STARSPOt PHOTOMETRY: OBSERVATIONAL REVIEW AND INTERPLAY WITH SPECTROSCOPY

KLAUS G. STRASSMEIER
Institut für Astronomie, Universität Wien,
Türkenschanzstraße 17, A-1180 Wien, Austria

ABSTRACT Most of what we know about starspots comes from time variations of broad-band lightcurves. A review is presented of the current observational knowledge of starspots on RS CVn-like F, G, and K stars, T Tauri, and W UMa-type stars. Recent Doppler maps are compared with photometric results.

INTRODUCTION
In this review I will focus on results obtained with automatic photoelectric telescopes (APTs) and will discuss the starspot phenomenon throughout the Hertzsprung-Russell diagram (HRD). Particular weight will be given to results obtained in connection with Doppler imaging. Progress in the study of spotted, late-type stars has come mostly through the analysis of their light curves. Their regular variations – modulations with the rotation period – and their quasi-regular long-term variations, such as the change of the mean brightness due to a spot cycle, have told us most of what we know about starspots.

OBSERVATIONAL EVIDENCE FOR THE EXISTENCE OF STARSPOtS
The solar analog
Sunspots are local magnetic fields with field strengths of ~ 1000 G which block the emerging flux from the interior and cool down the photosphere by about 2000–3000 K. Typically, sunspots cover $10^{-4}$ to $10^{-5}$ of the solar surface and only during solar maximum reach about $10^{-3}$. The ACRIM experiment, a radiometer on the SMM spacecraft, has measured dips of up to 0.2% of the solar irradiance when large spot groups where moving in and out of view (Foukal and Lean 1986). This verifies the assumption that light variations in active late-type stars are associated with the presence of surface magnetic fields. Magnetic activity is essentially found in regions of the HRD where stars with convective envelopes occur. Table 1 gives an overview of "spotted" stars throughout the HRD and their observed spot parameters. Despite their different evolutionary status, these stars have several things in common: convection, rapid rotation, they are generally not known as pulsators¹ and, they all show Ca II H and K emission due to an extended chromosphere.

¹ although, in principle, pulsation could also drive a dynamo
### Table 1: Starspot Morphology Throughout the HRD

<table>
<thead>
<tr>
<th></th>
<th>spot occurrence (spectral range)</th>
<th>spot temperatures $\Delta T = T_{phot} - T_{spot}$</th>
<th>spot coverage $f$ (%)</th>
<th>activity components</th>
<th>differential rotation</th>
<th>lifetimes, variation timescales</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Tauri</td>
<td>G5 - M1</td>
<td>hot + cool spots hot: $-1800...7450$ cool: $&gt;200...1300$</td>
<td>hot: 0.07...3$\pm$1 cool: 3...17$\pm$3</td>
<td>one/two-spot (prefer. one) mass accretion</td>
<td>0.1% relative (on V410 Tau) 20% (BP Tau)</td>
<td>1200 days (650 rot.) for V410 Tau, 2-8 days ($\leq$ 1 rot.)</td>
</tr>
<tr>
<td>BY Dra single</td>
<td>K5 - M5</td>
<td>cool spots 280 ... 850</td>
<td>2 ... 11</td>
<td>one/two-spot polar spot</td>
<td>years? (e.g., AU Mic) $\leq$ 1 yr (e.g., EV Lac)</td>
<td></td>
</tr>
<tr>
<td>BY Dra binaries</td>
<td>F8 - M5</td>
<td>cool spots $\geq140 ... 1600$ (for BY Dra)</td>
<td>2 ... 23</td>
<td>one/two-spot polar spot?</td>
<td>60 yr cycle (V833 Tau) few days ($\leq$ 1 rot.)</td>
<td></td>
</tr>
<tr>
<td>lower m-s Hyades</td>
<td>F8 - K5-8</td>
<td>cool spots</td>
<td>$&lt; 1$</td>
<td>$\leq$2% variabil. in $b, y$</td>
<td>5 ... 21%</td>
<td>$\leq$3 yr (HD 206860) $\approx$10 days (e.g., VB31)</td>
</tr>
<tr>
<td>Sun</td>
<td>(G2)</td>
<td>cool spots 1700 ... 3000 but $\Delta T(\dot{B}, age)$</td>
<td>$\leq$0.1 in max. 0.01 ... 0.001</td>
<td>spot groups isolated spots $\pm 40^\circ$ lat.</td>
<td>20%</td>
<td>several rotations for spot groups, hours for pores</td>
</tr>
<tr>
<td>RS CVn binaries</td>
<td>IV: F9 - K3-4 III: G5 - K3</td>
<td>cool spots 600 ... 1900</td>
<td>0.15 ... 16</td>
<td>one/two-spot polar spot</td>
<td>$\leq$3%</td>
<td>$\approx$1 yr, maybe longer days ($\leq$ 1 rot.)</td>
</tr>
<tr>
<td>Algol binaries</td>
<td>G - K</td>
<td>hot and/or cool? $\pm 500$ ($\beta$ Per)</td>
<td>one-spot</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W UMa binaries</td>
<td>A8 - K3-5</td>
<td>hot + cool spots hot: $-600...1200$ cool: $200...1350$</td>
<td>hot: $\approx$20 cool: 0.6...4</td>
<td>mass transfer one/two-spot polar spot</td>
<td>8-9 yr cycle (VW Cep)</td>
<td></td>
</tr>
<tr>
<td>FK Comae type</td>
<td>G2-3 - K1</td>
<td>cool spots 400 ... 800</td>
<td>0 ... 7</td>
<td>one/two-spot polar spot</td>
<td>&quot;very small&quot;</td>
<td>phase coherence for decades, short-term var.</td>
</tr>
</tbody>
</table>
Figure 1: Light curve variations of HD 17433 due to starspots. The full line is a fit with an evolving spot model (adopted from Strassmeier and Bopp 1991).

Evidence from photometry
(1) The modulation of the continuum light accompanied by color variations in the sense that the star becomes redder when the light curve has a minimum. Increasing color amplitudes at longer wavelengths are also in agreement with the picture of cool, dark spots. Fig. 1 shows examples of $V$-band light variations typical for spotted stars.

(2) Photometric periods are in agreement with spectroscopically determined periods from rotational velocities but with the additional advantage that they are unequally more precise. This implies that the photometric period is the rotation period of the spotted star. A fact further strengthened by the long-term Mount Wilson Ca II H and K observations (Wilson 1978, Baliunas and Vaughan 1985) which showed, e.g., for $\delta$ CrB (Baliunas 1988), that the Ca II S-index varies with the same period as simultaneous broad-band photometry.

(3) Linear polarization appears to depend on the chromospheric activity level and is, when detectable, also modulated with the photometric period and its detection suggests a magnetic origin (Huovelin et al. 1988, Kemp et al. 1987).

(4) Infrared excess seems to be present in spotted stars, however, as pointed out by Busso et al. (1988), the excess is not correlated with the degree of activity nor with the evolutionary status, thus its origin is still not clear.

Evidence from spectroscopy
(1) The spectral flux ratio of II Peg, taken as the ratio of spectra when the (presumably) most spotted and the least-spotted hemispheres were in view, showed a steep rise to the red (Vogt 1981a). This flux ratio, actually the relative energy distribution of the spotted region itself, showed pronounced molecular absorption features of TiO and VO, characteristic of very cool stars.

(2) The existence of "bright" bumps in the profile of a rotationally-broadened absorption line which are correlated with phase (Fekel 1980). A cool spot emits less light than the surrounding photosphere and produces, at the rotation velocity
of the spot on the stellar surface, a lack of photons absorbed by the line and thus an apparent emission bump (Vogt and Penrod 1983). This led to the application of the Doppler-imaging technique to spotted, late-type stars.

(3) The direct detection of surface magnetic fields with different techniques, e.g., Fourier transform methods (Robinson et al. 1980), line profile modeling (Marcy and Bruning 1984, Saar 1988), Stokes V profile modeling or Zeemann-Doppler imaging (Donati and Semel 1991).

Using the method of speckle imaging, Lynds et al. (1976) were able to produce a direct image of the red supergiant α Ori – the first of its kind – which showed two large "spots" on the surface. However, using better data, Wilkerson and Worden (1977) could not confirm any structure on the stellar disk. Thus the most convincing proof for the existence of starspots, a direct stellar image, is still needed.

MODELING THE PHOTOMETRIC VARIATIONS

Geometric spot models

Basically there are two different modeling procedures, a more physical one which includes effects such as gravitationally deformed binary components, reflection effect, secondary contribution, a.s.o., and the classical light curve rectification technique. A variety of computer spot modeling programs with different degrees of sophistication were developed (Torres and Ferraz-Mello 1973, Bopp and Evans 1973, Friedemann and Gürtler 1975, Budding 1977, Eaton and Hall 1979, Bopp and Noah 1980, Vogt 1981b, Poe and Eaton 1985, Rodonó et al. 1986, Dorren 1987, Strassmeier 1988, Kang and Wilson 1989). The basic set of integral equations were outlined, e.g., by Strassmeier (1988). The most serious problem is the ambiguity of the light curve fit as demonstrated in the review by Vogt (1983) and others.

Assumptions and a priori knowledge

The following four points briefly discuss the necessary observations and a priori knowledge before one can obtain a reasonably constrained solution with a geometric spot model.

(1) The first step is to determine the photometric period and assume it to be the rotation period of the spotted star. Periods obtained from data taken at different epochs can vary by several percent (see the summary in Hall and Busby 1990). Hall (1972) [see also Hall and Henry 1990] attributed these differences to the existence of differential rotation on the stellar surface in accordance with the solar behaviour.

(2) The next step is to estimate the orbital inclination, i, and to assume that the rotation axis of the spotted star is perpendicular to the orbital plane. For example, this was carried out for the non-eclipsing, SB1 binary HK Lac by Olah et al. (1985), using the observed mass function, the spectral classification of the spotted star, the invisibility of the secondary star in the spectrum, and the absence of eclipses. This yields inclinations with uncertainties of about ±10° to
Figure 2: Spot temperatures and coverages (in % of the stellar surface) from modeling the broad-band light curve variations.

20°.

(3) Find the brightest magnitude ever observed and assume it to be the “unspotted” or “least spotted” brightness level.

(4) Determine the temperature difference, photosphere minus spot (ΔT), from the V-I color amplitude — actually the difference least-spotted hemisphere minus most-spotted hemisphere — which ranges from “undetectable” (say, ≤0.01 mag) to about 0.05 mag with uncertainties in the spot temperature of about 100 to 200 K. Furthermore, assume ΔT is the same for each individual spot or spot group and is constant within the time of observation.

Spot temperatures and coverages

Table 2 and Fig. 2 summarize the results from modeling the light and color curves of 28 late-type stars, where ΔT is the spot temperature difference, nspots is the number of spots, and f is the spot covering fraction in percents of the entire stellar surface. This database is supplemented with spot modeling results for eleven T Tauri stars taken from Bouvier and Bertout (1989) and five W UMa binaries and is plotted in Fig. 2. We arrive at the same (though preliminary) conclusion as Bouvier and Bertout — there is no evident difference between spots on pre-main sequence and spots on post-main sequence stars nor between singles and binaries. There also seems to be no obvious correlation between temperature and size for any of the plotted types of variable stars. The large range of spot temperatures and coverages is probably the only significant feature in this figure. For sunspots, Parker (1979) showed that young spots must emit MHD waves which cool them within about 3 minutes (the time for the energy to
Table 2: Starspot Temperatures and Coverages

<table>
<thead>
<tr>
<th>star</th>
<th>$\Delta T$ (K)</th>
<th>$\Delta T/\Delta$</th>
<th>$n_{spots}$ (--)</th>
<th>$f$ (--)</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS CVn</td>
<td>650-1580</td>
<td>0.14-0.34</td>
<td>2</td>
<td>10.0-19.7</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>1300,1600</td>
<td>0.28-0.34</td>
<td>2</td>
<td>...</td>
<td>(2)</td>
</tr>
<tr>
<td>BY Dra</td>
<td>$\geq$140</td>
<td>0.04</td>
<td>1</td>
<td>2-23</td>
<td>(3)</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>0.15</td>
<td>2</td>
<td>3.6-11</td>
<td>(4)</td>
</tr>
<tr>
<td>VY Ari</td>
<td>1200</td>
<td>0.26</td>
<td>2,3</td>
<td>9.5-14.5</td>
<td>(5)</td>
</tr>
<tr>
<td>EI Eri</td>
<td>1880</td>
<td>0.34</td>
<td>2,3</td>
<td>6.4-10.3</td>
<td>(6)</td>
</tr>
<tr>
<td>VT11 Tau</td>
<td>1800</td>
<td>0.32</td>
<td>2</td>
<td>8-20</td>
<td>(7)</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>0.29</td>
<td>2</td>
<td>5-19.3</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>0.25</td>
<td>2</td>
<td>6-7.9</td>
<td>(4)</td>
</tr>
<tr>
<td>$\sigma$ Gem</td>
<td>620</td>
<td>0.14</td>
<td>2</td>
<td>3.3-12.1</td>
<td>(8)</td>
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<tr>
<td></td>
<td>570</td>
<td>0.13</td>
<td>2</td>
<td>6.4</td>
<td>(3)</td>
</tr>
<tr>
<td>BF Lyn</td>
<td>1500</td>
<td>0.32</td>
<td>2</td>
<td>...</td>
<td>(9)</td>
</tr>
<tr>
<td>AR Lac</td>
<td>230-1330</td>
<td>0.05-0.29</td>
<td>2</td>
<td>2.9</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>0.26</td>
<td>2</td>
<td>3.4</td>
<td>(4)</td>
</tr>
<tr>
<td>SV Cam</td>
<td>2020</td>
<td>0.35</td>
<td>1</td>
<td>0.4-6</td>
<td>(10)</td>
</tr>
<tr>
<td></td>
<td>1550</td>
<td>0.29</td>
<td>1</td>
<td>5</td>
<td>(11)</td>
</tr>
<tr>
<td>RT And</td>
<td>1070</td>
<td>0.17</td>
<td>1</td>
<td>0.15-6.1</td>
<td>(12)</td>
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<td>BH Vir</td>
<td>980-1290</td>
<td>0.06-0.21</td>
<td>2</td>
<td>1.9-21</td>
<td>(15)</td>
</tr>
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<td></td>
<td>2010-2300</td>
<td>0.34-0.39</td>
<td>2</td>
<td>0.52-0.66</td>
<td>(15)</td>
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<tr>
<td></td>
<td>1100</td>
<td>0.18</td>
<td>1</td>
<td>0.4-1.44</td>
<td>(16)</td>
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<tr>
<td></td>
<td>1300-1400</td>
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<td>1</td>
<td>1.5</td>
<td>(17)</td>
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<tr>
<td>II Peg</td>
<td>730-1020</td>
<td>0.17-0.23</td>
<td>1,2</td>
<td>9-13</td>
<td>(3)</td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>0.26</td>
<td>1</td>
<td>10</td>
<td>(18)</td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>0.27</td>
<td>2</td>
<td>11.7</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>950</td>
<td>0.20</td>
<td>2</td>
<td>16</td>
<td>(26)</td>
</tr>
<tr>
<td>HK Lac</td>
<td>980-1200</td>
<td>0.2-0.28</td>
<td>2</td>
<td>8</td>
<td>(3)</td>
</tr>
<tr>
<td>HR 7275</td>
<td>1200</td>
<td>0.26</td>
<td>2</td>
<td>9</td>
<td>(3)</td>
</tr>
<tr>
<td>IM Peg</td>
<td>920</td>
<td>0.21</td>
<td>2</td>
<td>7</td>
<td>(3)</td>
</tr>
<tr>
<td>$\lambda$ And</td>
<td>800</td>
<td>0.16</td>
<td>2</td>
<td>2.8-5.5</td>
<td>(19)</td>
</tr>
<tr>
<td></td>
<td>1020</td>
<td>0.22</td>
<td>2</td>
<td>17</td>
<td>(3)</td>
</tr>
<tr>
<td>UX Ari</td>
<td>1420</td>
<td>0.30</td>
<td>2</td>
<td>8</td>
<td>(3)</td>
</tr>
<tr>
<td>LX Per</td>
<td>730</td>
<td>0.15</td>
<td>2</td>
<td>5</td>
<td>(3)</td>
</tr>
<tr>
<td>SZ Psc</td>
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<td>0.26</td>
<td>1,2</td>
<td>...</td>
<td>(20)</td>
</tr>
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<td>UZ Lib</td>
<td>few100</td>
<td>...</td>
<td>2</td>
<td>...</td>
<td>(21)</td>
</tr>
<tr>
<td>CC Eri</td>
<td>...</td>
<td>1</td>
<td>1</td>
<td>3.3</td>
<td>(22)</td>
</tr>
<tr>
<td>YY Gem</td>
<td>...</td>
<td>1</td>
<td>1</td>
<td>2.5</td>
<td>(22)</td>
</tr>
<tr>
<td>AU Mic</td>
<td>850</td>
<td>0.24</td>
<td>2</td>
<td>1.7-11</td>
<td>(4)</td>
</tr>
<tr>
<td>ER Vul</td>
<td>1000</td>
<td>0.16</td>
<td>1,2</td>
<td>13</td>
<td>(23)</td>
</tr>
<tr>
<td>RT CrB</td>
<td>340-1000</td>
<td>0.06-0.19</td>
<td>2</td>
<td>8-25</td>
<td>(24)</td>
</tr>
<tr>
<td>EV Lac</td>
<td>280</td>
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<td>1</td>
<td>6.6-12.5</td>
<td>(26)</td>
</tr>
<tr>
<td>FK Com</td>
<td>500-800</td>
<td>0.10-0.16</td>
<td>5</td>
<td>5-7</td>
<td>(14)</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>0.12</td>
<td>1</td>
<td>13</td>
<td>(13)</td>
</tr>
<tr>
<td>HD 199178</td>
<td>580</td>
<td>0.11</td>
<td>1</td>
<td>10</td>
<td>(27)</td>
</tr>
</tbody>
</table>

References:
(3) Poe and Eaton (1985)    (17) Scaltriti et al. (1985)
(4) Rodono et al. (1986)    (18) Vogt (1981b)
(8) Strassmeier et al. (1986b) (22) Budding (1977)
(9) Strassmeier et al. (1989b) (23) Hill et al. (1990)
(14) Rucinski (1981)

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cross the spot) while observations (Chou 1987) reveal cooling times between 0.5 to 9 hours, i.e., a factor of 10 to 100 longer than predicted. From Tables 1 and 2 we see that starspots are larger than sunspots by about a factor of 100 to 1000, therefore their respective cooling times should be substantially longer and one and the same starspot could have been observed at quite different temperatures which would explain the observed large range of ΔT in Fig. 2. For example, one of the best studied stars in the sample, AR Lac, was reported with two spots of ΔT = 1320±590 K and 770±700 K in 1978, and with 550±450 K and 230±180 K in 1981 (Kang and Wilson 1989). Note that the large uncertainties came mostly from the availability of only B and V data instead of red and near-infrared light curves which would constrain the temperatures much better. A similar example is RT CrB (Zhai and Chen 1989) with ΔT ≈ 340 to 1000 K. High time-resolution monitoring of V-I color variations with an APT could give us some first estimates of cooling times of starspots and, moreover, provide some clues to explain the obvious discrepancy between theory and observation in the case of sunspots.

A spectroscopic technique to derive starspot temperatures and coverages is the spectrum synthesis of TiO-band observations at 8860 Å (Ramsey and Nations 1980), who applied it to V711 Tau and found ΔT ≈ 1000 K. Contemporaneous and subsequent work (Vogt 1981a, Huenemoerder and Ramsey 1987, Huenemoerder et al. 1989a,b, Saar and Neff 1990) yielded spot temperatures and coverages for II Peg, UX Ari, V833 Tau, and HD 82558, in agreement with photometric results. Spot temperatures from spectral line profile modeling are still too uncertain and sparse to be taken into account, e.g., for HD 32918, ΔT≈500 K (Piskunov et al. 1990).

MODELING THE SPECTROSCOPIC VARIATIONS

Doppler imaging is a technique to derive a resolved image of a star by using the relation between wavelength position across a spectral line and spatial position across the stellar disk (Struve 1930, Deutsch 1970). Cool spots on the surface produce distortions in the line profiles which can be followed throughout a rotation cycle of the star (for references on this technique I'd like to refer the reader to the recent review of Collier-Cameron 1991).

A comparison between results from Doppler imaging and photometric spot modeling can be made in the case of V711 Tau (HR 1099). In Fig. 3 we compare a Doppler map (Vogt 1988) from 1981 with an independently derived map from contemporaneous photometry (Rodonó et al. 1986). [Note to Fig. 3: the upper two images in the first column of the Doppler maps are to be compared with the photometric maps]. The agreement is very encouraging since both techniques required a big spot at or close to the rotation pole as well as a second spot at the equator (a third, very small spot was missed by the photometric technique).

Four teams in Strassmeier et al. (1991) applied their Doppler-imaging versions to data of the RS CVn binary EI Eri (HD 26337). Fig. 4 shows maps for the 1988.85 epoch obtained with three different techniques (only one rotational phase is shown). The lower panel in Fig. 4 compares their theoretical V-band light
curves with contemporaneous APT photometry (the shown maps correspond, from left to right, to the dotted, full, and dashed light curves, respectively). All four imaging techniques (one has been published earlier and is not repeated here) yielded similar images with spots at or close to the rotation pole — a feature not known from the solar paradigm. So far, Doppler maps have been derived for six late-type stars. Large polar spots were seen on V711 Tau (Vogt and Penrod 1983, Vogt 1988), HD 199178 (Vogt 1988), UX Ari (Vogt and Hatzes 1991), and EI Eri (Strassmeier 1990). Middle and high-latitude spots (even touching the pole) were seen on AB Dor (Kürster and Schmitt 1991). An equatorial belt of spots and an appendage to middle latitudes were determined for HD 32918 (Piskunov et al. 1990).

STARSPOUTS THROUGHOUT THE H-R DIAGRAM

Photometric starspot models of RS CVn stars have recently been reviewed by Eaton (1991). Reviews of evidence of magnetic and related cycles can be found in, e.g., Maceroni et al. (1990a), Hall (1990), Catalano (1990), and Baliunas and Vaughan (1985). I will therefore concentrate on some aspects not, or only marginally, covered by these authors. These are mainly the questions of morphology and onset of spot activity throughout the Hertzsprung-Russell diagram.

Spots on F, G, and K stars

Convection zones are thought to appear at a spectral type near F0. From observations of CIV and HeI line strengths in ~80 late A and F stars, Wolff et al. (1986) found the onset of chromospheric activity (CA) near B-V=0.28, i.e., near spectral type F0. Starspots, i.e. photospheric activity, seem to occur at somewhat later spectral types. Differential photometry of 24 Hyades main-sequence stars at Lowell Observatory (Radick et al. 1987) confirmed 18 to be variable — all later than spectral type F8. Another study, using over 12,000 differential UBV measures of 49 late-type CA binaries made with the prototype APT (Strassmeier...
et al. 1989a), yielded 54 Cam (F9IV+F9IV) as the “earliest” subgiant with the characteristic starspot “wave”. Zeilik et al. (1983) report a 0.04 mag modulation in HD 108102, a double-lined (F8V+F8V) binary. Another RS CVn-type system, σ² CrB (F6V+G0V), shows strong chromospheric Ca II H and K emission from both components but only the G0 star seems to have also starspots. The earliest class III giants in the “Chromospherically Active Binary Star” catalog (Strassmeier et al. 1988a) are α Aur (G1III+K0III; Strassmeier and Fekel 1990), AY Cet (wd+G5III), 93 Leo (A6V+G5III-IV), and ε UMi (~F0V+G5III), but only AY Cet and 93 Leo show signs of a starspot wave. No giant in a detached binary system earlier than spectral type G5 is known to have starspots. The most “prominent” example is Capella’s G1III secondary, which is otherwise known to be chromospherically active (e.g., Ayres and Linsky 1980) but no conclusive evidence for photometric variability exists (see Jackisch 1963). Of course, the G5 onset might be a selection effect since there is at least one single class III giant with starspot activity: FK Comae (G2-3 III; see, e.g., Jetsu et al. 1991). Another early giant with starspot activity is δ CrB (Baliunas 1988). However, note that δ CrB was originally classified as G3.5III-IV, but has recently been reclassified as G5III-IV by Keenan and McNeil (1989). Most single, early-G giants do not show photometric variability (Strassmeier and Hall 1988) such as ψ³ Psc (G0III), 31 Com (G0III), 42 Cap (G2IV), or HR 1023 (G5III).

Spots on pre-main sequence stars

The T Tauri stars are long known for their irregular brightness variations. Some stars, most noticeably V410 Tau, are also periodic variables (Rydgren and Vrba 1983) and the idea that these periodic or quasi-periodic variations might be due to rotational modulation by dark starspots goes back to Hoffmeister (1965). In the meantime, a growing number of spotted T Tauri’s is known. Phenomenologically, three groups could be identified. Strictly periodic variables such as V410 Tau (Vrba et al. 1988, Herbst 1989, a.o.), DN Tau (Bouvier et al. 1986), DH Tau, DI Tau, GG Tau, AA Tau, HP Tau (Vrba et al. 1989), DF Tau, FK1, FK2, WK2, GW Ori, LHα-332-20/1, CoD-33°10685, RY Lup, SR12, SR9 (Bouvier and Bertout 1989), stars with a periodic component superimposed on an irregular light variation such as T Tau (Herbst et al. 1986), SY Cha (Schaefer 1983), UX TauA (Bouvier and Bertout 1989), BP Tau (Simon et al. 1990), TW Cha (Bouvier et al. 1988), and stars where no periodicity has been found such as RY Tau, SU Aur, CO Ori, RU Aur (Herbst and Levreault 1990, Herbst et al. 1987). Bouvier (1990) showed that the correlation between x-ray fluxes and rotation of T Tauri stars is the same as that found for cool dwarfs and active binaries in agreement with the likely analogy between spots on pre-main sequence and post-main sequence stars obvious from Fig. 2.

It is generally believed that the irregular light variations are due to a circum-stellar disk left over from an earlier epoch of star formation and that a hot spot results from steady mass accretion onto the surface. Herbst and Levreault (1990) rule out the possibility that cool spots are also responsible for the irregular light variations. It is no surprise, therefore, that mostly weak-emission
Figure 4: A comparison of Doppler maps of EI Eri from three different mapping techniques (upper panels) and their respective theoretical light curves (lower panel). See also the text (adopted from Strassmeier et al. 1991).

line stars (the so-called naked T Tauri's) show periodic light variations, while the classical, strong-emission stars tend to also show irregular variations, and extreme T Tauri's do not show periodicities at all. In at least one case, DN Tau (Vrba et al. 1986), a cool and a hot spot are found to be spatially associated, while on other stars, e.g., GW Ori (Bouvier and Bertout 1989), the light and color variations would be consistent with a hot or a cool spot solution.

Spots on W UMa-type contact binaries
Dark spots on W UMa systems were first proposed by Binnendijk (1970) to explain the asymmetric eclipses in some systems and Mullan (1975) followed up with a more detailed investigation. In his original list of RS CVn and related binaries, Hall (1976) included W UMa binaries as stars with an "uneven surface brightness distribution". Of course, there are surface brightness variations not caused by starspots such as polar brightening due to $T \propto g^{0.08}$ (effect of the gravitationally deformed component), ellipticity effect, a "bright" and a "dark" hemisphere on the cooler component due to irradiation (reflection effect), a hot spot on the mass-gaining component due to mass transfer, common envelope oscillations, and others. To gain some information on local temperature variations solely due to starspots, all the mentioned effects must be isolated and subtracted. It is therefore not surprising that only a few systems have been studied with modern light curve synthesis programs allowing for starspots. Table 1 summarizes some starspot parameters of W UMa stars as determined with modern synthesis.
STARSPOT PHOTOMETRY

programs. Note that the entry “hot spot” refers to solutions with a hot, circular region at the substellar point of the secondary component which is not magnetic in origin, e.g., VW Boo (Rainger et al. 1990), or BX And (Bell et al. 1990a). Spot coverage factors for W UMa binaries are hard to be put on a common scale with other stars (Table 1) due to their contact, common-envelope configuration and must be looked at with care when intercompared (Fig. 2).

Using short-wavelength IUE spectra, Eaton (1983) demonstrated the existence of active chromospheres on several W UMa’s having more active primaries but less active secondaries. From photometry the situation is not as clear. In the case of AG Vir (A2+A8), Bell et al. (1990b) demonstrate the ease with which the spot phenomenon can be invoked to explain the light curve variations and to provide conflicting results. Their study (see their Fig. 9) shows the ambiguity between a deep-contact plus cool-spot model and a marginal-contact plus warm-spot\(^2\) model. A similar ambiguity was encountered for VZ Psc (Maceroni et al. 1990b): a near-contact plus cool-spot model or a deep-contact model with no spots (Hrivnak and Milone 1989). The fact that the absolute dimensions from the near-contact plus cool-spot solution are in better agreement with the late spectral types, and that the fits are generally better, argues in favor of the existence of spots on VZ Psc, but the evidence remains inconclusive. In the case of AC Boo (Linnell 1991), the light curve modulation persists into totality, when one component is eclipsed, and the spots can be unequivocally placed onto the foreground component. A similar case is VW Cep (G5+K0). Bradstreet and Guinan (1990) presented near-simultaneous photometry and UV spectroscopy. Their photometry showed sometimes a secondary minimum deeper than the primary minimum and eclipse asymmetries appeared to be greatest at times when the system is least luminous. This suggests the existence of starspots cooler by about 500 K. Furthermore, Bradstreet and Guinan present evidence for spatial connection between these starspots and chromospheric and TR-emission regions. There is also good evidence that locations of starspots change with time. In U Peg (Zhai et al. 1988) the spot was shifting in longitude and latitude by an amount much too large to be caused by observational and model uncertainties. The temperature difference (photosphere minus spot) had also changed by \(\approx 60\) % from 1961 to 1970. Spot migration periods were derived from light curve variations, e.g., for W UMa \(\approx 500\) days (Rigterink 1972), and VW Cep \(\approx 720\) days (Leung and Jurkevich 1969) while Bradstreet and Guinan (1990) observed a cyclic behaviour with 155 and 320 days (they interpreted these periods as the beat periods between the orbital and the rotational period).

The onset of spot activity in contact or semi-detached systems is not clear since the sample of spotted components is too limited but Olson (1987) reports spot activity on the G4III-IV component in the Algol binary U Sagittae. The “earliest” W UMa system with cool starspots seems to be the A7-9 component of AG Vir (Bell et al. 1990b). However, as discussed by these authors, the detection

\(^2\)Not to be confused with the hot spot due to mass transfer or irradiation
was not conclusive. Another early W UMa-type component with spot activity is U Peg (spectral type G2, Lu 1985).

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PART II.

CCD IMAGING WITH

ROBOTIC TELESCOPES