ACTA ASTRONOMICA
Vol. **66** (2016) pp. 381–390

Photometric Observations of LO Peg in 2014–2015

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Received April 10, 2016

ABSTRACT

We performed new observations of an ultra-fast rotator of the spectral class K – the LO Peg star – in SAO RAS in 2014 and in Zvenigorod Observatory of INASAN in 2015. The light curves were used to build the maps of temperature inhomogeneities on the LO Peg surface in order to determine the longitudes corresponding to the location of active regions. The obtained measurements suggest the ongoing evolution of movements of active regions and probably the cyclic character of such movements. According to our estimations, the area of the star surface covered with spots decreases and by now it reached 14% of the total visible area of its surface. New observations of the star in *V* filter allowed us to specify LO Peg long-term variability cycles. Based on spectropolarimetric observations of LO Peg the null result for measurements of mean longitudinal component of magnetic field is obtained.

Key words: *Stars: activity – starspots – Stars: magnetic field*

1. Introduction

LO Peg is a young star of K3 spectral class. Its age is estimated as 10 Myr to 300 Myr (López-Santiago *et al.* 2006). Besides, it is a member of the AB Dor stellar group (Zuckerman *et al.* 2004). It has common spatial motion and an independent age estimation of 30–150 Myr. Equatorial rotation rate of the star is 65 km/s. This fact allows us to classify it as a superfast rotator of the late spectral class.

During recent years many studies dedicated to photometric and polarimetric investigation of the star were published. The review of main LO Peg properties presented below is according to the references from (Karmakar *et al.* 2016).

Effective temperature of the star is 4750 K (Pandey *et al.* 2005), which corresponds to the spectral class K3. The strong lithium line and the emission in the Hα, CaII H+K lines are observed in the spectrum, which indicates magnetic activity of the object. Rotational modulation of brightness variability is indicative of the presence of surface temperature inhomogeneities (cold spots) of the star. Photometric variability of the star was studied by many authors (Jeffries *et al.* 1994, Dal and Tas 2003, Pandey *et al.* 2005, Robb and Cardinal 1995). Results of multicolor polarimetric observations were published in Pandey *et al.* (2005). The Doppler mapping of the LO Peg surface was performed by means of high resolution spectral observations (Lister *et al.* 1999, Barnes *et al.* 2005, Piluso *et al.* 2008).

The most comprehensive study of LO Peg activity was presented by us in Karmakar *et al.* (2016). It is based on more than 24 years long photometric observations of the star and includes results of extensive analysis of photometric variability, the study of activity cycles, estimations of differential rotation of the star and its flaring activity, and, besides, results of analysis of LO Peg observations with the Swift satellite.

This article presents the results of LO Peg observations in 2014–2015 in Special Astrophysical Observatory of RAS and Zvenigorod Observatory of INASAN which have not been included in Karmakar *et al.* (2016). Additionally, we present here the analysis of LO Peg spectropolarimetric observations with the polarimeter at the Russian 6-m telescope in order to measure the value of the longitudinal component of its magnetic field.

2. Photometric Observations and Data Processing

LO Peg photometry has been performed using the data acquired by the Mini-MegaTORTORA (MMT-9) wide-field optical monitoring system (Beskin *et al.* 2010, Biryukov *et al.* 2015).

The system consists of nine channels equipped with Canon EF85/1.2 objectives and Andor Neo sCMOS detectors with 2560×2160 6.4 μm pixels, has 900 square degrees field of view and routinely performs automatic high temporal resolution monitoring of the sky looking for rapid optical transients on sub-second time scales. In this regime every field is being observed with 0.1 s temporal resolution for about 1000 s, and then the system repoints to the next direction chosen to eventually visit every point of the northern sky at least once per several days. Before and after the monitoring, a deeper "survey" images with 60 s exposure in white light are also acquired. Typical detection limit of these images is about $V \approx 14.5$ mag. The white light sensitivity of the detector is a wide band with sensitivity peaking between 4500 Å and 7500 Å.

We extracted from the data archive of Mini-MegaTORTORA a set of 67 "survey" images covering the region of LO Peg between Jul 31, 2014 and Dec 19, 2014. The images were pre-processed to subtract the bias and correct the flat field, and then cropped from the original size of $10^{\circ} \times 10^{\circ}$ to about $1^{\circ} \times 1^{\circ}$ centered on the object. These cropped images were then used to perform differential photometry of LO Peg using nearby BD+22 4417 ($V = 9.04$ mag) star as a standard and BD+22 4420 as a control star, analogous to the setup used by Tas (2011). The LO Peg brightness measurement precision was, on average, 0.02 mag.

Besides, an additional photometric observations of LO Peg were carried out at Zvenigorod Observatory of INASAN in July 2015. The "Veloce RH 200" telescope equipped with a set of Johnson *UBVRI* photometric filters was used. Registration was made with the "FliProline 16803" CCD detector. The camera chip size is 4096×4096 pixels, the pixel size being 9×9 microns. The exposure time was chosen individually for each filter and night, spanning from 20 s to 60 s, in such a way that the amount of ADUs obtained for the star under investigation and comparison stars would be about half of the camera's dynamic range. The field of view of the resulting frame is $3^{\circ} \times 3^{\circ}$. In such setup every frame includes a great number of objects, giving us a wide choice of comparison stars for differential photometry. The same objects (BD+22 4417 and BD+22 4420) were used as the standard and comparison star, respectively, as in observations carried out in SAO RAS. The processing of frames was made with the MaxImDL software package. The processing was analogous to that of performed on data obtained in SAO RAS. Precision of a single measurement was about 0.009 mag.

3. Temperature Maps

The method of reconstruction of a map of surface temperature inhomogeneity is described by us in detail in Savanov and Strassmeier (2008). Additional information on the map production method can be found in Jaervinen *et al.* (2008) and Savanov (2010).

Each of individual light curves, rebinned and averaged into 20 equidistant phase bins, was analyzed with the iPH code. This code solves the inverse problem of restoration of temperature inhomogeneity of a star from a light curve in the two-temperature approximation, in which the temperatures of the quiet photosphere and spots are fixed. The description of the code and its testing were presented in Savanov and Strassmeier (2008). As in Piluso *et al.* (2008), we assumed that the LO Peg photosphere temperature is $T_{\rm eff} \approx 4500$ K, and the spots temperature is 750 K lower (Savanov and Dmitrienko 2011), which is comparable with a temperature estimation of 3500 K (Piluso *et al.* 2008) of the coldest regions of the star.

We used the data from the Kurucz model grid. The parameters we assumed are the same as we used in Karmakar *et al.* (2016).

When modeling, the star surface was divided into elementary areas of $6^\circ \times 6^\circ$ size for which the filling factors f – the unknowns – were determined. Fig. 1 shows results of temperature inhomogeneity restoration on the LO Peg surface for two consecutive observational sets. Note the variability of individual light curves and the difference of their respective temperature maps.

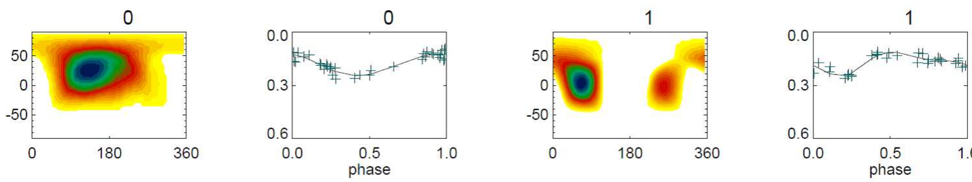

Fig. 1. Examples of results of temperature inhomogeneity restoration on the LO Peg surface from SAO RAS observations. The surface maps are presented in a common scale. The darker areas correspond to higher values of the filling factor f. Observed light curves and theoretical ones built for the restored model are also shown.

From the built maps we determined the longitudes corresponding to the highest values of f. In most cases there are concentrations of spots at two longitudes (one of them is well defined, the location of the second one is determined with a large error), which were registered as two independent active regions. The location determination accuracy of active longitudes is a star surface region with size of order of 6°–12° on the average (or 0.02–0.04 in units of phase).

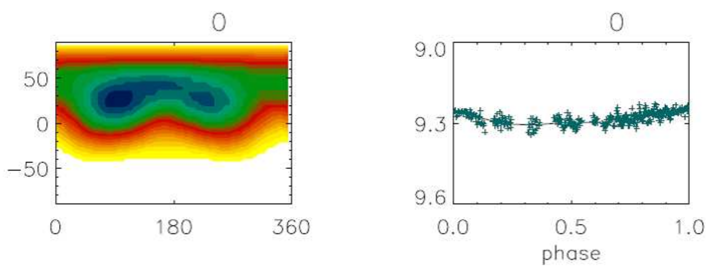

Fig. 2. Example of results of temperature inhomogeneity restoration on the LO Peg surface from Zvenigirod observations (the notation is analogous to that of Fig. 1).

Data presented in Figs. 1 and 2 allow us to conclude that there are different states of the star' activity manifested during the period of our observations. The observational nights of data acquired in SAO RAS were grouped into two sets: the first one with duration of 57 d, and the second one – 84 d (35 and 32 photometric measurements respectively). When transiting from the first set to the second one the shape of star light curve underwent essential changes. Next set of observational data was obtained in Zvenigorod eight months later. Its duration was 12 d. The light curve shape changed again. Note that the curve shapes of the observational sets under review are similar to those determined previously for LO Peg (*e.g.*, see the patterns of phased light curves in Tas 2011).

We used data of photometric observations of the first two sets only to build the surface maps and to analyze locations of active regions, while the data of the third set, beside that, were also used to determine the star surface portion which is covered with spots and to refine the parameters of LO Peg long-term variability cycles.

We presented the detailed analysis of locations of active regions on the LO Peg surface in Karmakar *et al.* (2016). Three last added measurements indicate the ongoing evolution of movements of active regions and, possibly, the cyclic character of these movements with the characteristic time 5–5.5 yr. Note that this value is close to that of the cycles of LO Peg photometric variability of 5.2 yr (see below).

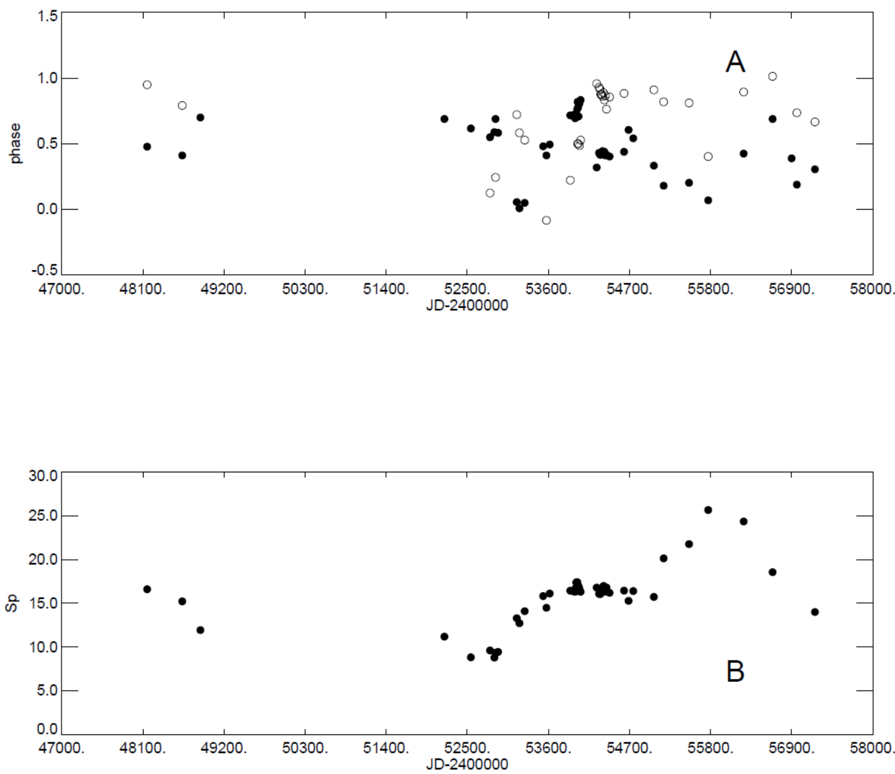

Fig. 3. *Top panel*: Phases of active regions on the LO Peg surface: more active regions are denoted by dark circles, less active regions – by light circles. *Bottom panel*: The changes of spottedness of the LO Peg surface. Spottedness is defined as fraction of area weighted by filing factor.

As the star brightness increased (see the upper diagram in Fig. 4), the star surface area covered with spots decreased, and by now it reached 14% of the total visible surface area (the lower part of Fig. 3).

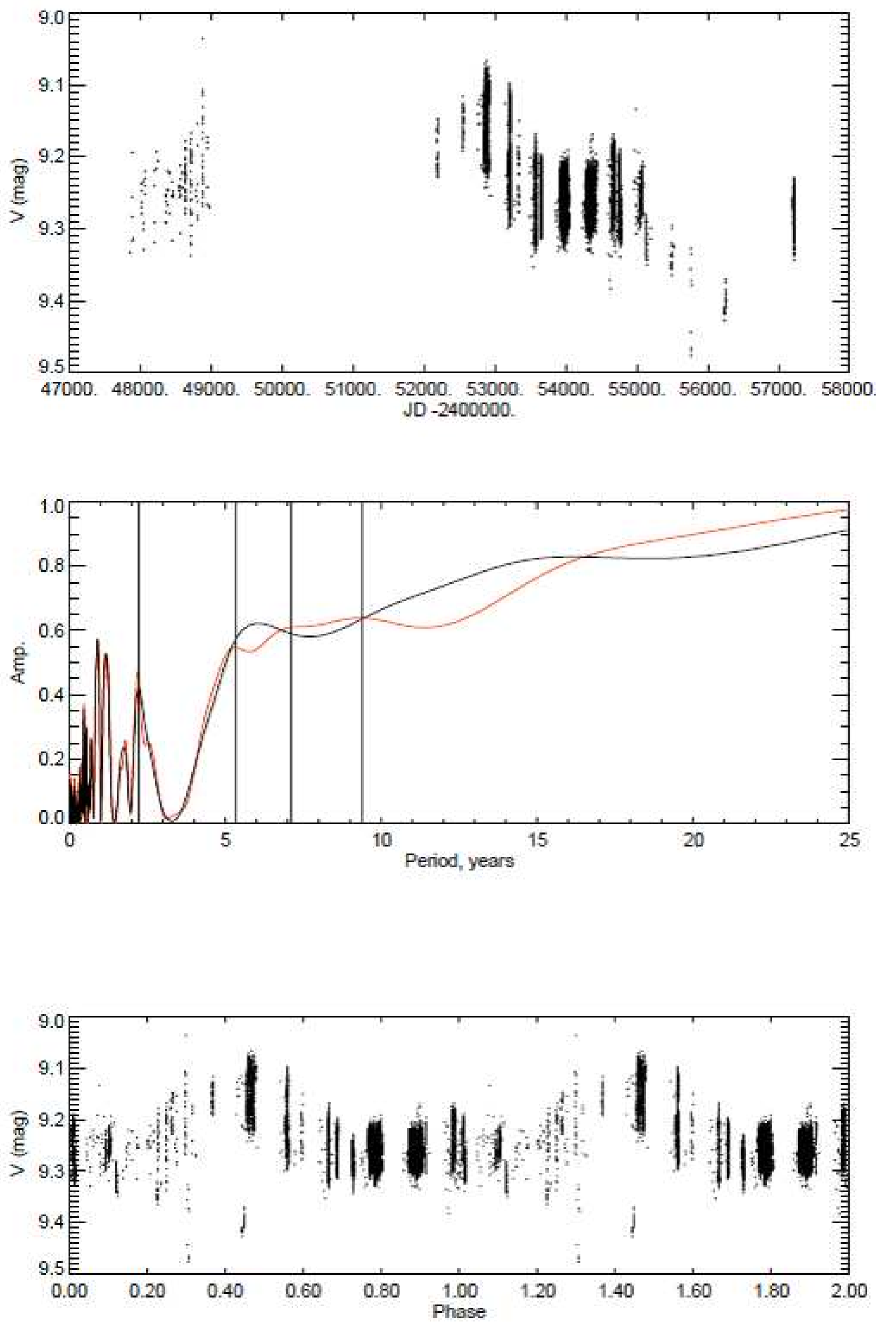

Fig. 4. *Top panel*: observations of the star in the *V* filter. *Middle panel*: the amplitude power spectrum, the thin (red) line is for the whole data set, the thick one – without observations of 2015. The possible periods of long term term variability cycles of 2.2 yr, 5.2 yr, 7.1 yr and 9.4 yr are marked by vertical lines. The folding of available photometric observations with a period of 9.4 yr is shown in the *lower panel*.

4. Activity Cycles

New observations of the star in the V filter allowed us to refine the periods of LO Peg long-term variability. Previously Karmakar *et al.* (2016) concluded about two periods $P=2.98$ yr and $P=7.44$ yr in LO Peg, and noted that to confirm the existence of the third longer cycle ($P=11.8$ yr) new data were necessary.

The complete data set of observations of the star in the V filter, which includes 13 907 measurements, is presented in the upper panel of Fig. 4. The amplitude power spectrum built from these data is shown in the middle panel of Fig. 4. One may notice the change of the power spectrum shape after taking new observations of 2015 into account. In the region of long-term variability cycles longer than 5 yr there are no definite peaks in the power spectrum but the cycles of 5.2 yr, 7.1 yr and 9.4 yr started to manifest. As an example the plot of all available photometric observations folded with a cycle of 9.4 yr is shown in the bottom panel of Fig. 4. Nevertheless, the presented 9.4 yr cycle may be related to the length of the main data segment and 9 yr is also comparable to the gap in observations between JD: 2 449 000–2 452 000. Long term luminosity change on several timescales is evident but it is still too early to consider the obtained values of possible cycle variations as reliable with present amount of data.

Our recent observations of 2015 have shown that the star comes out of its state of minimum brightness and practically almost reached its state as in 2005–2010.

5. Magnetic Field

We supplemented the study of LO Peg photometric variability with the results of our analysis of polarimetric observations. The observational material for the determination of the longitudinal magnetic field $\langle B_z \rangle$ of the star was obtained with the Main Stellar Spectrograph of the Russian 6-m telescope of SAO RAS. Observations were carried out on the night of July 27/28, 2012. Observation phases for two obtained estimations of $\langle B_z \rangle$, determined according to ephemerids from Tas (2011), were equal to 0.90 and 0.12. A circular polarization analyzer in combination with a rotating $\lambda/4$ plate were used (Chountonov 2004). The observational program included observations of the object – LO Peg, and the acquisition of spectra of a standard of magnetic field, as well as stars with zero total magnetic field which were recorded for the control of measurements. Note that at the same period the program of observations of another chromospherically active star – FK Com – was carried out. We published results of these observations in Puzin *et al.* (2014), where the description of the data processing and analysis methods were given. Here we repeat in briefly.

The spectral resolution was $R=15\,000$. The CCD of 2000×2000 pixel size was used in observations. The obtained material covers the spectral range 4386–4945 Å. We performed the standard data processing in the MIDAS system using the ZEEMAN package (Kudryavtsev 2000). The preprocessing included the construction and subsequent subtraction of an averaged bias frame from all operational frames, wavelength calibration with the use of a Th-Ar lamp, extraction of one-dimensional spectrum and its normalization to the continuum.

To determine the value of the longitudinal component of magnetic field $\langle B_z \rangle$ for LO Peg, we have chosen a method suggested by Landstreet (1982) and discussed in detail by Bagnulo *et al.* (2002). Analogous method was already used by us in Puzin *et al.* (2014), Savanov *et al.* (2013) and Savanov *et al.* (2011), including the analysis of polarization observations of the subdwarf Bal09 performed with the Main Stellar Spectrograph of the Russian 6-m telescope of SAO RAS in 2010 and 2012. The values of $\langle B_z \rangle$ for the standards of magnetic field (α^2 CVn and γ Equ) and stars with zero total magnetic field were estimated by the same method.

As in Savanov *et al.* (2013) and Savanov *et al.* (2011), the value of the longitudinal component of magnetic field $\langle B_z \rangle$ is determined by the ratio of the Stokes parameters V/I from the equation

$$\frac{V}{I} = -g_{\text{eff}} \frac{e}{4\pi m_e c^2} \lambda^2 \frac{1}{I_\lambda} \frac{dI}{d\lambda} \langle B_z \rangle \tag{1}$$

where g_{eff} is the effective Lande factor, λ is a wavelength, $\langle B_z \rangle$ is a value of the longitudinal component of magnetic field.

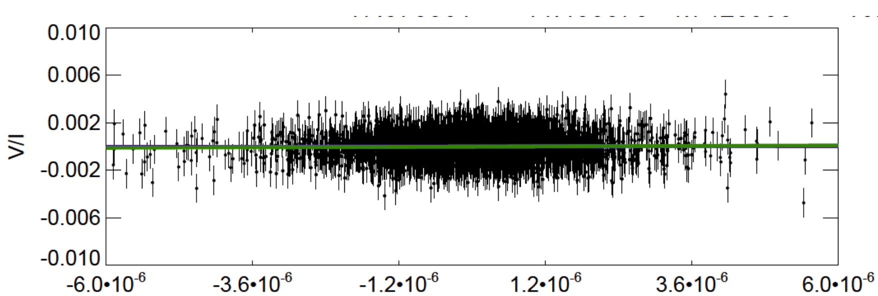

Fig. 5. Results of determination of the longitudinal component of magnetic field $\langle B_z \rangle$ for LO Peg obtained by regression analysis from observations of July 27, 2012. The regression line slope is proportional to B_z. The abscissa is a value proportional to $\lambda^2 \frac{1}{I_\lambda} \frac{dI}{d\lambda}$.

In Savanov *et al.* (2013) and Savanov *et al.* (2011) we argued that in many spectropolarimetric measurements the choice of the value of g_{eff} close to 1 is well justified. Besides, $g_{\text{eff}} = 1.2$ serves as a good approximation for spectra of Ap stars (the standards of magnetic field α^2 CVn and γ Equ). Therefore in this study we chose $g_{\text{eff}} = 1.2$.

As in Puzin *et al.* (2014), within the context of our investigation, $\langle B_z \rangle$ of LO Peg was determined by regression analysis. This method allows obtaining simultaneously the errors of regression parameters and, consequently, the error of $\langle B_z \rangle$. The estimations of $\langle B_z \rangle$ for two measurements are 17 ± 14 Gs and 7 ± 14 Gs, respectively.

Therefore, we may conclude that we did not detect the magnetic field for the star under consideration (within the errors of our measurements of $\langle B_z \rangle$).

Note that our observations were obtained for the rotation phases 0.90 and 0.12. According to Karmakar *et al.* (2016), the light curve obtained between the intervals 44 and 45, covering our spectropolarimetric observations, most probably has a wide minimum (there is no well defined active region). A light curve of similar shape was registered during observations in 2009 on HJD = 2 455 064.36 (Tas 2011), but due to the lack of data, the results of construction of surface temperature maps should be considered of low significance. As a consequence, the positions of active magnetic regions were determined with a large errors.

6. Conclusions

New observations of an ultra-fast rotator of spectral class K – the LO Peg star – were carried out in SAO RAS (with no photometric filter installed, in the "white" light) in 2014 and in Zvenigorod Observatory of INASAN in the Johnson filters *UBVRI* in 2015.

The light curves were used to build the map of temperature inhomogeneities on the LO Peg surface. From the built maps we determined the longitudes corresponding to the location of active regions. The obtained measurements suggest the ongoing evolution of movements of active regions and, probably, the cyclic character of such movements with a characteristic time of 5–5.5 yr.

According to our estimations, the area of the star surface covered with spots decreases, and by now it reached 14% of the total visible area of its surface.

New observations of the star carried out in the *V* filter allowed us to specify LO Peg long-term variability cycles. It was established that the power spectrum shape has changed after taking into consideration new observations from 2015.

Spectropolarimetric observations of LO Peg were analyzed for the purpose of measuring the longitudinal component of magnetic field. The obtained results can be interpreted as evidence of absence of detection of magnetic field in the star.

Acknowledgements. This research has been done under the Indo-Russian DST-RRBR project reference INT/RUS/RFBR/P-167 (for India) and Grant RFBR Ind a 14-02-92694 (for Russia). This work was supported by the Ministry of Education and Science of the Russian Federation as part of the project RFMEFI60414X 0099 under the Federal Targeted Programme 'Research and Development on Priority Directions of Scientific and Technological Complex of Russia for 2014–2020'. Also the work is partially performed according to the Russian Government Program of Competitive Growth of Kazan Federal University. Observations on Mini-MegaTORTORA are supported by the Russian Science Foundation grant No. 14-50-00043.

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