Long-term spot topography and multi-band flare analysis of active ultra-fast rotator LO Peg

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We present analyses of optical photometric and X-ray observations of the star LO Peg. Nearly 26 yrs of optical observations show that LO Peg is a periodic variable with a photometric period of 0.422853 ± 0.000005 d. Light curves observed at 47 epochs in V-band show changes in minima, amplitude and shape indicating that the variability is due to the presence of surface inhomogeneities. The surface coverage of spots was found to be in the range of 9-26 %. Most of the time, the spots were resolved as two active longitudes. The corona of LO Peg consists of a two temperature plasma of 3.24×10^6 K and 11.95×10^6 K. The average X-ray luminosity in the 0.3-10.0 keV energy band was found 3.56×10^{29} erg s^{-1}. Flaring features in optical V-band with flare energies of the order of 10^{33} erg were also noticed.

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1. Introduction

Magnetic activities of cool ultra fast rotators (UFR; vsin$i > 40$ km s^{-1}) are important as they are in the saturation or supersaturation ($L_X/L_{bol} \leq 10^{-3.0}$) regions of rotation activity diagram (e.g., Feigelson et al. 2003). Speedy Mic (P=0.3804; $L_X/L_{bol}=10^{-2.27}$), AB Dor (P=0.5139; $L_X/L_{bol}=10^{-2.93}$), HK Aqr (P=0.4312; $L_X/L_{bol}=10^{-3.37}$) and LO Peg (P=0.42312; $L_X/L_{bol}=10^{-3.0}$) are some famous examples of late-type active UFRs. Some of them are very active, e.g. AB Dor is showing ~ 4 flares per rotation period (Karmakar & Pandey 2015). However, others are relatively less active. Dark spots on the surface, flares from radio to X-rays are common magnetic activities in these cool UFRs (Strassmeier 2009). Stellar magnetic activities in these stars are not well understood due to the lack of spatial information. Therefore, indirect techniques e.g. Doppler imaging (Vogt & Pernoid 1983) and inversion techniques (Savanov & Strassmeir 2008) are useful. The high resolution and high signal-to-noise ratio spectroscopic observations with a good phase coverage as required for Doppler imaging are limited, therefore, long-term traditional photometric observations are important to understand the active region evolution and the stellar activity cycles (e.g. Olah et al. 1997; Pandey et al. 2005, Savanov 2010, Patel et al. 2013).

In this paper, we present analyses of long term optical and *S*wift X-ray observations of an UFR LO Peg. It is a young, K5V-K8V type and member of AB Doradus moving group (Zuckerman et al. 2004). Presence of strong flaring activity was identified by Jeffries et al.(1994) and Eibe et al. (1999) from H_α and He I D3 observations. Pandey et al. (2009) showed strong modulation in broad band linear polarization and suggested that it 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. The previous X-ray observations LO Peg from ROSAT estimated its X-ray luminosity to be $10^{29.7}$ erg s^{-1} (Pandey et al . 2005). However, present observations span over ~ 4 years to study the long term observations.

2. Observations and data reduction

LO Peg was observed with *Swift* satellite for several occasions from April 30, 2008 to July 2, 2012 (Obs IDs:00037810 ; PI S. B. Pandey & J. C. Pandey). The observations were made in soft X-ray band (0.3-10.0 keV) with X-Ray Telescope (XRT; Burrows et al. 2005) in conjunction with UV/Optical Telescope (UVOT; Gehrels et al. 2004) in UV bands (170-650 nm). The XRT exposure time of LO Peg ranges from 0.3 ks to 5.0 ks. X-ray light curves and spectra of LO Peg were accumulated from on-source counts obtained from circular regions on the sky centered on the X-ray peaks. The X-ray light curves and spectra for the source and background were extracted using the XSELECT package for the 0.3-10.0 keV energy band of both the cases. The background was accumulated from several neighboring regions at nearly the same offset as the program star.

We also observed LO Peg several times between October 25, 2009 and December 18, 2013 in Johnson U, B, V and R photometric bands with 1.04-m telescope of ARIES, Nainital using $2k \times 2k$ CCD camera, which covers $\sim 13' \times 13'$ of the sky. We make use of the various data in V band from literature (Jeffries et al. 1994, Pandey et al. 2005, 2009, Tas 2011) and archive. The archival data were taken from Hipparcos (Perryman et al. 1997), SuperWasp (Street et al. 2003, Pollacco et al.
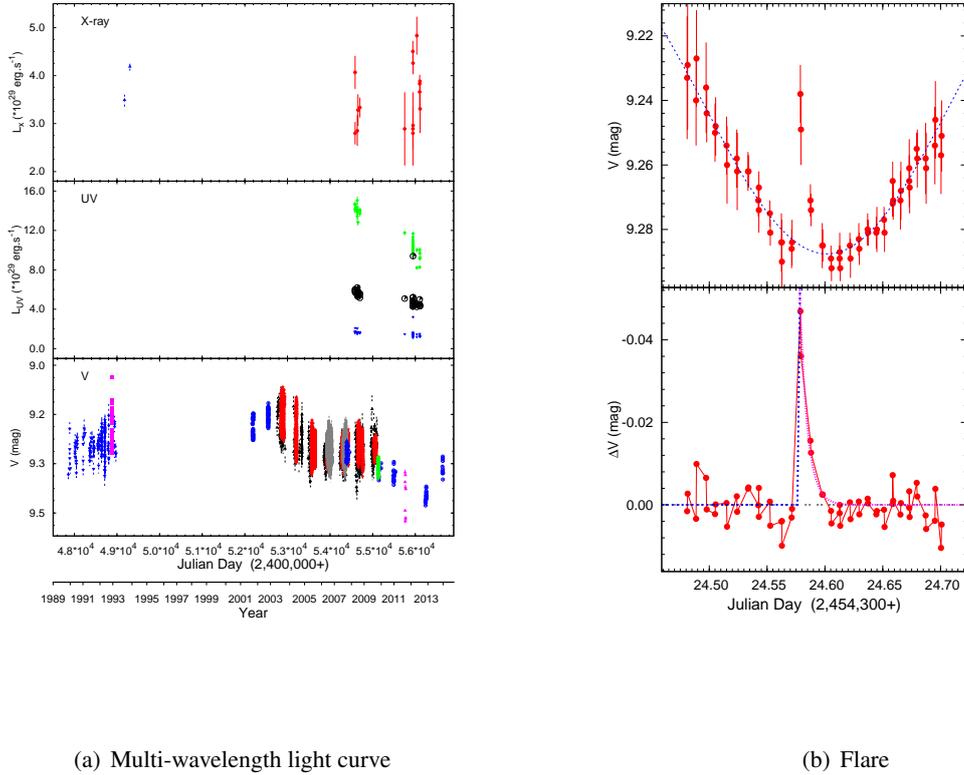
(a) Multi-wavelength light curve

(b) Flare

Figure 1: (a) Multiwavelength X-ray, UV and optical light curves of LO Peg. (b) V-band light curve showing flaring feature, the bottom panel shows detrended light curve.

2006) and All Sky Automated Survey (ASAS; Pojmansky 2002) observations. Optical broad band data were reduced using the standard tasks in IRAF.

3. Analysis and Results

### 3.1 Multi-wavelength light curves and Inhomogeneity map

The long term multiwavelength light curve of LO Peg is shown in Figure 1 (a). The long as well as short term variability was clearly observed in the V-band light curve. The long term variability in X-ray and UV band was also noticed. The periodogram analysis of V band data shows photometric period of LO Peg to be 0.422853 ± 0.000005 days. In order to see the short term variability/fluctuations, we have manually checked V-band light curve of each night observations. Apart from the short term rotational modulation, we have identified the flaring like feature in the V-band light curves. Top panel of Figure 1(b) shows the example of such flare like feature, where V-band light was enhanced suddenly and decayed gradually. In order to extract the flaring features only, we have removed the rotational modulation by fitting the sinusoidal function. The lower panel of Figure 1(b) shows the detrended light curve, where flaring feature is clearly noticed. We found 12 such flares from V-band data and flare frequency was derived to be ~ 1 flare per three days. Assuming that the star is a blackbody radiator, the flare energy is calculated as the excess energy

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(a) HJD=2453572.99

(b) HJD=2453617.51
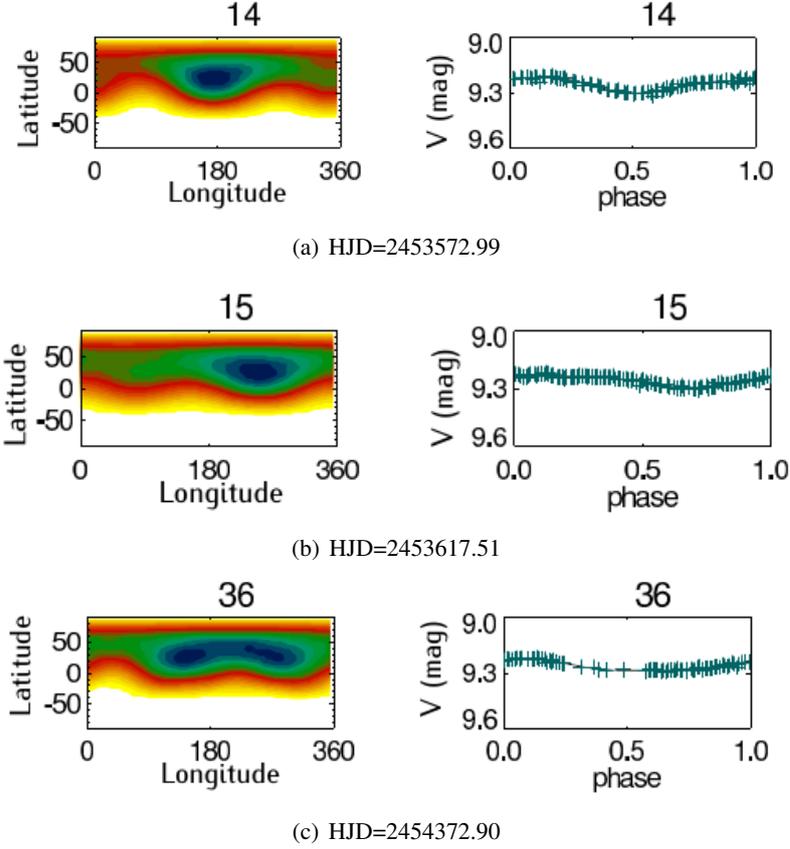
(c) HJD=2454372.90

Figure 2: Surface inhomogeneity map (left panel) and corresponding phase folded V-band light curve (right panel) at three epochs of HJD= 2453572.99, 2453617.51 and 2454372.9.

released at the time of flare. Flare energies of these flares were derived to be of the order of 10^{33} erg.

In order to generate the surface map of LO Peg, we used the light-curve inversion code (iPH) developed by Savanov & Strassmeier (2008) and Savanov (2009). The entire light curve of all observations were divided into 47 sets without gaps on the curve on the phase diagram and without changes of its shape. The resultant light curves were not constant, and showed the change in shape, amplitude and minimum of light. The amplitude of these light curves were in the range of 0.06 - 0.20 mag. Each individual light curve was analysed using the iPH code. We adopt the temperature of LO Peg photosphere to be $\sim$ 4500 K and and the temperature of the spots to be 750 K lower than surface temperature (Piluso et al. 2008). We used the data from the Kurucz's model grid in our computations. Reconstruction of the temperature-inhomogeneity maps was carried out for angle of inclination of 45 degrees. Figure 2 shows the inhomogeneity map at three mean epochs. Most of the time, spots were concentrated into two groups at two different longitudes, where the differences of longitude were not constant. The total areas covered by group of spots were in the range of 9-26% of the total visible stellar surface. The spot area in LO Peg is very similar to that found in other K-type stars like V1147 Tau (Patel et al. 2013, Savanov 2010) and are more than that for the evolved RS CVn-type binaries.
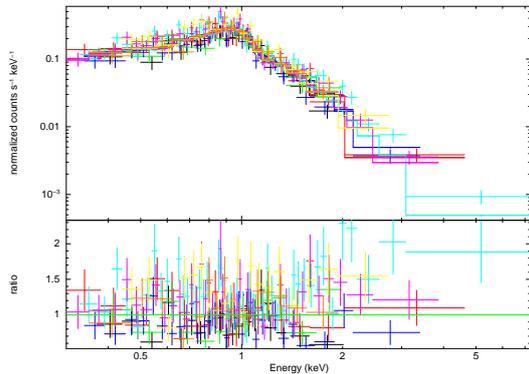
Figure 3: Background subtracted X-ray spectra of LO Peg with the best fit two temperature plasma model apec. The bottom panel shows the residual in terms of ratio.

3.2 X-ray spectra

Figure 3 shows the background subtracted X-ray spectra of LO Peg as observed from Swift XRT. For all set of observations, the X-ray spectra of LO Peg were fitted with two temperature plasma model APEC (Smith et al. 2001), with variable elemental abundances, Z. The interstellar hydrogen column density (N_H) was left free to vary. All the parameters were found to be constant within 1σ level for all observations; therefor, these parameters were kept fixed at the average value to determine the unabsorbed flux. The variation of unabsorbed flux is shown in the top panel of Figure 1. The derived value of temperatures and corresponding emission measures were 0.28 ± 0.04 keV and $3.1 \pm 0.09 \times 10^{52}$ cm^{-3} cm³, 1.03 ± 0.05 keV and $4.6 \pm 0.06 \times 10^{52}$ cm^{-3} cm³, respectively. Abundances were found to be 0.13 ± 0.02 solar unit. These values are similar to those derived from the ROSAT observations (Pandey et al. 2005).

4. Summary

We have carried out analyses of long term optical and X-ray observations of an active UFR LO Peg. The variable shapes and amplitudes of light curves of LO Peg at 47 epochs indicate the temperature inhomogeneities on its surface. A modeling of these observations reveals that the stellar surface of LO Peg is spotted up to 26 per cent, which is very similar to that found in K-type stars. A total of 12 flares during the observations were found indicating ~ 1 flare per eight rotation of LO Peg. The corona of LO Peg was well represented by two temperature plasma of 0.28 and 1.03 keV. The X-ray luminosity of LO Peg over the ~ 4 years of the observations were found to be constant with an average value of $3.56 \pm 0.11 \times 10^{29}$ erg s^{-1}. Detail study of multi-wavelength data will be published elsewhere (Karmakar et al. 2015)

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