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Broad-Band Spectral Indices Variability of BL Lacertae by Wavelet Method

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Abstract. BL Lacertae is one of the famous AGN that shows convincing evidence to support periodic variability. We compile R-band data and radio 22 GHz database from the available literature to build the light curves and to calculate broad-band spectral indices. This paper employs the wavelet periodic estimation method. The analysis results indicate that the most possible period is 7.02–7.36 yr in the selected wave-bands. The broad-band spectral indices have a possible period of 4.11 yr as a half value in selected wave-bands. The results confirm that the variability period in the radio 22 GHz is in agreement with the optical R band of about 7.01 yr, as also mentioned in other literatures.

Key words. Galaxies: BL Lacertae objects—individual: BL Lacertae: broad-band spectral indices—periodic variation—methods: numerical: wavelet analysis.

1. Introduction

BL Lacertae ($z = 0.0688 \pm 0.0002$; Miller & Hawley 1977) is a famous subclass object of active galactic nuclei (AGNs) which is well known by the pronounced variability at all wavelengths, from the radio to γ-ray band. It has been one of the targets of the Whole Earth Blazar Telescope (WEBT) in two or more observation campaigns after 1999 (see e.g., Villata *et al*. 2002, 2004, 2009), and has also been the observations target in other monitoring bands of X-ray satellites ASCA, BeppoSAX (Ravasio *et al.* 2002) and the radio bands of SAORAS and UMRAO (see e.g., Teräsranta *et al*. 2005; Bach *et al*. 2007), whose data details are in WEBT-website. The abundance observation results indicate that the study of AGNs variability can show valuable information about their nature (Fan & Lin 2000). Recently, we compiled a database as shown in the paper of Villata *et al.* (2009). A further work in this paper, was using the wavelet method to analyse the possible period among R-band light curve, 22 GHz radio band, and the broad-band spectral

indices (BSI) of these two bands. There are many methods of time series data analysis to study the periodicity or quasi-periodicity in the light curves of blazars. Wavelet analysis developed in the mathematical literature in 1980's and was used commonly in the 1990's. Wavelets can be appropriate for analysing non-stationary time series, whereas Fourier analysis generally is not (Collineau & Brunet 1993). In this paper, we organize as follows: the light curves and data of BL Lacertae are presented in section 2. In section 3, we present the results, while the discussions and conclusions are given in section 4.

2. Data

The observational data of BL Lacertae at the optical R-band and radio 22 GHz band used in this paper are compiled from Villata *et al.* (2009). These data are assembled from the observations during the WEBT campaign from 16 observatories (20 telescopes) and radio observations were carried out from 1 to 43 GHz at 6 observatories. More processed details were explained in Villata *et al.* (2002). The top panel of Figure 1 shows optical R-band flux-density light curve. The flux densities have been

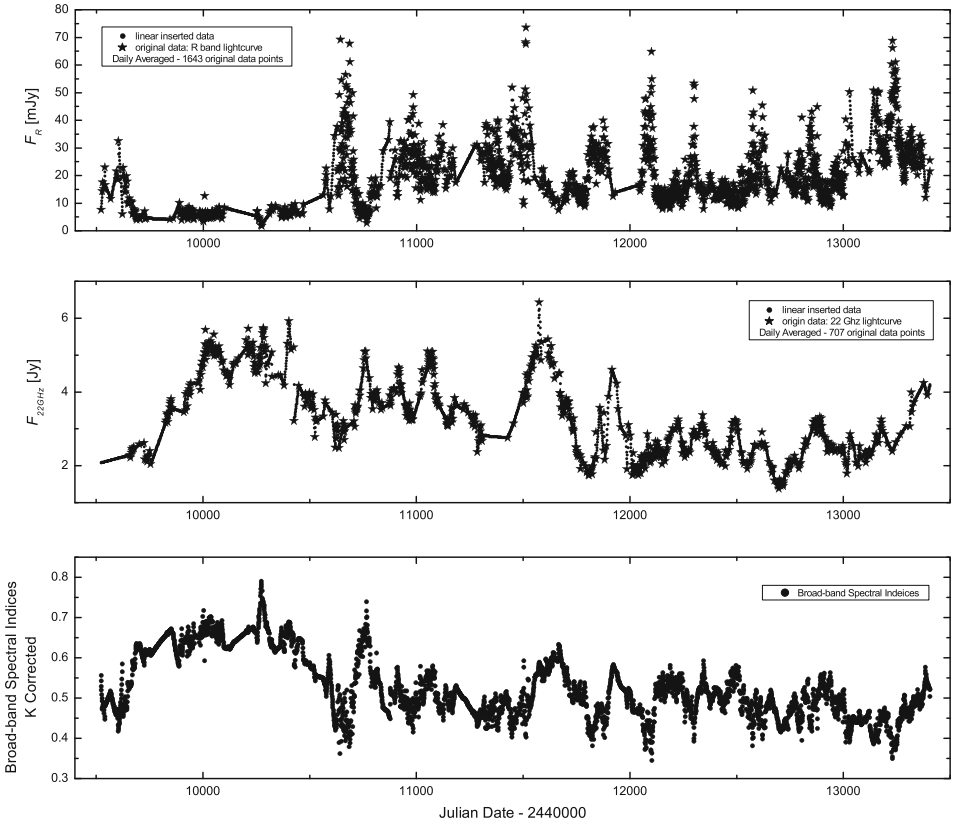

Figure 1. The light curve of BL Lacertae in flux density. *Top panel*: R-band mJy; *middle panel*: 22 GHz Jy; *bottom panel*: broad-band spectral indices (BSI).

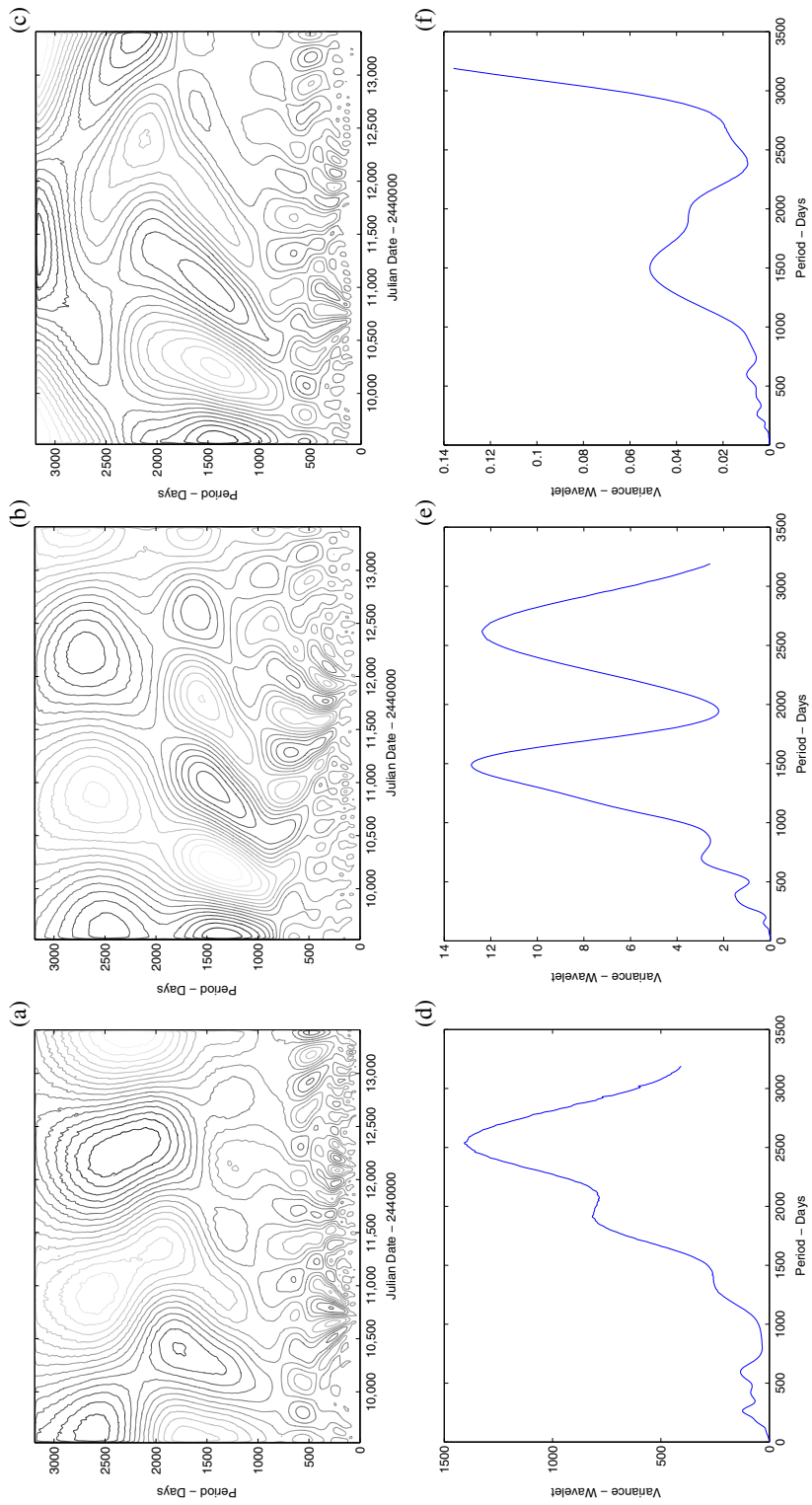

Figure 2. Wavelet analysis results. (**a**, **b**, **c**) Counter map of the R-band, 22 GHz, BSI respectively. (**d**, **e**, **f**) Variance of wavelet in the figures 2(a–c).

corrected for the galactic extinction and the host galaxy contribution has been subtracted according to Villata *et al.* (2002, 2004). In this paper, we take an average of 10 days to build the light curve. The star-shaped data points are up to 1643, which denote the original data; and the dot-shaped data points denote the linear inserted data. Radio light curves at 22 GHz are shown in the middle panel of Fig. 1. These data were collected as already calibrated flux densities and complemented by data from VLA/VLBA polarization calibration database. In this paper, we averaged the light curves every 10 days and got 707 averaged points, the point symbols are the same as in the top panel of Fig. 1. Before we draw the figure, we take K-correction by $F_\nu^{\rm in} = F_\nu^{\rm ob}(1+z)^{(\alpha_\nu - 1)}$ (Zhang *et al.* 2003). Here we adopted $\alpha_{(r)} = 0.0$, $\alpha_{(\rm IR,O)} = 1.0$ (Ramanamurthy *et al.* 1995; Cheng *et al.* 2000), $\alpha_{(\chi)} = 1.5$, $\alpha_{(\gamma)} = 2.0$ (Hartman *et al.* 1999). Then, the bottom panel of Fig. 1 shows light curve of broad-band spectral indices between the corresponding R-band flux-densities and radio flux-densities at 22 GHz. As the function given by Ledden & O'Dell, $\alpha_{(1,2)} = -(\log(F_1/F_2))/(\log(\nu_1/\nu_2))$, here ν_1 and ν_2 are the frequencies corresponding to the flux densities F_1 and F_2.

3. Wavelet method result

The wavelet method is described in Collineau & Brunet (1993), Meyers *et al.* (1993) and Zhang *et al.* (2009, 2011). The results are given in Fig. 2. From the figures we can see that there exist a strong periodicity. In Fig. 2(d), one obvious peak can be considered as a period for 2562 days (7.02 yr) in the R-band light curve data. In Fig. 2 (e), two obvious peaks are 2686 days (7.36 yr) and 1500 days (4.11 yr) in radio 22 GHz light curve. In Fig. 2(f), one obvious peak can consider as a period for 1500 days (4.11 yr) in broad-band spectral indices (BSI) variability data, but the possible period of 2562 days (7.02 yr) as in the R-band disappears.

4. Discussion and conclusion

We have found that BL Lacertae has a clear period of around 2562 days (7.02 yr) to 2686 days (7.36 yr), this value is very close to the results by Fan & Lin (2000) and Ciaramella *et al.* (2004). Here, we can take this possible period as a main period. In addition, we also found a possible period from the broad-band spectral index variability, the possible period in the spectral index variability is almost half of the main period.

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