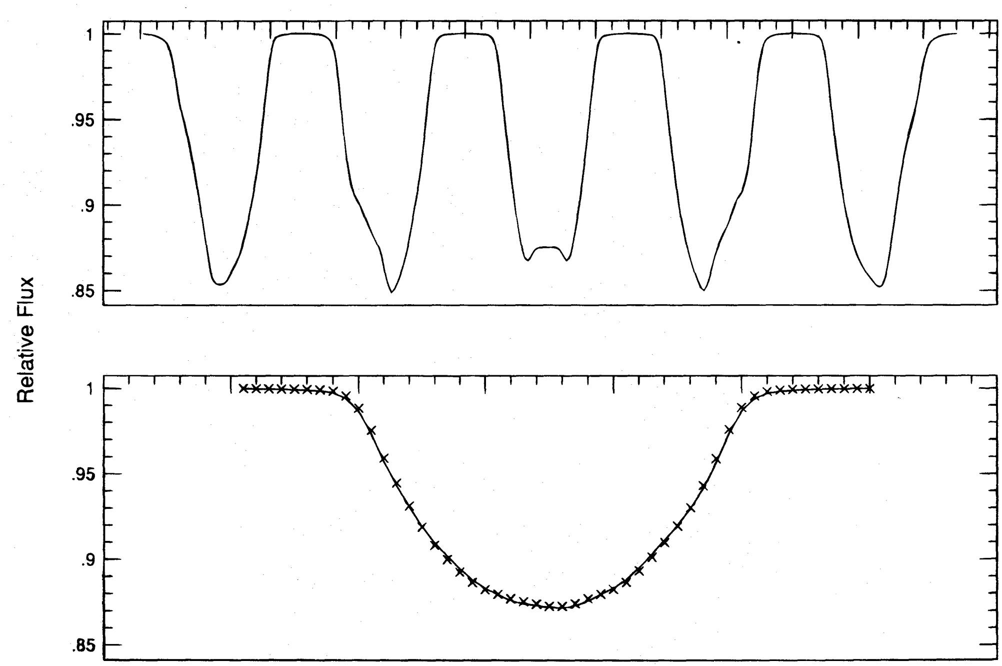

FIG. 2.—*Top:* The spectral line profiles at five rotation phases (separated by 0.063 in phase) of the Ca I 6439 Å profile from a star with a cool (ΔT = 1200 K) spot with a radius of 15° at latitude +20°. The star has a $v \sin i$ of 50 km s^{-1} and an inclination of 60°. *Bottom:* The mean Ca I profile (*line*) for the five phases and the profile from an unspotted star (*crosses*).

2.3. *Modeling*

2.3.1. *Gravity Darkening*

Gravity darkening is one mechanism that can produce an inclination effect on the shape of the observed spectral line profiles. For rapidly rotating stars centrifugal force provides partial hydrostatic support for the atmosphere near the equator. Consequently, the temperature at the equator can be significantly cooler than the pole (von Zeipel 1924; Collins 1963). The star would thus show a cool band about the equator, and this feature should have its greatest influence on the shape of the observed line profile when the star is viewed pole-on. Flat-bottomed profiles are seen in the weak lines of the spectrum of Vega (Gulliver et al. 1991). Recently, Gulliver, Hill, & Adelman (1994) argued that these flattened profiles could be explained if Vega were a rapidly rotating star viewed pole-on. They were able to model the peculiar profile using a temperature difference of $\Delta T = 390$ K and a gravity difference of 0.08 dex between the pole and equator.

If the spectral line of interest is temperature insensitive, then gravity darkening alone cannot produce a flattened line profile. As one approaches the cooler equator (or equivalently the stellar limb for low-inclination objects), the decreased flux raises the wings of the star due to the well-known "continuum effect" which also produces the pseudo-emission feature in the spectra of rapidly rotating spotted stars (see Vogt & Penrod 1983). This should make the line more V-shaped. However, a flattening of the line profile could occur if the line strength increases with decreasing temperature. This would serve to lower the depth of the wings and if this effect is greater than the continuum effect, then a flat-bottomed profile will result.

The Ca I 6439 Å line strength as a function of effective temperature was measured using a number of "standard" stars—objects having a spectral type near those of RS CVn stars. The stars used for these measurements are listed in Table 2. Spectra were obtained using the Sandiford Echelle Spectrograph at McDonald Observatory's 2.1 m telescope. Temperatures and gravities are from McWilliam (1990). The points in Figure 3 show the measured variation of the equivalent width of Ca I with temperature and the line represents a second-order polynomial fit to the data points. The measured equivalent width values are also listed in Table 1. Errors were estimated via repeated measurements of the same line using different continuum points and these resulted in less than a 10% variation in the equivalent width. There is a smooth trend of decreasing line strength with increasing effective temperature, and there is no obvious indication that stars with different stellar gravities have a Ca I line strength that departs markedly from this trend. Thus we expect that results of Figure 3 to be applic-

TABLE 2

STANDARD STARS

Star	Spectral Type	log g	$T_{\rm eff}$ (K)	$W_{\lambda 6439}$ (mÅ)
α Tau	K5 III	1.59	3910	245
HR 8980......	K5 III	1.59	3910	248
HR 9040......	K0 III	2.56	4440	222
ι Cet	K1.5 III	2.34	4500	237
τ Cas..........	K1 III	2.55	4560	210
HR 6857......	K2 III–IV	3.02	4640	215
HR 1256......	K0 III	2.77	4700	203
HR 8948......	K0	2.78	4730	199
HR 31	K0 IV	3.42	4770	201
β Gem	K0 III	2.90	4850	204
ϵ And	G8 III	3.16	4930	190
τ^2 Eri	K0 III	3.18	5000	189
β Aql	G8 IV	3.37	5100	173
HR 3771......	G4 III–IV	3.42	5250	161

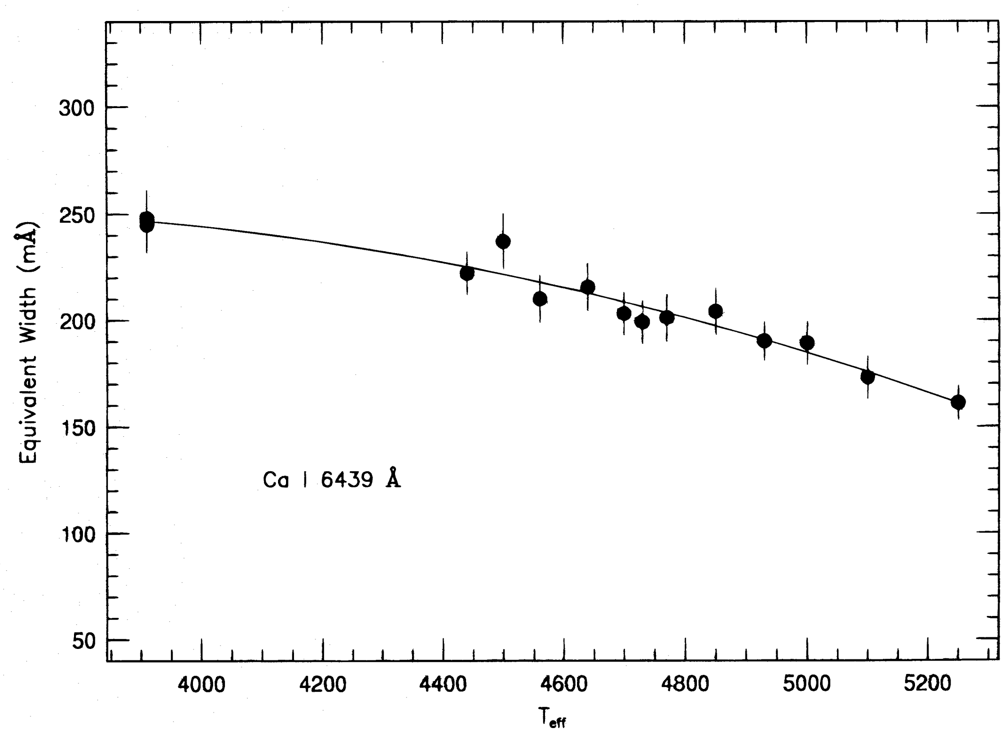

FIG. 3.—The equivalent width of the Ca I 6439 Å as a function of effective temperature. Data points are for the stars listed in Table 2. The line represents a second-order polynomial fit to the data.

able to the spotted stars of Table 1 in spite of the somewhat higher values of the surface gravities for these stars.

The difference in gravity between the pole and equator due to centrifugal force is no more than about 0.04 dex for the stars in Table 1. The temperature difference between the pole and equator can be estimated using von Zeipel's law (von Zeipel 1924; Collins 1963) and this amounts to $\Delta T \approx 200$ K. From Figure 3 this results in an increase in the line strength of about 8% whereas the flux level decreases by about 20%. It thus seems unlikely that the increase in line strength is sufficient to produce a flat-bottomed line shape.

To confirm this, a synthetic spectral line flux profile from a gravity-darkened star viewed nearly pole-on was generated. The star was divided into 10 annular zones each having a temperature consistent with gravity darkening. The local specific intensity profile in each annulus was taken to be the line flux profile of the standard star closest in effective temperature to that of the annular zone. It was felt that the line profiles from actual stars provided a better approximation to the local line shapes of the spotted stars even though the standard stars had a small amount of stellar rotation (the projected rotational velocities for the standard stars were all less than about 3 km s^{-1}). A disk integration was performed using a stellar grid of 120 × 120 cells. At each cell the limb angle was calculated and the corresponding local line profile was taken from the appropriate annular zone.

The results of the gravity darkening simulations are shown in Figure 4. This simulation is somewhat artificial in that by modeling the gravity darkening as a series of annular zones centered on disk center one is assuming that the star is viewed nearly pole-on and as such should show no appreciable rotational broadening. However, if Vega is any indication, gravity darkening should have its greatest influence on the spectral line profile for stars with low inclinations and, by broadening the line profile to higher rotational velocities, one can best see these effects. This simulation should qualitatively produce the effects of a gravity-darkened star viewed at low, but nonzero inclinations.

The crosses in Figure 4 indicate a rotationally broadened spectral line flux profile for a star having no gravity darkening and a $v \sin i$ of 50 km s^{-1} (henceforth referred to as the immaculate profile). (In comparing line shapes from rapidly rotating stars it is irrelevant as to the precise value of the $v \sin i$ that is used in the simulation. All that matters is that the shape of the line profile is dominated by rotational broadening and a $v \sin i$ of 50 km s^{-1} is sufficient for this purpose.) The solid line represents the spectral line profile from a star having the same projected rotational velocity, but with a temperature difference between pole and equator of $\Delta T \approx 200$ K. There is essentially no difference between the gravity-darkened and immaculate line profiles (i.e., no gravity darkening). Here, the decreasing flux (continuum effect) as one approaches the equator almost exactly cancels the effects of line strengthening. The dotted line represents the more heavily-darkened case of $\Delta T = 400$ K between pole and equator (this gravity darkening corresponds to a star with an equatorial velocity of 170 km s^{-1}). In this instance the continuum effect dominates over the line strengthening and the resultant spectral line profile is actually more pointed than the immaculate profile. Given the pole-to-equator (or disk-to-limb for pole-on stars) temperature difference dicated by gravity darkening and using local spectral line profiles provided by slowly rotating unspotted stars with spectral types near those of RS CVn stars, it is impossible to reproduce the flat-bottomed line

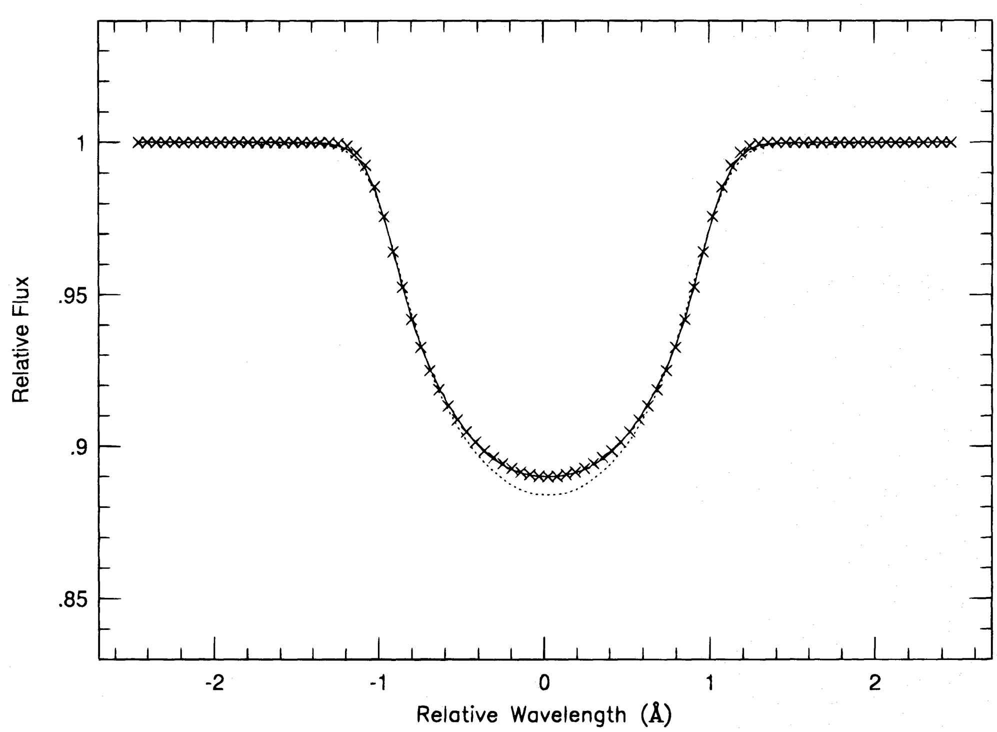

FIG. 4.—Line flux profile simulations for gravity darkening. The crosses represent the Ca I spectral line profile from a star with a uniform temperature distribution rotating with a projected velocity of 50 km s^{-1}. The solid line represents the gravity-darkened Ca I line profile for a star with a temperature difference of 200 K between pole and equator, and the dashed line a temperature difference of 400 K.

profiles to the degree seen for the two low-inclination RS CVn stars in Figure 1.

2.3.2. *Differential Rotation*

Another mechanism that can alter the shape of the line profile is differential rotation. Solar-type differential rotation, i.e., an equator that rotates more rapidly than the polar regions, produces a line profile shape that is more V-shaped with respect to a rotationally broadened profile (Gray 1977). However, for a star with polar acceleration the line profile shape can become more flat-bottomed (Bruning 1981). In both cases the effects on the line profile become more pronounced at low stellar inclinations (Bruning 1981) so it is possible for differential rotation to produce the changes in the line shapes seen in Figure 1.

Synthetic spectral line profiles were generated for a star having differential rotation represented by a Maunder rotation formula,

$$\omega = \omega_e - \omega_1 \sin^2 \phi \, , \qquad (1)$$

where ϕ is the latitude, ω_e the equatorial angular velocity, and $\omega_e - \omega_1$ is the polar angular velocity, ω_p. The amount of differential rotation can be parameterized by α, the ratio of the difference between polar and equatorial velocities to the equatorial velocity:

$$\alpha = \frac{\omega_e - \omega_p}{\omega_e} \, . \qquad (2)$$

An $\alpha > 0$ implies equatorial acceleration and $\alpha < 0$ implies polar acceleration. For the Sun $\alpha = 0.2$.

Figure 5 shows the spectral line profile from a star having a $v \sin i$ of 50 km s^{-1} and a differential rotation parameter, $\alpha = -0.5$ (Changing the inclination causes the wings of the line to vary slightly in width. To facilitate comparisons between the simulations the profiles were rebinned so that they all had the same width in the wings. Since we are interested only in overall line *shapes* this procedure is valid.) The solid line represents a stellar inclination of $i = 90°$ and the dashed line for $i = 35°$. The crosses represent the profile for a star having no differential rotation. There is indeed a slight flattening of the line profile that increases at lower inclinations, but the effect is quite subtle and not nearly enough to account for the large changes in the mean profile shapes seen in Figure 1. To produce a flattening of the line profiles comparable to that seen in HR 1099 and EI Eri requires extremely large negative values of α. Figure 6 shows the same simulation as for Figure 5 only this time for $\alpha = -1$. Once again the solid line refers to an inclination of 90° and the dashed line for $i = 35°$. Note that even though the line profile is indeed more box-shaped, it lacks the central hump that is seen in the mean profile of EI Eri and HR 1099.

2.3.3. *Facular Band*

Limb brightening can also produce a flat-bottomed line profile (Hatzes & Vogt 1992) but, to be consistent with the result of Figure 1, this limb brightening must have its greatest effect for stars with low inclinations. This could be accomplished by having a bright band centered on the stellar equator. (At low inclinations, such a band would be analogous to limb brightening.) One phenomenon with a well-known solar analog that can produce such a bright band is faculae. On the Sun, faculae are 900 K hotter than the photosphere (Allen 1973, p. 187) and are associated with sunspots. They can appear before the emergence of magnetic flux and often persist after sunspots have faded. Vogt & Penrod (1983) suggested that magnetic flux on RS CVn stars emerges at the equator. If a large filling factor of faculae is also associated with this presumed equatorial band of magnetic flux emergence, then faculae might conceivably provide the bright band needed to alter the spectral line shapes.

The degree to which a bright band flattens the spectral line profile depends on the temperature difference between it and the photosphere and on the width of the band. One could consider a very hot band extending to high stellar latitudes, but at some point this just mimics the cool polar

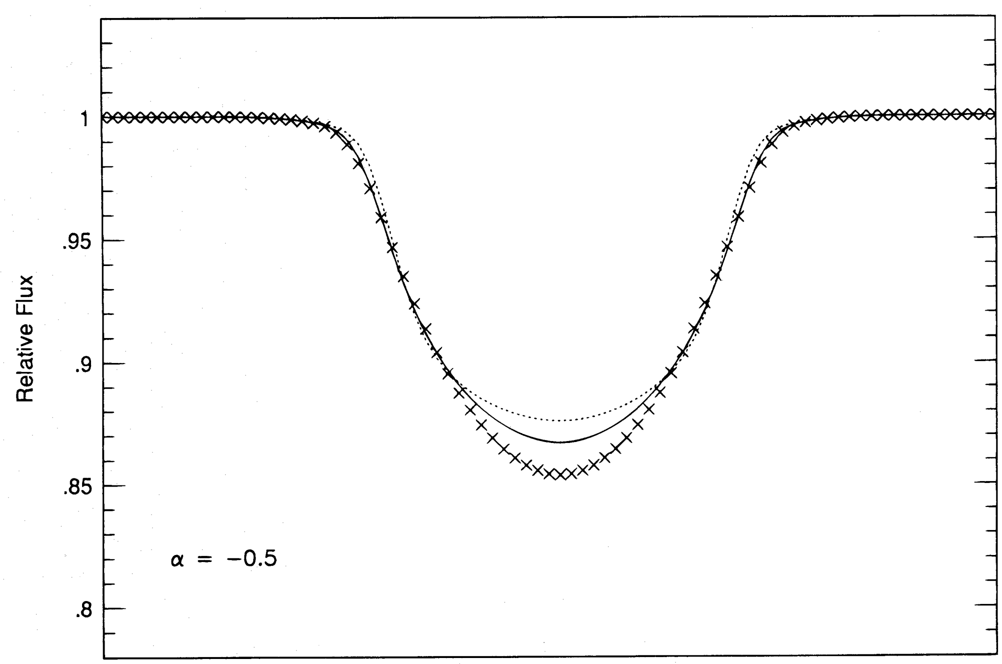

FIG. 5.—Spectral line profiles for a differentially rotating star having $\alpha = -0.5$. The solid line is for a star with a stellar inclination of 90° and the dashed line is for an inclination of 35°. The crosses represent the spectral line profile for a star with no differential rotation.

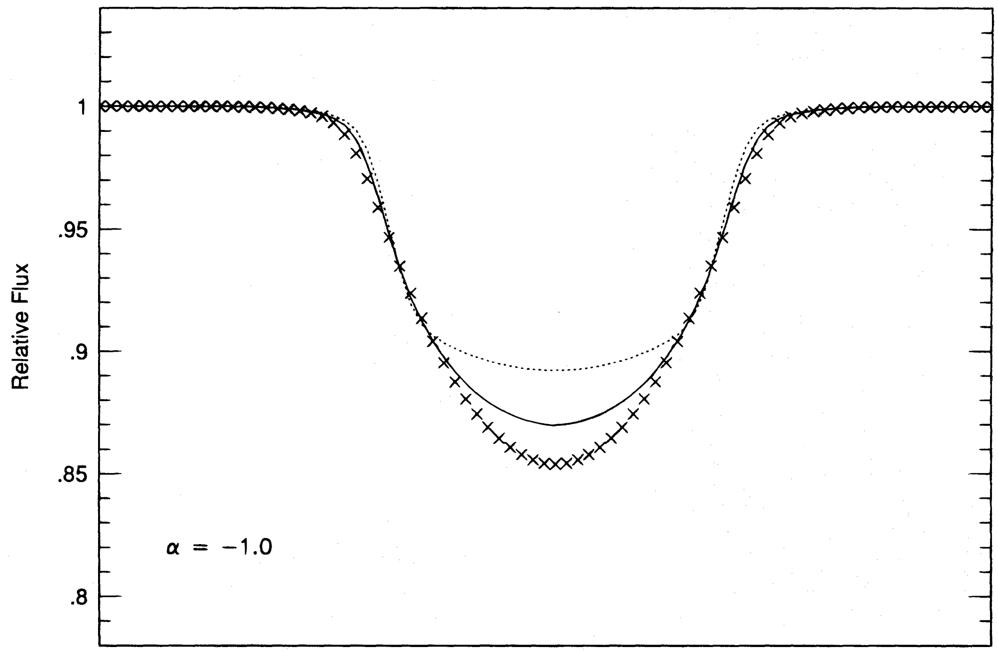

FIG. 6.—Spectral line profiles for a differentially rotating star having $\alpha = -1.0$. The solid line is for a stellar inclination of 90° and the dashed line is for an inclination of 35°. Again, the crosses represent the spectral line profile for a star with no differential rotation.

spot model (the zebra effect) considered in § 2.3.4. In simulating a bright band we wished to consider a case distinctly different from the polar spot case described below. Therefore for this simulation a bright band centered on the equator and extending to ±40° latitude was used. To investigate the temperature sensitivity, two temperature differences ($\Delta T = T_{\rm band} - T_{\rm photosphere}$) were considered: 400 K and 800 K. This corresponds roughly to facular bands with filling factors of 50% and 100%, respectively. Since the data of our standard stars extended only up to an effective temperature of 5250 K, the temperature of the band was fixed at 5250 K and two photospheric temperatures were considered, 4850 K and 4450 K.

Figure 7 shows the results of this simulation for a star with near-zero inclination and $v \sin i = 50$ km s^{-1}. Again this artificial simulation is used to maximize the effects of

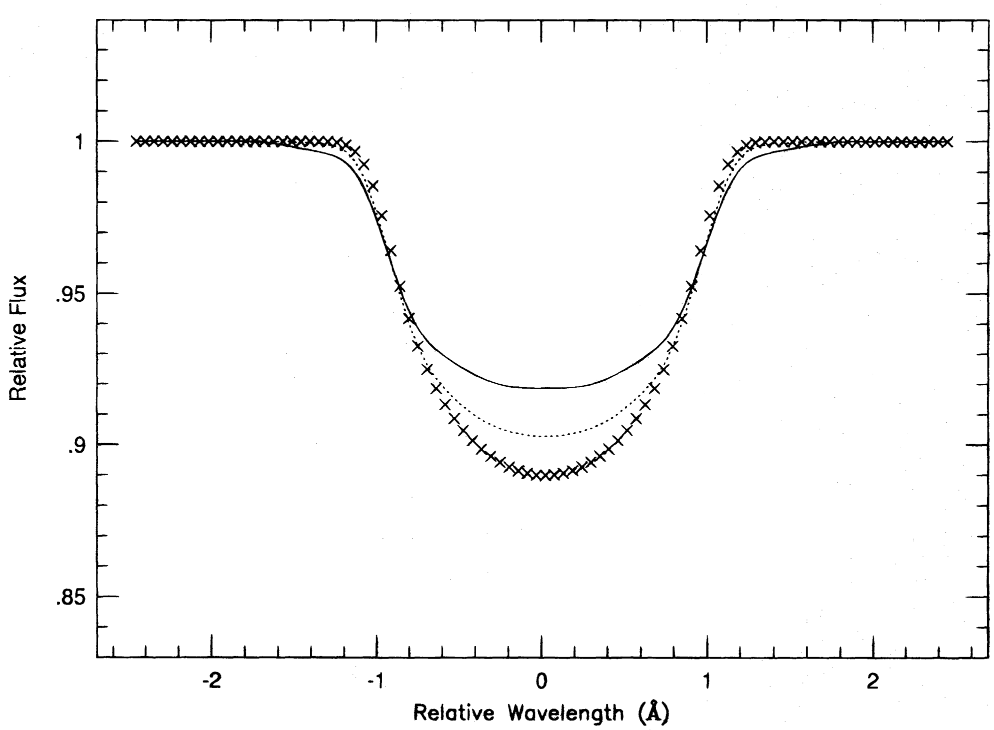

FIG. 7.—Line profile simulations for a bright "facular" band about the equator of a star viewed from an inclination angle of 0°. Crosses represent the Ca I profile from having a uniform temperature distribution and a $v \sin i$ of 50 km s^{-1}. The dotted line represents the case with a band extending to ±40° latitude and having a temperature of 400 K above the photospheric temperature. The solid line represents the case of a band with a temperature difference of 800 K. Once again the profiles have been scaled so as to match the wings of the immaculate line profile.

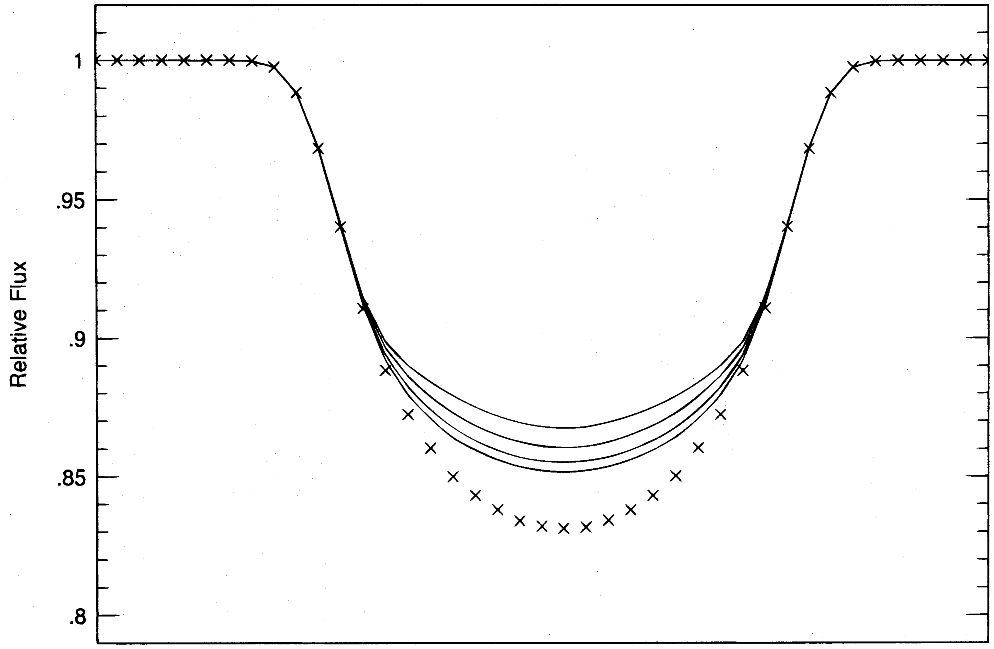

FIG. 8.—Simulations (*solid lines*) showing the variations in spectral line shape for a bright equatorial band viewed with stellar inclinations of (*top to bottom*) 35°, 50°, 65°, and 85°. The band has a temperature 800 K above the photospheric temperature and extends to $\pm 40°$ stellar latitude.

the band on the shape of the line profile. In producing the synthetic profiles a stellar disk was divided into 10 annular bands and with the outer three zones set to a temperature of 5250 K and the inner zones set to the photospheric temperature being considered. Local line profiles were taken from the observed Ca I profiles of the standard stars in Table 2. The solid and dotted lines represent the two cases where the photosphere is 4450 K and 4850 K, respectively. Although the Ca I 6439 Å line strength decreases in the hot band, the increased local continuum flux due to the higher temperature more than compensates for this and results in a relatively flat-bottomed shape for the spectral line flux profile.

Although a bright equatorial band does succeed in producing a box-shaped spectral line profile, it does not reproduce the strong variation of line core flattening with stellar inclination that is observed. Figure 8 shows the predicted spectral line profiles for the Ca I 6439 Å line as a function of stellar inclination from a bright equatorial band extending to $\pm 40°$ latitude and with a temperature 800 K above the photosphere. Again, the crosses represent the rotationally broadened profile from an immaculate star.

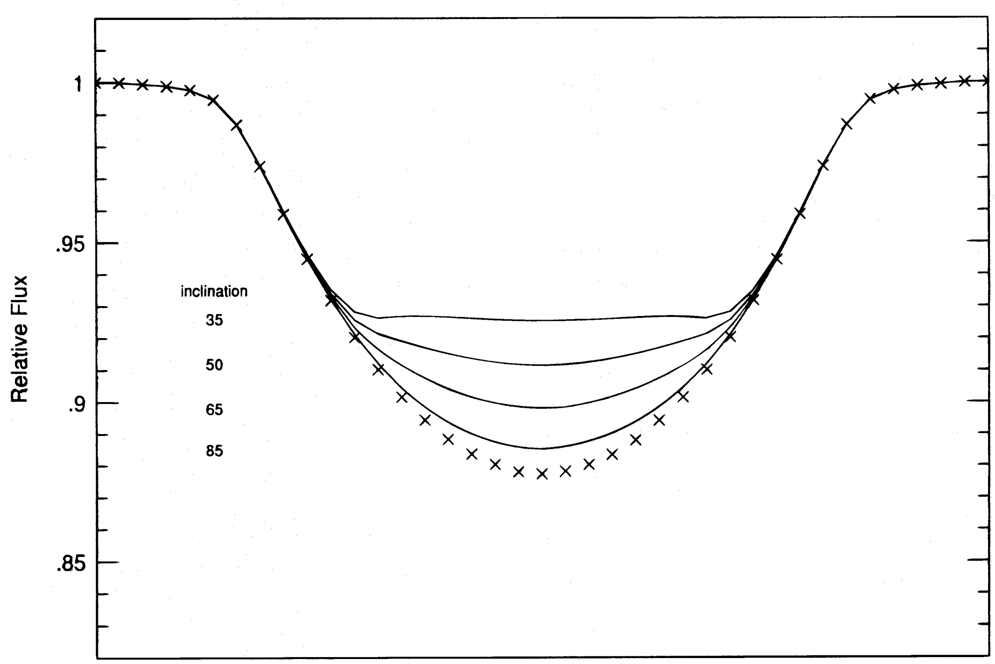

FIG. 9.—Spectral line flux profiles from a star with a $v \sin i$ of 50 km s^{-1} which has a polar spot of radius 35° and is viewed from inclinations of (*top to bottom*) 35°, 50°, 65°, and 85°. The points represent the spectral line flux profile from an immaculate star.

There is not a strong change in shape with stellar inclination and the flat-bottomed shape seems to persist at all inclinations.

2.3.4. *Polar Spot*

An alternative explanation which can also account for the observed differences in the mean line shapes of RS CVn–type stars is that they are due to the presence of a dark (cool) polar spot on each of the four stars (as seen in the Doppler images) and viewed with different projected areas due to the various stellar inclinations. For rapidly rotating spotted stars at a given wavelength position in a spectral line, the height of the "pseudo-emission" distortion above the immaculate (unspotted) profile is proportional to the fraction of the constant radial velocity chord on the surface of the star that passes through a spotted region (Vogt & Penrod 1983). If dark polar spots on RS CVn stars are of comparable size, then this fraction should be larger for the low-inclination stars.

Figure 9 shows the expected line flux profile for a star with a polar spot viewed from various inclinations. In this case, the polar spot has a radius of 35° (comparable to the radii of the polar spots for the stars in Table 1, and the star has a projected rotational velocity of 50 km s^{-1}. The temperature of the spot was assumed to be 1200 K below the photospheric value of 5000 K. The crosses represent the spectral line profile from the unspotted star. The solid lines represent profiles from a star having a polar spot and viewed from different stellar inclination angles. As expected, as one views the star from higher inclinations (more equator-on), the projected area of the polar spot decreases and the observed spectral line flux profile shape approaches that of a pure rotationally broadened profile from an unspotted star.

3. DISCUSSION

It has been argued that the persistent flat-bottomed spectral line profiles seen in the spectra of many RS CVn stars are due to a stellar atmospheric effect rather than the presence of cool polar spots. We certainly do know that much of what we call a "spot" on these RS CVn stars is significantly *cooler* than the immediate photosphere since the integrated (flux) spectra of spotted stars show pronounced increases in TiO band absorption as the spot comes into view (Vogt 1981; Ramsey & Nations 1980; Huenemoerder, Ramsey, & Buzasi 1989). Many others have determined spot temperatures from modeling broadband photometric data (Eaton 1992 and references therein). Invoking such cool spots to model the line profile variations through Doppler imagery leads to images which consistently show large, cool polar spots. This result has now been found for a large number of RS CVn stars by many Doppler imaging researchers using different imaging codes and spectrographic instrumentation. Not all RS CVn stars show polar spots, however. Hatzes (1993) found only intermediate-latitude spots in his Doppler image of the relatively slowly rotating RS CVn star σ Gem. So if the flattening of the line core is due to some subtle problem with the way the line transfer physics is handled, then it would have to be different for this otherwise apparently normal RS CVn star.

We have shown here that one can indeed produce a flattened spectral line flux profile via limb brightening from a bright (facular) equatorial band if the greater continuum flux in the band dominates over the line strength decrease from disk center to limb (or alternatively from photosphere to bright regions). At some level, though, the argument may become more a matter of semantics and also depends on what one takes as the threshold level for the normal stellar surface brightness. A bright band encircling the equator of a normal star can also be considered as a cool spot on a slightly hotter than normal star. Is the zebra white with black stripes, or vice versa?

No doubt the real situation is a more complex combination of both bright and dark regions. Perhaps these stars have both some bright low-latitude encircling facular regions, and large cool polar spots, and both effects combine to produce the resultant flat-bottomed line flux profiles. However, invoking only a bright equatorial band (without a cool polar spot) to explain the line profiles runs into difficulty since one should then see (as shown above) significant flat-bottomed Ca I profiles in *both* high- and low-inclination stars. The four RS CVn stars examined here, albeit a small sample, exhibit a *substantial* difference in the mean spectral line shape between low- and high-inclination RS CVn stars, in the sense that the low-inclination stars show the most flattened line cores. So, while this observed inclination dependence argues strongly against the bright band model, it is at the same time quite simply explained by the cool polar spot model.

Gravity darkening is another well-known way to alter the atmospheric parameters of a star as well as to provide a preferred axis of symmetry. One thus may expect to see differences between the mean shapes of low- and high-inclination stars. However, our simulations, using the expected pole-to-equator temperature profile and local line profiles provided by standard (and presumably unspotted) late-type stars with spectral types similar to those of RS CVn stars, are not able to reproduce the flat-bottomed profiles seen in the low-inclination RS CVn stars.

Differential rotation, with the poles of the star rotating faster than the equator, is another mechanism capable of producing a box-shaped profile which is a strong function of stellar inclination. However, to produce the amount of line distortion seen in EI Eri and HR 1099 requires unreasonable differential rotation rates ($\alpha < -0.5$) and there is no observational evidence to support this. On the contrary, Hall (1991) demonstrated from long-term photometric monitoring of a large sample of spotted RS CVn stars with periods comparable to that of EI Eri and HR 1099, the differential rotation rate is at least a factor of 10–20 smaller than the solar value. This value is considerably smaller than that required to produce a noticeable distortion in the spectral line shapes. Furthermore, even large amounts of differential rotation cannot produce the central "hump" seen in the mean Ca I 6439 Å profile of HR 1099 and EI Eri.

Evidence for low values of differential rotation rates on RS CVn stars also come from Doppler imaging. Vogt & Hatzes (1991) were able to measure directly the differential rotation rate (as inferred from spot longitude motions) for the RS CVn type star UX Ari using a sequence of Doppler images and they derived a value of $\alpha = -0.02$. Although the sign of α is consistent with a flattening of the line profile, the magnitude of the effect is more than a factor of 25 too small to cause the line shapes that are observed for the low-inclination RS CVn stars. Furthermore, Doppler images for many RS CVn stars were derived from data spanning 3–4 months, and these always provided excellent fits to the observed profiles. RS CVn stars have rotation periods on the order of days, so the presence of such a large amount of differential rotation would probably shear away any large spots that are present on time scales much shorter than the data acquisition time, and consequently the Doppler imaging technique would be incapable of fitting the observed spectral line profiles. It is unlikely that a Doppler image could be derived with data spanning such a long time base. Thus differential rotation does not appear to be a viable mechnanism for producing the flat-bottomed line profiles in the spectra of RS CVn stars.

A bright equatorial band can also produce a flattening in the line profile which increases with decreasing stellar inclination. Although the bright facular band model cannot be entirely excluded as a contributing explanation for the flat-bottomed line shapes of RS CVn stars, we believe that the high degree of line core flattening seen in the spotted stars with low inclination provides strong evidence for the presence of polar spots.

Another hypothesis for the presence of flat-bottomed spectral line profiles in RS CVn stars is that they are due to filling-in of the line cores due to chromospheric or photospheric emission. However, the mean line shapes do not seem to correlate with the level of chromospheric activity. HR 1099 and AR Lac both have high levels of such activity as exhibited by strong Ca II *h* and *k* emission and variable Hα that is consistently in emission (Strassmeier et al. 1993 and references therein). EI Eri, on the other hand shows strong Hα absorption and its Ca II *h* and *k* emission is only moderately strong (Fekel, Moffet, & Henry 1986). Yet, the mean shape of the Ca I 6439 Å line of HR 1099 is similar to that of EI Eri and is significantly different to that of AR Lac, in spite of having a level of activity more comparable to the latter star.

Not all RS CVn stars have polar spots and it has yet to be established what physical conditions causes most RS CVn stars to have polar spots and others, like σ Gem, to lack such a feature. Although polar spots may not be a ubiquitous feature, so far *all* Doppler images of rapidly rotating RS CVn– and FK Comae–type stars with periods less than about 10 days have polar spots. This feature has also been seen on the weak T Tauri star HDE 283572 (Joncour, Bertout, & Bouvier 1994). No polar spot was imaged for the FK Comae–type YY Men (Piskunov, Tuominen, & Vilhu 1990), but this result is controversial as their line-fitting residuals were not random. Kürster et al. (1992) derived images of this star at two different epochs and using different imaging techniques and all these images showed a prominent polar spot.

It thus appears that polar spots are a common feature among a variety of spotted stars. Consequently, we strongly believe that the best explanation for the persistent flat-bottomed shapes of the mean spectral lines of many spotted stars is the presence of cool, long-lived polar spots. These polar spots are not merely "high-latitude" features but, rather, are spots that actually straddle the pole, often times quite symmetrically. The well-accepted basic "cool spot" model for the light variations of RS CVn stars is also consistent with the appearance of TiO features and color changes when the spot comes into view, and such cool spots then appear at the pole in Doppler imagery whence they easily fit the temporal variations of line flux profiles modeled in the Doppler imaging process. As shown in the present paper, these large cool polar spots also now provide a simple explanation (which gravity darkening, differential rotation, limb brightening, or other unknown radiative transfer effects in the line flux calculation cannot) for the observed inclination dependence of the flattening of the line flux profile core.

A more detailed investigation of the mean spectral line shapes is clearly in order. Even though the line shapes shown in Figure 1 are suggestive of a trend with stellar inclination, this is apparent from a sample of only four stars, which is clearly insufficient to conclusively establish such a trend. It may well be that our choice of stars for this study may have conspired to show such changes in the line shape with inclination which may not be evident in a larger sample of spotted stars. A number of factors can influence the line shapes (differences in spot distributions, level of chromospheric activity, plage and facular filling factors, etc.) besides the stellar inclination. A survey of mean line shapes among a larger sample of spotted stars may average these various effects and will more clearly disentangle geometrical effects due to inclination from the star-to-star intrinsic variations in the means spectral line profile shapes.

The analysis in § 2.3 has established that the flattening in the line cores of spotted stars cannot be caused entirely by (1) the temperature dependence on the spectral line strength, (2) gravity darkening, and (3) differential rotation. A bright facular band produces flattened spectral line profiles, but the changes in the line shape with inclination are not as extreme for a polar spot. A more thorough investigation of the changes in line shape with inclination may help distinguish between the polar spot and facular band hypotheses.

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