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Long-Term Optical Spectra Variability of BL Lacertae Object S5 0716+714

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Abstract. Based on the long-term data from observations, we present an evidence for its spectral index variability behaviour in optical bands for BL Lacertae object S5 0716+714. We find that the spectral index variability period is in agreement with the flux variability period of about 1180 days in optical bands. We also find that the spectral index variability has periods of about 71 and 60 days which cannot be compared with the amplitude of long-term variability.

Key words. BL Lac object individual: S5 0716+714—optical spectral index variability period—methods: periodogram analysis method, wavelet analysis method.

1. Introduction

S5 0716+714 is a typical BL Lac object, and it is very striking due to its observational properties. Heidt & Wagner (1996) found a period of 4 days through flux variations. Nieppola *et al.* (2006) gave a synchrotron peak frequency of $\nu_{\text{peak}} = 2.88 \times 1014$ Hz, and it was assigned LBL status. Because of its long-term observation data are very abundant; Wagner & Witzed (1995) found a period between 1 day and 7 days earlier on 1990 February and the light-curves are similar in appearance among optical U, B, V, R, I bands and radio bands. Katajainen *et al.* (2000) find that a 60∼70 days period existed. And Raiteri *et al.* (2003) found a 3.3-year period in optical R band based on a huge dataset from 1994 to 2002. Using the observation, many authors analysed the spectral index in optical band during out-burst. The optical variability is a common phenomenon for the BL Lac objects (Zheng *et al.* 2007). In order to study the inner mechanism of radiation emission of S5 0716+714, we used different methods for the optical spectral index by correlating with its variability based on the collected B-, V-, R- and I-band data. Section 2 describes the sample and data reduction, section 3 presents our results, and section 4 gives some short discussions.

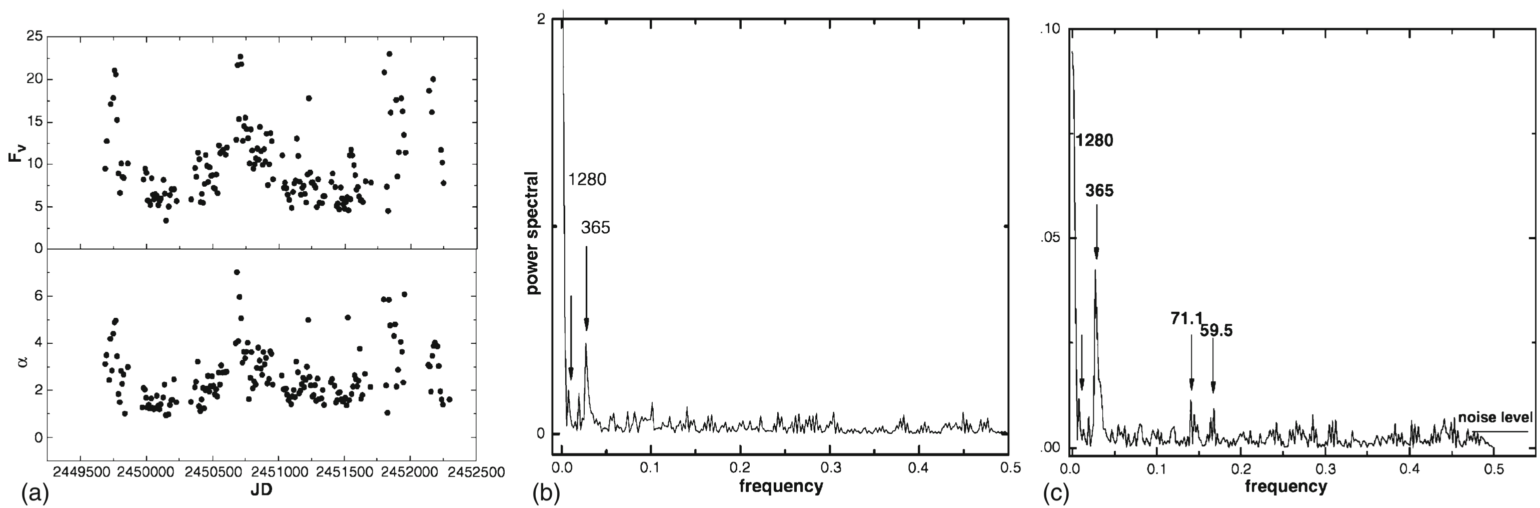

Figure 1. In **(a)**, the upper part shows the light curve in the *V* band, and the lower part shows the spectral curve, from JD 2449450 to JD 2452500, and flux is given from 0 Jy to 25 Jy and spectral index is given from 0 to 8. **(b)** and **(c)** show results of the *V*-band flux density and the optical spectral index. X-axes show the frequency in time domain, from 0 to 0.5 in 10 days, and Y-axes show the power spectral density 0~2, 0~0.1, respectively.

2. Sample and data reduction

We summarize all the literature which report the observations, and compile the available B-, V-, R- and I-bands optical data on S5 0716+714 from 1994–2006. The number of valid data points is up to 16818, compared with the data precision between the CCD photometry and the photograph metering. In order to study the long-term behaviours of the optical spectral index variability, we average the magnitude values by a daily-time and reform these to flux densities. All of the averaged magnitude are corrected for foreground galactic interstellar reddening using the colour excess $E(B-V)$, which is deduced from maps of dust infrared emission (Schlegel *et al.* 1998). From the value of $E(B-V)$, we evaluate B, V, R and I extinction coefficients with a formula from Cardelli *et al.* (1989), assuming $R_V = 3.1$ (Rieke *et al.* 1985). We convert apparent magnitude to optical flux density using the zero-magnitude equivalent flux density reported by Mead *et al.* (1990). We construct the historical light curve and optical spectral curve based on the data with the literature from 1994–2006 (see Fig. 1a). As one can see from Fig. 1(a) upper part, S5 0716+714 has intense variability of flux density in the optical band. There are significant peaks in the light curve on 1995, 1997 and 2000. These peaks correspond to large outbursts. In Fig. 1(a) lower part, the spectral curve reached a high value during the 1995 outburst, then increased to 4.08 (JD 24450700) at the 1997 outburst. During the 1997 outburst, the spectral index changed from 1.20 to 4.08. During the 2000 super flares, the variability of the spectral index was very large, and the amplitude was up to $\Delta\alpha = 5.04$ (from 1.03 (JD 2451830) to 6.07). The spectral index variability seems to be the periodicity corresponding with the flux density.

3. Results

3.1 *Periodogram analysis*

By the method in the literature: If the power spectrum density $s_j(\omega)$ is continuous on $\omega = \omega_0$, the periodogram $P_f(\omega)$ must have a maximum value in $[-\pi, \pi]$ (Lomb 1976). This indicates that when N is larger, $P(\omega)$ shows an obvious peak at $\omega = \omega_0$ (Horne & Baliunas 1986). Using the periodogram analysis method, for the flux density and spectral index, the results are obtained and shown in Fig. 1(b). From Fig. 1(b), S5 0716+714 exhibits a significant period in the optical band, this shows a maximum value corresponding to the period of 1280 days. This period is in agreement with the results reported by Raiteri *et al.* (2003). Figure 1(c) shows the spectral index variability period, and the maximum value also corresponds to the period of 1280 days. This period is in agreement with the flux variability period. Besides this long-term period, in Fig. 1(c), we found new peaks of 71 days and 60 days with significant value, these two obvious peaks of 71 days and 60 days should be the periods in the spectral curve, and the periods reported by Katajainen *et al.* (2000) in 60–70 days is very close to our results.

3.2 *Wavelet analysis*

In order to satisfy using, we have the restriction that $\omega = 6.2$ to define $T \approx a$ (Meyers *et al.* 1993). If we integrate $W_f(a, b)$ in the time domain, we will get the discrete form of wavelet variance (Collineau & Brunet 1993). In order to find out the periods of S5 0716+714 with wavelet analysis method, Fig. 2 respectively show that the analysis results of the flux density curve in the V band and spectrum index curve of S5 0716+714 varies in the wavelet transform domain. The corresponding wavelet variance curves are shown in Fig. 2, second panel and fourth panel. From Fig. 2, first panel we can find that the most significant undulancy exists in the interval of $T_1 =$ 800∼1500 days. Besides this, the undulancy exists also at places corresponding to $T_2 = 400\sim800$ days and $T_3 = 200\sim400$ days. From the wavelet variance diagram of Fig. 2, second panel, one can see that a maximum value exists at the place $T_1 = 1180$ days implying that the maximum of the curve periods with flux density is $T_1 = 1180$ days, and that the places of $T_2 = 630$ days and $T_3 = 370$ days are not significant. The contour map of the real part of the wavelet transform coefficient derived from spectral index curve is shown in Fig. 2, third panel. One can see that the undulancy is not in continuum and balance, and is predicted that these do not exist in a stable

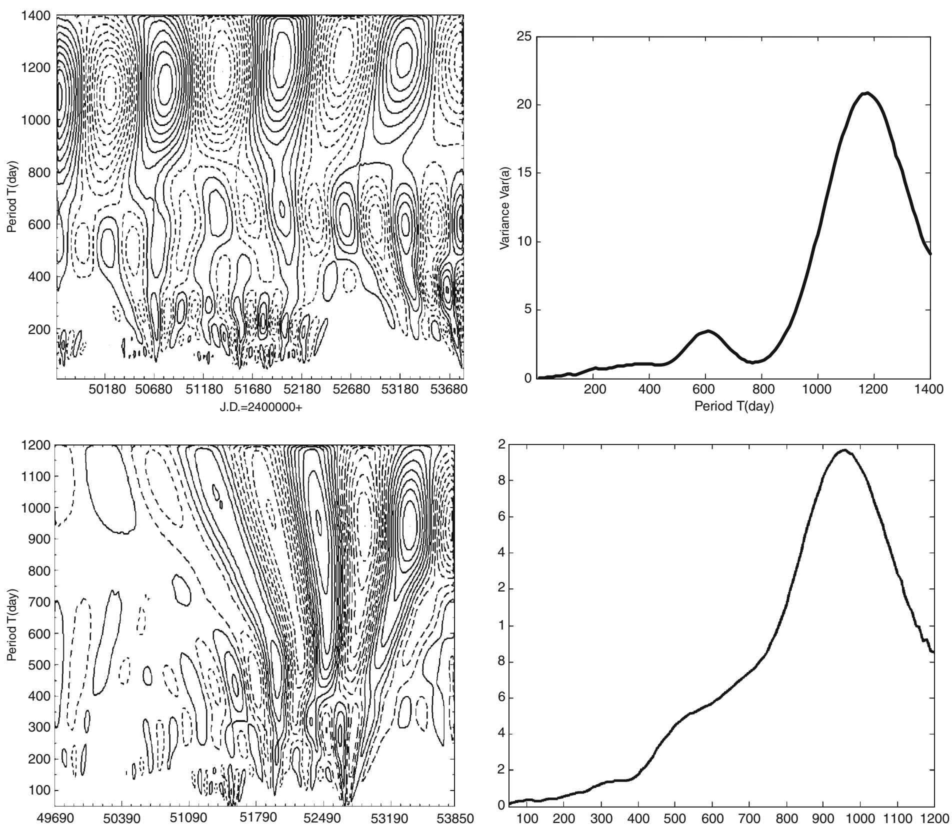

Figure 2. The contour map and the variance curve of analysis results, the first and third panels show contour map, the X-axes are the JD date corresponded to the light curves of flux and spectral index, Y-axes are the periods for 0∼1400 and 0∼1200 days respectively. the second and fourth panels show the variance curve, the X-axes are the periods shown in the first and third panels, Y-axes are the variance of wavelet transform coefficient, for 0∼25 and 0∼2, respectively.

period. But in the interval of $T_1 = 750{\sim}1500$ days, undulancy may exist. From the wavelet variance diagram of Fig. 2, fourth panel, one can see that a maximum value exists at the place $T_1 = 970$ days implying that the maximum of the curve periods with spectral index density is $T_1 = 970$ days. By a global analysis of the variations in the method, the most evident period is 1180 days.

4. Conclusion

S5 0716+714 is one of the most frequently studied BL Lac objects. In this work, some results give the details in the paper for long-term optical spectral variability analysis. Based on the optical data available in literature, our results indicate in the following:

- The optical light curve of S5 0716+714 are variable with time. The main flux period of the light curve is 1180 days, which is in agreement with the magnitude variability period, as found by Raiteri *et al.* (2003).
- Both periodogram analysis method and wavelet analysis method give a significant period of around 1180 days in spectral index light curve. This period is shown to be unstable in the wavelet analysis method, but is consistent in the optical light curve.

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