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RADIO VARIABILITY AND RANDOM WALK NOISE PROPERTIES OF FOUR BLAZARS

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ABSTRACT

We show the results of a time series analysis of the long-term light curves of four blazars: 3C 279, 3C 345, 3C 446, and BL Lacertae. We used densely sampled light curves spanning 32 years at three frequency bands (4.8, 8, 14.5 GHz), provided by the University of Michigan Radio Astronomy Observatory monitoring program. The spectral indices of our sources are mostly flat or inverted ($-0.5 < \alpha < 0$), which is consistent with optically thick emission. Strong variability was seen in all light curves on various time scales. From the analyses of time lags between the light curves from different frequency bands and the evolution of the spectral indices with time, we find that we can distinguish high-peaking flares and low-peaking flares according to the Valtaoja et al. classification. The periodograms (temporal power spectra) of the light curves are in good agreement with random-walk power-law noise without any indication of (quasi-)periodic variability. We note that random-walk noise light curves can originate from multiple shocks in jets. The fact that all our sources are in agreement with being random-walk noise emitters at radio wavelengths suggests that such behavior is a general property of blazars. We are going to generalize our approach by applying our methodology to a much larger blazar sample in the near future.

Key words: galaxies: active – methods: statistical – radiation mechanisms: non-thermal

1. INTRODUCTION

Strong and complex flux variability is one of the characteristics of active galactic nuclei (AGNs), which have received much attention because they can give us valuable information on the internal conditions of accretion zones and plasma outflows. Multiple studies have found AGN variability throughout the electromagnetic spectrum on various time scales, from a few tens of minutes to a few tens of years (e.g., Rani et al. 2010; Trippe et al. 2011; Park & Trippe 2014). A number of physical phenomena, such as shocks in continuous (Marscher & Gear, 1985) or discontinuous (Spada et al., 2001) jets or orbiting plasma hotspots (Abramowicz et al., 1991), have been proposed to explain the various characteristic variability patterns of AGN.

Fourier Transform, power spectrum, and periodogram methods (see Priestley 1981 for a review) are powerful tools for quantitative study of AGN variability. Power spectra of AGN light curves can usually be described as power laws $A_f \propto f^{-\beta}$ with $\beta > 0$, corresponding to *red noise* (Benlloch et al., 2001; Webb et al., 1988; Fan, 1999; Aller et al., 2003). The light curves where pure Gaussian *white noise* is dominant have flat power spectra ($\beta = 0$), whereas *random walk noise* light curves, generated by the integration of white noise, show steep ($\beta = 2$) power spectra (see also Park & Trippe 2012 for a detailed technical discussion).

In addition to temporal variability, spectral properties and variations of emission as function of frequency can be used to investigate emission processes of AGN. The evolution of the spectral index and the time delays between the light curves from different frequencies are associated with various emission mechanisms, such as standard shock-in-jet models and/or shock-shock interactions in jets (e.g., Fromm et al. 2011; Rani et al. 2013).

2. DATA AND TARGET SELECTION

We exploited the AGN monitoring database of the University of Michigan Radio Astronomy Observatory (UMRAO). The data are densely sampled, faster than monthly at least, high quality with low observational errors, and continuously spanning at least 30 years in time. In addition, fluxes measured at three frequency bands (4.8, 8, 14.5 GHz) are available. We chose four blazars as our targets, which have minimum flux densities of 2 Jy and show strong flux variability. Figure 1 shows flux densities as function of time for our targets.

3. TEMPORAL VARIABILITY

We obtained power spectra using the normalized *Scargle periodogram.* We refer the reader to Scargle (1982) for details. To determine whether the power spectra are consistent with pure red noise or not, we performed

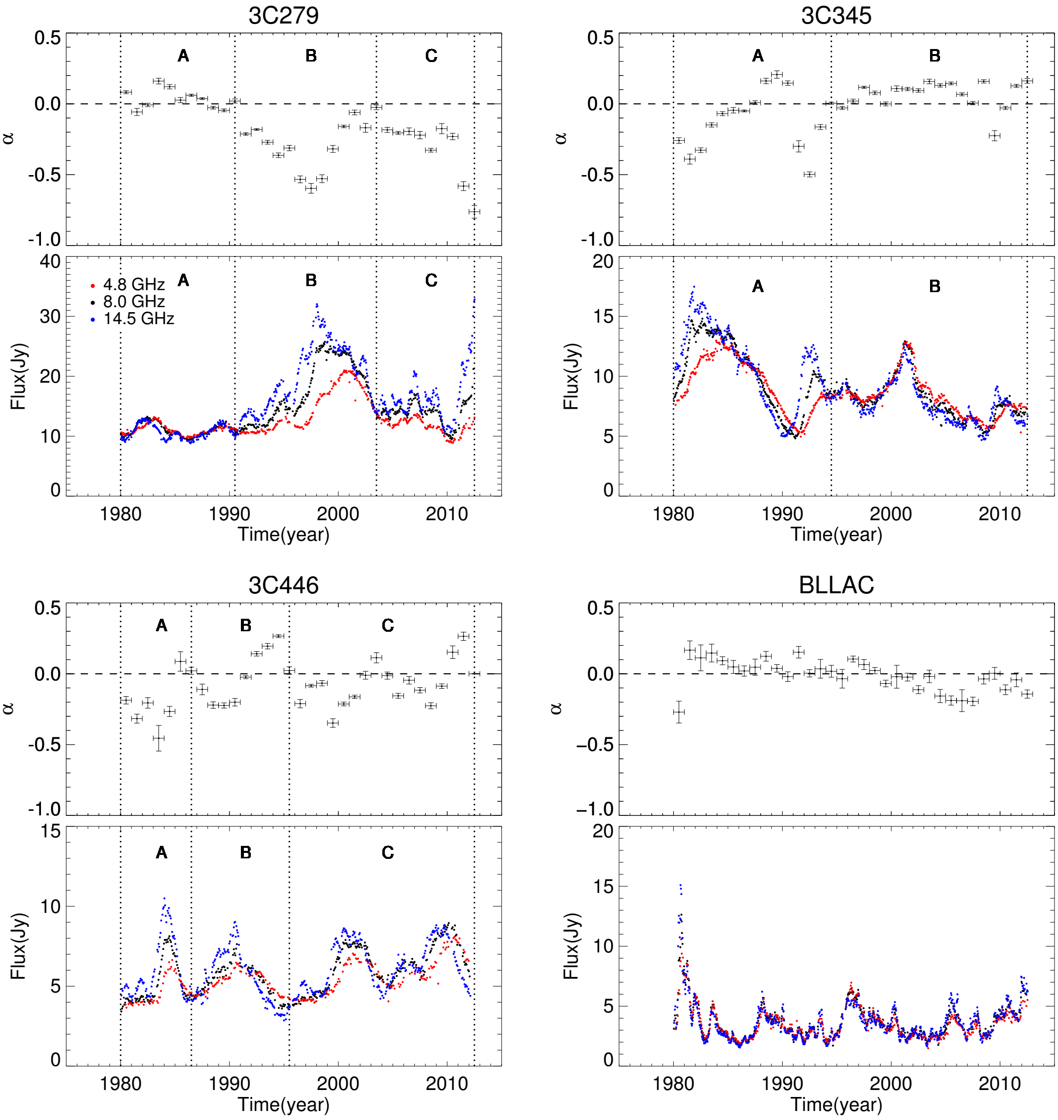

Figure 1. Flux densities and spectral indices α as function of time for our four blazars. Red, black, and blue data points indicate fluxes at frequencies 4.8, 8, and 14.5 GHz, respectively. All light curves show strong variability and multiple, complex flares. We divided our light curves into two or three phases according to behavior of the flares. Error bars along the horizontal and vertical axes in the spectral index diagrams denote the size of the time window (1 yr) and the statistical 1σ errors, respectively.

Monte Carlo simulations based on Timmer & König (1995). We generated 10,000 simulated light curves with various input power spectral indices β and applied the same sampling patterns as those from observations for each source. From the set of artificial power spectra, we obtained average power spectra and 99.9% significance levels and compared with the observations (See Park & Trippe 2014 for details). Then, we determined the best-fit models for the observed power spectra and checked the presence of strong power above the confidence levels. We present the results for only two sources in Figure 2.

The results tell us that all the observed power spectra are in good agreement with the simulated ones generated by $\beta \approx 2$ light curves without any indication of (quasi-)periodic oscillations. One result that is of particular importance is that the peaks on the underlying red-noise power spectra are also reproduced by the simulations. This indicates that the strong peaks are not derived from actual periodic oscillations and the sampling patterns of the light curves can change the intrinsic power spectra significantly (Uttley et al., 2002).

Mathematically, power law noise with $\beta = 2$ can be generated by the integration of white noise. Specifically, when we generate noise by incrementing a running sum of white noise, we obtain random walk noise light curves and their power spectra follow a power law with $\beta = 2$ (Press, 1978). Therefore, we can conclude that our sources have random walk noise power spectra. The underlying physics generating such power spectra is still unclear. However, we can infer that mechanisms making adjacent data points in the light curves be correlated could be candidates, considering that random walk

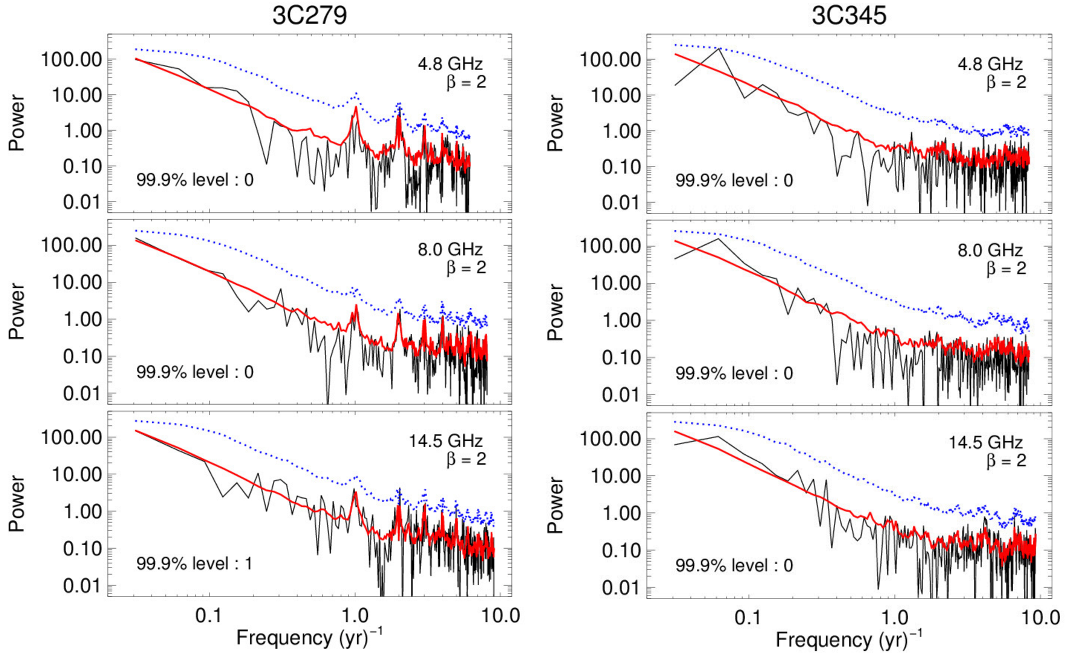

Figure 2. Power spectra for two blazar light curves. We show the power spectra at three observing frequencies separately. Solid black lines are the observed power spectra and solid red lines denote average power spectra of 10,000 simulated red noise light curves. Blue dotted lines correspond to the 99.9% significance levels obtained from the simulations. In each diagram the number of data points exceeding the significance levels are noted. We used $\beta = 2$ for the simulations, which provide the best fit for the observed power spectra. One excess value detected in the power spectrum of 3C 279 at 14.5 GHz is consistent with statistical fluctuation, taking into account large number of trials (one value out of 295 frequencies probed).

noise can be generated by the integration of white noise. We expect that multiple shocks in jets could explain the results, as synchrotron emission from relativistic electrons in jets is dominant in the radio emission of blazars (Beckmann & Shrader, 2012). This idea is supported by existing theoretical models such as shocks in discontinuous (Spada et al., 2001) jets. According to this model, what we observe is the integrated emission from a number of shocked plasmas distributed along the jets, which is consistent with random walk noise emission at radio wavelengths.

4. SPECTRAL PROPERTIES

We investigated the spectral properties of our sources from our multifrequency data, including the evolution of spectral indices and the time delays between the light curves belonging to different frequency bands. We set a time window of 1 year and obtained the spectral index by fitting all data in each window to a standard power law model. We present the spectral indices as function of time in Figure 1. All sources show mostly flat or inverted spectral indices, which are consistent with optically thick synchrotron emission. This result is in line with the fact that our sources are blazars and we observe the sources through their jets. In addition, we can distinguish two types of behavior of the flares. For example, phase A of 3C 345 shows that the fluxes at higher frequencies precede the ones at lower frequencies with significantly higher amplitude of flux, while the light curves at different frequencies are almost simultaneous with approximately identical amplitudes in phase B. To quantify the time delays, we applied the discrete correlation function (DCF) to each pair of frequency bands for each source (See Park & Trippe 2014 for details). As we anticipated, the results proved that there are time delays in phase A of 3C 345, but no delay was found in phase B (See Figure 3).

These results can be explained well by the "generalized shock model" of Valtaoja et al. (1992), which is based on the famous shocks in jets model (Marscher & Gear, 1985). The key of this theory is that AGN flares at radio frequencies can be described as the evolution of synchrotron turnover flux S_m versus turnover frequency ν_m. In this model, it is assumed that the shape of the synchrotron spectrum remains constant over time. As the shock evolves, the turnover frequency decreases with time due to the expansion of the shocked region. During the first stage, inverse Compton scattering is dominant which leads to the increase of S_m. In the second stage, synchrotron losses become more important and the turnover flux density remains almost constant while the turnover frequency continues to decrease. In the last stage, adiabatic losses become the dominant energy loss mechanism and both S_m and ν_m decrease (See Fromm et al. 2011, for details).

What we actually observe, however, depends on whether the observing frequencies are located below or above the frequency at which the shock emission reaches its maximum (See Fig. 1 of Valtaoja et al. 1992). In the former case, the flare becomes optically thin when

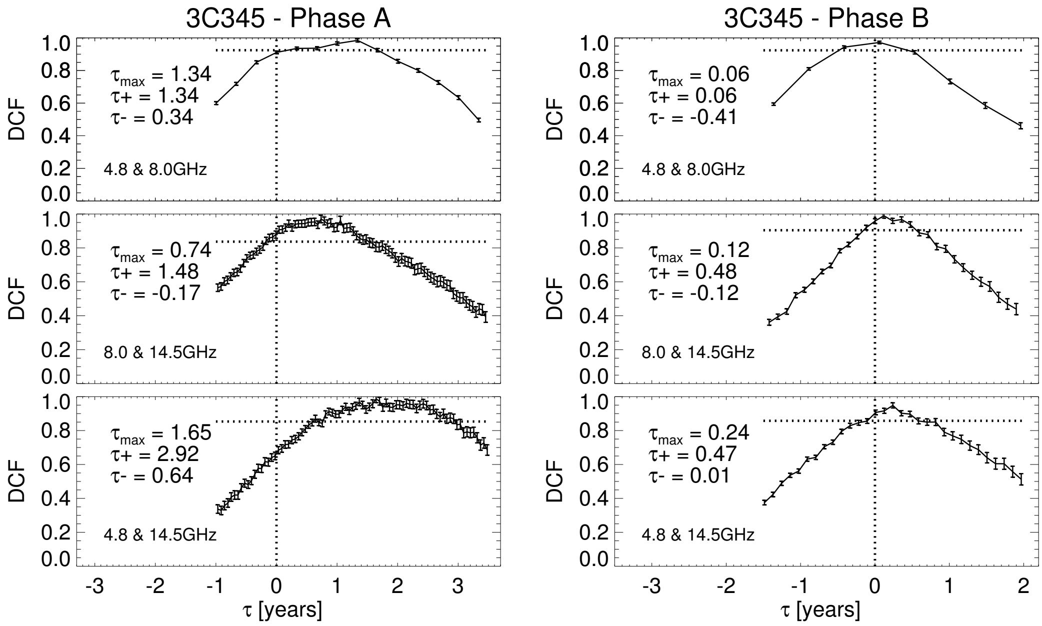

Figure 3. Discrete correlation function (DCF) as a function of time lags τ for each pair of 4.8, 8, and 14.5 GHz light curves of 3C 345. The time lags at which DCFs reach maximum are noted with $\tau_{\max}$ values. In our convention, a positive (negative) time lag indicates that the higher frequency precedes (follows) the lower frequency. More detail descriptions about the figures are given in Park & Trippe (2014).

the turnover passes the observing frequency. Accordingly, the fluxes at higher frequencies precede the ones at lower frequencies with higher amplitude as in phase A of 3C 345. This type of flare was named a *high-peaking flare*. In the latter case, however, the observed fluxes at different frequencies are in the optically thin regime of the synchrotron spectrum, so that light curves at different frequencies closely track each other with almost no time delay, as in phase B. This type of flare is called a *low-peaking flare*. We conclude that each flare in the light curves of our sources corresponds to either a high-peaking flare or a low-peaking flare and the synchrotron emission from shocks in jets is the main contributor in generating complex flares.

5. SUMMARY AND CONCLUSION

We studied high-quality radio light curves of four luminous blazars and investigated their temporal variability and spectral properties. From our analyses, we made the following conclusions:

- The power spectra of all four blazars are well described by random walk noise power spectra ($\beta = 2$) without any significant (quasi-)periodic signal. The clarity of our results suggest that random walk noise light curves at radio wavelengths could be a general characteristic of blazars. Therefore, we are going to generalize our approach by applying our methodology to a much larger blazar sample in the near future.
- The spectral indices of our sources are mostly flat or inverted, in agreement with optically thick synchrotron emission. The complex behavior of the flares in the light curves can be well explained by the generalized shock model of Valtaoja et al. (1992).
- Careful time series analysis of high-quality blazar light curves provides information on the source structure even if a target is not resolved spatially, as our results indicate that multiple shocks in jets can form the strong and complex radio variability of the sources.

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