PHOTOMETRIC VARIABILITY IN CHROMOSPHERICALLY ACTIVE STARS.
III. THE BINARY STARS

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ABSTRACT

Differential \textit{UBV} photometry of 49 late-type chromospherically active binary stars has been obtained. All observations were made with the 0.25 m prototype automatic photoelectric telescope (APT) in the years 1983–1987. A total of 12,353 differential \textit{UBV} magnitudes have been acquired and are used to determine seasonal photometric periods, amplitudes, mean brightnesses, maximum spot amplitudes, “unspotted” differential magnitudes, and times of minimum light. Standard Fourier techniques were used to investigate the cause of the light variability. We found eight stars which do not exhibit light variations due to spot activity but rather due to ellipticity and/or reflection effect. Others show combinations of all three effects. Light curve changes on a time scale of one rotation cycle seem to be common in almost all spotted stars of our sample. Some of the systems also show substantial differences between their rotational (photometric) and orbital period. The data are plotted in Julian date diagrams, as well as in seasonal phase plots.

Subject headings: photometry — stars: binaries — stars: chromosphere — stars: variables

I. INTRODUCTION

The presence of spots on stars produces periodic variations in light which make it possible to determine a star’s rotation period with a much higher precision than that allowed by spectroscopic rotational velocity measures. Starspots can cover 10% or more of a star’s surface and produce broad-band light variations in the range of 0.01–0.45 mag (e.g., Hall 1976; Vogt 1981; Rodonò et al. 1986). This photospheric activity is almost always accompanied by a hyperactive chromosphere. In this paper we will call these stars “chromospherically active” (CA). Such stars are usually either close binaries in which tidal forces cause the rotation to synchronize with the orbital motion or very young rapidly rotating single stars. Numerous surveys have been undertaken in order to determine the properties of such active systems. These programs include those of Reglero et al. (1987), Fekel, Moffett, and Henry (1986, hereafter FMH), Bopp (1984), and Bopp et al. (1983) in the northern hemisphere and those of Collier-Cameron (1987\(a, b\)), Balona (1987), Lloyd-Evans and Koen (1987), and Hearshaw (1979) in the southern hemisphere. The basic results of those surveys are also included in a new catalog called \textit{Chromospherically Active Binary Stars} (Strassmeier et al. 1988\(a\), hereafter CABS).

In our first paper of this series (Strassmeier and Hall 1988\(a\), hereafter Paper I) we presented 15 CA stars, singles and binaries, which exhibited no photometric variability and thus did not have total projected spot coverages in excess of approximately 0.5% of one hemisphere. Our second paper (Strassmeier and Hall 1988\(b\), hereafter Paper II) focused on five rapidly rotating single stars with rotationally modulated light curves.

We now discuss photometric variability in 49 close binary stars. With the exception of two systems (HD 25893 and HR 4430), all stars are listed in the CABS catalog. HR 4430 has been found recently to exhibit Ca II H and K emission (see discussion in § III of this paper and references therein), and HD 25893 is a close visual double but not a component of a close binary in Kopal’s (1955) sense. Another eight systems (33 Psc, 5 Cet, \(\xi\) And, HR 1970, HD 136901, HR 6626, and V350 Lac) are chromospherically active, but their light variations are due to either the ellipticity or the reflection effect or a combination of both. A fourth paper in this series will present all “nightly mean” (the mean of three variable-to-comparison star) \textit{UBV} measures for the stars discussed in the first three papers (Boyd et al. 1988).

II. OBSERVATIONS

The differential \textit{UBV} photometry presented in this paper was made with the 10 inch automatic photoelectric telescope (APT) in Phoenix, Arizona, and later on Mount Hopkins near Tucson, Arizona. This telescope and its operation have been described elsewhere (e.g., Boyd, Genet, and Hall 1984\(a\); Balunas et al. 1985). The photometer head consists of an uncooled 1P21 photomultiplier, a 60” diaphragm, and filters selected to match the standard Johnson \textit{UBV} system.

Our observations began on 1983 October 1 and lasted until the first quarter of 1987, a total time of 3.7 yr. As is discussed in more detail in Paper I and Paper II, several problems were encountered during this period. Table 1 lists a short summary

\(^1\)Henri Chrétien Fellow 1987.
of these problems and their influence on parts of the data. Table 2 is a tally of our observations. It lists the total number of observed “nightly means,” the number of observations actually used in the analysis, the number of data affected by problems C and D and their applied (vertical) shifts, the number of observations excluded due to problems A, B, and E, and the data points excluded due to a 3σ test. The treatment of problems C and D has been described in detail in Paper II.

The APT algorithms are not capable of deciding whether a gross light variation is due to, e.g., thin clouds or to a huge but real dimming of the star. Thus, our data contain a few measurements that are apparently grossly in error. Gaussian statistics tell us that, in a sample of data where the deviations from the mean are purely random, 99.73% of the deviations should be less than 3σ. We therefore perform a 3σ test in order to remove the few measurements grossly in error. The number of observations removed is listed in Table 2. It can be seen that, altogether, only about 0.3% were excluded.

From a study of three presumably constant stars in Paper I we found mean internal standard deviations of ±0.005, ±0.005, and ±0.009 mag in the V, B, and U passbands, respectively. The mean external standard deviation of a “nightly mean” from a yearly mean was ±0.0115, ±0.0145, and ±0.0234 mag in V, B, and U, respectively.

### III. RESULTS AND DISCUSSION

Our first step in the analysis was to determine the photometric period and, if possible, intrinsic period changes from season to season. Using a least-squares program in which sine curves of various incremented periods are fit one by one to the data we derived periods for each observing season or, sometimes, even for several separated data sets within a season. For stars where it is not absolutely clear which period is the correct one or where the period varies, we give (seasonal) periodograms in Figures 98–113. The results are listed in Table 3 for the stars with no photometric wave, i.e., no spot activity, and in Table 4 for stars with spots.

The second step was to examine the cause of the light variability. If the ellipticity effect is at work we should observe a period exactly half the orbital period. In addition, minimum light must occur at times of conjunction. The reflection effect, however, requires a periodicity equal to the orbital period, and a time of light minimum must occur at conjunction with the cooler component in front. Spot activity can produce almost any type of light curve, from a simple sine curve to an asymmetric double- (or even triple-) humped light curve with different and variable amplitudes. Moreover, spot activity migrates in time if plotted versus orbital phase. The stars for which we have detected spot activity are listed in Table 4. For stars with no visible spot activity Table 3 lists the UBV amplitudes, mean differential UBV magnitudes, the photometric period found from the V and B data, a time of minimum light, and the cause of the light variability. Note at this point that some of the stars listed in Table 4 also do show ellipticity and/or reflection effect. These systems are HR 4430 (E,R), α Tri (E), HD 136905 (E), HD 165590 (E), HR 7428 (E), HD 185151 (E), and ER Vul (E), where E stands for ellipticity effect and R for reflection effect. Some of the systems are also eclipsing.

The third step was to fit a sinusoidal curve to the data by use of the truncated Fourier series

\[ I = A_0 + A_1 \cos \Theta + B_1 \sin \Theta, \]

where \( \Theta \) is the photometric phase and \( A_0, A_1, A_2, \) and \( B_1 \) are the Fourier coefficients. Treating each observing season as a separate data set we derived times of minimum light and seasonal mean spot amplitudes, as well as the maximum spot amplitudes and the seasonal mean brightness level.

Finally, we examined our \( \Delta V \) versus Julian date plots in order to provide more information on a very important parameter for any further spot modeling analysis—the immaculate or “unspotted” brightness level of the star. Given the length of spot cycles, however, it may take decades to unambiguously determine such unspotted levels. Our Table 4 lists the maximum differential brightness found from the data presented in this paper along with the above mentioned parameters. We did not try to add the brightness of our comparison stars in order to give apparent magnitudes instead of differential (i.e., variable minus comparison) magnitudes. This is because some of our comparison stars have only rather uncertain UBV values, and we suggest that every potential user of our data apply her or his own favorite value.
Figures 1–49 show the V data plotted versus Julian date. Figures 50–97 give seasonal phase plots computed, if not otherwise indicated, with the orbital period and a time of minimum light. It must be pointed out that these phase plots do not properly account for intrinsic amplitude variability, which occurs very frequently on a time scale comparable to the photometric period; thus, they add nonreal scatter to the phased data and can diminish or even obscure a low-amplitude variability originally visible in the ΔV versus JD plot and detected by our period-finding technique. In such cases we have split observing seasons into several data sets and plotted them separately. Figures 98–113 are periodograms useful to judge the reality of our periods. For stars without a corresponding periodogram the results are unambiguous and are
### Table 3

**Variable Chromospherically Active Binary Stars with No Spot Wave**

<table>
<thead>
<tr>
<th>STAR NAME</th>
<th>HD</th>
<th>SPECTRAL TYPE*</th>
<th>$P_{oh}$ (days)</th>
<th>$P_{phm}$ (days)</th>
<th>$T_{con}$ (2,440,000 +)</th>
<th>$V$ (mag)</th>
<th>$B$ (mag)</th>
<th>$U$ (mag)</th>
<th>$V$ (mag)</th>
<th>$B$ (mag)</th>
<th>$U$ (mag)</th>
<th>TYPE OF VARIABILITY</th>
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<tr>
<td>33 Psc .......</td>
<td>28</td>
<td>K0 III</td>
<td>72.93</td>
<td>36.06 ± 0.26</td>
<td>6384.0 ± 2.3</td>
<td>-1.249</td>
<td>-1.100</td>
<td>-0.983</td>
<td>0.006 ± 0.002</td>
<td>0.006 ± 0.013</td>
<td>0.006 ± 0.012</td>
<td>Ellipticity effect</td>
</tr>
<tr>
<td>5 Cet .........</td>
<td>352</td>
<td>F + K1 III</td>
<td>96.41</td>
<td>48.16 ± 0.05</td>
<td>6249.95 ± 0.18</td>
<td>-0.280</td>
<td>+1.268</td>
<td>+2.733</td>
<td>0.191 ± 0.005</td>
<td>0.197 ± 0.006</td>
<td>0.181 ± 0.012</td>
<td>Ellipticity effect</td>
</tr>
<tr>
<td>34 θ And .......</td>
<td>4502</td>
<td>K1 II</td>
<td>17.7692</td>
<td>8.917 ± 0.002</td>
<td>6337.13 ± 0.10</td>
<td>-0.320</td>
<td>-0.157</td>
<td>+0.030</td>
<td>0.022 ± 0.015</td>
<td>0.015 ± 0.016</td>
<td>0.124 ± 0.017</td>
<td>Reflection effect</td>
</tr>
<tr>
<td>HR 1970 ........</td>
<td>38099</td>
<td>K4 III</td>
<td>143.04</td>
<td>70.09 ± 0.81</td>
<td>6064.2 ± 1.7</td>
<td>+1.390</td>
<td>+1.703</td>
<td>+2.252</td>
<td>0.055 ± 0.005</td>
<td>0.072 ± 0.005</td>
<td>0.082 ± 0.007</td>
<td>Ellipticity effect</td>
</tr>
<tr>
<td>HR 5110 .........</td>
<td>118216</td>
<td>F2 IV + K2 IV</td>
<td>2.6131738</td>
<td>2.634 ± 0.0002</td>
<td>6568.89 ± 0.17</td>
<td>+0.152</td>
<td>+0.290</td>
<td>+0.269</td>
<td>0.016 ± 0.006</td>
<td>0.014 ± 0.007</td>
<td>0.031 ± 0.009</td>
<td>Reflection effect</td>
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<tr>
<td>UV CrB ........</td>
<td>136901</td>
<td>K1 III</td>
<td>18.670</td>
<td>9.322 ± 0.006</td>
<td>6426.21 ± 0.09</td>
<td>+0.902</td>
<td>+0.917</td>
<td>+0.740</td>
<td>0.162 ± 0.004</td>
<td>0.178 ± 0.004</td>
<td>0.209 ± 0.006</td>
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</tr>
<tr>
<td>HR 6626 ........</td>
<td>161832</td>
<td>K3 III</td>
<td>99.557</td>
<td>49.66 ± 0.04</td>
<td>6167.2 ± 1.2</td>
<td>-0.054</td>
<td>+0.725</td>
<td>+1.712</td>
<td>0.036 ± 0.005</td>
<td>0.041 ± 0.007</td>
<td>0.053 ± 0.015</td>
<td>Ellipticity effect</td>
</tr>
<tr>
<td>V350 Lac .......</td>
<td>213389</td>
<td>K2 III</td>
<td>17.755</td>
<td>8.882 ± 0.004</td>
<td>6604.26 ± 0.08</td>
<td>+1.816</td>
<td>+2.772</td>
<td>+3.967</td>
<td>0.071 ± 0.004</td>
<td>0.16 ± 0.006</td>
<td>0.22 ± 0.10</td>
<td>Ellipticity effect</td>
</tr>
</tbody>
</table>

* Taken from the CABS catalog (Strassmeier et al. 1988a).
<table>
<thead>
<tr>
<th>STAR NAME</th>
<th>HD NUMBER</th>
<th>SPECTRAL TYPE</th>
<th>PERIOD (days)</th>
<th>ΔV(max)</th>
<th>PHOTOMETRIC PERIOD (days)</th>
<th>TIME OF MINIMUM LIGHT (HJD 2,440,000 +)</th>
<th>MAXIMUM WAVE AMPLITUDE</th>
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<tr>
<td>39 Cet</td>
<td>7672</td>
<td>G5 III</td>
<td>56.815</td>
<td>-0.572</td>
<td>-0.485</td>
<td>0.102</td>
<td>0.065</td>
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<tr>
<td>AR Psc</td>
<td>8357</td>
<td>G8 IV</td>
<td>14.300</td>
<td>+1.195</td>
<td>0.045</td>
<td>0.188</td>
<td>0.171</td>
</tr>
<tr>
<td>AR Psc</td>
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<td></td>
</tr>
<tr>
<td>ι Tri</td>
<td>13480</td>
<td>G5 III</td>
<td>11.732</td>
<td>-1.600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX Ari</td>
<td>21242</td>
<td>K0 IV</td>
<td>6.43791</td>
<td>+0.850</td>
<td>+0.975</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td>V837 Tau</td>
<td>22403</td>
<td>G2 V</td>
<td>1.92994</td>
<td>+0.850</td>
<td></td>
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<tr>
<td>V711 Tau</td>
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<td>K1 IV</td>
<td>2.83774</td>
<td>+1.360</td>
<td></td>
<td></td>
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<tr>
<td>V491 Per</td>
<td>25893</td>
<td>G8 IV</td>
<td>?</td>
<td>+1.048</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Eri</td>
<td>26337</td>
<td>G5 IV</td>
<td>1.94722</td>
<td>+1.574</td>
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<td>V492 Per</td>
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<td>K1 III</td>
<td>21.295</td>
<td>-0.495</td>
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<td>RZ Eri</td>
<td>30050</td>
<td>K0 IV</td>
<td>39.2826</td>
<td>+0.530</td>
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<tr>
<td>BD +0° 908</td>
<td>31738</td>
<td>G5 IV</td>
<td>?</td>
<td>-0.593</td>
<td></td>
<td></td>
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<tr>
<td>12 Cam</td>
<td>32357</td>
<td>K0 III</td>
<td>80.17447</td>
<td>-0.127</td>
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<tr>
<td>V1149 Ori</td>
<td>37824</td>
<td>K1 III</td>
<td>53.580</td>
<td>+0.489</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>σ Gem</td>
<td>62044</td>
<td>K1 III</td>
<td>19.60458</td>
<td>-1.197</td>
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TABLE 4
Chromospherically Active Binary Stars with a Spot Wave

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TABLE 4 — Continued

<table>
<thead>
<tr>
<th>Star Name</th>
<th>HD Number</th>
<th>Spectral Type</th>
<th>Orbital Period&lt;sup&gt;b&lt;/sup&gt; (days)</th>
<th>$\Delta V$(max)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Photometric Period&lt;sup&gt;d&lt;/sup&gt; (days)</th>
<th>Time of Minimum Light (HJD 2,440,000 +)</th>
<th>Mean $\Delta V$ Magnitude</th>
<th>Maximum Wave Amplitude&lt;sup&gt;e&lt;/sup&gt;</th>
<th>1983–84 or 1984</th>
<th>1984–85 or 1985</th>
<th>1985–86 or 1986</th>
<th>1986–87 or 1987</th>
</tr>
</thead>
<tbody>
<tr>
<td>54 Cam</td>
<td>65626</td>
<td>F9 IV</td>
<td>11.0764</td>
<td>+0.697</td>
<td>10.19 ± 0.23</td>
<td>10.16 ± 0.05</td>
<td>10.35 ± 0.10</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<tr>
<td>LR Hya</td>
<td>91816</td>
<td>K3–4 V</td>
<td>6.86569</td>
<td>+0.337</td>
<td>5072.5 ± 0.3</td>
<td>6073.2 ± 0.5</td>
<td>6422.14 ± 0.25</td>
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<td>...</td>
<td>...</td>
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<td>...</td>
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<tr>
<td>ξ UMa</td>
<td>98230</td>
<td>G5 V</td>
<td>3.9805</td>
<td>+0.260</td>
<td>4.86 ± 0.03</td>
<td>6067.73 ± 0.34</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<td>...</td>
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<tr>
<td>HR 4430</td>
<td>99967&lt;sup&gt;b&lt;/sup&gt;</td>
<td>K2 III</td>
<td>74.861</td>
<td>+0.137</td>
<td>115.6 ± 0.15</td>
<td>122.1 ± 1.1</td>
<td>112.7 ± 0.1</td>
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<tr>
<td>93 Leo</td>
<td>102509</td>
<td>G5 IV–III</td>
<td>71.6900</td>
<td>-0.707</td>
<td>660 ± 0.03</td>
<td>6549.8 ± 0.5</td>
<td>6787.4 ± 2.8</td>
<td>...</td>
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<tr>
<td>DK Dra</td>
<td>106677</td>
<td>K1 III</td>
<td>64.44</td>
<td>-0.242</td>
<td>63.9 ± 1.5</td>
<td>65.9 ± 0.9</td>
<td>66.8 ± 0.6</td>
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<tr>
<td>BM CVn</td>
<td>116204</td>
<td>K1 III</td>
<td>20.625</td>
<td>+1.588</td>
<td>65.9 ± 0.5</td>
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<td>65.9 ± 0.5</td>
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<td>GX Lib</td>
<td>136905&lt;sup&gt;a&lt;/sup&gt;</td>
<td>K1 III</td>
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<td>σ&lt;sup&gt;c&lt;/sup&gt; CrB</td>
<td>146361</td>
<td>G0 V</td>
<td>1.139791</td>
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<tr>
<td>HR 6469</td>
<td>157482&lt;sup&gt;i&lt;/sup&gt;</td>
<td>G5 IV</td>
<td>2018.0</td>
<td>-0.430</td>
<td>...</td>
<td>...</td>
<td>81.9 ± 0.4</td>
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<td>29 Dra</td>
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<td>39</td>
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<td>Z Her</td>
<td>163930</td>
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<td>3.992801</td>
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<td>...</td>
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<tr>
<td>V772 Her</td>
<td>165590&lt;sup&gt;k,l&lt;/sup&gt;</td>
<td>G0 V</td>
<td>0.8794998</td>
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<td>0.869 ± 0.004</td>
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<tr>
<td>V815 Her</td>
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<td>G5 V</td>
<td>1.8098368</td>
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<td>...</td>
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<td>47 ο Dra</td>
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<td>138.420</td>
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*a* Spectral type of the spotted component.

*b* Taken from the CABS Catalog (Strassmeier et al. 1988a).

*c* Unspotted magnitude in the sense variable minus comparison.

*d* From $V$ data only.

*e* The total range of variability taken from the JD plots.

*f* Close visual system but high-dispersion spectroscopic observations in the red show only one component (Fekel, Moffet, and Henry 1986).

*g* Shows also ellipticity effect with $P_{\text{phot}} = 1/2 P_{\text{orb}}$.

*h* Shows also reflection effect with $P_{\text{phot}} = P_{\text{orb}}$.

*Triple system.*
Fig. 1.—33 Psc minus HD 587 vs. Julian date

Fig. 2.—5 Cet minus HD 315 vs. Julian date

Fig. 3.—ς And minus HD 5516 vs. Julian date

Fig. 4.—HR 1970 minus HD 37984 vs. Julian date

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Fig. 5.—HR 5110 minus HD 118623 vs. Julian date

Fig. 6.—HD 136901 minus HD 136643 vs. Julian date

Fig. 7.—HR 6626 minus HD 162868 vs. Julian date

Fig. 8.—V350 Lac minus HD 212593 vs. Julian date

Fig. 9.—39 Cet minus HD 7147 vs. Julian date

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Fig. 10.—(a) HD 8357 minus HD 7446 vs. Julian date; (b) HD 8357 minus HD 7918 vs. Julian date

Fig. 11.—6¿ Tri minus HD 14373 vs. Julian date

Fig. 12.—UX Ari minus HD 20825 vs. Julian date
Fig. 13.—HD 22403 minus HD 23075 vs. Julian date

Fig. 14.—V711 Tau minus HD 22484 vs. Julian date

Fig. 15.—HD 25893 minus HD 25975 vs. Julian date

Fig. 16.—HD 26337 minus HD 26409 vs. Julian date

Fig. 17.—HD 28591 minus HD 28620 vs. Julian date
Fig. 18.—RZ Eri minus HD 30535 vs. Julian date

Fig. 19.—HD 31738 minus HD 31594 vs. Julian date

Fig. 20.—12 Cam minus HD 33618 vs. Julian date

Fig. 21.—HD 37824 minus HD 38309 vs. Julian date
Fig. 22.—σ Gem minus HD 60318 vs. Julian date

Fig. 23.—54 Cam minus HD 65301 vs. Julian date

Fig. 24.—HD 91816 minus HD 91566 vs. Julian date

Fig. 25.—(a) ξ UMa minus HD 98262 vs. Julian date; (b) Light curve for ξ UMa(B) in B

153
Fig. 26.—HR 4430 minus HD 101133 vs. Julian date

Fig. 27.—93 Leo minus HD 101484 vs. Julian date

Fig. 28.—DK Dra minus HD 108399 vs. Julian date

Fig. 29.—HD 116204 minus HD 116010 vs. Julian date

154
Fig. 30.—HD 136905 minus HD 136544 vs. Julian date

Fig. 31.—17\textsuperscript{a} CrB minus HD 145802 vs. Julian date. Note the single measurement at the extreme right end of the JD axis at 2,446,700, which would be consistent with the sinusoidal long-term light variation described in the text.

Fig. 32.—HR 6469 minus HD 156891 vs. Julian date

Fig. 33.—29 Dra minus HD 164780 vs. Julian date. In this particular case we could not correct for problem C (see Table 1), which affected data till JD 2,446,102.5, but, as discussed in the text, the 0.1 mag increase of the mean light level from 1984 to 1985 is real.
Fig. 34.—Z Her minus HD 164043 vs. Julian date

Fig. 35.—HD 165590 minus HD 165524 vs. Julian date

Fig. 36.—HD 166181 minus HD 166093 vs. Julian date

Fig. 37.—47 o Dra minus HD 175511 vs. Julian date

Fig. 38.—HD 178450 minus HD 177878 vs. Julian date
Fig. 39.—HR 7275 minus HD 177483 vs. Julian date

Fig. 40.—HR 7428 minus HD 184170 vs. Julian date

Fig. 41.—HD 185151 minus HD 185269 vs. Julian date

Fig. 42.—ER Vul minus HD 200270 vs. Julian date
Fig. 43.—HK Lac minus HD 210731 vs. Julian date

Fig. 44.—AR Lac minus HD 210731 vs. Julian date

Fig. 45.—IM Peg minus HD 216635 vs. Julian date

Fig. 46.—HD 217188 minus HD 217428 vs. Julian date

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Fig. 47.—λ And minus HD 223047 vs. Julian date

Fig. 48.—HD 222317 minus HD 222390 vs. Julian date

Fig. 49.—II Peg minus HD 224930 vs. Julian date

Fig. 50.—Phase plot for 33 Psc computed with the ephemeris HJD 2,446,384.0 + 72.93E (Table 3). The very small amplitude is caused by the ellipticity effect. No spot activity with an amplitude larger than σ_int is present.
Fig. 51.—Phase plot for 5 Cet computed with the ephemeris HJD 2,446,249.95 + 96.41$E$ (Table 3). The cause of the light variability is a combination of the ellipticity plus the reflection effect.

Fig. 52.—Phase plot for ζ And computed with the ephemeris HJD 2,446,332.69 + 17.7692$E$ (Table 3). Both the ellipticity and the reflection effect produce the light variability.

Fig. 53.—Phase plot for HR 1970 computed with the ephemeris HJD 2,446,064.2 + 143.04$E$ (Table 3). The amplitude is most likely due to a small ellipticity effect.

Fig. 54.—Phase plot for HR 5110 computed with the ephemeris HJD 2,446,568.9 + 2.613174$E$ (Table 3). The very small amplitude of only 0.005 mag is caused by the reflection effect.
Fig. 55.—Seasonal phase plots for HD 136901 computed with the ephemeris HJD 2,445,697.59 + 18.670E (Table 4). The light-curve shape is dominated by both the ellipticity and the reflection effect.

Fig. 56.—Phase plot for HR 6626 computed with the ephemeris HJD 2,446,167.2 + 99.557E (Table 3). The approximately 0.04 mag amplitude is due mostly to the ellipticity effect but also to a smaller reflection effect.
Fig. 57.—Phase plot for V350 Lac computed with the ephemeris HJD 2,446,599.82 +17.755E (Table 3). The ellipticity is the major cause of the light variability. A small reflection effect, however, causes the height of the two light maxima to be unequal.

Fig. 58.—Phase plots for 39 Cet computed with the ephemeris HJD 2,446,242.6 +75.12E (Table 4), where 75.12 days is the photometric period. Data from three observing seasons are shown.
Fig. 59.—(a) Seasonal phase plots for HD 8357 with HD 7446 as the comparison star. (b) Phase plot for HD 8357 with HD 7918 as the comparison star. Both data sets are plotted versus photometric phase with the ephemeris HJD 2,446,076.46 + $P_{\text{phm}}E$, where $P_{\text{phm}}$ is the appropriate seasonal photometric period listed in Table 4.
Fig. 60.—Phase plot for 6i Tri computed with the ephemeris HJD 2,446,476.32 + 14.732 E (Table 4). The ellipticity effect produces the double sine wave variability of the light curve. Note the variation of the shape of the light curve from the 1983–1984 season (upper panel) to the 1985–1986 season (lower panel) due to a migrating spot wave.

Fig. 61.—Seasonal phase plots for UX Ari computed with the ephemeris HJD 2,445,696.11 + 6.43791 E (Table 4).
Fig. 61—Continued

Fig. 62.—Seasonal phase plots for HD 22403 computed with the ephemeris HJD 2,446,328.71 + P_{phm} E (Table 4), where P_{phm} is the appropriate seasonal photometric period listed in Table 4.
Fig. 63.—Seasonal phase plots for V711 Tau computed with the ephemeris HJD 2,445,701.395 + 2.83774E (Table 4).

Fig. 64.—Seasonal phase plots for HD 25893 computed with the ephemeris HJD 2,445,700.79 + P_{phm}E (Table 4), where P_{phm} is the appropriate seasonal photometric period listed in Table 4.
Fig. 64—Continued

Fig. 65.—Seasonal phase plots for HD 26337 computed with the ephemeris HJD 2,445,699.83 + 1.94722 E (Table 4). Note the season-to-season shifts of the light minima and also the amplitude variability within one season (lower panel).
Fig. 65.—Continued

Fig. 66.—Seasonal phase plots for HD 28591 computed with the ephemeris HJD 2,445,707.5 + 21.295E (Table 4).

Fig. 67.—Seasonal phase plots for RZ Eri computed with the ephemeris HJD 2,446,426.5 + 31.4E (Table 4).
Fig. 68.—Seasonal phase plots for HD 31738 computed with the ephemeris HJD 2,446,070.71 + $P_{\text{phm}}E$ (Table 4), where $P_{\text{phm}}$ is the appropriate seasonal photometric period listed in Table 4.

Fig. 69.—Seasonal phase plots for 12 Cam computed with the ephemeris HJD 2,445,720.6 + 80.17447$E$ (Table 4).
Fig. 69—Continued

Fig. 70.—Seasonal phase plots for HD 37824 computed with the ephemeris HJD 2,445,691.0+53.580E (Table 4).
Fig. 71.—Phase plots for $\sigma$ Gem computed with the ephemeris HJD 2,445,702.0 + 19.60458E (Table 4). The 1983–1984 and the 1984–1985 seasons have been split into two individual data sets each.
Fig. 71.—Continued

Fig. 72.—Seasonal phase plots for 54 Cam computed with the ephemeris HJD 2,445,702.5 + $P_{\text{phim}}E$ (Table 4), where $P_{\text{phim}}$ is the appropriate seasonal photometric period listed in Table 4.

Fig. 73.—Phase plots for HD 91816 for the 1985 observing season computed with the ephemeris HJD 2,446,067.73 + 4.86$E$ (Table 4), where 4.86 days is the (photometric) period found from our periodogram analysis. Phase plots with the orbital period as well as other possibilities for $P_{\text{phim}}$, i.e., 2.57, 3.57, 7.50, and the 3.1 day period of Bopp et al. (1984), showed substantially larger residuals and are not plotted here. See the text for further discussion.
Fig. 74.—Seasonal phase plots for HR 4430 computed with the ephemeris HJD 2,445,685.55 + 74.861E (Table 4). Note that a combination of ellipticity effect, reflection effect, and starspots produce the light variability.
Fig. 75a (b)

Fig. 75.—(a) Seasonal phase plots for 93 Leo computed with the ephemeris HJD 2,445,681.5 + $P_{\text{phom}} E$ (Table 4), where $P_{\text{phom}}$ are the separate photometric periods listed in Table 4. (b) 93 Leo: the same 1984–1985 data as in (a) but plotted versus orbital phase with $P_{\text{orb}} = 71.6900$ days. No satisfying light curve could be produced (for further discussion see text).

Fig. 76.—Seasonal phase plots for DK Dra computed with the ephemeris HJD 2,445,671.1 + 64.44$E$ (Table 4). Note the dramatic amplitude increase from the 1983–1984 to the 1984–1985 season. The scatter at the light maximum around phase 0.7 in the 1985–1986 season indicates amplitude changes on much shorter time scales.
Fig. 77.—Seasonal phase plots for HD 116204 computed with the ephemeris HJD 2,445,691.5 + 20.625E (Table 4). The scatter around the light maximum at phase 0.5 in the 1983–1984 season already indicates the change from an originally double-humped light curve to the single-humped curve seen in 1985–1986.
Fig. 78.—Seasonal phase plots for HD 136905 computed with the ephemeris HJD 2,446,067.3 + 11.1345E (Table 4). Note the decrease of the secondary maximum at phase ~ 0.9 from the 1985 season to the 1986 season, which indicates the presence of a spot wave. The double-sine structure of the light curve, however, is due to the ellipticity effect.
Fig. 79.—Seasonal phase plots for 17σ² CrB computed with the ephemeris HJD 2,445,699.86 + P_phm E (Table 4), where P_phm is the appropriate seasonal photometric period listed in Table 4.

Fig. 80.—(a) Several light curves for the triple system HR 6469, plotted versus orbital phase with the 2.23 day orbital period of the eclipsing close binary and a time of primary eclipse given in Boyd et al. (1985a). (b) Several light curves for the triple system HR 6469, plotted versus photometric phase with the 81.9 days photometric period (Table 4) of the G5 IV component.
HR 6469 (1984-86) $P = 2.23$ DAYS

HR 6469 (1984-86) $P = 81.9$ DAYS

Fig. 80a — Continued

HR 6469 (1983-84) $P = 81.9$ DAYS

HR 6469 (1984-86) $P = 81.9$ DAYS

Fig. 80b
Fig. 80b—Continued

Fig. 81.—Phase plot for 29 Dra for the 1985 season computed with the ephemeris HJD 2,446,168.4 + P_{phot}E; where P_{phot} is the photometric period listed in Table 4.

Fig. 82.—Phase plot for Z Her for the 1985 season plotted versus orbital phase (P_{orb} = 3.99 days) and an estimated time of light minimum for the spot wave listed in Table 4.

Fig. 83.—Seasonal phase plots for HD 165590. The initial epoch is an estimated time of minimum light of the spot wave and the period is the orbital period. The double-sine structure, probably best seen in the 1985 season, is caused by the ellipticity effect, whereas the scatter is caused by the migrating spot wave.
Fig. 84.—Seasonal phase plots for HD 166181 computed with the ephemeris HJD 2,446,084.56 + $P_{\text{phot}}E$ (Table 4), where the $P_{\text{phot}}$ is the appropriate seasonal photometric period in Table 4.
Fig. 84—Continued

Fig. 85.—Seasonal phase plots for 47 O Dra for the combined 1984–1986 data. Phase has been computed from a time of minimum light and, from the upper panel to the lower panel, with the orbital period (138.420 days), half the orbital period, and the 54.6 day photometric period found by Hall and Persinger (1986). The best fit in the upper panel shows that the light variability of 47 O Dra very likely has a period near the orbital period.
Fig. 86.—Light curves for HD 178450 for the observing seasons 1984, 1985, and 1986. Phase has been computed with the ephemeris HJD 2,445,699.59 + $P_{\text{phot}} E$ (Table 4), where $P_{\text{phot}}$ is the appropriate photometric period listed in Table 4 and discussed in the text.
Fig. 87.—Seasonal phase plots for HR 7275 computed with the ephemeris HJD 2,445,696.0 + 28.59E (Table 4). Note the rapid amplitude changes visible in the 1983–1984 season (upper panel) and, even more dramatically, from the 1984 to the 1985 season.
Fig. 88.—Phase plots for HR 7428 for the combined 1983–1984 and 1985–1986 data, respectively. Phase has been computed with the ephemeris HJD 2,445,717.2 + 108.5707E (Table 4). Two effects, ellipticity and a migrating wave, produce the light variability.

Fig. 89.—Seasonal phase plots for HD 185151 computed with the ephemeris HJD 2,446,045.8 + 40.1425E (Table 4). A combination of the ellipticity effect and a migrating spot wave produces the light variability of this star.

Fig. 90.—Light curves for the eclipsing binary ER Vul vs. photometric phase (upper panel) and vs. orbital phase (lower panel). Note that the eclipse points have been removed in the upper panel. Short-term nonperiodic brightness fluctuations complicate the light-curve structure; see the text.
Fig. 91.—Seasonal phase plots for HK Lac computed with the ephemeris HJD 2,445,717.9 + 24.4284E (Table 4).
Fig. 92.—Seasonal phase plots for AR Lac computed with the ephemeris HJD 2,445,700.66 + 1.98322195E (Table 4). Note the complex light curve structure in 1983–1984.

Fig. 93.—Seasonal phase plots for IM Peg computed with the ephemeris HJD 2,445,698.1 + 24.649E (Table 4). Note the "filled" light-curve minimum in the combined 1985–1986 season plot.
Fig. 93—Continued

Fig. 94.—Seasonal phase plots for HD 217188 computed with the ephemeris HJD 2,446,738.8 + 91.17E (Table 4), where the initial epoch is a time of light minimum and the period is the photometric period. Dramatic amplitude changes during the 1985 season can be seen in the lower panel. The time scale of these changes is approximately one rotation cycle.
Fig. 95.—Seasonal phase plots for λ And computed with the ephemeris HJD 2,445,719.3 + $P_{\text{phot}}$ (Table 4), where the initial epoch is a time of minimum light and $P_{\text{phot}}$ is the corresponding seasonal photometric period found from the periodogram analysis.
Fig. 96.—Seasonal phase plots for HD 222317 computed with the ephemeris HJD 2,445,700.5 + 6.20197E (Table 4).

Fig. 97.—Seasonal phase plots for II Peg computed with the ephemeris HJD 2,446,066.51 + 6.724183E (Table 4).
Fig. 98.—Periodogram for 39 Cet. The period range includes $1/2P_{\text{orb}}$ (left arrow) and $P_{\text{orb}}$ (right arrow). The best fit to the combined 1983–1987 data is given at a period of 75.12 days.

Fig. 99.—Periodogram for 6ι Tri for the three observing seasons from 1983–1984 through 1985–1986. The dominant period at $1/2P_{\text{orb}}$ is caused by the ellipticity effect.
Fig. 100.—Periodograms for HD 22403 for the two seasons 1984-1985 and 1985-1986. The arrow indicates $P_{\text{orb}}$. Only one period occurs in both data sets, i.e., $P_{\text{min}} \approx 1.89$ days. Note that the sum of the squares of the residuals has two pronounced minima, at 1.89 and 2.13 days. The former, which has the slightly deeper minimum, is the true period. The latter is the alias. Because our observations were made daily at almost the same time, several aliases at $\approx 2.0$ days show up.
Fig. 101.—Periodograms for HD 26337. The arrow indicates the orbital period. Note the similarity to HD 22403 in Fig. 100. The shorter period is the true period, the latter the alias.
Fig. 102.—Periodograms for HD 31738. No orbital period is known yet. Only one period shows up in both data sets, i.e., \( P \approx 4.55 \) days. The shorter period in the upper panel is very likely an alias.

Fig. 103.—Several periodograms for HD 91816, where the upper periodogram is for the first half of the observing season, the middle panel for the second half. Both sets have approximately the same number of data points. The lower panel is a periodogram of the combined data. Basically there are three possible periods, at approximately 2.6, 3.6, and 4.8 days. The last is the most significant. The arrows indicate \( 1/2 P_{\text{orb}} \) and \( P_{\text{orb}} \). A further period at 7.5 days, the broad dip only partially seen in the middle panel, is perhaps an alias of a shorter period. Phase plots with the 2.6, 3.6, and 7.5 day periods, did not show any periodic structure. Note that the 3.1 day period reported by Bopp et al. (1984) does not show up in our data.
Fig. 104.—Periodogram for 93 Leo. Only the 1984–1985 season allows a reliable period determination (see Fig. 27 and text). The right arrow indicates the 71.69 day orbital period and the left arrow is at $1/2P_{\text{orb}}$. It seems that 93 Leo is a further example of an asynchronous rotator.
Fig. 105.—Periodograms for $17 \sigma^5$ CrB. The arrow indicates the 1.14 day orbital period. Note that several aliases show up in the periodogram for the 1985–1986 season which had a baseline of only 66 days and a total of only 43 nightly means.
Fig. 106.—Periodogram for HD 165590. The arrow indicates the 0.88 day orbital period. Note that the photometric period was smaller than $P_{\text{orb}}$, in 1984 and slightly larger in 1985 and 1986.
Fig. 107.—Periodogram for 47 o Dra for the combined 1984–1986 data. The arrows indicate $1/2P_{\text{orb}}$ and $P_{\text{orb}}$, respectively (see text).

Fig. 108.—Periodograms for HD 178450. The arrow indicates the orbital period. Note that, in the middle panel, the one period closest to $P_{\text{orb}}$ is the true one (see discussion in the text).
Fig. 108—Continued

Fig. 109.—Periodogram for HR 7428 for the combined 1984-1986 data. The arrows indicate the 108 day orbital period and $1/2P_{\text{orb}}$.

Fig. 110.—Periodogram for HD 185151 for the combined 1984-1986 data. The arrows indicate the 40 day orbital period and $1/2P_{\text{orb}}$. 

Fig. 110.—Periodogram for HD 185151 for the combined 1984-1986 data. The arrows indicate the 40 day orbital period and $1/2P_{\text{orb}}$. 

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Fig. 111.—Periodogram for ER Vul for the combined 1984–1986 data. The arrows indicate the 0.698 day orbital period and $1/2 P_{orb}$. We believe that the best fit at 0.5356 days is apparently an alias. The dip at $1/2 P_{orb}$ indicates a small ellipticity effect.

Fig. 112.—Periodograms for AR Lac. The arrow indicates the 1.98 day orbital period. The correct photometric period is always the dip nearest to the orbital period. All other periods are aliases (see also the similar cases HD 26337 and HD 22403).
Fig. 113.—Periodograms for HD 222317. The arrows indicate the 6.2 day orbital period and $1/2 P_{\text{orb}}$. The 1984–1985 season data show a significant period near $P_{\text{orb}}$ with a shorter period around 4 days as an alias. The 1985–1986 season data show a less significant period farther from $P_{\text{orb}}$ and may or may not be real. Thus, we conclude a spot wave was present in 1984–1985 but perhaps not detectable a year later.
only listed in Table 4. Section IIIa contains the discussion of the eight stars that did not show a photometric spot wave and § IIIb contains the stars with a spot wave.

a) Stars with No Photometric Spot Wave

i) 33 Psc = HR 3 = HD 28

Barksdale et al. (1985a) have found light variations in V with an amplitude of only 0.006 mag, a period which is (within their uncertainties) exactly half the orbital period, and times of minimum light which coincide with times of conjunction. Therefore, they concluded that the ellipticity effect is the principal cause of the light variation.

Our new photometry includes three observing seasons from 1983 through 1985 (Fig. 1). The best sine curve fit to the data was achieved with a period of 36.06 days (Table 3), one-half the orbital period. A Fourier analysis resulted in the same amplitude as was seen by Barksdale et al. (1985a), namely 0.006 ± 0.002 mag in V for the cos 2θ term (Table 3). The cos θ term due to the reflection effect was undetectable. Figure 50 is a plot of our differential V magnitudes versus orbital phase.

ii) 5 Cet = HR 14 = HD 352

The variability of this K1 giant was first noticed by Lines and Hall (1981). They observed an amplitude of slightly more than 0.2 mag in V and a period very close to the orbital period of 96.41 days and suggested 5 Cet to be an ellipsoidal variable with possible eclipses. More recently, Eaton and Barden (1986) showed that the K giant fills or nearly fills its Roche lobe.

Our differential UBV photometry covered three observing seasons from 1983 through 1986 (Fig. 2). It is obvious that a combination of the ellipticity and the reflection effect causes the different depths of the minima and that the system does not eclipse. From a Fourier analysis allowing only for cos θ and cos 2θ terms we found a full amplitude of 0.19 mag due to the ellipticity effect and 0.02 mag due to the reflection effect (Table 3). There is no hint of spot activity in this otherwise very active star (Fig. 51).

iii) ζ And = HR 215 = HD 4502

The CABS catalog lists a K1 II spectral classification (Bidelman 1954). However, assuming synchronous rotation \( P_{\text{orb}} = P_{\text{phot}} \), the measured \( v \sin i \) of 36 km s\(^{-1}\) (Huisong and Xuefu 1987), and the orbital period of 17.7692 days (Gratton 1950) would translate into a minimum radius of approximately 12.6 \( R_\odot \). With Gratton’s value of \( i = 71^\circ \) the absolute radius for ζ And would be only about 13.4 \( R_\odot \), which is inconsistent with the bright giant luminosity classification of Bidelman (1954). The star is a well-known ellipsoidal variable (Stebbins 1928).

Our differential UBV photometry covered three observing seasons from 1983–1984 through 1985–1986 (Fig. 3). A plot of the \( V \) data versus orbital phase is shown in Figure 52. The light curve shows a double-wave variation with the orbital period. The light minimum at phase 0.0 is somewhat shallower than that seen at phase 0.5, indicating a small reflection effect. A Fourier fit to all our \( V \) data revealed a small cos θ amplitude of 0.016 ± 0.006 mag; thus, the light variations in ζ And can be attributed to both the ellipticity and the reflection effects, although the ellipsoidal variations are much more dominant. However, there is still a significant disagreement between our peak-to-peak amplitude of 0.055 mag and that of approximately 0.15 mag found by Belyakina, Burnashev, and Zhilin (1977) and the 0.14 mag amplitude found earlier by Stebbins (1928). This long-term amplitude difference could be due to a spot wave, but nothing quantitative can be derived from the present data set. Further monitoring of ζ And is therefore highly desirable.

iv) HR 1970 = HD 38099

The star is a single-lined spectroscopic binary with an orbital period of 143.04 days (Radford and Griffin 1975) containing a K4 giant. Recently, Hall et al. (1986) found HR 1970 to be a new ellipsoidal variable star with a total range of 0.029 mag in \( V \) and 0.033 mag in B. A periodogram analysis gave a period of 70.21 ± 0.76 days, one-half the orbital period (a phase plot is given in their Fig. 2). Our period-searching program found a photometric period of 70.09 ± 0.81 days, consistent with the period of Hall et al. (1986). Note that their data set is entirely the same as that presented in this paper. Figure 4 is a plot versus Julian date, and Figure 53 a plot versus orbital phase.

v) HR 5110 = HD 118216 = BH CVn

This system is unusual in several aspects; it is apparently semidetached, the mass ratio is far from unity, and the orbital inclination is quite small, \( i \sim 9^\circ \) (Eker 1985). Hall et al. (1978) discovered its light variability and attributed the full amplitude \( (0.010 \pm 0.002 \text{ mag in } V) \) to the differential reflection effect because of the coincidence in time between light minimum and conjunction with the hotter star behind. This has been confirmed by Dorren and Guinan (1980).

Our photometry covers three observing seasons from 1983–1984 through 1986 (Fig. 5). Figure 54 is a plot of the \( V \) data versus orbital phase and Table 3 lists the results from the Fourier analysis. The amplitude in \( V \) is very small (0.005 mag) and is only half the value obtained earlier by Hall et al. (1978). Thus, we could argue that the difference is due to a spot wave, but visual inspection of our phase plot in Figure 54 makes it clear that this would be speculation. More precise photometry is needed to decide whether HR 5110 has spots or not. Because the cooler, (possibly) spotted component star contributes so little light, this would be very difficult.

vi) HD 136901 = UV CrB

The CABS catalog lists a new orbit for HD 136901 with an orbital period of 18.670 days. Heard (1956) classified the star as K1 III. Boyd, Genet, and Hall (1984b) found the light variability of 0.16 mag in \( V \) with a period of 9.63 ± 0.05 days.

Our new photometry made between 1984 and 1986 (Fig. 6) showed the photometric period to be half the orbital period. A periodogram analysis gave the best fit at photometric periods of 9.342 ± 0.007, 9.324 ± 0.006, and 9.301 ± 0.039 days for the 1984, 1985, and 1986 seasons, respectively. Doubling our photometric periods gives rotation periods of 18.684,
18.648, and 18.602, respectively. With a mean rotation period of 18.645 ± 0.035 days and the rotational velocity of \( v \sin i = 42 \pm 2 \text{ km s}^{-1} \) (FMH) the minimum radius is 15.5 ± 0.7 \( R_\odot \). Since the radius of the giant star is large, FMH suspected that the light variations might be due to the ellipticity effect. The preliminary orbital elements in the CABS catalog are

\[
\text{JD(he|)} = 2446593.7157 + 18.670E,
\]

where the initial epoch is a time of conjunction with the secondary star behind. By extrapolating our times of minimum light forward to this time of conjunction, we conclude that all three seasonal light minima coincide with conjunction to within −0.04, +3.1, and −0.54 days, respectively. Thus, the light variation of 0.162 ± 0.004 mag of HD 136901 is primarily due to the ellipsoidal shape of its K1 giant. Visual inspection of our phase plots in Figure 55 clearly shows different depths of the two light minima, indicating a substantial reflection effect. A Fourier analysis with \( P_{\text{orb}} \) for the individual observing seasons gave times of light minima which are consistent with times of conjunction. The full amplitude due to the reflection effect is 0.030 ± 0.009 mag in \( V \).

\[ \text{vii) HR 6626 = HD 161832} \]

HR 6626 is another recently discovered ellipsoid variable (Hall et al. 1986). The orbital period is 99.557 days according to Mayor and Griffin (1980). A periodogram analysis by Hall et al. (1986) gave the best fit at a period of 53.5 ± 2.4 days.

Our differential UBV photometry presented in this paper has been made from 1984 through 1987 (Fig. 7). A periodogram analysis gave the best fit at a period of 49.66 ± 0.04 days, which is very close to one-half of the orbital period. As was already shown by Hall et al. (1986), times of minimum light coincide with times of conjunction, so the ellipticity effect is the major cause of the light variability in HR 6626. The results from a Fourier analysis are listed in Table 3 and are plotted versus orbital phase in Figure 56. Visual examination of our phase plot might show small differences in the depth of the light minima, indicating a reflection effect. A Fourier analysis with \( P_{\text{orb}} \) revealed a small but significant amplitude of 0.011 ± 0.003 mag in \( V \). Thus, a combination of the ellipticity and reflection effect can be seen in the light curve.

\[ \text{viii) V350 Lac = HR 8575 = HD 213389} \]

The photometric variability was first noticed by Herbst (1973) and has a period which is one-half of the orbital period and is therefore very likely due to the ellipsoidal shape of the primary. More recently, Percy and Welch (1982) confirmed the total range of variability to be 0.1 mag in \( V \).

Our differential UBV photometry covers three observing seasons from 1983–1984 through 1985 (Fig. 8). The best fit to the data was found with a sine curve and a period of 8.882 ± 0.004 days, almost exactly half the orbital period of 17.755 days (Northcott 1947). A Fourier analysis in all three colors (Table 3) gave a total range of variability of 0.07 mag in \( V \) due to the ellipticity effect. The \( \cos \theta \) term due to the reflection effect was only poorly defined and gave an amplitude of 0.011 ± 0.006 mag. A plot of the differential \( V \) magnitudes versus orbital phase is shown in Figure 57. Visual examination of this figure might show a somewhat unusual concentration of points toward the upper envelope of the light curve. This could happen if a small spot wave changes its amplitude, but that needs to be verified and cannot be taken as an indication of spots on V350 Lac.

\[ \text{b) Stars with a Photometric Spot Wave} \]

\[ \text{i) 39 Cet = HR 373 = HD 7672 = AY Cet} \]

39 Cet is one of the few stars listed in the CABS catalog with a white dwarf as a hot companion (Simon, Fekel, and Gibson 1985). The late-type component, a G5 giant (Cowley and Bidelman 1979), is the known variable star AY Cet and has moderately strong Ca lines and K emission (Bopp 1984). The photometric variability of 39 Cet was first noted by Olsen (1974). A more intensive study by Eaton et al. (1983a) included Olsen’s data from 1971 and 1972 and resulted in a mean photometric period of 77.65 ± 0.05 days, much longer than the orbital period of 56.815 days listed in the CABS catalog. Thus, 39 Cet is very likely another example of a highly asynchronous rotator. Poretti et al. (1986) presented more recent UBV photometry made between 1981 and 1984 along with an analysis of previously published data. They found a rotation period of 77.22 days and a 1820 day brightness variation which they explained as a possible spot cycle.

Our UBV photometry covers the time from 1983 through 1986 with a few observations in 1987 (Fig. 9). As is apparent from Figure 9 and Figure 58, the amplitude is variable from season to season and changed from approximately 0.06 to 0.19 mag within 1 yr (Table 4). Note that we did plot the observations affected by problem E (see Table 1) in our Figure 9 but did not include them in our analysis. Those points indicate an even larger amplitude. A periodogram analysis for the 1983–1987 data gave the best fit at a period of 75.12 ± 0.03 days (Fig. 98), substantially shorter than previous period determinations. However, one has to remember that rotation periods deduced from rotational modulation of light curves of spotted stars yield the rotation period at the spot’s latitude. Simon, Fekel, and Gibson (1985) calculated three sets of physical parameters for both components according to three assumed distances which are still consistent with the observed mass function. Their preferred solution included a low orbital inclination of \( i = 29^\circ \), which might make a photometric amplitude as large as 0.2 mag difficult to explain. Assuming that the photometric period is the rotation period and using the measured rotation velocity of \( v \sin i = 6 \pm 2 \text{ km s}^{-1} \) (Simon, Fekel, and Gibson 1985), we derive a minimum radius of 9 ± 3 \( R_\odot \) for the spotted primary.

\[ \text{ii) HD 8357 = AR Psc} \]

This star has been identified as the optical counterpart of the hard X-ray source H0123+075 (Garcia et al. 1980) and exhibits strong “activity” in virtually all wavelength regions (Nations and Seeds 1986a and references therein). Its optical variability of 0.08 mag in \( V \) has been discovered by Hall, Henry, and Louth (1982), who also determined the photometric period of 12.3 ± 0.1 days. The CABS catalog lists the most recent orbit determination, with \( P_{\text{orb}} = 14.300 \) days and \( e = \)
Our photometric observations covered three observing seasons from 1983–1984 through 1985–1986. For the last 2 months of the 1985–1986 season we observed HD 8357 with two different comparison stars (Figs. 10a and 10b). Photometric periods of 12.108 ± 0.036 and 12.378 ± 0.025 days have been found for the 1984–1985 and 1985–1986 seasons, respectively. No reliable period determination was possible for the 1983–1984 data because of a very small and uncertain amplitude of 0.045 mag compared to the 0.18 mag of the following season. Phase plots for the separate observing seasons are given in Figure 59a (HD 8357 minus HD 7446) and Figure 59b (HD 8357 minus HD 7918). FMH measured a projected rotation velocity for the G8 IV primary of $v \sin i = 6$ km s$^{-1}$, yielding a minimum radius of $1.45 \pm 0.5 R_\odot$. The strong activity seen throughout the whole electromagnetic spectrum on the one hand and the relatively sharp lines with $v \sin i = 6$ km s$^{-1}$ on the other hand, might indicate that the rotation axis is seen at a low inclination.

The photometric and spectroscopic behavior of this well-known RS CVn star have been summarized in the CABS catalog (Strassmeier et al. 1988a and references therein).

Our differential $UBV$ photometry covered nearly four complete observing seasons from 1983 through 1987 (Fig. 12). Each season was treated as a separate data set, and standard periodogram analysis and Fourier analysis have been applied (Table 4). Seasonal phase plots are given in Figure 61. The photometric periods range from 6.412 ± 0.009 to 6.443 ± 0.009 days, in close agreement with the orbital period of 6.43791 days (Carlos and Popper 1971). With the $v \sin i = 37 \pm 2$ km s$^{-1}$ listed in the CABS catalog and our mean photometric period of 6.431 days we derive a minimum radius for the active K0 IV component of $4.7 \pm 0.3 R_\odot$.

A significant dimming of the $V$ amplitude between the 1985 and the following 1986 season indicates long-term spot variability. Several authors (Zeilik et al. 1982; Wacker et al. 1986) report an unusual wavelength dependence of their intermediate- and broad-band photometry; i.e., the color indices being reddest when the light is brightest. This behavior might be explainable with the not well determined contribution of the hotter component to the total light.

The Ca II H and K emission in this double-lined binary (Fekel 1985) arises from the hotter component, a rapidly rotating ($v \sin i = 30 \pm 2$ km s$^{-1}$; FMH) G2 V star (Carquillat et al. 1979). The light variability of $\sim 0.09$ mag has been discovered by Raveendran et al. (1985). It is interesting to note that HD 22403 is one of the earliest main-sequence CA stars that have been found to have light variations presumably due to spot activity. See also HR 9024 in Paper II for the earliest giant with spot activity.

In this paper we present differential $UBV$ photometry covering the 1984–1985 and the 1985–1986 observing seasons. The data are plotted versus Julian date in Figure 13. The orbital period of 1.9299 days (Carquillat et al. 1979) already indicates the difficulties in obtaining good phase coverage. A periodogram analysis of our photometric data indicates a 1.883 ± 0.005 and a 1.895 ± 0.0065 day rotation period for the 1984–1985 and the 1985–1986 season, respectively. Two phase plots with these periods are shown in Figure 62. Periodograms for the two observing seasons are given in Figure 100. Four periods show up ranging from approximately 1.88 to 2.13 days, but only one real period can be seen in both data sets (Table 4). A sine curve fit with the period listed in Table 4 gave an amplitude of 0.027 ± 0.009 mag in 1984–1985 and 0.023 ± 0.006 mag in 1985–1986 (compare this scenario with the period determination of HD 26337 in this paper). With the cited $v \sin i$ and our rotation period we derive a minimum radius for the G2 dwarf of $1.12 \pm 0.08 R_\odot$.

The new observations presented in this paper were made throughout four observing seasons from 1983 through 1987.
vii) HD 25893 = ADS 2995 = V491 Per

This star is the brighter component of the close visual binary ADS 2995. High-dispersion spectroscopy in the red by FMH showed no sign of a secondary component; FMH also classified the primary as G8 IV spectral type. Bidelman (1983) noted the Ca H and K emission. The small light variability of only ΔV ∼ 0.03 mag has been discovered by Boyd, Genet, and Hall (1984b). They also found a preliminary ephemeris using an estimated value for the photometric period of 7.37 ± 0.06 days. The 3 months of data presented earlier by Boyd, Genet, and Hall were obtained in the first quarter of 1984 and are included in this paper and were reanalyzed in the same way as our new data.

Our new UBV photometry covers altogether three observing seasons from 1983–1984 through 1985–1986. This is shown in Figure 15 for the V passband. A periodogram analysis for the individual seasons gave the best fits at 7.43, 7.53, and 7.51 days, respectively (Table 4). The V amplitudes resulting from a sine curve fit are only 0.027 ± 0.004, 0.015 ± 0.004, and 0.024 ± 0.004 mag for the 1983–1984, 1984–1985, and 1985–1986 seasons, respectively. Table 4 lists the corresponding maximum amplitude found from visual inspection of Figure 15. The phase plot in Figure 64 for the 1983–1984 data shows all the problems with such low-amplitude variations, but the periodic variability of HD 25893 is nevertheless moderately well established. However, we point out that our photometry includes the fainter (V = 8.2 mag) visual component which is only 1.5° away.

viii) HD 26337 = El Eri

El Eri (G5 IV, v sin i = 50 km s⁻¹) has been the object of a detailed study at Vanderbilt University. Its spectroscopic behavior in the optical and UV has been investigated by Fekel et al. (1987), whereas the photometric behavior was studied by Hall et al. (1987). Recently, simultaneous Doppler imaging and UBVRI photometry of this star have been carried out by Strassmeier (1988).

The photometric variability of HD 26337 was discovered by Fekel et al. (1982). A detailed study of six years of photometry enabled Hall et al. (1987) to identify the period of 2.049 days found earlier by Bopp et al. (1983) as an alias. The correct photometric period is 1.945 ± 0.005 days and the correct orbital period is 1.9472 ± 0.0003 days (Fekel 1987; see also Balona 1987). Earlier photometry has been published by Lloyd-Evans and Koen (1987).

The available data for HD 26337 (Fig. 16) have been already included in the paper by Hall et al. (1987). In this paper we treat the different observing seasons as separate data sets and find that they yield quite different photometric periods, which are listed in Table 4. Separate seasonal phase plots are given in Figure 65. Details of the periodogram analysis are shown in Figure 101. Note that the dip around 2.04 days is the alias; the arrow indicates the orbital period. From this figure we can see that the period changed by an amount of approximately 0.043 days, i.e., 15 times the mean error of one period determination. This was a change from 1.5% faster than synchronous rotation to 0.7% slower than synchronous rotation over a time of 620 days.
VARIABILITY IN CHROMOSPHERICALLY ACTIVE STARS. III.

Our differential $UBV$ photometry was made from 1984-1985 through 1985-1986 (Fig. 19), thus covering two observing seasons. A periodogram analysis of the individual seasons (Fig. 102) gave two similar good fits at $3.70\pm0.04$ and $4.51\pm0.04$ days for the 1984-1985 season, but only one period ($4.59\pm0.04$ days) for the 1985-1986 season (Table 4); therefore, it seems that the 3.7 day period is an alias. As can be seen from Figure 102 the periodicity is more clearly defined in the 1985-1986 data than in the foregoing season. Phase plots for the separate seasons are shown in Figure 68. Fourier analysis for both seasons gave amplitudes in the range of 0.025-0.016 mag in $V$. The much larger variability seen in Figure 102 in $V$ may indicate a long-term spot cycle.

Our new $UBV$ photometry covered three observing seasons from 1983-1984 through 1986-1987 (Fig. 20). The light curve undergoes fairly rapid changes on a time scale very likely shorter than one rotation cycle. It appeared double-humped in 1983-1984 with increasing amplitude, still double-humped but with different maxima in 1984-1985, and single-humped with a full amplitude of 0.3 mag in $V$ in 1985-1986. A probably even larger amplitude might have been seen in 1987, but poor time coverage of our photometry in 1987 did not allow determination of the full range of variability. This can be seen in Figure 69. A periodogram analysis for the separate observing seasons yielded rotation periods of $78.22\pm0.05$, $85.2\pm1.7$, and $84.9\pm0.7$ days for the 1983-1984, 1984-1985, and 1985-1986, respectively (Table 4). Hall (1986) predicted a rotation period of $45.2\pm2.5$ days for the pseudosynchronous case, a value quite different from our observed period. If the value of $e = 0.35\pm0.02$ found by Abt, Dukes, and Weaver (1969) for the orbital eccentricity is real, then BM Cam departs from pseudosynchronous rotation by a factor of 1.8 and the near equality of $P_{\text{phm}}$ and $P_{\text{orb}}$ is a puzzling coincidence (Hall 1986).

The spectroscopic properties of this bright K1 III star have been reviewed by Eker (1986). The light variability of $\sim0.08$ mag in $V$ has been discovered by Hall, Henry, and Landis (1977). Recently, ten years of differential $UBV$ photometry have been used by Strassmeier et al. (1988) for a spot-model analysis. They found a cyclic variation of the total spotted area with a period of $\sim 2.7$ yr, a maximum spot coverage of $12\%$ in 1986, and a maximum amplitude of 0.15 mag for the spot wave in 1984. From the spot migration rate they determined a photometric period of 19.410$\pm$0.012 days and noted some anomalies in the migration curve.

Our periodogram analysis results are summarized in Table 4. Most of the photometry presented in this paper (Fig. 22) has been included already in the paper by Strassmeier et al. Nevertheless, we plot our observations in Figure 71 in order to demonstrate the rapid light-curve changes. Of particular interest is the new 1987 light curve. After spot modeling it could be used to test the 2.7 yr spot-area cycle suspected by Strassmeier et al. (1988).

The spectroscopic properties of this bright K1 III star have been reviewed by Eker (1986). The light variability of $\sim0.08$ mag in $V$ has been discovered by Hall, Henry, and Landis (1977). Recently, ten years of differential $UBV$ photometry have been used by Strassmeier et al. (1988) for a spot-model analysis. They found a cyclic variation of the total spotted area with a period of $\sim 2.7$ yr, a maximum spot coverage of $12\%$ in 1986, and a maximum amplitude of 0.15 mag for the spot wave in 1984. From the spot migration rate they determined a photometric period of 19.410$\pm$0.012 days and noted some anomalies in the migration curve.

Young and Konigis (1977) noted the presence of Ca II H and K emission and listed a spectral classification of F8 V. Harper (1939) found 54 Cam to be a double-lined spectroscopic binary with equal components of spectral type G0 and an orbital period of 11.0764 days and $e = 0.107$. More recent observations by F. C. Fekel (listed in the CABS catalog) established the similarity of the two components, both of spectral type F9 IV with $v\sin i = 10\pm2$ and $14\pm2$ km s$^{-1}$, respectively. Differential photometry from 1978 through 1980 by Eaton et al. (1981) showed 54 Cam to be a variable star.
with a period of $10.163 \pm 0.009$ days and a $V$ amplitude between 0.03 and 0.06 mag. 54 Cam is another example of a pseudosynchronous rotation (Hall 1986).

The new photometry presented in this paper was made from 1984 through 1986 (Fig. 23). As can be seen from our phase plots in Figure 72 the variability is only moderately well defined. A periodogram analysis of the individual observing seasons, however, established photometric periods consistent with the value found by Eaton et al. (1981). A Fourier analysis, allowing only for $\cos \Theta$ and $\sin \theta$ terms and using the periods listed in Table 4 resulted in coefficients attributable to a distortion-wave amplitude of $0.014 \pm 0.003$, $0.010 \pm 0.003$, and $0.032 \pm 0.005$ mag in 1983–1984, 1984–1985, and 1985–1986, respectively.

Using the mean value of our photometric periods, i.e., $10.23 \pm 0.13$ days, and the rotational velocities listed in the CABS catalog we may derive minimum radii of $2.8 \pm 0.5$ and $2.0 \pm 0.5 R_\odot$ for the two components, respectively, consistent with their subgiant classification.

xiv) $HD~91816 = LR~Hya$

Bopp et al. (1984) confirmed the binarity of this dK0 star (Bidelman 1981) and found a photometric variability with a period of 3.1448 days and an amplitude of 0.02 mag in $V$. FMH found equally broadened lines corresponding to $v \sin i = 6 \pm 2$ km s$^{-1}$. Their radial velocities are consistent with a period twice the photometric period. An updated orbit is given in the CABS catalog: $P_{orb} = 6.86569$ days, $e = 0.014$, $i = 61^\circ \pm 3^\circ$ (Fekel et al. 1988).

Our photometry covered only the 1984–1985 observing season (Fig. 24). A periodogram analysis revealed three different possible periodicities of $2.57 \pm 0.01$, $3.57 \pm 0.02$, and $4.86 \pm 0.03$ days (see Fig. 103 and figure caption). The largest of these, at 4.86 days, results in the greatest reduction of the sum of the squares of the residuals, so we have chosen it for the phase plot in Figure 73. No firm conclusion should be made about the photometric period, however, because of the ambiguity and the large scatter.

xvii) $\xi~UMa(B) = 53~UMa = HD~98230$

The $\xi~UMa(AB)$ system consists of two single-lined spectroscopic binaries within a separation of only 2″ (e.g., Heintz 1967). Wilson (1963) and Young and Koniges (1977) found moderately strong Ca II H and K emission from the B component, while the A component shows no detectable emission. Bopp (1987) revised the spectral classifications to GO V for $\xi$ UMa(A) and G5 V for $\xi$ UMa(B). The orbital periods for the A and B components are $669.18$ and $3.9805$ days, respectively. The estimated accumulative uncertainty of Northcott’s time of conjunction for about 210 elapsed epochs is approximately 2 days. We therefore conclude that the ellipticity effect is the major cause of the light variability. On the other hand, we note that the light maxima are not equally bright and the light minima not equally faint, suggesting the presence of starspots and possibly an additional reflection effect (Fig. 74).

Our differential photometry with a 60″ diaphragm includes both spectroscopic binaries, but we assume that the moderately “active” G5 V component is responsible for the small long-term brightness variation seen in Figure 25. The observations plotted in Figures 25a and 25b for the $V$ and $B$ bandpasses, respectively, were made between 1984 and 1986, covering three observing seasons. These data indicate a long-term variability with an amplitude of $\sim 0.05$ mag in $V$ and $\sim 0.055$ mag in $B$. Similar plots for the magnitude differences between the check star (HD 98353) and the comparison star (HD 98262) did not show any variability above our $\sigma_{\text{rms}}$ level, indicating that $\xi$ UMa is the likely variable.

A periodogram analysis gave the best fit at $797 \pm 10$ days for the $V$ data and $831 \pm 12$ days for the $B$ data, and we have entered the mean value in Table 4. Although we have allowed for a wide range of periods around the orbital period of 4 days, no short-term periodicities could be found in our data. At first this might seem somewhat surprising because spot activity is generally to be expected in chromospherically active binary stars (Hall 1987) and long-term brightness variations can be attributed to varying amounts of spot age. The small mass function of only $f(m) = 5.17 \times 10^{-6}$ and the small rotational broadening of $v \sin i = 2.8$ km s$^{-1}$ (Soderblom 1982) indicate a nearly pole-on orbit, so perhaps the rotational light modulation is so small as to be undetectable. Therefore, we suggest as a tentative explanation that the 810 day brightness variation might be due to a cyclic variation of the spot’s (or spot group’s) position in latitude; i.e., more dimming when spots are near the visible pole, less dimming when spots are far from the pole. A better time coverage, however, is necessary to establish the long-term periodicity.

xviii) $HR~4430 = HD~99967 = EE~UMa$

HR 4430 is a known single-lined spectroscopic binary with $P_{orb} = 74.861$ days (Northcott 1947). Lloyd-Evans (1977) reported a nondetection of Ca II H and K emission, and, as a consequence of this, HR 4430 was not included in the CABS catalog. Most recently, however, a high-resolution KPNO CCD observation showed moderately strong Ca II H and K emission and slightly broadened lines of $v \sin i = 16 \pm 2$ km s$^{-1}$ (Strassmeier et al. 1988c).

Its photometric variability has been discovered by Boyd, Genet and Hall (1984b). The photometry presented in this paper was made between 1984 and 1986, covering three observing seasons (Fig. 26). With these new data we are able to confirm the suggestion by Boyd, Genet, and Hall that the light variations are actually a combined effect of ellipticity and spots. A periodogram analysis for the individual seasons gave periods of $38.15 \pm 0.09$, $37.30 \pm 0.09$, and $39.45 \pm 0.84$ days for the 1983–1984, 1984–1985, and 1985–1986 seasons, respectively. All these periods are very close to half the orbital period (i.e., 37.43 days). The orbital elements found by Northcott (1947) give a time of conjunction at JD 2430826.0 ± 1.0 days. Extrapolating forward to the epochs of our photometric minima in Table 4, we find coincidences of $O - C = -0.4$, +1.9, and −6.2 days for the three minima, respectively. The estimated cumulative uncertainty of Northcott’s time of conjunction for about 210 elapsed epochs is approximately 2 days. We therefore conclude that the ellipticity effect is the major cause of the light variability. On the other hand, we note that the light maxima are not equally bright and the light minima not equally faint, suggesting the presence of starspots and possibly an additional reflection effect (Fig. 74).

A Fourier analysis of all data points plotted in Figure 26 with $1/2P_{orb}$ and $P_{orb}$ gave $V$ amplitudes of $0.085 \pm 0.004$ and $0.011 \pm 0.005$ mag, respectively. Similar analysis carried out for the individual seasons using the photometric periods listed in Table 4, gave $V$ amplitudes of 0.12, 0.10, and 0.11 mag.
respectively. The differences between these values and the 0.085 mag amplitude, which we attribute to a spot wave, are listed in Table 4.

Using a mean photometric period of $38.3 \pm 0.3$ days as half the rotation period and the $v \sin i$ cited above, we estimate a minimum radius of $24 \pm 3 R_\odot$, probably consistent with the K2 giant classification.

A revised spectroscopic orbit for this bright double-lined spectroscopic binary (A6-7 V + G5 IV–III; $P_{\text{orb}} = 71.6900 \pm 0.0006$ days, $e = 0$) has been presented by Batten et al. (1983). Young and Koniges (1977) reported the presence of emission in the H and K lines of Ca II. Photometry in 1976 and in 1979 by Hall et al. (1980b) showed 93 Leo to be a variable star with an amplitude of $0.03 \pm 0.007$ mag in 1976 and $0.028 \pm 0.005$ mag in 1979, when their photometry was plotted versus the orbital period. They did not carry out an explicit search for the best photometric period.

Our new $UBV$ observations began in 1984 and lasted until early 1987, covering almost four entire observing seasons (Fig. 27). A periodogram analysis yielded somewhat uncertain photometric periods for the 1983–1984 and the combined 1985–1986 and 1986–1987 data (Fig. 104), mostly due to the small amplitude and the long period. The only reliable value for a photometric period is found from the 1984–1985 season, i.e., $55.0 \pm 0.4$ days, substantially smaller than the 71.7 day orbital period. This would indicate that, with zero eccentricity, 93 Leo is an additional example of a highly asynchronous rotator (others among the CA binaries being λ And, AY Cet, HD 181809, and α Aur). Unfortunately, we could not confirm this by reanalyzing the above mentioned 1976 and 1979 data with a period-finding technique, because those data were not available. Phase plots are given in Figure 75 where we have plotted our seasonal data versus photometric phase in Figure 75a, and, in order to demonstrate the unlikeliness of $P_{\text{phot}} - P_{\text{orb}}$, versus orbital phase in Figure 75b. Supposedly, 1984–1985 was the only year, of those years with photometry, when 93 Leo had significant spot activity.

Bopp et al. (1979) found this star to be a double-lined spectroscopic binary with almost exactly identical components of spectral type K0 III—later revised to K1 III by FMH, who also found equal rotational velocities of $v \sin i = 10 \pm 2$ km s$^{-1}$ for both components. The orbital period is $64.44 \pm 0.01$ days (Bopp et al. 1979). The 0.08 mag photometric variability has been discovered by Bopp et al. (1977b). Four years of photometry (1977–1980) have been discussed by Eaton et al. (1982). They found a photometric period of $63.75 \pm 0.16$ days and $V$ amplitudes of up to 0.28 mag.

In this paper we present new $UBV$ photometry made between 1984 and 1987 (Fig. 28). It is evident that the amplitude changes from year to year, e.g., by more than a factor of 2 between the 1983–1984 and 1984–1985 seasons. A periodogram analysis for the individual observing seasons gave periods of $63.9 \pm 1.5$, $63.9 \pm 0.9$, and $63.8 \pm 0.6$ days for the 1983–1984, 1984–1985, and 1985–1986 seasons, thus consistent with the period determination of Eaton et al. from earlier observations. Our data are plotted versus phase for all four seasons in Figure 76 using the best determined value of the photometric period, i.e., $63.8 \pm 0.6$ days.

The orbit for this K1 III (Keenan 1940) binary has been given by Griffin and Fekel (1988). The orbital period is 20.265 days and the orbit is judged to be circular (for further details see the CABS catalog). FMH found rotationally broadened lines with $v \sin i = 15 \pm 2$ km s$^{-1}$, Boyd, Genet, and Hall (1984b) discovered the photometric variability of approximately 0.06 mag in $V$ and derived a photometric period of $21.7 \pm 0.2$ days by estimating times of well-defined minima and maxima. Recently, Mohin and Raveendran (1988) reported $BV$ photometry made on 57 nights during 1983–1984, 1984–1985, and 1986–1987. They obtained a photometric period of $21.9 \pm 0.2$ days for their 1987.14 light curve. Their poor phase coverage during the 1983–1984 and 1984–1985 season did not allow for a period determination for the earlier seasons.

Our differential $UBV$ photometry began the 1984 and lasted through mid-1986, thus covering almost three observing seasons (Fig. 29). From our Julian date plot in Figure 29 it is evident that the amplitude is steadily increasing since we have started the observations in 1984.0 (see also Table 4). Short-term changes on a time scale of one rotation cycle are also visible, e.g., in our 1985 data set plotted along with the other seasons in Figure 77. The period remained more or less constant with seasonal values of $21.13 \pm 0.21$, $20.66 \pm 0.03$, and $20.57 \pm 0.15$ days for the 1984, 1985, and 1986 data, respectively. Our improved rotation period of $20.66 \pm 0.03$ days, i.e., the best-defined value from Table 4, and the $v \sin i$ measure by FMH result in a minimum radius of $6.1 \pm 0.8 R_\odot$.

The single-lined K1 III spectroscopic binary has been extensively studied by Fekel et al. (1985). It has an orbital period of 11.1345 days. Photometric variability was discovered by Burke et al. (1982) and confirmed shortly thereafter by Bopp et al. (1983). Additional photometry presented in Fekel et al. (1985) confirmed earlier suggestions by FMH that the ellipticity effect is the prime source of the light variability.

Our photometry was made in mid-1985 and in mid-1986 (Fig. 30). Two phase plots for the individual observing seasons are shown in Figure 78. Periodograms for both data sets gave photometric periods of $11.0 \pm 0.6$ and $10.75 \pm 0.13$ days. A Fourier analysis, allowing only for cos $\theta$ and cos 2$\theta$ terms, resulted in $V$ amplitudes of $0.009 \pm 0.005$ mag for a sine curve with $P_{\text{orb}}$, $0.059 \pm 0.006$ mag with $1/2P_{\text{orb}}$, and $0.027 \pm 0.010$ mag with the 10.75 day photometric period, respectively. Thus, the ellipticity effect is the main source for the observed amplitude. Visual inspection of our phase plots in Figure 78, however, might tell us something else. Comparing the two panels in Figure 78, we note the change of the height of the second light maximum around phase $\sim 0.9$ in the 1986 season and also different heights of the minima and maxima in the 1985 season plot, typical hints of the presence of a migrating spot wave. Moreover, a Fourier analysis of the individual observing seasons with the photometric periods listed in Table
4 gave amplitudes of $0.028 \pm 0.016$ and $0.062 \pm 0.009$ mag for the 1985 and 1986 seasons, indicating much stronger spot activity in 1986 than in 1985. Thus, we arrive at the conclusion that both the ellipticity effect and a spot wave are the reasons for the light variability of HD 136905.

xxiii) $\sigma^2 \text{CrB} = 17 \text{CrB} = HD 146361 = TZ \text{CrB}$

Bakos (1984) redetermined the orbit of this double-lined F6 V + G0 V (Barden 1985; Abt 1981) spectroscopic binary with an orbital period of 1.1397912 days. Young and Konigès (1977) found equally strong Ca II H and K emission from both components. Bopp (1984) derived individual H and K emission-line fluxes of $1.0 \times 10^7$ ergs cm$^{-2}$ s$^{-1}$ for both components, which makes $\sigma^2 \text{CrB}$ one of the most active main-sequence objects yet observed.

The photometric observations are somewhat puzzling. Skillman and Hall (1978) reported two types of variability in $\sigma^2 \text{CrB}$: an approximately $\Delta V = 0.05$ mag variability with roughly the orbital period and a shorter one with approximately 0.1 days and a total amplitude of $\sim 0.05$ mag. The former was interpreted as a spot wave, whereas the latter was suggested to be a $\delta$ Scuti-type variability from the F-component. The $\delta$ Scuti-type variability was confirmed by additional observations in 1979 at David Dunlap Observatory (Percy and Welch 1980), but the more extensive data set presented and discussed in Bakos (1984) did not show the $\sim 0.1$ day light variation. Instead, Bakos found hints of a long-term variability and suggested a periodicity of approximately 3.5 yr. Nightly monitoring in $UBV$ by Vivekananda Rao et al. (1985) agreed with Bakos in finding no indication of a $\delta$ Scuti-type variability in $\sigma^2 \text{CrB}$.

Our new photometry presented in Figure 31 was made from 1984 to 1986, thus covering three consecutive observing seasons. At this point, it seems appropriate to note that our photometry—as well as all previous photometry—including $\sigma^2 \text{CrB}$ (1.1 mag fainter in $V$, 5.3'' away) in our 60'' diaphragm. Seasonal phase plots are shown in Figure 79. A periodogram analysis over wide ranges of periods—from hours to years—gave, first, no hint of an approximately 0.1 day periodicity, second, established the $\sim P_{2:2}$ variability, and, third, also revealed a 2.0 yr periodicity. The rotation periods found are $1.166 \pm 0.001$, $1.168 \pm 0.0008$, and $1.172 \pm 0.002$ days for the 1983–1984, 1984–1985, and 1985–1986 seasons, respectively. These periodic variations can be attributed to rotational modulation due to spot activity. Taking the mean of our seasonal periods listed in Table 4, i.e., $1.1687 \pm 0.0013$ days, we find that the spotted component in $\sigma^2 \text{CrB}$ (presumably the cooler G0 V component) rotates slightly asynchronously, by about 2.5%. Periodograms for the separated seasons are shown in Figure 105. Note that the 1985–1986 season has a fairly short baseline and relatively few points; we are presuming that the two possible periodicities at approximately 1.11 days are spurious (see lower panel in Fig. 105). With the rotational velocity of $v \sin i = 25 \pm 5$ km s$^{-1}$ (Barden 1985) we find a minimum radius for the G0 star of $0.58 \pm 0.11 R_\odot$, consistent with its dwarf classification.

A long period of 733 $\pm$ 15 days also shows up in our periodograms. This period can be seen as a sinusoidal variability in Figure 31, qualitatively similar to the long-term variability suspected by Bakos (1984) but 2.0 yr instead of 3.5 yr in length. A similar long-term, very likely periodic, variability might be also visible in $\xi$ UMa(B), 29 Dra, and $\lambda$ And (see Figs. 24, 33, and 47).

The photometric observations are somewhat puzzling. Skillman and Hall (1978) reported two types of variability in $\sigma^2 \text{CrB}$: an approximately $\Delta V = 0.05$ mag variability with roughly the orbital period and a shorter one with approximately 0.1 days and a total amplitude of $\sim 0.05$ mag. The former was interpreted as a spot wave, whereas the latter was suggested to be a $\delta$ Scuti-type variability from the F-component. The $\delta$ Scuti-type variability was confirmed by additional observations in 1979 at David Dunlap Observatory (Percy and Welch 1980), but the more extensive data set presented and discussed in Bakos (1984) did not show the $\sim 0.1$ day light variation. Instead, Bakos found hints of a long-term variability and suggested a periodicity of approximately 3.5 yr. Nightly monitoring in $UBV$ by Vivekananda Rao et al. (1985) agreed with Bakos in finding no indication of a $\delta$ Scuti-type variability in $\sigma^2 \text{CrB}$.

xxiv) HR 6469 = HD 157482 = V819 Her

HR 6469 is a spectroscopic triple system with a close pair of spectral types F2 V + G0 V, and a third component of spectral type G5 IV (see the entry in the CABS catalog and references therein). The active component is the G5 IV star (Lyons 1982, cited as private communication in FMH). The period of the long orbit is 2018 days (McAlister et al. 1983). The close pair was found to be an eclipsing binary (Boyd et al. 1985a) with an orbital period of 2.23 days. Those authors also found a long-period $V$ variability with a total amplitude of 0.04 mag and a period of 83.2 $\pm$ 0.7 days.

Our differential $UBV$ photometry was acquired from 1983 through 1987, covering four observing seasons (Fig. 32). On one night the APT has been dedicated to observe a full eclipse (Boyd and Wasson 1987). Those data points can be easily identified in Figure 32 along with other points made during the eclipse. After removing the eclipse points we performed a periodogram analysis for the whole data set, yielding a photometric period of 81.9 $\pm$ 0.4 days. This is very likely the rotation period of the G5 IV component. A Fourier analysis of the separated seasons with this period resulted in the wave amplitudes listed in Table 4. The observations are plotted versus orbital phase with the 2.23 day period in Figure 80a and versus photometric phase with the 81.9 day period in Figure 80b.

The star 29 Dra is a 39 day spectroscopic binary (see the CABS catalog), containing a hot white dwarf and a K0–2 III primary (Fekel and Simon 1985). The K giant was shown to exhibit strong Ca II H and K emission lines (FMH, and references therein). Hall et al. (1982) found 29 Dra to be a variable star with $\Delta V \sim 0.12$ mag and a period of 31.5 $\pm$ 1 days.

Our new $UBV$ photometry, shown in Figure 33, has been made from 1983 through 1987, covering almost four observing seasons. However, only one season, i.e., 1985, provides enough data points for a periodogram analysis. A phase plot for this season is shown in Figure 81. The best fit was obtained with a period of 28.8 $\pm$ 0.3 days, substantially shorter than the 39 day orbital period. Unfortunately, no value for the orbital eccentricity is available at this time. If it turns out that $e = 0$, 29 Dra would be another example of a highly asynchronous rotator similar to $\lambda$ And, 39 Cet, and $\alpha$ Aur. On the other hand, assuming pseudosynchronization (Hut 1981; Hall 1986), we might expect an orbital eccentricity of $e \sim 0.24$. From Figure 1 in Hall et al. (1982) we can see an increase of the mean light level from $AF = 0.43$ mag in early 1984, and increasing monotonically each year up to $\Delta V = 0.23$ by 1987. Note that the faint light levels at the beginning cannot be due to our
This classic RS CVn binary (F4 V−IV+K0 IV; Popper 1956) with strong Ca II H and K emission (Hiltner 1947) from the cooler component is also a double-lined eclipsing binary with an orbital period of 3.9928012 days (Hall and Kreiner 1980). Evren et al. (1982) presented photometry made from 1978 to 1981. They found a migration period of the characteristic spot “wave” of 1.4 yr toward decreasing orbital phase. This translates directly into the photometric period of 3.962 days listed in the CABS catalog. The maximum wave amplitude ever observed was 0.038 mag in F in 1981 (Evren et al. 1982).

Our photometry was made in 1985 (Fig. 34). A periodogram analysis gave the best fit at a photometric period of 3.970 ± 0.007 days, only approximately 0.6% less than the orbital period. A Fourier analysis with this period, allowing only for cos Θ and cos 2Θ terms, resulted in coefficients of

\[
A_0 = 1.001 \pm 0.001, \quad A_1 = 0.011 \pm 0.002, \quad B_1 = -0.011 \pm 0.002,
\]

corresponding to a wave V amplitude of 0.035 ± 0.003 mag in 1985. No signs of an ellipticity or reflection effect could be found in the light curve. Our data are phased together with the orbital period listed in Hall and Kreiner (1980) and are plotted in Figure 82.

V772 Her is another triple system ([G0 V + M1 V?] + G5 V) containing a close eclipsing binary (Morby et al. 1977; Batten et al. 1979). Contrary to HR 6469, where the third component is the active star, V772 Her is the hotter component in the single-lined spectroscopic binary. The third star, however, can be seen in the spectrum. Note that the C component in ADS 11060 (V = 10.62 mag, K7: V separation AB ↔ C is 28.2") is also a close double-lined spectroscopic binary containing a chromospherically active star (Abt 1986; see also in the CABS catalog). Photometric observations by Scarfe (1977) showed V772 Her to be an eclipsing binary. No secondary eclipse can be seen. Boyd et al. (1985b) found that the light variations outside eclipse are caused by both a spot wave and an ellipticity effect. They also found a photometric period of 0.873 ± 0.002 days for the spot wave in 1984. HD 165590 is currently the theme of a master’s thesis at Vanderbilt University (Bruton 1988).

Our new UBV photometry has been made between 1984 and 1986 and is plotted as ΔV versus Julian date in Figure 35. The three data sets in Figure 35 correspond to three observing seasons, but only the 1985 season has been covered completely. After removing eclipse points we have used least squares to fit sinusoidal light curves to each season. The periods with the best fit are 0.869 ± 0.004, 0.8795 ± 0.0007, and 0.8795 ± 0.0012 days, for the 1984, 1985, and 1986 seasons, respectively (Table 4 and Fig. 106), thus remarkably close to the orbital period of 0.879498 days given by Bakos and Tremko (1982). A Fourier analysis of the migrating wave gave full V amplitudes of 0.038 ± 0.015, 0.027 ± 0.008, and 0.040 ± 0.009 mag for the three observing seasons, respectively (Fig. 83). The full V amplitudes corresponding to the ellipticity effect are 0.037 ± 0.015, 0.024 ± 0.008, and 0.009 ± 0.012 mag, respectively.

This star is a long period (138.420 ± 0.016 day, e = 0.114) SBI binary (Young 1920) with strong Ca II H and K emission (Hossak 1954). Keenan and Pitts (1980) classified it as spectral type G9 III, and Huisong and Xuefu (1987) measured rotationally broadened lines with \( v \sin i = 13 \pm 3 \text{ km s}^{-1} \). Photometric observations made between 1978 and 1985 have been discussed by Hall and Persinger (1986). They found a photometric period of 54.6 days and a V amplitude of 0.034 ± 0.005 mag for the 1984–1985 data set and no variability at all during the 1978–1983 time span. From their periodogram analysis they concluded that neither the ellipticity effect nor the reflection effect is at work in o Dra.

The analysis in this paper includes the 1984–1985 data of Hall and Persinger (1986), which were acquired with the same telescope used for our data. The new photometry has been obtained between 1985 and 1986. A plot of all APT data is given in Figure 37. In a periodogram for the combined data set, shown in Figure 107, there is a dip at the 54.6 day period found by Hall and Persinger, but four other dips appear as well, all of greater statistical significance. Fourier analysis of the combined data with the orbital period, half the orbital period, and the 54.6 day period gave V amplitudes of 0.030 ± 0.004, 0.005 ± 0.004, and 0.015 ± 0.004 mag, respectively. Thus we can say no statistically significant ellipticity effect has been
observed. The three panels of Figure 85 are phase plots with these three periods. Of them, only the one with the orbital period reveals a clearly visible light variation. This corresponds to the dip in our periodogram (Fig. 107) at 142.8 ± 1.5 days, which is very close to the 138.420 day orbital period. The deepest dip of all, around 170 days, may be an alias produced by the annual windows in our data set. By extrapolating the time of conjunction given by Young (1920) forward to our time of minimum light, we conclude that those times coincide to within ±8 days with an accumulative error of ~3 days for Young’s time of conjunction and an uncertainty of ±2.5 days for our time of minimum light. Thus, the major cause of the light variations in 47 Dra is the reflection effect. Visual inspection of the upper panel in Figure 85 shows unusually large scatter which makes us believe that there is additional spot activity with an estimated amplitude of ~0.01 mag.

\[ \text{xxx) HD 178450} = \text{V1478 Lyr} \]

This star has recently been the subject of a detailed spectroscopic study by Fekel (1988b). It is a single-lined G8 V spectroscopic binary with an orbital period of 2.130514 ± 0.000007 days. The inclination of the system is 67° ± 12°. The moderately strong Ca II H and K emission lines have been already detected by Joy and Wilson (1949). Henry’s (1981) photometry in 1980 showed HD 178450 to be a variable star with a \( V \) amplitude of 0.033 ± 0.005 mag and a period of 2.185 ± 0.005 days.

In this paper we present new \( UBV \) photometry made between 1984 and 1986 covering three observing seasons (Fig. 38). A periodogram analysis showed a variable photometric period on a time scale shorter than one observing season. Periodograms for the separate seasons are given in Figure 108, where the upper and lower panels correspond to the JD 2,445,970-2,446,050 and the JD 2,446,100-2,446,200 data sets in Figure 38, respectively. The middle panel, for the whole 1985 season, shows several dips at periods slightly longer than the orbital period. Splitting the 1985 data into three sets with a \( V \) amplitude of 0.033 ± 0.005 mag and a period of 2.185 ± 0.005 days.

The deepest dip of all, around 170 days, may be an alias produced by the annual windows in our data set. By extrapolating the time of conjunction given by Young (1920) forward to our time of minimum light, we conclude that those times coincide to within ±8 days with an accumulative error of ~3 days for Young’s time of conjunction and an uncertainty of ±2.5 days for our time of minimum light. Thus, the major cause of the light variations in 47 Dra is the reflection effect. Visual inspection of the upper panel in Figure 85 shows unusually large scatter which makes us believe that there is additional spot activity with an estimated amplitude of ~0.01 mag.

Sine-curve fits with the three seasonal periods in Table 4 gave mean \( V \) amplitudes of 0.072 ± 0.008, 0.070 ± 0.010, and 0.067 ± 0.008 mag for the 1984, 1985, and 1986 seasons, respectively. Phase plots for the separate observing seasons are given in Figure 86. FMH determined \( \psi_\text{sin}i = 21.2 \pm 2 \text{ km s}^{-1} \). This value, combined with our best value for the rotation period (2.158 ± 0.006 days), yields \( R \psi_\text{sin}i = 0.89 \pm 0.09 R_\odot \) or, because \( i = 67° \pm 12° \), \( R = 1.0 \pm 0.2 R_\odot \).

\[ \text{xxx) HR 7428} = \text{HD 179064} = \text{V1762 Cyg} \]

The strong Ca II H and K emission lines noted first by Joy and Wilson (1949) have been confirmed by FMH. The latter authors classified the primary component in this SB1 system as K1 IV–III. The orbital period of 28.59 days is from Young (1944). Differential photometry from 1978 to 1980 by Fried et al. (1982) showed HR 7275 to be a variable star. They found a mean photometric period of 27.78 ± 0.13 days and a maximum amplitude of 0.22 mag in \( V \), presumably due to spot activity. Parts of our data (1983–1985) have already been included in a study by Nations and Seeds (1986b) and Seeds and Nations (1986). Long-term modeling of the light variations, also by Nations and Seeds (1987), suggests a wave-migration period of 4 yr, somewhat longer than the 2.7 yr found by Fried et al. (1982).

Our photometry acquired with the 10 inch APT is shown in Figure 39. The observations covered almost four consecutive observing seasons. A periodogram analysis gave photometric periods of 27.875 ± 0.070, 27.873 ± 0.025, and 27.85 ± 0.15 days for the combined 1983 and 1984, the 1985, and the 1986 seasons, respectively. All three values are consistent with the earlier period found by Fried et al. (1982). Seasonal phase plots are given in Figure 87. Dramatic amplitude changes, from about 0.2 mag in 1983 to only 0.02 mag in 1984 and back to more than 0.2 mag in 1985, indicate the enormous degree of variable spot activity on HR 7275.

\[ \text{xxxii) HR 7428} = \text{HD 184398} = \text{V1817 Cyg} \]

Gratton (1950) noted the presence of strong Ca II H and K emission and Levato (1975) classified the spectrum as A0 V + K2 III–II. The rotational velocity of the cooler component \( (\psi_\text{sin}i = 21 ± 3 \text{ km s}^{-1}) \) has been measured by Huisiong and Xuefu (1987). Sanford (1925) computed the orbit with an orbital period of 108.571 days. Photometric observations by Barksdale et al. (1985b) indicated the presence of an ellipticity effect, a small reflection effect, and also smaller photometric effects, which they though might indicate spots.

Our \( UBV \) photometry covers three consecutive observing seasons from 1983–1984 through 1986 (Fig. 40). Phase plots for two data sets are given in Figure 88. A periodogram analysis (Fig. 109) gave the best fit at periods of 53.8 ± 0.3 and 54.6 ± 0.18 days for the combined 1983–1985 and 1985–1986 data, respectively. Since this is so nearly half the known orbital period and coincides to within two days of a time of conjunction given by Lucy and Sweeney (1971), we can say that the light curve of HR 7428 is dominated by the ellipticity effect. A Fourier analysis yielded \( V \) amplitudes of 0.032 ± 0.003 and 0.040 ± 0.002 mag for the two data sets. From a Fourier analysis with exactly the orbital period, we found \( A_1 = \)
ER Vul is a double-lined eclipsing binary with an orbital period of 0.69808 ± 0.00002 days (Al-Naimiy 1981). Both components are rapidly rotating main-sequence stars of spectral type G0 V and G5 V (Northcott and Bakos 1967) each with broadened lines corresponding to \( v \sin i = 85 \pm 5 \) km s\(^{-1}\) (Barden 1985). Ca II H and K emission has been reported by Bond (1970). Hall (1980) lists ER Vul with a maximum spot amplitude of 0.04 mag but the light-curve shape is sometimes distorted by short-term nonperiodic brightness fluctuations in excess of the spot amplitude (Akan et al. 1987).

Our photometry covered only the 1985 observing season (Fig. 42) with a total of 71 \( UBV \) measures. A search for a photometric period resulted in the detection of a moderately well defined spot wave with a period of 0.6942 ± 0.0005 days. Our data plotted versus photometric phase are shown in the upper panel of Figure 90. Note the obvious eclipse points hanging down from the otherwise well-defined wave. The lower panel is a plot versus orbital phase with the ephemeris given in Table 4. Note primary and secondary eclipse, as well as the large scatter produced by the starspot wave which is not phased with this period. Fourier analysis with one-half of the orbital period gave a \( V \) amplitude of 0.085 ± 0.010 mag.

After removing the eclipse points we performed a Fourier analysis with the 0.6942 day photometric period yielding a mean (seasonal) spot amplitude of 0.061 ± 0.012 mag in \( V \). Although both stars are rapidly rotating and have similar spectral types, the spots can be attributed to the brighter G0 V component (Al-Naimiy 1981); thus, ER Vul is one of the earliest dwarf stars for which photometric variability due to spots has been confirmed. Recently, Ibanoglu, Evren, and Tunca (1987) suggested that both components are “active.”
but different heights for the maxima, normally what can be known. The photometric variability has been discovered by Boyd et al. (1985c). Their observations were made in 1982 and in 1984. The 884 day interval between their observations allowed a variety of photometric periods ranging between 24.3 ± 0.3 days for Herbst's 1971 data and their 1979 data. Eaton et al. (1983b) presented additional photometry made from 1978 through 1981. They found a mean photometric period of 24.39 ± 0.03 days and a maximum spot amplitude of 0.24 mag in V in 1979.

Our differential UBV photometry was made from 1983 through 1986 (Fig. 45). A periodogram analysis for the individual observing seasons yielded photometric periods consistent with earlier values, namely 24.31 ± 0.09, 25.0 ± 0.3, 24.35 ± 0.4, and 25.1 ± 0.8 days for the observing seasons from 1983–1984 through 1986–1987. Fourier analysis of the same data sets gave mean V amplitudes of 0.154 ± 0.007, 0.155 ± 0.010, 0.162 ± 0.005, and 0.081 ± 0.011 mag, respectively. Seasonal phase plots are given in Figure 93. As can be seen, e.g., from the 1986 observations in Figure 45, the amplitude changes sometimes within a time scale of only one rotation cycle. Visual inspection of Figure 45 gave the maximum spot amplitudes listed in Table 4, with 0.221 ± 0.005 mag in 1986.5 being the largest value of all. FMH measured a rotation velocity of \( v \sin i = 24 ± 2 \) \( \text{km} \text{s}^{-1} \). This value and our best photometric (= rotation) period of 24.35 ± 0.04 days give a minimum radius of 11.5 ± 1.0 \( R_\odot \) (notice that the 21 \( R_\odot \) mentioned in the discussion in FMH is a misprint and should be 12 \( R_\odot \)). With this value for \( R_{\text{min}} \) and the rather large value of the inclination which is necessary to explain the relatively large amplitudes of the starspot wave, an MK classification of III seems to be more appropriate.

Bidelman (1981) found Ca II H and K emission lines of moderate strength in this K0 III star, which were confirmed later by FMH. Their radial velocity measurements showed a range of 9 \( \text{km} \text{s}^{-1} \); for that reason Strassmeier et al. (1988a) listed this star in the CABS catalog, even though no orbital period is known. The photometric variability has been discovered by Boyd et al. (1985c). Their observations were made in 1982 and in 1984. The 884 day interval between their observations allowed a variety of photometric periods ranging between 76.6 and 93.8 days, whereas the separated seasonal data sets gave 86 ± 6 days for 1982 and approximately 84 days for 1984.

Our additional UBV photometry has been made in 1985 and in 1986 and is plotted in Figure 46 along with the 1984 data from Boyd et al. A periodogram analysis of all data gave a photometric period of 91.17 ± 0.20 days. Visual inspection of the light curves in Figure 46 shows us equally deep minima but different heights for the maxima, normally what can be expected from a combination of the ellipticity and the reflection effect. Asymmetries in the light-curve wings indicate the presence of spot activity. The seasonal phase plots in Figure 94 with the 91 day photometric period do not help with the interpretation. So we arrive at the conclusion that, based on the present data, we cannot decide which of the two—complex spot activity alone or a combination of ellipticity and reflection effect with only relatively weak spot activity—is the correct explanation for the observed light curve. A determination of the orbital period would help decide.

The star \( \lambda \ And = HR 8961 = HD 222107 \) is probably the best known example of an asynchronous rotator among CA binaries (\( P_{\text{orb}} = 20.5212 \) days, \( P_{\text{dtrm}} = 53.952 \) days). Its properties are reviewed in the CABS catalog: spectral type G8 IV–III, SB1, \( v \sin i = 10 \) \( \text{km} \text{s}^{-1} \), Ca II H and K emission, filled-in Hα line, spot-wave amplitudes up to 0.28 mag in V. Photometry by Calder (1938) showed \( \lambda \ And \) to be a variable star. The most recent observations are those by Boyd et al. (1983), Scaltriti et al. (1984), and Guinan and Wacker (1985) and references therein. Kemp et al. (1987) reported discovery of optical polarization and curious anticorrelation between the time scales of light and polarization variability.

In this paper we present UBV photometry made from 1983 through 1987 (Fig. 47). As can be seen from our phase plots in Figure 95, as well as from Figure 47, the light curve appeared double humped in 1983–1984 and in 1985–1986, but single humped in 1984–1985. The seasonal maximum amplitudes changed therefore from 0.073 mag in 1983–1984 to 0.122 in 1984–1985 and back to 0.090 mag in 1985–1986. Because our period-finding technique fits sine curves to the asymmetric light curves we cannot expect photometric periods as accurate as, e.g., a least-squares analysis of times of light minima. Our periods are listed in Table 4. Visual inspection of Figure 47 might indicate a sinusoidal variation of the mean-light level with a period of around 3.0 yr.

Imbert (1969) found this G5 V (Heard 1956) star to be an SB1 binary with Ca II H and K emission and an orbital period of 6.20197 ± 0.00003 days. Later, Fekel (1985) found doubled lines in the spectrum and classified the secondary as K V; consequently, an SB2 orbit has been given in the CABS catalog. Hall et al. (1986) reported HD 222317 to be a new variable star with the very small amplitude of 0.013 mag in V and a photometric period of 6.092 ± 0.037 days. Because their time of light minimum disagreed with a time of conjunction and because the photometric period was about 1.5% shorter than the orbital period, they concluded that starspots must be the cause for the 0.01 mag variability.

In this paper we present additional photometry made in 1985 and 1986 and reanalyze the same data set used by Hall et al. (1986). Both sets, our new data and those of Hall et al., have been acquired with the same telescope and are plotted versus Julian date in Figure 48. The results from our periodogram analysis are shown in Figure 113. We found a photometric period of 6.09 ± 0.04 days for the 1984 data (Fig. 113, upper panel) in total agreement with the value given by Hall et al., but a substantially different period of 5.69 ± 0.02
days for the 1985 season (Fig. 113, lower panel). Although those periods represent the best fit to our data we think they need to be confirmed by other complementary photometry. A Fourier analysis with these periods gave amplitudes of 0.010 ± 0.003 and only 0.005 ± 0.003 mag for the 1984 and the 1985 seasons, respectively. The latter amplitude is so close to our instrumental limitation that we doubt its reality; the former amplitude, however, though small and not well defined, is certainly real. Phase plots for the two observing seasons are given in Figure 96. The CABS catalog lists a not yet published rotational velocity measurement of $v \sin i = 7 \pm 2$ km s$^{-1}$ for the G5 star. This value, combined with our photometric period for the 1984 season (6.09 ± 0.04 days), gives a minimum radius of 0.84 ± 0.25 $R_\odot$, consistent with the dwarf classification.

Our new photometry has been made from 1984 through 1987 and is plotted versus Julian date in Figure 49, although only two observing seasons have been covered continuously. A periodogram analysis gave the best fit at periods of 6.727 ± 0.017 and 6.744 ± 0.010 days for the years 1983–1984 and the 1984–1985 season. A Fourier analysis with these periods resulted in seasonal mean amplitudes of 0.148 ± 0.013 and 0.162 ± 0.015 mag in V for the two seasons, respectively. Maximum amplitudes of up to 0.29 mag were seen at the end of 1985 and about 0.23 mag at the end of 1984 (Table 4). Phase plots for the individual observing seasons are shown in Figure 97.

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REFERENCES

Noted added in proof.—RZ Eri = HD 30050: a recently published redetermination of the orbital elements by Popper (A.J., 96, 1040 [1988]) verifies the large eccentricity derived by Cesco and Sahade (Ap. J., 101, 370 [1944]). With our measured rotation period of 31.4 days, 8 days shorter than the orbital period, RZ Eri seems to be another example of an asynchronous rotator among our sample of CA binary stars. 29 Dra = HD 160538: previously suggested orbital period in the CABS catalog now believed wrong, new \( P_{\text{orb}} \approx 915 \) days and \( e = 0 \) (Fekel 1988, private communication).

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