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Abstract:
Using new high-resolution and high signal-to-noise ratio spectroscopic observations carried out in 1992–1996, nine new surface images of II Peg have been obtained. The technique employed was the recently developed Occamian approach, which does not use any prior smoothness assumption, but the resulting solution is nevertheless stable with respect to measurement errors and uncertainties in the adopted stellar parameters. The surface imaging was applied to Fe\textsc{i} and Ni\textsc{i} lines simultaneously, and a number of blending atomic and molecular lines were included into the line list. Two high latitude spots were found to dominate in all seasons, and no polar cap was seen. The positions of the spots were constantly migrating to larger longitudes with approximately the same rate. Since phases were computed from the orbital period, this longitudinal motion of the spot configuration means the spots have a shorter rotational period, which is just about the mean photometric one. The longitude separation between the spots was approximately constant and equal to about 180 degrees. They can be considered as two long living active longitudes.

1. Introduction

II Peg (HD 224085) is known as one of the most active RS CVn stars. Broadband photometry of II Peg show $V$-band variations up to 0.5 mag with a mean period of 6.71 days suggesting that the photometric variability is due to rotational modulation. These variations are accompanied in phase by color variations of 0.07 mag in $V - R$, with the faintest phases being the reddest, which can be interpreted in terms of cool surface spots analogous to sunspots, but much enhanced in scale. The long-term studies (Henry et al. 1995, and references therein) based on available photometric data from 1974 have shown radical changes of the photometric wave, from almost sinusoidal, to irregular or flat. It was shown that the changes in the light curves are consistent with re-arrangements of the spot distribution over the stellar surface. A crude interpretation from a two-spot model has revealed the surface fraction of the active component covered by spots to be as large as 40\%, and indicated that the spotted regions migrate at different rates towards decreasing orbital phase.

Vogt (1981) and Huenemoerder \& Ramsey (1987) made a quantitative study of the effect of spots in the TiO bands. They found that a substantial fraction

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of the photosphere must be spotted (with a spot coverage of 35% to 40%), while Neff et al. (1995) found that cool starspots \( (T \approx 3500 \text{ K}) \) are always visible, with a fractional projected coverage of the visible hemisphere varying from 54% to 64% as the star rotates. Recently, O’Neal & Neff (1997) have detected excess of OH absorption due to cool spots on the surface of II Peg and found for one epoch, a spot filling factor between 35% and 48%. First surface images of II Peg for the 1992–1994 seasons reported by Hatzes (1995) have revealed polar or high-latitude spots and several equatorial and sub-equatorial spots with total coverage of about 15% of the visible surface.

The present study is based on new high-resolution and high signal-to-noise ratio spectroscopic observations carried out in 1992–1996 with different instruments. Also, a new inverse technique is employed for surface imaging. It is the recently developed Occamian approach, which does not use any prior smoothness assumption, but the resulting solution is nevertheless stable with respect to measurement errors and uncertainties in the adopted stellar parameters.

2. Observations

II Peg was observed with different instruments in 1992–1996. The most important information on the data set is given in Table 1. The reduction of the data included bias and scattered light subtraction, flat field correction, extraction of spectral orders (for échelle data), and wavelength calibration.

<table>
<thead>
<tr>
<th>Season</th>
<th>Sp. region and resolution</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992 Aug.</td>
<td>6160–6200 ( \text{Å} )</td>
<td>Coudé spectrograph, 2m telescope, Rozhen</td>
</tr>
<tr>
<td></td>
<td>( \lambda/\Delta \lambda \approx 30,000 )</td>
<td>MUSICOS spectrograph, 2m telescope, Pic du Midi</td>
</tr>
<tr>
<td></td>
<td>6110–6190 ( \text{Å} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \lambda/\Delta \lambda \approx 40,000 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 spectra</td>
<td></td>
</tr>
<tr>
<td>1993 Dec.</td>
<td>6150–6200 ( \text{Å} )</td>
<td>stellar spectrograph, McMath telescope, NSO</td>
</tr>
<tr>
<td>1994 Nov.</td>
<td>( \lambda/\Delta \lambda \approx 90,000 )</td>
<td></td>
</tr>
<tr>
<td>1995 Jan.</td>
<td>46 spectra</td>
<td></td>
</tr>
<tr>
<td>1994 July</td>
<td>5500–8500 ( \text{Å} )</td>
<td>échelle spectrograph SOFIN, 2.56m NOT, La Palma</td>
</tr>
<tr>
<td>1995 July</td>
<td>( \lambda/\Delta \lambda \approx 83,000 )</td>
<td></td>
</tr>
<tr>
<td>1996 Aug.</td>
<td>58 spectra</td>
<td></td>
</tr>
<tr>
<td>1996 Aug.</td>
<td>6140–6200 ( \text{Å} )</td>
<td>Coudé spectrograph, 2.6 m telescope, Crimea</td>
</tr>
<tr>
<td></td>
<td>( \lambda/\Delta \lambda \approx 41,000 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>37 spectra</td>
<td></td>
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</tbody>
</table>
3. Calculations

3.1. Local Line Profiles

A list of atomic line parameters has been obtained from VALD (Piskunov et al. 1995) and checked by fitting the spectrum of a standard star. β Gem was chosen as the standard because of its close effective temperature and known atmospheric parameters. A number of molecular lines were added to the list since, although being weaker than atomic lines, they are so numerous that they can effectively reduce the continuum level. The most significant contribution to the photospheric spectrum of Π Peg from molecular lines is due to rotational transitions of a number of vibrational bands of the CN red system. Another important molecule for our calculation is TiO, whose bands are known to dominate in the spot spectrum of Π Peg in the visible region. The main sources of the molecular line parameters are the following: wavelengths are from the laboratory measurements by Davis & Phillips (1963) and Phillips & Davis (1996); band oscillator strengths and molecular constants are from the RADEN database (Kuznetzova et al. 1993); lower level excitation energies and rotational intensity factors are calculated. A code used for synthetic spectrum calculations is described in detail by Berdyugina (1991). It includes calculation of opacities, intensities and fluxes in the continuum and atomic and molecular lines. Also, number densities of atoms and molecules are calculated under the assumption of their dissociative equilibrium. Stellar model atmospheres with \( T_{\text{eff}} = 3500 \ K - 6000 \ K \) and \( \log g = 3.2 \) have been interpolated from the grid by Kurucz (1993). For proper accounting of the limb darkening, local line profiles were calculated for 10 limb angles on the stellar disk. A microturbulence of 2 km s\(^{-1}\), a macroturbulence of 4 km s\(^{-1}\), and a proper instrumental profile for a given set of observations have been included in the calculations as well.

3.2. Inversion

The inclination of the star \( i = 45^\circ \) estimated in Paper 1 (Berdyugina et al. 1998) was used in the inversion, though we found no significant distortion of spot configurations within \( 35^\circ \leq i \leq 65^\circ \). A projected rotational velocity \( v \sin i \) of 22.6 km s\(^{-1}\) was adopted, and phases were calculated from the new orbital ephemeris: \( 2449582.9303 + 6.724336E \) (Paper 1).

The problem was considered as the reconstruction of the brightness distribution on the stellar disk. It was linearized (in matrix form), but since it is not truely linear due to the continuum normalization, the coefficients in the matrix were changed after each iteration. A \( 6^\circ \times 6^\circ \) grid was used in the calculations. The recovery technique employed was the recently developed Occamian approach (Terebzh 1995). It considerably differs from both the maximum entropy method and Tikhonov regularization which are widely used in surface imaging. The common approach of those methods is to exploit prior assumptions to find a unique, smooth solution. The Occamian approach does not assume any specific smoothness, but the resulting solution is nevertheless stable with respect to measurement errors and uncertainties in the adopted stellar parameters.
Figure 1. Images of the primary of II Peg.
Figure 2. Images of the primary of II Peg (continued).
4. Images

The surface imaging was applied simultaneously to Fe i 6173 Å, 6180 Å, and Ni i 6175 Å, 6177 Å, 6178 Å. Figures 1 and 2 display the images of II Peg from 1992 to 1996. Images are shown with a coordinate grid of 45° in both latitude and longitude, and the inclination of the rotation axis is 45° as was adopted in the calculations. The accuracy of the brightness values decreases toward lower latitudes. Thus, high latitude spots are more reliable, while equatorial and sub-equatorial features seem to be mainly due to inconsistencies of the calculations and observations. For most data sets phase coverage was quite satisfactory, except for two seasons: December 1993 and January 1995, when phase gaps were as large as 0.54 and 0.41, respectively. The darkest regions in the images are about 10% in brightness of the unspotted photosphere, that corresponds to ΔT_{eff} ≈ 1200 K. In comparison to Hatzes' (1995) results for the close season (July 1994) the position and structure of the dominant group is very similar, but there is some difference in the near-equatorial spot.

The common properties of the images of II Peg in 1992–1996 are that two high-latitude spots dominate in almost all seasons and no polar cap is seen. The positions of the spots are constantly migrating to larger longitudes with approximately the same rate. Since phases were computed from the orbital period, this longitude motion of the spot configuration means its shorter rotational period. A plot of the reconstructed spot longitudes versus time is shown in Fig. 3. The mean rate of the spot migration is found to be (0.117 ± 0.009)° day⁻¹, which results in their rotational period P_{rot} = 6.7095 ± 0.0013 days. It is very close to the photometric period P_{photom} = 6.7103 days, averaged from values found by Henry et al. (1995). The difference in the rotational and orbital periods can be interpreted either as non-synchronous rotation or differential rotation. The longitude separation between the spots is approximately constant and equal to about 180°. This can be considered as two long living active longitudes, although one of them is more blurred.

5. Conclusions

- Two high-latitude spots dominate on the surface of the primary of II Peg in 1992–1996, and no polar cap is seen.

- The positions of the spots are constantly migrating to larger longitudes with approximately the same rate.

- The rotational period of the spots is very close to the photometric period.

- Two long-living active longitudes separated by about 180° can be deduced from the spot positions.

Acknowledgments. We are grateful to Dr. Sumner Davis for the computer-readable catalogue of laboratory wavelengths of TiO and CN bands and to Dr. Ludmila Kuznetsova who provided band oscillator strengths and molecular constants from the RADEN database.
Figure 3. A plot of the reconstructed spot longitudes on II Peg versus time. Symbols in circles are from Hatzes (1995).

References

Kurucz, R.L. 1993, CD No. 13