Mapping Stellar Surface Structures on the RS CVn Star II Peg

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Abstract:
Chromospherically active late type stars exhibit most of the characteristics of the active Sun on a globally much enhanced scale. We analyse high signal-to-noise spectroscopic data obtained in September and October 1993 of single-line RS CVn binary star II Peg. The results are used to construct a Doppler image of the spot distribution at that epoch. A multicomponent spot model is suggested with $\sim$30% of total spot coverage.

1. Introduction

A wide variety of solar activity phenomena (e.g., spots, flares) is observed in chromospherically active late-type stars, but on a much enhanced scale. The RS CVn binaries have at least one late-type, post-main sequence component which, as a result of tidal locking, rotates rapidly. This rapid rotation, combined with deepening convective zones, results in enhanced dynamo action. When the resulting magnetic fields rise to the stellar surface they result in a wide variety of solar-like activity, including non-radiatively heated chromospheres and coronae, large-scale starspots and enormous flares.

II Peg is a relatively bright ($V_{\text{max}} \sim 7.4$), K2IVe, single-line, spectroscopic binary with synchronous orbital and rotational periods of $\sim 6.72 \text{ d}$ (Vogt 1981). The star has been intensively studied at all wavebands, from X-rays to microwave (e.g., Byrne et al. 1998) showing that it is one of the most active RS CVn’s.

As with other RS CVn’s, II Peg undergoes a photometric modulation of its visible and IR light which is attributed to dark starspots being carried onto and off the visible disk by axial rotation. Many studies of this phenomenon have been carried out over the past two decades. A recent study by Byrne et al. (1995) revealed a complex distribution of at least 3 spots of different temperatures, in addition to a non-modulating component required to depress the observed maximum light from the historical maximum recorded by Chugainov (1976). The presence of this, often dominant, non-modulating component is a major shortcoming of photometric mapping of spot distributions on late-type stars. There are, however, two spot mapping techniques available which can, in principle, contribute to this limitation, viz. Doppler imaging and TiO mapping.

Doppler imaging relies on the relatively large rotational $v \sin i$ of RS CVn stars, combined with the different continuum brightness of the spot and non-spot photospheres, to construct an image the stellar surface (Vogt, Penrod, & Hatzes CD–2082)
1987). Stars such as II Peg, however, with \(v \sin i = 21 \text{ km s}^{-1}\) (Vogt 1981) are only resolvable with very high spectral resolutions. Hatzes (1993) succeeded in deriving a Doppler image for II Peg for the 1992 season covering \(\sim 20\%\) of the star’s surface area.

Neff & O’Neal (1995) used the relative fluxes of two different TiO molecular bands to derive a total spot area coverage on II Peg of \(\sim 60\%\) in October 1989, when the observed maximum light was not very different from that in 1992. O’Neal & Neff (1997), on the other hand, derived \(\sim 35-48\%\) area coverage in June 1996 using infra-red bands of the OH molecule at 1.5\(\mu\)m. In this paper we use the results of optical spectroscopy of II Peg taken in 1993 to derive a Doppler image for that epoch.

Table 1. The log of the observations of II Peg. Phases have been calculated according to the ephemeris of Vogt (1981).

<table>
<thead>
<tr>
<th>Night</th>
<th>HJD 2449200 +</th>
<th>Date</th>
<th>Phase</th>
<th>Phase (Hα)</th>
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<td>0.365</td>
<td>0.35</td>
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<td>26/09/93</td>
<td>0.516</td>
<td>0.54</td>
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<td>27/09/93</td>
<td>0.652</td>
<td>0.63</td>
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<tr>
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<td>…</td>
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<td>…</td>
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<tr>
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<td>10</td>
<td>64.7219</td>
<td>04/10/93</td>
<td>0.710</td>
<td>0.69</td>
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</table>

2. Observations and Data Reduction

On clear nights between 24 September and 4 October 1993 the solar-stellar spectrograph at the US National Solar Observatory’s 1.6m McMath-Pierce telescope at Kitt Peak, Arizona, USA was used (Byrne et al. 1997b) to obtain high resolution \(\lambda/\Delta \lambda \sim 25,000\) spectra in two \(\sim 100\AA\) wavebands centered on Hα and Li i 6707Å. Several spectra were taken at each wavelength interval to increase the final signal-to-noise, to guard against flares or other rapid variability and to make cosmic ray correction easier.

Data reduction was carried out using routines within the IRAF astronomical software package (Tody et al. 1986). The CCD images were bias and flat field corrected. Individual spectra were extracted and wavelength calibrated with respect to ThAr calibration lamp spectra taken at regular intervals during the night. A log of the observations will be found in Table 1. The wavelength calibrated spectra were normalised to our best estimate of the local continuum by reference to spectra of slowly rotating giants of similar spectral type to II Peg using the procedures outlined in Byrne et al. (1995). Individual spectra were
then averaged to increase the signal-to-noise. Fig. 1 shows the nightly averaged, normalised spectra in the region of the Hα emission line.

3. Results and Discussion

In total five photospheric absorption lines were used to derive Doppler images, viz. Fe I 6546.239Å, Fe I 6703.567Å, Fe I 6705.131Å, doublet Li I 6707.85Å and Ca I 6717.681Å. Template line profiles were synthesized using a model atmosphere for a $T_{\text{eff}} = 4,700$ K, $\log g = 4.0$ star from Kurucz (1992).

Table 2. The derived parameters of the spots ($90^\circ =$equator).

<table>
<thead>
<tr>
<th>Spot #</th>
<th>Filling Factor A</th>
<th>Radius</th>
<th>$T_{\text{eff}}$ [K]</th>
<th>Latit. Center</th>
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<td>3600</td>
<td>125°</td>
</tr>
<tr>
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<tr>
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<td>8.6%</td>
<td>34°</td>
<td>3600</td>
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<tr>
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<tr>
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<td>3600</td>
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<td>1.5%</td>
<td>14°</td>
<td>3600</td>
<td>165°</td>
</tr>
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</table>
Figure 2.  (solid line) The photometric V band light curve from spectroscopic spot solution as a function of phase; (dashed line) spots located at the equator; (dots) the photometric spot solution; and (triangles) the V band photometric observations from SAAO and September/November 1993 season. Maximum V magnitude 7.18 has been assumed (see text).

These spectra were convolved with a rotational $v \sin \iota = 21$ km s$^{-1}$ derived from Fourier analysis of the observed line profiles (and agreeing with the value for this quantity derived by Vogt 1981), an instrumental profile with FWHM = 0.155Å derived from the ThAr comparison lamp spectra and a macroturbulence of 1.5 km s$^{-1}$, which must be considered uncertain due to the limitations imposed by the spectral resolving power of the spectrograph. The inclination of II Peg was taken for our present purposes as 75° (Scaltriti et al. 1993) and spots were assumed circular in outline. The convolution and mapping programs have been described in detail by Zboril (1997, 1998). Table 2 gives the derived best-fit spot parameters while Fig. 3 compares the observed and fitted line profiles for two of the lines used.

The Doppler image recognises a total of four spots. Three are of comparable size, $R_{sp} = 31 - 34°$, while one is considerably smaller, $R_{sp} = 14°$. All are at comparable, intermediate latitude ($\sim 40°$). They basically agree with Hatzes' (1995) images from practically the same season (1993.75).

The UBVRI photometry is available from South African Astronomical Observatory obtained with 0.5m telescope from September 12 up to November 18 1993 (Byrne et al. 1997b). These data were analysed to extract spot parameters (program Spotpic, Amado 1997) using the spectroscopic solution as a starting iterate. The photometric solution is in table 2 (lower panel) and both synthetic and observed V light curves in figure 2. The maximum V magnitude 7.18 has
Figure 3. Theoretical (*dashed* line) and observed (*solid* line) Fe I 6705Å and Fe I 6703Å line profiles as a function of phase.
Figure 4. The Mercator projection of II Peg schematic spot distribution in September/October 1993 (90° = equator) with $T_{\text{eff}}^{\text{phot}} = 4700$K and $T_{\text{eff}}^{\text{spots}} = 3600$K.

been assumed in the synthetic light curve. The photometric solution suggests high latitude (typically $\sim 60^\circ$) spots and a larger radius for one of them. Thus, total spot coverage and longitudes seem to agree reasonably well as derived from spectroscopy and photometry. However, the temperature of all spots has been maintained from the spectroscopic solution, i.e., all spots have the same effective temperature. The final spot solution, adopting latitudes from the photometric solution, is shown in Mercator projection in Fig. 4.

A more detailed account of this work will appear in a forthcoming paper (Zboril et al. 1997).

In summary, the multiline and multielement spectroscopic and broad band photometric techniques provide us with the following results:

- Images from October 1993 show the complicated surface nature, relatively high latitude spots (assuming $i \sim 75.0^\circ$, pole-on star-0°) have been detected.

- Spot coverage derived from mapping technique is $\sim 25\%$ of the stellar surface.

- Spot temperatures, as derived from the spectroscopy, are lower than the surrounding photosphere by $\sim 1200$K with no conclusions on individual spot temperature differences.

- Given the phase sampling, the Hα emission does not correlate clearly with spot coverage, as reported by Hatzes (1993).
The photometric solution suggests high latitude spots as compared with the spectroscopic one, under the assumption of the maximal \( V \) magnitude \( m_V = 7.18 \) and spot temperatures derived from the spectroscopic solution.

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References

Hatzes, A.P. 1993, BAAS, 182, 4605
Zboril, M. 1997a, IrishAJ, 24, 43
Zboril, M. 1997b, IrishAJ, 24, 123
Star Clusters and Binary Star Dynamics

CD–2089