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Discovery of the variable phase-locked polarization in LZ Cephei

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Abstract. The early-type non-eclipsing binary LZ Cep has been observed with the UBVRI polarimeter during 25 nights in 1996–1997. A variable phase-locked linear polarization has been found. The principal Fourier components of the observed variations are the second harmonics of the orbital period. The most probable explanation of this variability is reflection of the radiation from each component of the binary off the facing hemisphere of its companion. We have constructed a simple numerical model of the reflection process which is capable of reproducing the amplitude and phase dependence of the polarized light-curve.

Key words: stars: binaries: close – stars: early-type – stars: individual: LZ Cep

1. Introduction

Various light scattering effects in interacting binaries often result in variable broad-band linear polarization. In many cases, polarimetry may yield valuable information on the structure of envelopes, gaseous streams and stellar winds (e.g. St.-Louis et al. 1988; Moffat & Piirola 1993; Harries & Hilditch 1997; Berdyugin 1998). In some systems these variations are synchronised with the orbital motion. The principal approach for analysis of the phase-locked variable polarization in close binaries has been outlined by Brown et al. (1978, hereafter BME). Information on distribution of light scattering material and the inclination of the orbit may be derived. Hence polarimetry serves as a useful tool for the study of close binaries in addition to the traditional spectroscopic and photometric techniques.

LZ Cep (HD 209481) is a double-lined spectroscopic binary consisting of O8.5 III and O9.5 V stars. It is a semi-detached interacting system, with the secondary star filling its Roche lobe. The light curve displays ellipsoidal variations with the amplitude about $0\overset{\mathrm{m}}{.}10$ without indications for eclipses (Hill et al. 1976). Recent high-quality spectroscopic observations have shown that the secondary is significantly overluminous in comparison with a zero-age main-sequence star of the same mass. The system is supposed to be at the final slow stage of case A mass transfer (Howarth et al. 1991, Harries et al. 1998).

LZ Cep has been chosen as a target for a programme of polarimetric investigation of early-type interacting binaries at the Crimean Astrophysical Observatory. The latest results of this programme include discovery of variable phase-locked polarization in V373 Cas (B0.5 II-Ib + B0.5 III) (Berdyugin, 1998) and in HD 187399 (B8III +?) (Berdyugin & Tarasov, 1998).

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2. Observations

The observations have been made with the UBVRI photometer-polarimeter (Korhonen et al. 1983) attached to the 1.25 m telescope of Crimean Astrophysical Observatory. The data have been collected over 25 nights in 1996–1997[1]. Each data point has been obtained by averaging of 12–16 single measurements. The observational error of the normalised Stokes parameters (q, u) is about of 0.02–0.04%. The instrumental polarization has been determined from regular observations of the standard non-polarized stars HD 144287 and HD 65583. It was found to be about 0.2% in U band and $\leq$ 0.05% in other passbands. In order to transform the observed polarization from the instrumental to the equatorial coordinate system, the highly polarized standard star HD 204827 was observed.

3. Polarization variability

The polarization variability of LZ Cep is shown in Fig. 1 as dependence of measured Stokes parameters on the phase of the orbital period. The ephemeris in Fig. 1 corresponds to ϕ=0 at JD 2446650.388 with a period of 3.070507 days (Harries et al. 1998). The amplitude of peak-to-peak variations is the largest (∼0.3%) in the U band and smallest (∼0.1%) in the I band. As seen from Fig. 1, correlation of the variability with binary's orbital motion is obvious. In accordance with the BME approach, variations of the normalised Stokes parameters are represented as functions of orbital phase by the Fourier series which include first and second harmonics terms:

[1] The data are available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html.

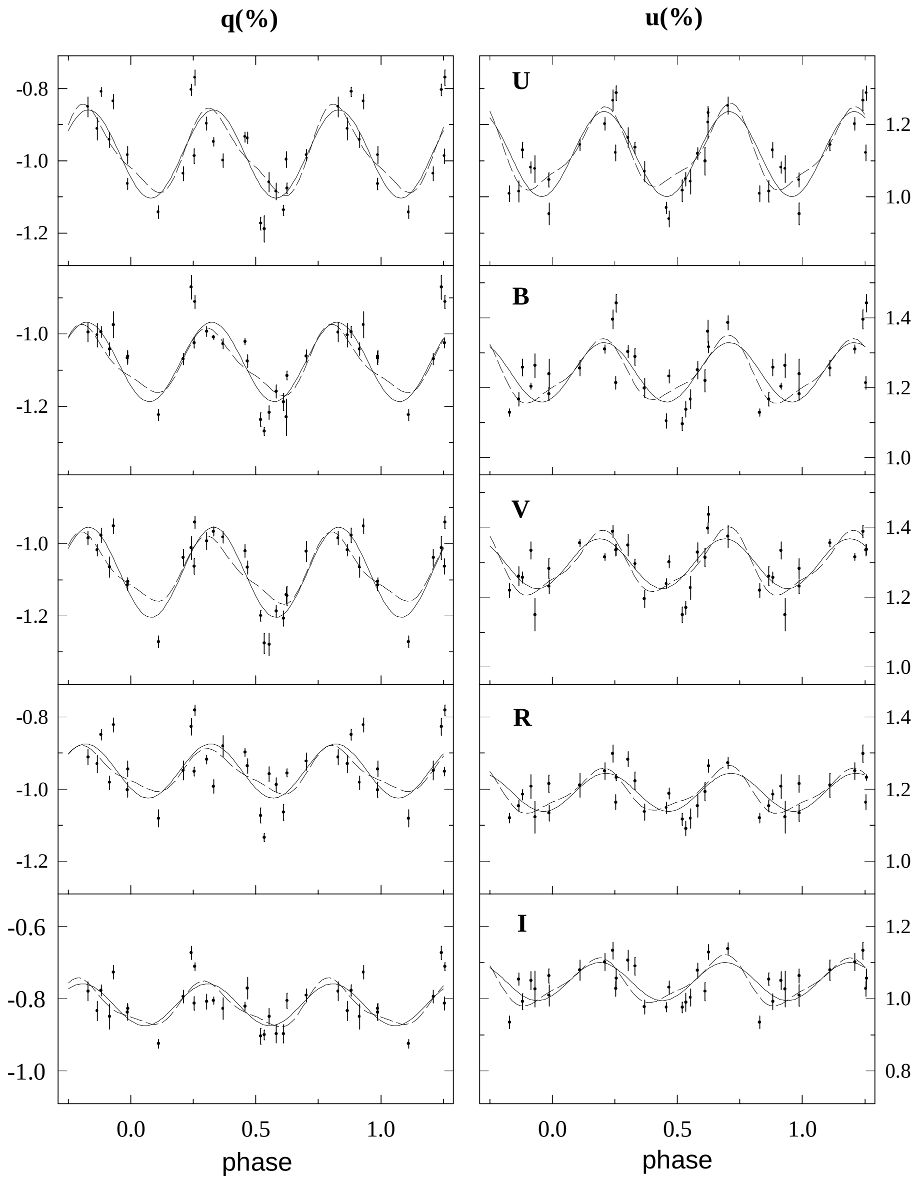

Fig. 1. Normalized Stokes parameters q and u for LZ Cep plotted against orbital phase for UBVRI passbands. Vertical bars are 2σ errors. The solid and dashed lines are the best fits of the data by the Fourier series and reflectional model, respectively.

$$\begin{aligned} q &= q_0 + q_1\, cos(\lambda) + q_2\, sin(\lambda) \\ &\quad + q_3\, cos(2\,\lambda) + q_4\, sin(2\,\lambda), \\ u &= u_0 + u_1\, cos(\lambda) + u_2\, sin(\lambda) \\ &\quad + u_3\, cos(2\,\lambda) + u_4\, sin(2\,\lambda), \end{aligned} \tag{1}$$

where $\lambda = 2\pi\phi$ and ϕ is the orbital phase.

The result of the Fourier fitting is shown in the Fig. 1 by solid line. It can be seen that the second harmonic variations clearly dominate the observed variability. The upper limit of the coefficients of the first harmonics is less than 0.02 for all passbands and the higher-than-second harmonic variations are even more negligible. For this reason, our final fit includes second harmonics only. The values of the Fourier coefficients are listed in Table 1.

The observed average value of polarization is rather large – about 1.5%. Since this binary is distant and has a significant reddening (=$0^{\mathrm{m}}\!.32$, Harries et al. 1998) it is quite natural to suppose that a substantial fraction of the observed vector is foreground in origin, arising from dichroic absorption by interstellar dust grains. According to Serkowski et al. (1975), the wavelength dependence of interstellar polarization follows the empirical law:

$$p(\lambda) = p_{max}\, e^{k\, ln^2(\lambda_{max}/\lambda)}, \tag{2}$$

where λ is a wavelength (in microns) and $k = 1.66\,\lambda_{max}$ (Whittet et al. 1992). The result of such an approximation for the average polarization of LZ Cep (the constant terms q_0 and u_0 in Fourier fitting) is shown in Fig. 2. The observed wavelength dependence is well-represented by the interstellar law. The best fit was obtained with P_{max}=1.66% and λ_{max}=0.51 μm. Therefore, the observed polarization of LZ Cep may be considered as a sum of a large intestellar component (with the typical interstellar wavelength dependence), and an intrinsic component whose magnitude is significantly smaller.

Table 1. Fourier coefficients, inclination i and weighting parameter γ for the UBVRI passbands

	U	B	V	R	I
q_0	-0.981±0.016	- 1.077±0.012	-1.080±0.010	-0.950±0.015	-0.817±0.010
q_3	-0.065±0.022	-0.066±0.016	-0.066±0.014	-0.048±0.020	-0.044±0.014
q_4	-0.104±0.022	-0.088±0.017	-0.106±0.014	-0.058±0.022	-0.038±0.015
u_0	1.118±0.011	1.244±0.014	1.296±0.011	1.191±0.010	1.048±0.010
u_3	-0.101±0.016	-0.073±0.020	-0.052±0.016	-0.048±0.013	-0.038±0.013
u_4	0.061±0.015	0.043±0.020	0.049±0.016	0.023±0.015	0.036±0.014
i	42°	63°	73°	69°	55°
γ	370	300	270	130	100

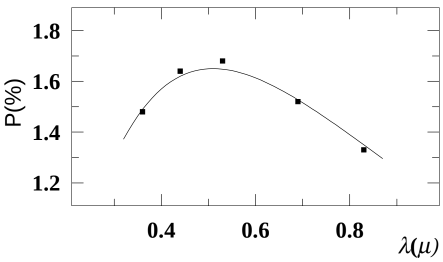

Fig. 2. Average polarization P of LZ Cep plotted against the effective wavelengths of the UBVRI passbands (0.36, 0.44, 0.53, 0.69, 0.83 μm). Solid line is the interstellar wavelength dependence approximation (see text)

4. Polarization mechanism

There are three possible mechanisms which can produce variable phase-locked polarization in the early-type binary like LZ Cep:

1. The light scattering off the circumbinary material (envelopes, streams, dense stellar wind). Several detailed spectroscopic investigations of LZ Cep have been carried out up to date (see Harries et al. 1998, and references therein), but no evidence for circumbinary material has been found so far. The stellar spectrum definitely lacks features which may be attributed to either an envelope or dense stellar wind. One must note, however, that it would be very difficult to find a spectroscopic signature of a narrow gaseous stream directed from the lobe-filling secondary to the primary. The light scattered off this stream may contribute to the observed variable polarization, although the likely electron-scattering optical-depth of such a feature would be such that the magnitude of polarization produced would be very small.

2. Tidal deformation polarization (TDP). It is very unlikely that TDP is responsible for such large variations as those observed in LZ Cep. The amount of TDP has been estimated for the visual primary (O9.5 Iab) in Cyg X-1 by Bochkarev et al. (1986) and Dolan (1992). They found that even if this star fills the Roche lobe, the total amount of TDP produced at the optical wavelengths is significantly smaller than 0.1%. Under this consideration, both primary and secondary stars in the LZ Cep system are seemed to be even less capable to produce a measurable magnitude of TDP.

3. Reflection of incident radiation from the close companions It seems that the most probable explanation for the observed intrinsic polarization in LZ Cep is a reflection effect. The photospheres of the two stars are of course highly ionized, and thus provide well-defined electron-scattering surfaces. A significant fraction of the radiation field from each star will be scattered in the photosphere of its companion (since the binary is close each star subtends a significant solid angle when view from the photosphere of its companion). As the geometry (photosphere-companion star-observer) is highly asymmetric and phase-dependent it is reasonable to suppose that reflection is the mechanism responsible for the polarization modulation.

5. Orbit inclination from the Fourier fit

Although the BME approach assumes the scattering by an optically thin cloud, it still may be applied, with some caution, to the reflection polarization. In the latter case a thin reflecting layer is considered to be present on the companion surface, while underlying photosphere is strongly absorbing. This layer acts as an optically thin gas cloud, giving rise to a phase-locked pattern of polarization which has similar geometrical characteristics to the BME model. Using standard formulae, we calculated the inclination i for all passbands (see Table 1). It is necessary to note, however, that this formulae often lead to a bias in the values of the inclination that are derived from it (Aspin et al. 1981; Simmons et al. 1982; Wolinski & Dolan 1994). On the other hand, accuracy of estimation definitely decreases toward the longer wavelengths as the amplitude of variations decreases. To account for that, the method proposed by Wolinski & Dolan (1994) has been aplied to derive the best estimate and confidence intervals for the inclination. The weighting parameter γ has been calculated for every passband and weighted average value of inclination i = 58° has been found. After that, using the diagram given in paper cited above, we derived the best estimate, 1σ and 2σ confidence intervals for the average inclination:

$\bar{i}$ = 57°; $46° \leq \bar{i} \leq 62°$; $0° \leq \bar{i} \leq 64°$

The resulting inclination, 57°, is rather in good agreement with the value of 53°, which was found by Harries et al. (1998) from a fit to the ellipsoidal photometric variations.

6. Reflection model

In order to investigate the validity of the reflection hypothesis we constructed a simple numerical model. The model consists of two spherical stars of radii R_1 and R_2 and temperatures of T_1

Table 2. Adopted parameters for the reflection model.

Parameter	Value	
	Primary	Secondary
Radius ($R_\odot$)	9.0	7.5
Temperature (K)	32 000	30 000
Limb-darkening	0.2	0.2
Albedo (α)	0.5	0.5
Separation ($R_\odot$)	24.6	
Inclination	53	

Table 3. The results of the least-squares fits of the data by reflectional model.

Band	Parameter			
	q_{is} (%)	u_{is} (%)	Ω (°)	β
U	-0.966 ± 0.005	$+1.151 \pm 0.004$	149.2 ± 1.0	0.51 ± 0.02
B	-1.077 ± 0.003	$+1.259 \pm 0.003$	152.1 ± 1.2	0.40 ± 0.01
V	-1.063 ± 0.004	$+1.312 \pm 0.004$	152.5 ± 1.3	0.40 ± 0.02
R	-0.945 ± 0.004	$+1.205 \pm 0.004$	152.1 ± 1.9	0.27 ± 0.02
I	-0.807 ± 0.004	$+1.057 \pm 0.004$	159.0 ± 1.9	0.27 ± 0.02

and T_2, at a separation a. Each stellar photosphere is divided into a large number of surface elements, distributed on a spherical polar grid. For each star we performed an integral over the stellar surface, first computing the flux emitted towards the observer (taking into account limb-darkening), and then computing (for each surface element on the companion star) the flux reflected towards the observer from the companion. This reflected flux depends on the stellar albedo, α. A fraction (β) of the reflected light was assumed to result from Thomson scattering, and the Stokes fluxes for this part of the reflected component were computed via the Rayleigh scattering phase matrix.

We fitted each of the polarized light-curve with the model, taking the stellar parameters and inclination from Harries et al. (1998), adopting 0.5 and 0.2 for the albedos and limb-darkening coefficients, and fitting for the interstellar polarization (q_{is} and u_{is}), the position angle of the line-of-nodes Ω, and the electron-scattering fraction of the reflected light β. The fits were made using a grid search followed by non-linear least-squares Marquardt minimization.

The fit results are listed in Table 3 and are shown in Fig. 1 by the dashed line. The fits are adequate, and the interstellar polarization values are in excellent agreement with the zeroth order Fourier terms listed in Table 1. The model polarization curves are dominated by the second harmonic of the period. Fourier fitting of the model polarization curves shows negligible power in the 1st and 3rd harmonics, as expected since the similar radii and temperatures of the two stars means that reflection from both the primary and secondary stars is of very nearly equal importance. In Sect. 5 the binary inclination was determined using a BME analysis. By peforming Fourier fits (zeroth and second-order harmonics only) to the data simulated by the reflectional model and using BME formulae we were able to recover the input inclination (53°) to an accuracy of $\pm 1°$, providing *a posteriori* justification for our application of the technique.

Although the range of β values determined from the fitting procedure are reasonable (indicating that about half the reflected light comes from electron-scattering) the model does not take into account multiple scattering–photons from the companion star which are scattered more than once in the heated hemisphere will result in flux that is less polarized than predicted from our single-scattering model. The values of β obtained should therefore be regarded as lower limits.

The effect of the reflection in integrated flux is very small (on the order of a three percent), which corresponds to about 0.03 magnitudes. The light-curve of LZ Cep (see Fig. 4 of Harries et al. 1998) is dominated by ellipsoidal variations due to the Roche geometries of the stars, with a range of 0.1 magnitudes, although there appears to be very marginal evidence in the $(O-C)$ plot for a systematic deviation from the fit at phase 0.5 (of about -0.04 magnitudes in U), which could be attributed to brightening due to reflection.

The wavelength dependence of the polarization amplitude is difficult to explain. Since electron-scattering is a grey process, one would expect the polarization to be constant with wavelength. If the components of the binary had significantly different temperatures, then one might expect the amplitude to fall with wavelength, since the relative dilution of the polarized flux by direct, unpolarized emission from the secondary star would increase. However, the temperatures of the components of LZ Cep are similar, and we must search for an alternative explanation. The limb-darkening, although small for early-type stars, does have an effect on the polarization, since the angular spread of the incident radiation on the reflecting surface decreases with increasing limb-darkening (the radiation field becomes more forward-peaked). Thus we expect the magnitude of the reflected polarization to decrease with decreasing limb-darkening. Although this trend is in the correct direction, the limb-darkening coefficient's wavelength dependence is too slow at 30 000 K to play a significant role. It is most probable that the decrease in polarization amplitude results from a wavelength dependence in the effective albedo, although detailed modeling of such an effect is beyond the scope of this study.

The derived values of Ω show variations as a function of pass-band which are greater than the fitting errors (see Table 3). The position-angle of the line-of-nodes is a geometrical parameter and should therefore be constant as a function of wavelength, and it is clear that the errors (which are derived from the covariance matrix diagonal) are underestimates of the true uncertainties on the fit parameters. The principal reason for this discrepancy is the presence of a stochastic component to the polarization variability, which exceeds the observational errors (see below). Such scatter is a ubiquitous feature of the phase-locked polarized light-curves of Wolf-Rayet+O binaries, and in those systems it is attributed to scattering offinhomogeneities (clumps) propagating through the stellar wind of the Wolf-Rayet star. The reflection hypothesis supposes that the polarized light is produced on well-defined electron-scattering surfaces (the stellar photospheres) and as such the polarized light-curve is expected to be much smoother. It is possible that the stochastic variability is the result of scattering off an intrabinary gas stream, or a tenuous stellar wind.

It seems as though the reflection mechanism may be a viable method for producing the polarized flux in LZ Cep, and indeed in any close binary lacking a dense circumstellar envelope. We intend to improve our model in order to make full use the diagnostic power of the phase-locked polarization. The principal enhancements currently required are the treatment of multiple scattering (which requires a Monte-Carlo radiative transfer in the photosphere), and the inclusion of Roche-lobe geometries for the two stars.

7. Conclusions

Collins & Buerger (1974) have shown that under certain conditions a large amount of polarization can arise as a result of light reflection in close binary system. In spite of this prediction, a few apparent cases of such 'reflectional' polarization have been reported so far. Rudy & Kemp (1977) claimed for this effect in u Her and Barbour & Kemp (1981) in HR 5110. In both cases the reported magnitude of variations is very small – well below 0.1% and there are clear indications that scattering on the gaseous streams or plasma concentrations cannot be ruled out as an alternative explanation. Recently some evidence for reflection effect in the polarization of V373 Cas has been found (Berdyugin 1998), although the scattering on the circumbinary material may also provide a significant contribution. The case of LZ Cep is very interesting, as it appears that reflection is solely responsible for the vast majority of the polarization variability. We note that observations of other close, early-type binary systems would provide a stringent test of the reflection model.

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