The Surface Brightness Contribution of II Peg: A Comparison of TiO Band Analysis and Doppler Imaging

H. V. Şenavcı[1], D. O'Neal[2], G.A.J. Hussain[3], J.R. Barnes[4]

[1] *Ankara University, Faculty of Science, Department of Astronomy and Space Sciences, TR-06100, Tandoğan, Ankara, Turkey*

[2] *Keystone College, Natural Science and Mathematics, La Plume, PA, 18440, USA*

[3] *ESO, Karl-Schwarzschild-Str. 2, 85748, Garching bei München, Germany*

[4] *Center for Astrophysics Research, University of Hertfordshire, College Lane, Hateld, Hertfordshire AL10 9AB*

Abstract. We investigate the surface brightness contribution of the very well known active SB1 binary II Pegasi, to determine the star spot filling factor and the spot temperature parameters. In this context, we analyze 54 spectra of the system taken over 6 nights in September - October of 1996, using the 2.1m Otto Struve Telescope equipped with SES at the McDonald Observatory. We measure the spot temperatures and spot filling factors by fitting TiO molecular bands in this spectroscopic dataset, with model atmosphere approximation using ATLAS9 and with proxy stars obtained with the same instrument. The same dataset is then used to also produce surface spot maps using the Doppler imaging technique. We compare the spot filling factors obtained with the two independent techniques in order to better characterise the spot properties of the system and to better assess the limitations inherent to both techniques. The results obtained from both techniques show that the variation of spot filling factor as a function of phase agree well with each other, while the amount of TiO and DI spot filling factors disagree by an order of magnitude.

1. Introduction

II Peg is a very well known active SB1 type RS CVn binary that has been classified by Rucinski (1977) and Vogt (1981). Berdyugina et al. (1998) determined that the primary component of the system is a K2IV sub-giant, while the unseen secondary component is an M-dwarf. They also obtained the orbital period, inclination, and the projected rotational velocity of the system as P = 6.72 days, i = 60, and v sini = 22.6 km/s, respectively. Regarding the activity behavior of II Peg, several studies have been performed by means of photometry, Zeeman Doppler Imaging, Doppler Imaging (hereafter DI), and molecular band analyses techniques, the most recent one by Xiang et al. (2014). These studies have revealed that the system has a large cool star-spot coverage showing complex migration behavior.

Among the techniques mentioned above, molecular band analyses have remarkable advantages as being more sensitive to cooler spots and detecting these features regardless of their distribution, even on slowly rotating stars (O'Neal et al. 2004). In this study, we investigate the surface brightness contribution of II Peg using TiO band analysis and DI, and present the results together with the comparison of these techniques.

2. Data

For both DI and TiO band analyses of II Peg, we used 54 time-series spectra obtained between the nights September 28 and October 3, taken from 2.1m Otto Struve Telescope equipped with SES (McCarthy et al. 1993) at the McDonald Observatory. These data are also used by O'Neal et al. (1998), in which the details can be found. We obtained the spectral resolution using the FWHM values from arc spectrum as around R $\sim$ 54000, which corresponds to the value of 5.5 km/s per pixel.

3. TiO Band Analysis

The TiO analysis is simply based on the determination of spot filling factors (f_s) and spot temperatures (T_S) by fitting the depths of the TiO bands near 7055Å and 8860Å. The whole point of the technique is to simultaneously determine spot filling factor and temperature, so both are left as variables. In order to perform the modeling, we construct empirical models to represent the unspotted ("quiet") photosphere and spots. The construction of these models are carried out in two different ways. First by fitting them using model atmospheres (ATLAS9) and the second using proxy (template) spectra of standard inactive G-K type (photosphere) and M type (spot) stars. Samples of the models together with observed spectra of II Peg for 7050Å and 8860Å band heads are given in the left and right panels of Fig. 1, respectively. The systematic difference between spot filling factors determined from proxies vs. models might come from using very low gravity red giants as spot proxies. The (non-existent) M subgiants would have smaller TiO band depth for the same effective temperature, so would need more area on the star to give the same TiO band depth in the combined spectrum.

To model each II Peg spectrum, we used different nonspot and spot comparison stars (proxies and models from ATLAS9) spanning the temperature range (3000 K $\leq T_S \leq$ 4000 K) over which the TiO-band technique is valid. Each possible pair of comparison stars was used to fit the active star spectrum, and an f_S was computed assuming those two temperature components. For each nonspot comparison star used (i.e., each assumed T_Q), we plot the relation between each assumed T_S and the resultant f_S for both the 7055Å and 8860Å bands

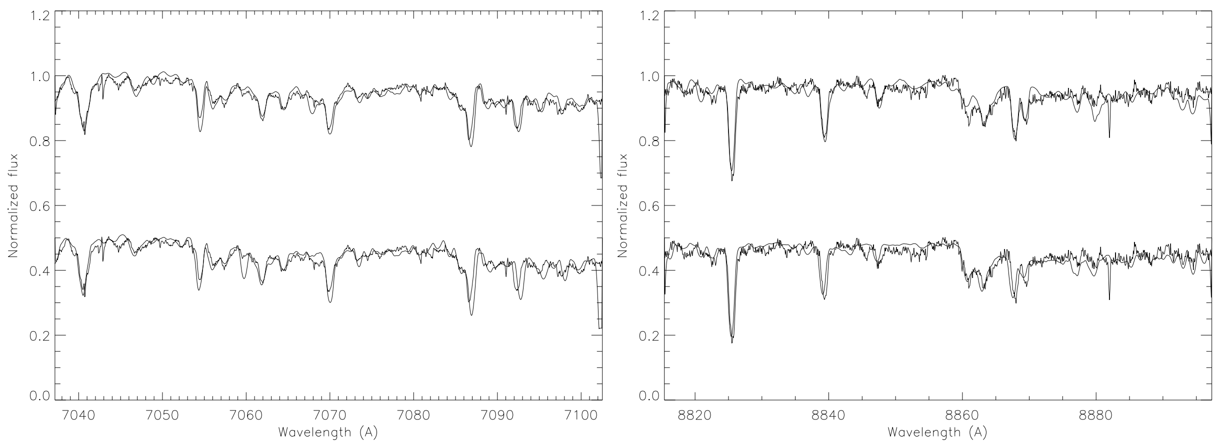

Figure .1: Left Panel: Fits to 7055Å region of II Peg spectrum #21 using proxy stars (top) and ATLAS9 models (bottom). In both cases, assumed T_S = 3425 K and assumed T_Q = 4750 K. Right Panel: Same as left panel but for 8860Å region of II Peg spectrum #41.

(a sample is shown in Figure 2). Therefore, the certain T_S and f_S values are determined, where the two relations intersect.

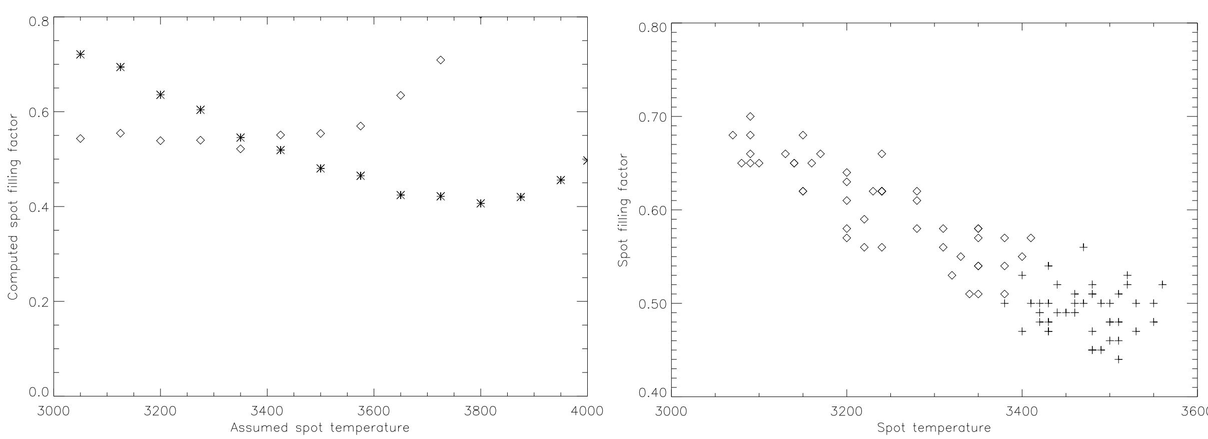

Figure .2: Left Panel: Fits with ATLAS9 models for II Peg spectrum #41. Asterisks: fits to 7055Å TiO bands with given spot temperature models. Diamonds: fits to 8860Å TiO bands. The computed T_S and f_S values are taken where the two curves cross. T_Q was assumed to be 4750 K for these fits. Right Panel: Spot filling factor f_S vs. spot temperature T_S for all II Peg spectra. Plus signs: fits with proxy stars. Diamonds: fits with ATLAS9 models. Uncertainties for spot filling factor and spot temperature are about 0.05 - 0.08 and 125 K, respectively.

4. Doppler Imaging

We applied the LSD routine (see Donati et al. 1997 for details) to obtain high S/N profiles of each spectrum in the time series. We used the linelist extracted from the Vienna Atomic Line Database (VALD) (Kupka et al. 1999). During the preparation of the linelist, several wavelength regions were removed. These correspond to strong chromospheric emission lines (e.g. H_α, Na D), the artefact and excess illumination (see Şenavcı et al. 2011), and strong telluric regions. We obtained S/N values between 700 - 800, which are lower than expected. This may be due to our spectral range (6500Å - 8900Å) including several telluric lines and molecular bands, rather than photospheric absorption lines. In addition, due to the lack information of molecular bands in VALD database (e.g. depth), we couldn't take into account the molecular bands in our linelist.

The surface maps of II Peg were obtained using the imaging code, DoTS (Collier Cameron 1997). DoTS implements a maximum entropy regularised iterative algorithm to obtain fits to the observed time series spectra. Images with spot filling factors are derived from a two-temperature model. To produce accurate spot surface maps of stars, it is necessary to fine-tune the fundamental system parameters (see Şenavcı et al. 2011 for details). Inaccurate system parameter measurements introduce artefacts into the surface reconstructions (Unruh 1996). In this context, we used preliminary system parameters derived by Berdyugina et al. (1998) and Xiang et al. (2014), which are in accordance with the LSD profiles we obtained. We then fine tune some of the parameters (e.g. EW, R, V_γ) to obtain the most accurate maps of II Peg. Best fit system parameters are listed in Table 1.

Table .1: System parameters

T_0 (HJD-2400000)	P (days)	q (M_2/M_1)	i (deg)	V_γ (km/s)	R_1 ($M_\odot$)	K_1 (km/s)	vsini (km/s)
43033.47	6.72422	0.5	60	-29.3 ± 0.5	3.25 ± 0.03	38.66	22.6

During the preparation of line intensity (EW) lookup tables, we used the photospheric temperature as T_{Ph} = 4750 K and spot temperature as T_S = 3425 K, together with the corresponding limb darkening coefficients. The resultant map (left panel) and fits to some LSD profiles (right panel) are given in Figure 3. The final chi-squared value after MEM iterations is $\chi^2 = 1.0$.

The pixel resolution of 5.5 km/s provides us the minimum resolvable spot size as around 22 deg, which is in accordance with our resultant map. As can be seen from Figure 3, there is a strong polar spot and 3 prominent spot regions located around the equator. This map, is very similar to that obtained by Xiang et al. (2014). We obtain a spot filling factor of 6.2% for the spot map of II Peg as shown in Figure 3. In the next section we compare this value with those obtained from TiO band fitting.

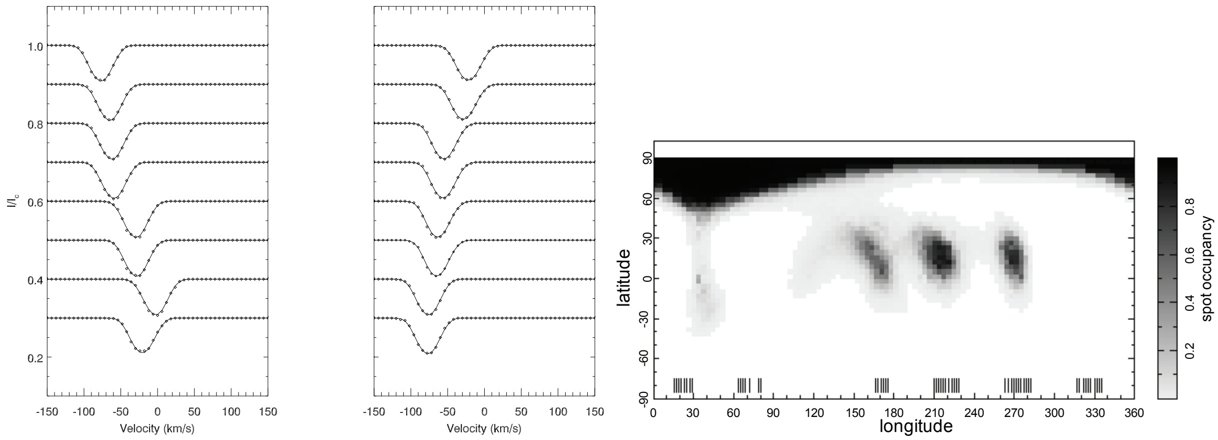

Figure .3: Left Panel: 16 sample LSD profiles covering the full orbital phase (0.067 - 0.957). Right Panel: Surface brightness distribution of II Peg, using 54 time series spectra of the system.

5. Results and Discussion

We investigate the surface inhomogeneities of the RS CVn type system II Peg, using TiO analysis and DI. TiO analysis yields an average spot filling factor of 0.5 and 0.6 with proxy stars and model atmosphere approximation, respectively. Doppler maps, on the other hand, is in accordance with other DI studies of the system and give a spot filling factor of 0.062. Our value is also typical of spot filling factors obtained for other active cool stars using Doppler imaging (typical spot filling factors <0.1). However, DI is only sensitive to the inhomogenously distributed spots with sizes larger than the resolution limit of the technique. TiO band fitting reveals the underlying level of cool spots that cannot be detected using DI alone (Solanki 1999).

We also compare the variation of spot filling factors with phase, in order to look for a correlation of f_S value obtained using two techniques. To do this, we first estimate the average phases of observations and then calculate the corresponding spot filling factors from TiO analysis and DI. Since the f_S value obtained from TiO analysis (convolved synthetic spectra) is nearly 10 times greater than that is obtained from DI, we normalized the spot filling factor values to unity, in order to perform a better comparison of two techniques (Fig. 4). It is clear from Figure 4 that the variation of spot filling factor with phase from two techniques are quite compatible with each other. This indicates that the most spotted phases are the same regardless of the technique, so the large spots detected by DI are also associated with an underlying larger filling factor of small, cool spots below the resolution limit of the DI technique. As a result, it can be said that, a considerable amount of spot coverage is hidden in a spot map from DI. However, performing TiO analysis together with the DI give a more complete picture of the spot properties as well as the brightness distributions on the surfaces of cool stars.

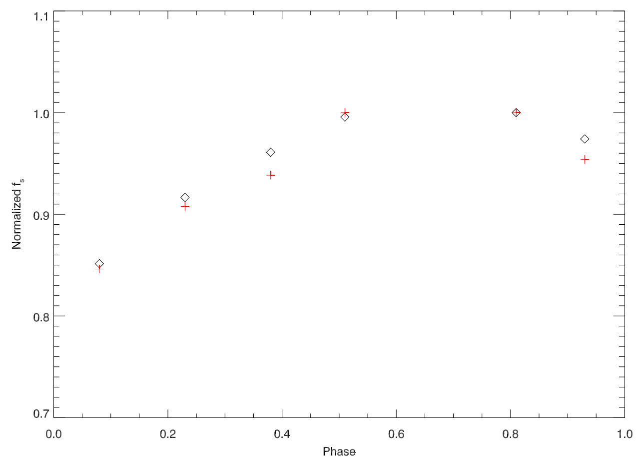

Figure .4: Spot filling factor f_S vs. phase for the average phases of II Peg spectra. Red plus signs: f_S values from DI. Diamonds: f_S values from TiO analysis using ATLAS9 models.

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