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LO Pegasi: an investigation of multiband optical polarization

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ABSTRACT

We present *BVR* polarimetric study of the cool active star LO Pegasi (LO Peg) for the first time. LO Peg was found to be highly polarized among the cool active stars. Our observations yield average values of polarization in LO Peg: $P_B = 0.387 \pm 0.004$ per cent, $\theta_{\rm B} = 88^\circ \pm 1^\circ$; $P_V = 0.351 \pm 0.004$ per cent, $\theta_{\rm V} = 91^\circ \pm 1^\circ$ and $P_R = 0.335 \pm 0.003$ per cent, $\theta_{\rm R} = 91^\circ \pm 1^\circ$. Both the degree of polarization and the position angle are found to be variable. The semi-amplitude of the polarization variability in *B, V* and *R* bands is found to be 0.18 ± 0.02, 0.13 ± 0.01 and 0.10 ± 0.02 per cent, respectively. We suggest that the levels of polarization observed in LO Peg could be the result of scattering of an anisotropic stellar radiation field by an optically thin circumstellar envelope or scattering of the stellar radiation by prominence-like structures.

Key words: polarization – stars: individual: LO Peg – stars: late-type.

1 INTRODUCTION

Magnetically active late-type stars have inhomogeneities on their surfaces that may cause variation in their spectral lines and light curves. The inhomogeneous distribution of magnetic regions on the surface of late-type dwarfs may also produce a broad-band linear polarization (Tinbergen & Zwaan 1981), and it is expected that the polarization of the integrated stellar light may change along with the stellar activity phenomenon (e.g. Huovelin et al. 1989; Mekkaden, Muneer & Raveendran 2007). Several active stars have small, variable amounts of linear polarization (<0.1 per cent) at optical wavelengths that are best interpreted as a result of scattering from cool circumstellar material (Scaltriti et al. 1993). Liu & Tan (1987) have shown that for most of RS CVn binaries the optical polarization is weak, generally below 0.45 per cent, averaging about 0.2 per cent. Pfeiffer (1979) found 0.32 per cent polarization in proto-type RS CVn and concluded that the polarization was due to scattering from cool, transient, circumstellar material probably ejected in the clouds. In BH CVn, the polarization in *U* band was found to vary synchronously with the binary period with a peak-to-peak amplitude of 0.03 per cent. It was attributed to the reflection of light coming from bright primary by the envelope of secondary (Barbour & Kemp 1981). In the late-type stars, linear polarization may be due to inhomogeneities or non-isotropic gas flow. The inhomogeneities are mainly due to the magnetic areas (star spots or plages) and circumstellar gas or dust envelopes. The most popular mechanisms that have been suggested as a source of linear polarization in late-type stars are Rayleigh, Mei and Thomson scattering in an optically thin medium (e.g. Brown & McLean 1977; Brown, McLean & Emslie 1978; Pfeiffer 1979; Piirola & Vilhu 1982; Yudin & Evans 2002) and magnetic intensification (e.g. Leroy 1962; Mullan & Bell 1976; Huovelin & Saar 1991; Saar & Huovelin 1993).

LO Pegasi (LO Peg) is a single, young, K3V-K7V-type and a member of the Local Association (Jeffries & Jewell 1993; Montes et al. 2001; Gray et al. 2003; Pandey et al. 2005). It is one of the fast-rotating active stars with a period of 0.42 days. LO Peg shows strong Hα and Ca II H and K emission lines (Jeffries et al. 1994). Evidence of an intense downflow of material and optical flaring on LO Peg has been presented by Eibe et al. (1999). Recently, Zuckerman, Song & Bessell (2004) have identified LO Peg as a member of a group of 50-Myr-old stars that partially surround the Sun. Optical photometric light curves and related studies of LO Peg have been carried out by Pandey et al. (2005). Its relation with polarimetric properties is still not known, and the same has been investigated here for the first time. The observations, the methods of data reduction, results and discussion along with the conclusions are given in forthcoming sections.

2 OBSERVATIONS

The broad-band B ($\lambda_{\rm eff} = 0.44\,\mu$m), V ($\lambda_{\rm eff} = 0.55\,\mu$m) and R($\lambda_{\rm eff} = 0.66\,\mu$m) polarimetric observations of LO Peg have been made in between 2007 October 19 and December 19 using ARIES Imaging Polarimeter (AIMPOL; Rautela, Joshi & Pandey 2004; Medhi et al. 2007), mounted on the Cassegrain focus of the 104-cm Sampurnanand telescope (ST) of Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital. The imaging was done by TK 1024 × 1024 pixel^2 CCD camera. Each square pixel of the CCD corresponds to 1.73 arcsec, while the entire field of view of CCD is ∼8 arcmin in diameter on the sky. The readout noise and gain of the CCD are 7.0e^- and 11.98e^- per ADU, respectively. For linear polarimetry, the retarder (half-wave plate) is rotated at 22°.5 intervals between exposures. Therefore, one polarization measurement was obtained from every four exposures (i.e. at the retarder

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Table 1. Observed polarized and unpolarized standard stars.

	Polarized standard				Unpolarized standard	
	Schmidt, Elston & Lupie (1992)		This work		This work	
Filter	P (per cent)	θ (°)	P (per cent)	θ (°)	q (per cent)	u (per cent)
	HD 25433				HD 21447	
B	5.23 ± 0.09	134.3 ± 0.5	5.17 ± 0.21	135.1 ± 1.0	0.019	0.011
V	5.12 ± 0.06	134.2 ± 0.3	5.13 ± 0.09	134.7 ± 0.8	0.037	−0.031
R	4.73 ± 0.05	133.6 ± 0.3	4.76 ± 0.13	132.9 ± 0.5	−0.035	−0.039
	HD 204827				HD 12021	
B	5.65 ± 0.02	58.20 ± 0.11	5.72 ± 0.09	58.6 ± 0.5	−0.108	0.071
V	5.32 ± 0.02	58.73 ± 0.08	5.35 ± 0.03	60.1 ± 0.2	0.042	−0.045
R	4.89 ± 0.03	59.10 ± 0.17	4.91 ± 0.20	58.9 ± 1.2	0.020	0.031
	BD+59°389				HD 14069	
B	6.35 ± 0.04	98.14 ± 0.16	6.36 ± 0.13	97.5 ± 0.5	0.138	−0.010
V	6.70 ± 0.02	98.09 ± 0.07	6.80 ± 0.07	98.2 ± 0.2	0.021	0.018
R	6.43 ± 0.02	98.15 ± 0.10	6.39 ± 0.04	99.5 ± 0.2	0.010	−0.014
	HD 19820				G191B2B	
B	4.70 ± 0.04	115.70 ± 0.22	4.66 ± 0.07	115.5 ± 0.2	0.072	−0.059
V	4.79 ± 0.03	114.93 ± 0.17	4.76 ± 0.10	114.2 ± 0.2	−0.022	−0.041
R	4.53 ± 0.03	114.46 ± 0.17	4.56 ± 0.17	114.2 ± 0.2	−0.036	0.027

position of 0°, 22°.5, 45° and 67°.5). The ordinary and extraordinary images of each source in the CCD frame are separated by 27 pixel along the north–south direction on the sky plane. Standard CCD procedures in IRAF[1] (bias subtraction, centroid determination) were applied to extract the flux of two stellar images in each CCD frame. Following relation was used to obtain the degree of polarization (P) and polarization potion angle (θ):

$$R(\alpha) = \frac{I_{\rm O}/I_{\rm E} - 1}{I_{\rm O}/I_{\rm E} + 1} = P\cos(2\theta - 4\alpha), \tag{1}$$

which is the difference between the intensities of the ordinary ($I_{\rm O}$) and extraordinary ($I_{\rm E}$) beams to their sum. Here, α is the angle which the retarder makes with north–south direction. The detail descriptions about the AIMPOL, data reduction and calculations of polarization, position angle are given in Rautela et al. (2004) and Medhi et al. (2007).

For calibration of polarization angle zero-point, we observed highly polarized standard stars, and the results are given in Table 1. The measured systematic differences were applied to the program stars. To estimate the value of instrumental polarization, a number of unpolarized standard stars have been observed. These measurements show that the instrumental polarization is below 0.03 per cent in all passbands. In fact, the instrumental polarization of ST has been monitored since 2004 within other projects as well (e.g. Medhi et al. 2007, 2008). These measurements demonstrated that it is invariable in all B, V and R passbands. The instrumental polarization was then applied to all measurements.

3 ANALYSIS AND RESULTS

The degree of polarization and the corresponding position angle for LO Peg in each B, V and R filters are given in Table 2. Both P and θ are found to vary with time. We have plotted the degree of polarization in V band (P_V) against Julian Date (JD) of the observations in top panel of Fig. 1, which clearly shows that P_V varies with JD. In order to ascertain the polarization variability in LO Peg, we have also observed polarization of two nearby stars, namely USNO-A2.0 1125-18467514 and TYC 2128-1288-1. The results of observed degree of polarization and position angle in V band of these two nearby stars are given in Table 3. The middle and bottom panels of Fig. 1 show the variation of P_V against JD for the stars USNO-A2.0 1125-18467514 and TYC 2128-1288-1, respectively. Lack of any significant variation in P for these stars implies that the observed polarization variation in LO Peg is intrinsic. The measurements on epoch JD = 245 4393.284 503 show higher values (∼10°) of position angle in comparison to the previous epoch observations, which were taken about 22 min earlier (see Table 2). Further, the same epoch observations show a sudden decrement/increment in B-, V- and R-band light curves. This effect is probably due to the observations taken at relatively high airmass. We assume that the data points at this epoch are of bad quality, therefore are not used for further analysis. The weighted mean of the degree of polarization and polarization position angle is calculated to be $P_B = 0.387 \pm 0.004$, $P_V = 0.351 \pm 0.004$, $P_R = 0.335 \pm 0.003$ per cent, and $\theta_B = 88° \pm 1°$, $\theta_V = 91° \pm 1°$, $\theta_R = 91° \pm 1°$.

Fig. 2 depicts the movements of the polarization vector in q and u plane (normalized Stokes parameters) for B (solid circle), V(solid square) and R (solid triangle) bands. The polarization parameters are changed due to variations in both Stokes parameters q and u.

LO Peg is located at a distance of 25 pc, and therefore has a negligible reddening. It is quite natural to assume that the observed polarization in LO Peg is not foreground in origin. Further, the observed polarization in any distant star located near the Galactic plane may have small negligible interstellar component. We have observed polarization of 17 field stars within a 8 arcmin radius around LO Peg. The results of V-band polarization are given in Table 4. The average values of the P_V and θ_V computed from the data obtained for the field stars are found to be 1.84 per cent and 94°, respectively.

3.1 Phase-locked polarimetric variability

The variability of the linear polarization in LO Peg exhibits a distinct dependence on the rotational phase. Therefore, to see the phase-locked polarimetric variability, we have folded the polarization data using the ephemeris HJD = 244 8869.93 + 0.423 75 E provided by

[1] IRAF is distributed by the National Optical Astronomy Observatory.

Table 2. Results of the degree of polarization and polarization position angle observed for LO Peg.

JD	Phase	*B*		*V*		*R*	
		P_B (per cent)	θ_B (°)	P_V (per cent)	θ_V (°)	P_R (per cent)	θ_R (°)
245 4393.194 613	0.2529	0.52 ± 0.09	87 ± 5	0.46 ± 0.08	87 ± 5	0.49 ± 0.06	88 ± 4
245 4393.208 640	0.2861	0.44 ± 0.06	95 ± 4	0.37 ± 0.01	99 ± 8	0.41 ± 0.05	89 ± 4
245 4393.221 914	0.3174	0.38 ± 0.02	89 ± 6	0.31 ± 0.04	91 ± 3	0.37 ± 0.02	89 ± 3
245 4393.237 712	0.3535	0.33 ± 0.07	98 ± 8	0.29 ± 0.02	97 ± 3	0.31 ± 0.03	99 ± 3
245 4393.254 632	0.3945	0.34 ± 0.02	85 ± 2	0.26 ± 0.07	89 ± 7	0.29 ± 0.01	88 ± 2
245 4393.269 319	0.4287	0.31 ± 0.06	93 ± 7	0.22 ± 0.05	89 ± 6	0.28 ± 0.06	90 ± 6
245 4393.284 503	0.4648	0.38 ± 0.07	105 ± 5	0.33 ± 0.08	107 ± 6	0.37 ± 0.01	105 ± 2
245 4394.049 720	0.2705	0.38 ± 0.04	83 ± 4	0.42 ± 0.01	88 ± 3	0.35 ± 0.03	88 ± 2
245 4394.064 950	0.3057	0.27 ± 0.01	87 ± 4	0.27 ± 0.02	88 ± 4	0.34 ± 0.02	88 ± 5
245 4394.078 097	0.3369	0.31 ± 0.06	91 ± 8	0.23 ± 0.04	96 ± 4	0.28 ± 0.03	96 ± 2
245 4394.090 643	0.3672	0.29 ± 0.01	85 ± 2	0.25 ± 0.03	91 ± 3	0.26 ± 0.01	91 ± 2
245 4394.104 149	0.3994	0.39 ± 0.02	85 ± 3	0.25 ± 0.02	86 ± 3	0.26 ± 0.06	86 ± 4
245 4394.115 896	0.4268	0.43 ± 0.02	87 ± 2	0.25 ± 0.04	90 ± 3	0.30 ± 0.01	90 ± 4
245 4394.132 122	0.4648	0.41 ± 0.01	85 ± 5	0.24 ± 0.05	84 ± 3	0.28 ± 0.02	84 ± 4
245 4394.144 725	0.4951	0.33 ± 0.01	79 ± 6	0.29 ± 0.04	82 ± 4	0.20 ± 0.04	82 ± 8
245 4394.160 279	0.5312	0.44 ± 0.05	82 ± 5	0.29 ± 0.06	84 ± 7	0.31 ± 0.05	84 ± 5
245 4394.173 994	0.5635	0.45 ± 0.09	79 ± 7	0.31 ± 0.07	87 ± 5	0.32 ± 0.01	87 ± 2
245 4394.195 231	0.6133	0.40 ± 0.04	80 ± 3	0.33 ± 0.08	86 ± 7	0.27 ± 0.05	86 ± 10
245 4394.207 499	0.6426	0.40 ± 0.09	79 ± 13	0.29 ± 0.06	84 ± 5	0.27 ± 0.08	84 ± 12
245 4394.219 419	0.6709	0.47 ± 0.03	86 ± 3	0.36 ± 0.09	83 ± 10	0.34 ± 0.09	83 ± 13
245 4394.237 207	0.7129	0.45 ± 0.05	87 ± 9	0.38 ± 0.10	87 ± 8	0.32 ± 0.05	87 ± 4
245 4394.248 885	0.7402	0.58 ± 0.02	80 ± 3	0.48 ± 0.07	91 ± 10	0.45 ± 0.04	91 ± 3
245 4394.260 643	0.7676	0.57 ± 0.02	81 ± 2	0.49 ± 0.03	85 ± 3	0.44 ± 0.07	85 ± 10
245 4394.273 964	0.7988	0.58 ± 0.02	79 ± 3	0.49 ± 0.01	89 ± 6	0.45 ± 0.01	89 ± 6
245 4407.216 597	0.3428	0.46 ± 0.03	90 ± 4	0.24 ± 0.01	95 ± 3	0.34 ± 0.01	89 ± 3
245 4408.203 042	0.6699	0.48 ± 0.02	82 ± 3	0.36 ± 0.03	88 ± 3	0.36 ± 0.02	84 ± 2
245 4421.047 389	0.9814	0.63 ± 0.05	98 ± 3	0.46 ± 0.08	98 ± 5	0.47 ± 0.04	93 ± 2
245 4421.058 511	0.0078	0.61 ± 0.07	104 ± 6	0.45 ± 0.04	105 ± 5	0.46 ± 0.05	103 ± 3
245 4421.103 554	0.1133	0.61 ± 0.03	101 ± 2	0.47 ± 0.04	100 ± 3	0.49 ± 0.09	97 ± 6
245 4421.132 452	0.1826	0.56 ± 0.05	100 ± 3	0.40 ± 0.05	93 ± 3	0.41 ± 0.06	99 ± 4
245 4422.165 401	0.6201	0.45 ± 0.04	80 ± 3	0.37 ± 0.03	86 ± 5	0.37 ± 0.03	85 ± 3
245 4454.050 914	0.8662	0.61 ± 0.04	101 ± 2	0.47 ± 0.05	99 ± 3	0.47 ± 0.06	98 ± 3

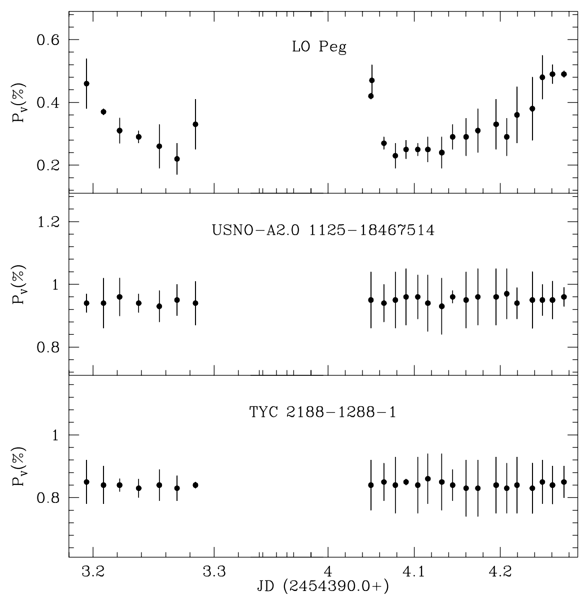

Figure 1. *V*-band polarimetric light curve of LO Peg (top panel), USNO-A2.0 1125-18467514 (middle panel) and TYC 2188-1288-1 (bottom panel)

dal & Tas (2003). Figs 3(a) and (b) show the plots of normalized Stokes vectors q and u in *B, V* and *R* bands as a function of photometric phase, respectively. It appears that both q and u vectors depend on the stellar longitude. Light scattering by circumstellar material in LO Peg could give rise to harmonic variations in observed polarization with rotational period. The Fourier fitting of the observational data with the orbital phase (ϕ) is commonly used to analyse the polarization variability in binaries (e.g. Berdyugin et al. 2006). However, this type of analysis is useful for polarimetric variability in single spotted star, because, e.g., a single spot can give power in the second harmonics due to scattering phase function:

$$P_\lambda(\phi) = A + \sum_{k=1}^{2} B_k \cos(k2\pi\phi) + \sum_{k=1}^{2} C_k \sin(k2\pi\phi), \qquad (2)$$

where ϕ is rotational phase. First, a first-order Fourier series was fitted to the polarimetric waves. To see the presence of second harmonic (if any) in the polarimetric waves, later we fit a second-order Fourier series to the data. Results of these fits with reduced χ^2 (χ^2_ν) are given in Table 5. The best fits with the polarimetric data are shown in Fig. 3, where dotted and continuous lines are the weighted first- and second-order Fourier fits, respectively. Fig. 3 and Table 5 clearly show that the fit of the second-order Fourier series improves the χ^2_ν for *B* and *V* filters. However, for *R* filter no significant improvement was found in the χ^2_ν while fitting the data with the second-order Fourier series. The semi-amplitudes of the

Table 3. *V*-band polarization and position angle of USNO-A2.0 1125-18467514 (star1) and TYC 2188-1288-1 (star2).

JD 245 4000.0+	star1 P_V (per cent)	θ_V (°)	star2 P_V (per cent)	θ_V (°)
393.194 613	0.94 ± 0.03	99 ± 2	0.85 ± 0.07	98 ± 10
393.208 640	0.94 ± 0.08	100 ± 3	0.84 ± 0.06	107 ± 6
393.221 914	0.96 ± 0.06	99 ± 3	0.84 ± 0.02	107 ± 2
393.237 712	0.94 ± 0.03	102 ± 2	0.83 ± 0.03	104 ± 9
393.254 632	0.93 ± 0.05	97 ± 5	0.84 ± 0.05	99 ± 8
393.269 319	0.95 ± 0.05	104 ± 5	0.83 ± 0.04	96 ± 7
393.284 503	0.94 ± 0.07	100 ± 3	0.84 ± 0.01	98 ± 2
394.049 720	0.95 ± 0.09	99 ± 4	0.84 ± 0.08	96 ± 9
394.064 950	0.94 ± 0.06	98 ± 8	0.85 ± 0.06	101 ± 6
394.078 097	0.95 ± 0.09	100 ± 7	0.84 ± 0.09	94 ± 8
394.090 643	0.96 ± 0.09	90 ± 8	0.85 ± 0.01	88 ± 2
394.104 149	0.96 ± 0.07	101 ± 3	0.84 ± 0.09	100 ± 11
394.115 896	0.94 ± 0.09	97 ± 12	0.86 ± 0.08	103 ± 6
394.132 122	0.93 ± 0.09	98 ± 8	0.85 ± 0.09	97 ± 5
394.144 725	0.96 ± 0.02	95 ± 2	0.84 ± 0.05	94 ± 2
394.160 279	0.95 ± 0.09	106 ± 5	0.83 ± 0.09	107 ± 9
394.173 994	0.96 ± 0.09	108 ± 8	0.83 ± 0.09	104 ± 4
394.195 231	0.96 ± 0.09	97 ± 12	0.84 ± 0.09	102 ± 5
394.207 499	0.97 ± 0.08	96 ± 11	0.83 ± 0.08	98 ± 7
394.219 419	0.94 ± 0.05	109 ± 3	0.84 ± 0.09	93 ± 5
394.237 207	0.95 ± 0.09	99 ± 5	0.83 ± 0.08	90 ± 5
394.248 885	0.95 ± 0.05	92 ± 6	0.85 ± 0.07	94 ± 6
394.260 643	0.95 ± 0.06	99 ± 3	0.84 ± 0.06	97 ± 8
394.273 964	0.96 ± 0.03	102 ± 2	0.85 ± 0.05	98 ± 3
407.216 597	0.93 ± 0.05	83 ± 2	0.84 ± 0.05	85 ± 2
408.203 042	0.96 ± 0.07	101 ± 3	0.85 ± 0.09	97 ± 5
421.047 389	0.94 ± 0.08	96 ± 7	0.84 ± 0.08	101 ± 7
421.058 511	0.94 ± 0.06	104 ± 2	0.85 ± 0.06	107 ± 2

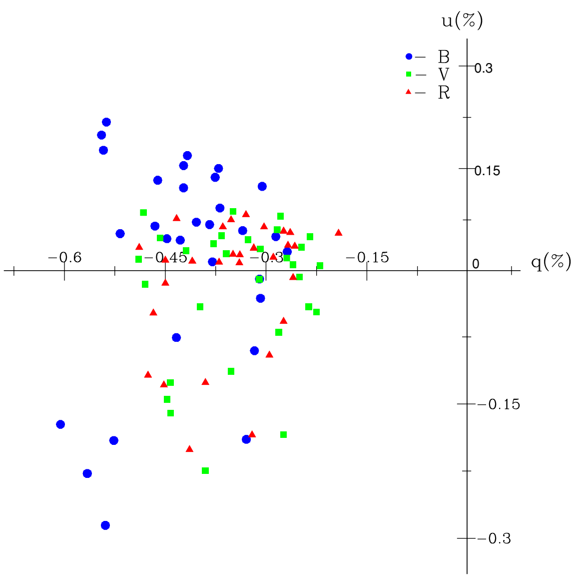

Figure 2. Normalized Stokes parameters of LO Peg plotted in the (q, u) plane for B(●), V(■) and R(▲) bands.

polarimetric waves are determined by using the relation $\Delta P = \sqrt{(B_1^2 + C_1^2)}$. The semi-amplitudes of q and u waves are thus determined to be 0.12 ± 0.03 and 0.17 ± 0.03, 0.10 ± 0.03 and 0.09 ± 0.02, and 0.10 ± 0.02 and 0.07 ± 0.02 in *B, V* and *R* bands, respectively.

Table 4. *V*-band polarization and the position angle of the stars lying within the radius of 8 arcmin from LO Peg.

ID	USNO A2- No.	*B* (mag)	P_V (per cent)	θ_V (°)
1	1125-18467514	12.5	0.76 ± 0.08	98 ± 9
2	1125-18470176	14.5	1.16 ± 0.09	96 ± 3
3	1125-18467687	15.5	1.96 ± 0.07	86 ± 3
4	1125-18466948	14.0	0.59 ± 0.04	85 ± 2
5	1125-18465461	14.5	2.19 ± 0.09	47 ± 2
6	1125-18463910	14.6	2.97 ± 0.09	178 ± 2
7	1125-18463552	15.5	3.21 ± 0.19	140 ± 2
8	1125-18466649	15.4	1.02 ± 0.05	87 ± 2
9	1125-18467076	14.8	0.71 ± 0.07	16 ± 3
10	1125-18472889	13.5	0.65 ± 0.10	98 ± 5
11	1125-18471384	12.6	0.67 ± 0.09	101 ± 7
12	1125-18470313	14.7	1.52 ± 0.09	98 ± 5
13	1125-18466610	15.5	3.40 ± 0.25	84 ± 2
14	1125-18468115	15.3	3.46 ± 0.02	102 ± 2
15	1125-18469000	15.8	0.74 ± 0.06	114 ± 3
16	1125-18473126	15.6	1.81 ± 0.07	112 ± 2
17	1125-18472836	15.9	3.27 ± 0.22	101 ± 3

3.2 Photometric variability

Photometric light curves in *B, V* and *R* bands are obtained from the polarimetric data. The stars USNO-A2.0 1125-18467514 and TYC 2188-1288-1 were used as comparison and check stars, respectively. Differential photometry in the sense of subtracting the comparison from the variable was done, as all the program, comparison and check stars were in the same CCD frame. Variations in the *B, V* and *R* magnitudes (ΔB, ΔV and ΔR) of the program star are shown in left-hand panel of Fig. 4. The different measures of comparison and check stars (ΔV_c) are shown in the bottom plot of left-hand panel of Fig. 4. The standard deviation (σ) of the different measures of the comparison and check stars was determined to be 0.012 in *B*, 0.008 in *V* and 0.012 in *R* filters. This implies that the comparison star was constant during the observations. The phase of minima was determined by a linear least-square fitting of the second-order polynomial at the minimum of light curve. The minima was thus determined to be 0.27 ± 0.05, 0.30 ± 0.05 and 0.30 ± 0.05 in *B, V* and *R* bands, respectively. Recently, Pandey et al. (2005) found that the phase minima in the light curve of the star LO Peg shifts with a rate of 0°.85 per day. Using this value of the phase shift and the mean epoch of present polarimetric observations (JD = 245 4403.37), the minimum of the phase was computed to be 0.3, which is similar to that obtained from the photometric light curve. We have also fitted the first- and second-order Fourier series to the photometric light curves, and these are shown by dotted and continuous lines, respectively in Fig. 4. The results of these fits are given in Table 5. The second-order Fourier fit over the first-order Fourier fit to these data reduces the χ^2_ν by 20 per cent at least. This implies that the photometric variability is probably due to two inhomogeneous regions on the surface of the star. The photometric amplitudes in *B, V* and *R* bands are determined to be 0.08, 0.05 and 0.05 mag, respectively.

To compare the photometric variations with that of polarimetric variations, we have plotted the degree of polarization as a function of photometric phase in the right-hand panel of Fig. 4. The dependence of polarization on the stellar longitude is clearly seen. The minimum of polarimetric light curve was determined to be 0.37, 0.40 and 0.40 in *B, V* and *R* filters, respectively. These values of

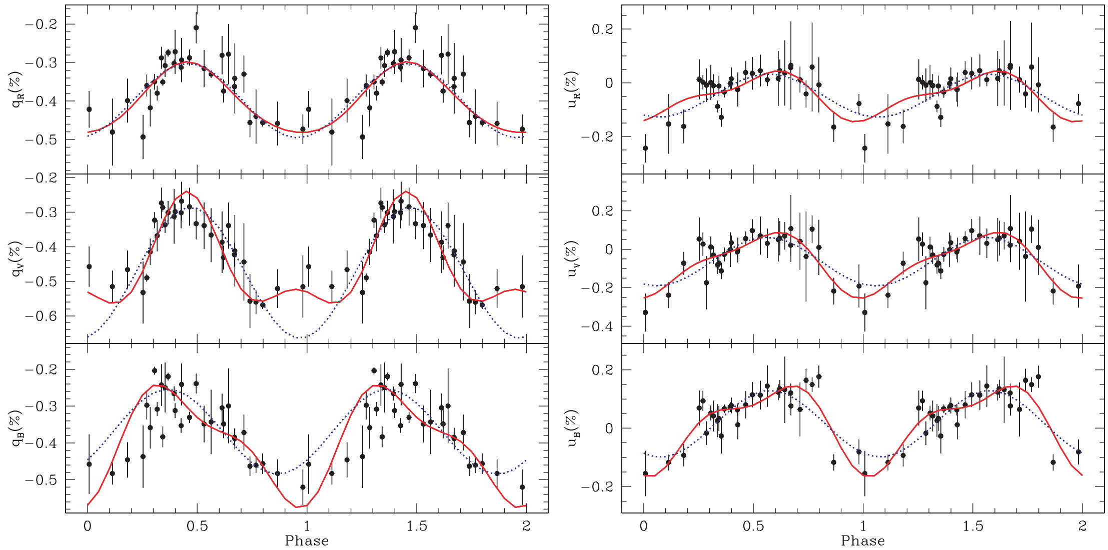

Figure 3. *B, V* and *R* polarimetry of LO Peg expressed in terms of the normalized Stokes parameters $q = P \cos 2\theta$ and $u = P \sin 2\theta$, plotted against rotational phase. The dotted and continuous lines are the weighted first- and second-order Fourier fits, respectively.

Table 5. Results from the Fourier fit.

Filter	A	B_1	C_1	B_2	C_2	χ^2_ν/d.o.f.
			q			
B	−0.445 ± 0.011	0.091 ± 0.011	−0.082 ± 0.018			2.37/28
	−0.476 ± 0.012	0.082 ± 0.012	−0.127 ± 0.019	−0.005 ± 0.014	−0.055 ± 0.013	2.04/26
V	−0.406 ± 0.007	0.033 ± 0.008	−0.167 ± 0.015			1.84/28
	−0.387 ± 0.010	0.036 ± 0.007	−0.122 ± 0.015	−0.038 ± 0.009	0.053 ± 0.011	1.49/26
R	−0.390 ± 0.005	0.027 ± 0.005	−0.097 ± 0.008			1.44/28
	−0.390 ± 0.009	0.023 ± 0.008	−0.093 ± 0.013	−0.007 ± 0.008	0.007 ± 0.008	1.44/26
			u			
B	−0.007 ± 0.012	−0.080 ± 0.013	−0.153 ± 0.018			1.57/28
	−0.029 ± 0.010	−0.078 ± 0.012	−0.183 ± 0.016	−0.004 ± 0.012	−0.084 ± 0.01	1.26/26
V	−0.035 ± 0.008	−0.033 ± 0.008	−0.084 ± 0.011			0.99/28
	−0.040 ± 0.007	−0.024 ± 0.010	−0.106 ± 0.011	0.022 ± 0.009	−0.025 ± 0.009	0.90/26
R	−0.021 ± 0.007	−0.031 ± 0.008	−0.067 ± 0.011			1.17/28
	−0.021 ± 0.007	−0.015 ± 0.012	−0.071 ± 0.010	0.024 ± 0.011	−0.015 ± 0.008	1.11/26
			Light curve			
B	−2.254 ± 0.003	0.036 ± 0.004	0.011 ± 0.004			0.84/28
	−2.254 ± 0.002	0.031 ± 0.003	0.014 ± 0.003	−0.012 ± 0.003	0.010 ± 0.002	0.60/26
V	−1.729 ± 0.002	0.024 ± 0.002	−0.002 ± 0.002			0.77/28
	−1.738 ± 0.001	0.023 ± 0.002	0.001 ± 0.002	−0.004 ± 0.002	0.005 ± 0.002	0.65/26
R	−1.564 ± 0.002	0.022 ± 0.002	−0.002 ± 0.002			1.03/28
	−1.563 ± 0.001	0.020 ± 0.002	0.0005 ± 0.002	−0.004 ± 0.002	0.006 ± 0.002	0.80/26

Note. d.o.f. is degree of freedom.

minima are slightly more than that of the corresponding photometric phase minima of the same epoch. This implies that variation in the degree of polarization of the star appears to be correlated with its photometric brightness. The significance of correlation has been calculated by determining the linear correlation coefficient r between the magnitude and the degree of polarization. The value of r between ΔB and P_B, ΔV and P_V, and ΔR and P_R was found to be −0.28, −0.47 and −0.16 with the corresponding probability of no correlation being 0.013, 0.008 and 0.043, respectively. The semi-amplitudes of polarimetric waves are determined to be 0.18 ± 0.02, 0.13 ± 0.01 and 0.10 ± 0.02 per cent in *B, V* and *R* bands, respectively.

4 DISCUSSION AND CONCLUSIONS

We have carried out analysis of the *B*-, *V*- and *R*-band polarimetric observations of the single late-type active dwarf LO Peg. A polarization up to 0.63 per cent in *B* band was observed. Our analysis shows that polarization in LO Peg is intrinsic rather than having an interstellar origin. Further, the existence of a time-dependent

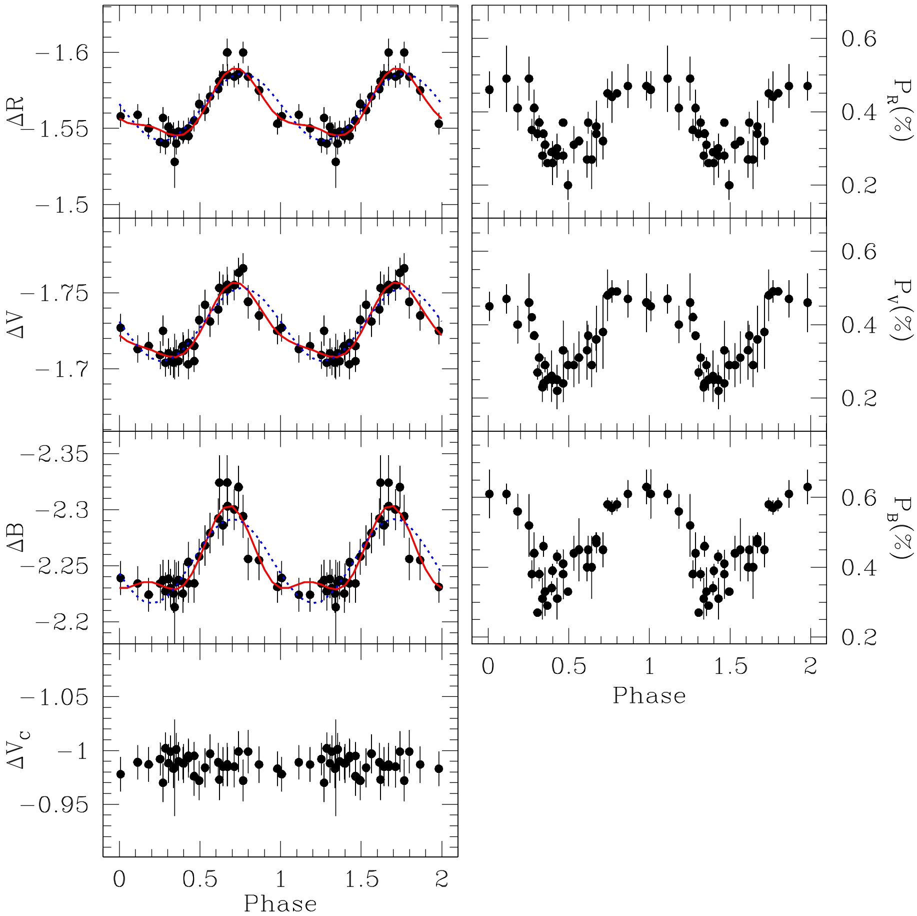

Figure 4. Left-hand panel: three upper plots show *B*-, *V*- and *R*-band light curves of LO Peg folded using the period 0.423 75 days. The lowermost plot shows the differential light curve of comparison star with respect to check star. Right-hand panel: *B, V* and *R* polarimetric light curve of LO Peg as a function of photometric phase. The dotted and continuous lines in the right-hand panel are the weighted first- and second-order Fourier fits, respectively.

polarization is a well-established criterion for intrinsic polarization (Zellner & Serkowski 1972). Such a large polarization was also observed for the active dwarfs MS Ser (0.4 per cent in *U* band; Alekseev 2003), LQ Hya (0.28 per cent in *U* band; Alekseev 2003) and TU Pyx (0.5 per cent in *V* band; Clarke, Smith & Yudin 1998). However, polarization in LO Peg was found to be much more than that of some solar-type (G-type) stars, where observed polarizations were of the order of 10^{-2} per cent (Leroy & Le Borgne 1989). The observed polarization in LO Peg was found to decrease towards longer wavelength. Similar trend has been observed for the most of active stars (e.g. Yudin & Evans 2002; Rostopchina et al. 2007). This could be due to a number of factors. For example (i) selective absorption by circumstellar dust, which grows towards shorter wavelengths. As a result, the ratio of the intensity of the scattered (polarized) light to the intensity of star's light coming directly to us (unpolarized) increases with decreasing wavelength of the radiation. (ii) Wavelength-dependent albedo, which decreases towards longer wavelengths resulting less scattering and thus polarization. The mechanism of the polarization in these stars is best interpreted by magnetic intensification or scattering by circumstellar material. Below, we discuss on the origin of polarization.

Magnetic polarization has been modelled in a number of studies, and the degree of polarization is assumed to depend linearly on the size of magnetized region (e.g. Mullan & Bell 1976; Calamai & Degl'Innocenti 1983; Degl'Innocenti 1983). However, later on it was demonstrated that this dependence becomes non-linear for large regions (see Huovelin & Saar 1991; Saar & Huovelin 1993). In particular, for a single circular region the degree of polarization will be proportional to a factor of *A*, which approximately depends on the area of the region (*f* in per cent) as (Saar & Huovelin 1993)

$$A(f) = \frac{P_S(f)}{P_S(f = 1\text{percent})} \approx -2.128 \times 10^{-4} + 1.076f - 4.812f^2 + 9.058f^3 - 6.26f^4. \quad (3)$$

Saar & Huovelin (1993) have also calculated a grid of expected degrees of polarization in *UBVRI* bands for the stars having temperatures from 4000° to 7000° K and log *g* from 2.0 to 4.5. We have used their results to compare with our observed values of maximum polarization of LO Peg. The maximum values of the degree of polarization (P_S) in *B, V* and *R* bands for the LO Peg were found to be 0.63 ± 0.05, 0.49 ± 0.05 and 0.48 ± 0.09 per cent, respectively. Fig. 5 represents the maximum degree of polarization for LO Peg in *B, V* and *R* bands. The maximum possible degree of polarization for total spot area of $f \approx 24$ per cent is derived from the calculations of Saar & Huovelin (1993) for a star corresponding to the spectral type of K7V and characteristic magnetic field of 2.7 kG. These values are overplotted as a solid line in Fig. 5. The maximum observed *B*-, *V*- and *R*-band polarization exceeds the theoretical values expected for the Zeeman polarization model. This is probably due to the presence of a supplementary source of linear polarization, such

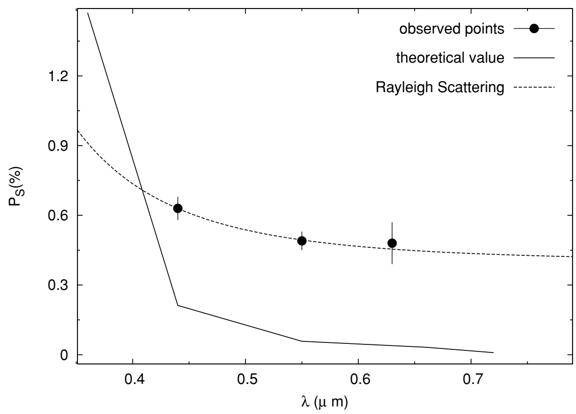

Figure 5. Wavelength dependence of the degree of polarization. The observed data points are represented by solid dots, and solid curve shows the expected theoretical values. Dashed line shows the Rayleigh scattering.

as remnant of circumstellar disc or envelope, which produces the linear broad-band polarization.

The present polarimetric observations of LO Peg show a clear variation in q and u. The maximum variability in the polarization was observed in B band. Variations up to 0.7 per cent in U band for a K dwarf MS Ser (Alekseev 2003, 2000), 0.1 per cent in B and V bands for F9 dwarf 59 Vir (Clarke et al. 1998) were also observed. The variations in the polarization appear to be correlated with the photometric variations (i.e. variation in P per cent closely followed the variations in brightness, in the sense that when the star was brighter P was higher). This implies that the surface brightness inhomogeneity seems to play a major role in the polarization variability of LO Peg. Inhomogeneities in the distribution of both the material in the circumstellar envelope and brightness on the surface of the illuminating star can provide the necessary asymmetry, and hence produces a net polarization in the integrated light (Menard & Bastien 1992). The dark spots and the possible associated plage regions produce the variation in the relative fluxes of the radiation in different bands across the stellar surface, which thereby produce the variation in observed polarization. The mechanism which can produce periodic linear polarization variability is Rayleigh or Thomson scattering in a non-spherically symmetric distribution of circumstellar material. This has been discussed by Brown & McLean (1977) and Simmons (1982) for a single star with a distortion produced by rotation. More recently, Al-Malki et al. (1999) have discussed the scattering polarization arising from light source anisotropy. However, the absence of near-infrared (IR) (Pandey et al. 2005) and mid-IR (Chen et al. 2005) excess indicates that no dusty disc is present up to a distance of ∼30 au around LO Peg. At this distance, the scattered radiation will be diluted which results in a low level of the polarization. The polarization arising from the scattering by an equatorial thin disc with an inclination angle of 70° is theoretically calculated to be <0.2 per cent (e.g. Hoffman, Whitney & Nordsieck 2003), which is less than that observed in LO Peg. Al-Malki et al. (1999) showed that a ∼0.5 per cent of polarization can be achieved from an anisotropic light source scattered by a Maclaurian spheroidal envelope ($a = b = 1$ and $c \approx 0.6$) with an optical depth of 0.1 and an angle of inclination of 60°. The axial inclination of LO Peg is 50° ± 10° (Eibe et al. 1999).

The other possible region for the polarization of LO Peg is the presence of the solar prominence-like structures, which are made of the condensed cool matter suspended in the corona by magnetic fields. Cool clouds of neutral material forced to corotate with underlying star have been detected in the fast-rotating K dwarf AB Dor, several G dwarfs in α Per and the active M dwarf HK Aqr and RE 1816+541 (Collier Cameron & Robinson 1989a,b; Collier Cameron & Woods 1992; Byrne, Eibe & Rolleston 1996; Eibe 1998). The characteristic dimensions and heights of these structures are considerably larger than solar prominences. The lifetimes and growth time-scales of these clouds vary from few days to few months (e.g. see Pfeiffer 1979; Jeffries 1993). Recent optical spectroscopic observations of LO Peg by Eibe et al. (1999) have suggested the evidence of downflow of material. They also suggested that the possibility of the condensations of cool prominence cloud cannot be ruled out. If most of the scatterer were gas atoms or molecules on the clouds, then the Rayleigh scattering from the star dominates in contributing the polarization (see Fig. 5). Assuming that the size of the cool prominence cloud is small as compared with the distance from the star, the polarization is given by (Pfeiffer 1979)

$$P = \frac{N\sigma f}{r_c^2 + N\sigma f}. \tag{4}$$

For the Rayleigh scattering,

$$\sigma f = \left(8\pi e^4/3m_e^2c^4\right)(\lambda_0/\lambda)^4[3(\cos^2\phi + 1)/16\pi], \tag{5}$$

where f is the angular scattering function, σ is the scattering cross-section, N is the number of scatterer, r_c is the distance of the cloud from the star and ϕ is the scattering angle. If we assume that cool prominence cloud contains mostly hydrogen in the ground state, the resonant wavelength λ_0 is 0.122 μm. Thus, for $P_V = 0.35$ per cent and assuming the cloud is located at the Keplerian corotation radius [$r_c = (GM_\star/\Omega^2)^{1/3} = 2.83R_\star$, $M_\star$ and $R_\star$ are stellar mass and radius, respectively, $\Omega = p/2\pi$ and p is rotational period] and scattered radiation received from the circumstellar cloud is completely polarized ($\phi = 90°$), equation (4) yields $N = 1.1 \times 10^{48}$. If the cloud is mostly hydrogen, this amounts to about 1.7×10^{24} g, which is of the order of 6 to 7 more than the estimated mass of the cloud of stellar prominences and of the order of ∼10 more than the solar quiescent prominence (Collier Cameron et al. 1990; Collier Cameron 1996; Low, Fong & Fan 2003). However, this value of mass is only an order larger than the mass-loss rate (2.0×10^{-11} $M_\odot$ yr^{-1}; Chen et al. 2005) observed for LO Peg. Each particle in the cloud can be considered to have an effective cross-sectional area of σf as seen by the observer. Therefore, the minimum projected area of the cloud on to the plane of the sky is $N\sigma f$. This leads to the minimum value of the area of the order of 10^{21} cm^2. This value of area is comparable to the stellar and solar prominence areas (Collier Cameron 1996). The estimated mass is too large to be produce by single solar-type prominence. This value would be an upper limit if all the scattering atoms in the star are not located in this compact, spherical cloud. Further, N would be considerably less if scatterers were closer to the star than the assumed distance.

The average values of the polarization position angles were found similar in B, V and R bands. This indicates that the scattering geometry is identical at all wavelengths. We have plotted the average values of polarization (P) of dwarfs against ($B - V$) colour to see the possible spectral-type dependence of polarimetric variations. The polarization values of other dwarf spectral classes are taken from Huovelin, Saar & Tuominen (1988) and Alekseev (2003). The distribution in the B and V bands indicates increasing linear polarization towards later spectral type. Similar trend was also observed by Huovelin et al. (1988) in U band for main-sequence stars. The values of linear polarization in B and V band for LO Peg are

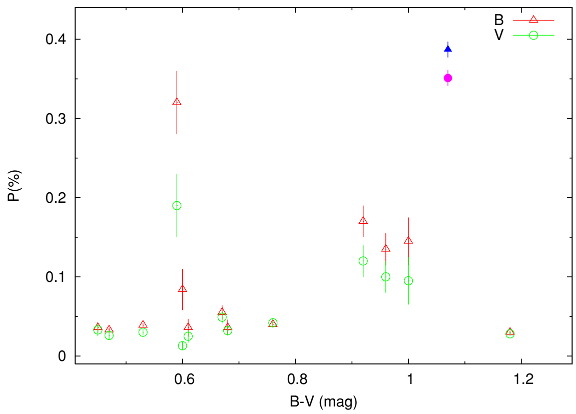

Figure 6. The average values of polarization (P) in B and V bands versus ($B-V$) colour. The polarization of LO Peg in B and V bands is represented by solid circle and solid triangle, respectively.

also shown in Fig. 6. It appears that the observed values of linear polarization for LO Peg follow the trend seen for the main-sequence stars.

If we compare the present photometric light curve of LO Peg with previous observations by Pandey et al. (2005), a shift in the phase of the minimum and a variable amplitude are quite evident. This implies that photometric variation is due to the inhomogeneities on the surface of the star. The best-fitting second-order Fourier series indicates that the presence of two inhomogeneous region on the surface of the star. Similar signature was also reported by Pandey et al. (2005).

Therefore, we conclude that high values of polarization observed in LO Peg require either a spheroidal envelope with an optical depth of 0.1 or a clumpy material (e.g. solar prominence-like structures) of mass of the order of $\sim 10^{-10}\,M_{\odot}$.

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