HINTS OF CORRELATION BETWEEN BROAD-LINE AND RADIO VARIATIONS FOR 3C 120

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ABSTRACT

In this paper, we investigate the correlation between broad-line and radio variations for the broad-line radio galaxy 3C 120. By the z-transformed discrete correlation function method and the model-independent flux randomization/random subset selection (FR/RSS) Monte Carlo method, we find that broad Hβ line variations lead the 15 GHz variations by a factor of 0.34 ± 0.01 yr. This time lag can be used to locate the position of the emitting region of radio outbursts in the jet, on the order of 5 lt-yr from the central engine. This distance is much larger than the size of the broad-line region. The large separation of the radio outburst emitting region from the broad-line region will observably influence the gamma-ray emission in 3C 120.

Key words: galaxies: active – galaxies: individual (3C 120) – galaxies: jets – quasars: emission lines – radio continuum: galaxies

1. INTRODUCTION

According to the reverberation mapping model (e.g., Blandford & McKee 1982), the broad emission line variations follow the ionizing continuum variations through the photoionization process. The variation correlations between broad lines and continua were observed with time lags in type 1 active galactic nuclei (AGNs; see, e.g., Kaspi & Netzer 1999; Kaspi et al. 2000; Peterson et al. 2005). The disturbances from the central engine in AGNs are transported with ionizing continua to broad lines. Theoretical research shows that the jets can be ejected from the inner accretion disk in the vicinity of the central black hole (e.g., Penrose 1969; Blandford & Znajek 1977; Blandford & Payne 1982; Meier et al. 2001). Rawlings & Saunders (1991) indicated a disk–jet symbiosis with comparable power channeled through the disk and the jet. Correlations between radio powers and broad-line luminosities are found for AGNs and are regarded as evidence for the disk–jet symbiosis (see, e.g., Celotti et al. 1997; Cao & Jiang 1999, 2001; Wang et al. 2003; Liu & Bai 2010). These previous results indicate that the disturbances in the central engine are likely propagated outward along the jets. Observations show that dips in the X-ray emission, generated in the central engine, are followed by ejections of bright superluminal radio knots in the jets of AGNs and microquasars (e.g., Marscher et al. 2002; Arshakian et al. 2010). The dips in the X-ray emission are well correlated with the ejections of bright superluminal knots in the radio jets of 3C 120 (Chatterjee et al. 2009) and 3C 111 (Chatterjee et al. 2011). The outbursts are physically linked to the ejections of superluminal knots (e.g., Turler et al. 2000). Then these outbursts of broad-line and jet emissions might respond to the stronger disturbances in the central engine. It is expected that there might be correlations with time lags between variations of broad-line and jet emissions. A method was proposed to connect the time lags, the size of broad-line region (BLR), and the location of jet emission for blazar 3C 273 (Liu et al. 2011a, hereafter Paper I).

BLRs are important to gamma-ray emission in blazars. The gamma rays from blazars are generally believed to be from a relativistic jet with a small viewing angle (Blandford & Rees 1978). The diffuse radiation field of BLRs could have a strong impact on the expected external Compton (EC) spectrum of the most powerful blazars (see, e.g., Sikora et al. 1994; Wang 2000; Liu & Bai 2006; Reimer 2007; Liu et al. 2008; Sitarek & Bednarek 2008; Tavecchio & Ghisellini 2008; Bai et al. 2009; Tavecchio & Mazin 2009). This strong impact arises from two factors. One of them is the seed photons from the BLR in the inverse Compton scattering, and the seed photons significantly influence the EC spectrum. The other is photon–photon absorption between the seed photons and the gamma-ray photons of the EC spectrum. There is an underlying physical factor that constrains how much the above two factors influence the gamma-ray spectrum. The underlying factor is the location of the gamma-ray emitting region relative to the BLR. If the gamma-ray emitting region is inside the BLR, the gamma-ray spectrum will shift to higher energies and the gamma-ray luminosity will become larger due to the relativistic effects. At the same time, the photon–photon absorption becomes more significant as the emitting region goes deeper into the BLR (see Liu & Bai 2006; Liu et al. 2008; Bai et al. 2009). As the emitting region is outside the BLR, the gamma-ray spectrum will shift to lower energies and the gamma-ray luminosity will become lower due to the relativistic effects. At the same time, the photon–photon absorption becomes insignificant as the emitting region moves away from the BLR. Thus, it is valuable to connect the BLR size with the location of the jet emission. It will be an important step for this connection to confirm the correlation between variations of broad-line and radio emissions of the jet and to estimate the relevant time lags. In this paper, we study this issue in the broad-line radio galaxy 3C 120.

The structure of this paper is as follows. Section 2 presents the methods. Section 3 presents the applications to 3C 120 and contains three subsections: Section 3.1 presents constraints on the time lag, Section 3.2 contains the data of 3C 120, and Section 3.3 presents an analysis of the time lag. Section 4 contains the discussion and conclusions. In this work, we assume the standard ΛCDM cosmology with H₀ = 70 km s⁻¹ Mpc⁻¹, ΩM = 0.27, and ΩΛ = 0.73.
2. METHOD

According to Equation (7) in Paper I, the relation between $R_{\text{BLR}}$, $R_{\text{radio}}$, and $\tau_{\text{ob}}$ is

$$R_{\text{BLR}} = R_{\text{radio}} \frac{c}{v_d - \cos \theta} \frac{c(\tau_{\text{ob}})}{1 + z},$$

(1)

where $R_{\text{BLR}}$ is the size of the BLR, $R_{\text{radio}}$ is the radio emitting location of the jet, $c$ is the speed of light, $v_d$ is the traveling speed of disturbances down the jet, equivalent to the bulk velocity of jet $v_j$, $\theta$ is the viewing angle of the jet axis to the line of sight, and $\langle \tau_{\text{ob}} \rangle = \tau_{\text{ob}}$ is the measured time lag of the radio emission relative to the broad lines. From the velocity $\beta = v_j/c$ and the viewing angle $\theta$, we have the apparent speed $\beta_a = \beta \sin \theta / (1 - \beta \cos \theta)$, which gives $\beta = \beta_a / (\beta_a \cos \theta + \sin \theta)$. Substituting this expression of $\beta$ for the velocity term in Equation (1), we have

$$R_{\text{BLR}} = R_{\text{radio}} \frac{\sin \theta}{\beta_a} \frac{c(\tau_{\text{ob}})}{1 + z}.$$  

(2)

From Equation (2), we have an expression to estimate $\langle \tau_{\text{ob}} \rangle$:

$$\langle \tau_{\text{ob}} \rangle = \frac{R_{\text{radio}}}{\beta_a} - \frac{R_{\text{BLR}}}{c} \frac{1 + z}{1}.$$  

(3)

3. APPLICATION TO 3C 120

3C 120, at redshift $z = 0.033$, has a one-sided jet with apparent superluminal motion in an approaching jet (Gómez et al. 2001). The central supermassive black hole of this object has a mass of a few times $10^7 M_\odot$ (Peterson et al. 1998a, 2004).

3.1. Constraint on the Time Lag

Very Long Baseline Array (VLBA) imaging observations revealed a very complex radio jet in 3C 120, containing objects such as superluminal components, stationary components, and trailing components in the inner jet (Gómez et al. 2001; Jorstad et al. 2005; Chatterjee et al. 2009; León-Tavares et al. 2010). There are two stationary features in the radio jet, D and S1 (León-Tavares et al. 2010). The feature D is located at the base of the jet, and could be the core of the jet. The feature S1 is most likely a standing shock formed in the jet. As the moving knots pass through the stationary feature S1, these knots will produce outbursts. The process was tested in the optical light curves of 3C 120 with peaks corresponding to moving component passages through S1. It is not possible to verify whether the radio flux density reacted to the passage of moving features in the same fashion as the optical continuum. The prominent superluminal feature o reaches it maximum flux density around 0.5 mas from the radio core (Gómez et al. 2001). The stationary feature S1 was identified at ~0.7 mas separation from the VLBA 43 GHz core (León-Tavares et al. 2010). Thus, the radio outbursts may originate in the region from D to S1 in the inner jet.

For 3C 120, Chatterjee et al. (2009) derived a distance of $\sim 0.5$ pc from the corona to the VLBA 43 GHz core region using the average time delay between the start of the X-ray dips and the time of ejection of the corresponding superluminal knots. For 3C 111, a distance of $\sim 0.6$ pc from the corona is estimated with the same method as in 3C 120 (Chatterjee et al. 2011). The 43 GHz VLBA observations give the global parameters of the jet for 3C 120, such as $\theta = 20.5 \pm 1.8$ (Jorstad et al. 2005). These global parameters are widely accepted in the literature. The 15 GHz components may correspond to the strongest events in the central engine (León-Tavares et al. 2010). Due to the optical depth, the 15 GHz outburst may follow the 43 GHz outburst. The emitting location of the 15 GHz outburst is estimated as the sum of the distance of 0.5 pc from the corona to the VLBA core and the de-projected distance of 0.0–0.7 mas from the VLBA core. Under the standard ΛCDM cosmology we considered, an angular separation of 1 mas in the sky corresponds to a projected linear distance of 0.66 pc. The de-projected distance of 0.7 mas from the radio core is equal to 0.7 × 0.66 pc/sin $\theta = 0.7 \times 0.66$ pc/sin 20$^\circ$ = 1.32 pc. The distance of the 15 GHz outburst emitting region from the central engine is $R_{\text{radio}} \sim 0.5$ pc–0.5 pc+1.32 pc = 0.5–1.82 pc = 1.63–5.93 lt-yr. For 3C 120, the Hβ line has a BLR size of $R_{\text{BLR}} = 43.8^{+27.7}_{-20.3}$ lt-day, i.e., $R_{\text{BLR}} = 0.12^{+0.08}_{-0.06}$ lt-yr (Peterson et al. 1998a). The apparent speeds of the moving components with well-determined motions are all within a range of $\beta_a = 4.0 \pm 0.2$ (Chatterjee et al. 2009). Based on Equation (3), $R_{\text{BLR}} = 0.12$ lt-yr, $\beta_a = 4.0$, $\theta = 20^\circ$5, $R_{\text{radio}} = 1.63–5.93$ lt-yr, and we derive $\tau_{\text{ob}} > 0$. This positive time lag means that the broad-line variations lead the radio variations.

3.2. Data of 3C 120

We make use of the 15 GHz light curve with a higher sampling rate of 59 times yr$^{-1}$. This radio light curve is published in Richards et al. (2011). For the Hβ line, Núñez et al. (2012) present a light curve with a very dense sampling of 20 times month$^{-1}$, and Grier et al. (2012) also present a light curve with a sampling of 20 times month$^{-1}$ in the reverberation mapping observations. These light curves are presented in Figure 1, and we analyze the cross-correlation between them.

3.3. Analysis of the Time Lag

The z-transformed discrete correlation function (ZDCF; Alexander 1997) is used to analyze the time lags characterized by the centroid of the ZDCF. The ZDCF method is straightforward in determining whether there is a time lag between different light curves, and it is applied first to analyze the time lags. The centroid time lag $\tau_{\text{cent}}$ is computed using all of the points with correlation coefficients not less than 0.8 times the maximum of the correlation coefficients in the ZDCF bumps closer to the zero lag. The uncertainties of each point in the ZDCF only take into account the uncertainties from the measurements by Monte Carlo simulations, so the uncertainties of the time lags are underestimated (see Liu et al. 2011b, hereafter Paper II). Thus, we use the model-independent flux randomization/random subset selection (FR/RSS) Monte Carlo method (Peterson et al. 1998b) to re-estimate the time lags and their uncertainties in the cross-correlation results. The FR/RSS method is based on the discrete correlation function method (Edelson & Krolik 1988) for the sparsely sampled light curves, and on the interpolated cross-correlation function method for the densely sampled light curves.

The Hβ line light curves with a very dense sampling were published in 2012 (Grier et al. 2012; Núñez et al. 2012). 3C 120 is densely observed from 2008.0 to 2012.5 in the 15 GHz radio monitoring program with the 40 m telescope at the Owens Valley Radio Observatory (Richards et al. 2011). First, it is obvious that the Hβ line light curve in Grier et al. (2012) can be well matched with the outburst in the 15 GHz light curve from 2011.0 to 2011.3, as the line light curve is moved right by 0.32 yr (see Figure 1(b)). The ZDCF method and the FR/RSS method
are performed to investigate the correlation between these Hβ line light curves and the 15 GHz light curve, and we estimate the time lags from the correlation. As these two line light curves are combined into one light curve, the calculated ZDCF is presented in Figure 2(a). The horizontal and vertical error bars in Figure 2(a) represent the 68.3% confidence intervals in the time lags and the relevant correlation coefficients, respectively. There are positive and negative correlations (see Figure 2(a)). The positive correlation has a time lag around 0.3 yr. The Hβ line variations lead the 15 GHz variations by a factor of ∼0.3 yr. This lag has the same sign as the lag estimated in Section 3.1. This indicates that the positive correlation is reliable. For the positive correlation, the ZDCF method gives \( \tau_{\text{cent}} = 0.305 \pm 0.011 \) yr. The FR/RSS method gives \( \tau_{\text{cent}} = 0.336^{+0.012}_{-0.010} \) yr with mean peak correlation coefficients of \( r = 0.59 \pm 0.07 \) in Monte Carlo simulations of 10,000 runs (see Figure 2(b)). This time lag is consistent with the lag derived from the ZDCF method. The broad Hβ line variations lead the 15 GHz variations. Hereafter, \( \tau_{\text{cent}} \) is equivalent to \( \tau_{\text{ob}} \).

4. DISCUSSION AND CONCLUSIONS

We simplify the ionizing continuum region to one point. This simplification indicates that the disturbances will simultaneously be transported outward with the ionizing continuum and the relativistic jet, i.e., it makes Equations (1)–(3) valid. This simplification will influence the time lag \( \tau_{\text{ob}} \). The disturbances in the accretion disk will take a certain amount of time to travel between their location of origin and the event horizon of the central black hole. Then the disturbances will take some time to pass through the ionizing continuum region to the event horizon. For 3C 120, the UV ionizing continuum region is located at \( \sim 5r_g \).
from the black hole, where \( r_g = GM_{\odot}/c^2 \) is the gravitational radius of the black hole (Chatterjee et al. 2009). The black hole mass is of the order of \( 10^7 M_\odot \) (Peterson et al. 1998a, 2004), and the size of \( \sim 5r_g \) is of the order of \( 10^{-3} \) lt-yr. If the disturbances are a thermal fluctuation propagating inward, it should have an effective speed \( \lesssim 0.01c \) (Chatterjee et al. 2009) to cause a time delay of \( \gtrsim 0.001 \) yr for the distance of \( \sim 5r_g \). This time delay should be negligible compared with the time lag \( \tau_{\text{ob}} = 0.34 \) yr. In the estimation of the magnitude of \( \tau_{\text{ob}} \) in Section 3.1, we use the distance of \( \sim 0.5 \) pc from the VLBA 43 GHz core region to the corona in the accretion disk–corona system, and ignore the size of the corona. The size of the corona may influence \( \tau_{\text{ob}} \). The coronal radius is \( \sim 40r_g \) (Chatterjee et al. 2009). The jet velocity near the central engine will be \( \sim 0.9c \) (see Paper I), and the radius of \( \sim 40r_g \) will cause a time delay of the order of \( 10^{-4} \) yr. The time delay is negligible.

From Equation (2), we have an expression to estimate \( R_{\text{radio}} \) from \( \beta_a, \theta, R_{\text{BLR}}, \) and \( \tau_{\text{ob}} \):

\[
R_{\text{radio}} = \frac{\beta_a}{\sin \theta} \left( R_{\text{BLR}} + \frac{c(\tau_{\text{ob}})}{1+z} \right).
\]

For \( \beta_a = 4.0 \pm 0.2, \theta = 20.5 \pm 1.8, R_{\text{BLR}} = 0.12^{+0.08}_{-0.06} \) lt-yr, and \( \tau_{\text{ob}} = 0.34 \pm 0.01 \) yr, we have \( R_{\text{radio}} = 5.24 \pm 0.16 \) lt-yr from the Monte Carlo simulations based on Equation (4). Thus, we have \( R_{\text{BLR}} \ll R_{\text{radio}} \) for 3C 120. The Fermi Large Area Telescope (LAT) detected gamma rays from 3C 120 (Kataoka et al. 2011), and it was suggested that the GeV emission of broad-line radio galaxies is most likely dominated by the beamed radiation of relativistic jets observed at intermediate viewing angles. The radio and gamma-ray emitting regions are closely connected with each other, and there is \( R_\gamma \lesssim R_{\text{radio}} \) between the radio emitting position \( R_{\text{radio}} \) and the gamma-ray emitting location \( R_\gamma \) (e.g., Dermer & Schlickeiser 1994; Jorstad et al. 2001; Kovalev et al. 2009; Sikora et al. 2009; Abd ol et al. 2010). It is unclear for 3C 120 whether \( R_\gamma \lesssim R_{\text{BLR}} \) or \( R_\gamma > R_{\text{BLR}} \), which will significantly influence the gamma-ray spectrum produced in the EC processes. The locations of gamma-ray emitting regions relative to the BLRs are still an open and controversial issue in the literature on blazars. There are three options for this issue.

The first option is that \( R_\gamma \ll R_{\text{BLR}} \) for the powerful blazars (e.g., Ghisellini & Madau 1996; Liu et al. 2008; Bai et al. 2009; Tavecchio & Mazin 2009; Ghisellini et al. 2010). The second one is that \( R_\gamma > R_{\text{BLR}} \) (e.g., Bai & Lee 2001; Lindfors et al. 2005; Sokolov & Marscher 2005; Sikora et al. 2008; Marscher et al. 2010; Zhang et al. 2009, 2010). The third option is that the same source can display both behaviors. That is, most of the time the dissipation region is inside the BLR, but there could be some epochs when the gamma-ray emitting region drifts outside the BLR. This was first advanced by Foschini et al. (2011), and a very clear case with multi-wavelength coverage was recently found by Ghisellini et al. (2013). The gamma-ray light curves
and the corresponding broad-line light curves should shed light on this issue.

The chosen parameters are average for the jet, and do not correspond to any of the components identified in Jorstad et al. (2005) and Chatterjee et al. (2009). The jet components will have different orientations and different velocities. This seems to be an issue for the choice of jet parameters in Equations (1)–(4). The reverberation mapping model assumes a linear response of broad emission lines to the ionizing continuum. In fact, the line response is not linear. It is most likely that the line and radio emissions respond nonlinearly to the events in the central engine. Thus, some weaker events in the central engine might not produce cumulative responses in the radio and broad-line variations. Both the radio and broad-line emissions may have good responses to the strongest events in the central engine, and their relevant outbursts should have good matching. There is a matching between these outbursts in the Hβ line and 15 GHz light curves that were densely sampled. However, the overall complexity of the light curves and the jet structure at radio bands may lead to difficulties in cross-identifying individual events in different bands. Thus, it is difficult to identify the radio knots and radio outbursts corresponding to the broad-line outbursts. We investigated the correlation and time lag between the radio and broad-line light curves by comparing their profiles and cross-correlating them.

The 15 GHz light curve was observed with the 40 m telescope at the Owens Valley Radio Observatory. The 40 m telescope cannot resolve the inner jet on pc scales, so the 15 GHz fluxes contain all the emission from the inner jet. It is difficult to identify the component responsible for the 15 GHz outburst. It is not possible to determine the relevant velocities of this component along the jet from the central engine to the emitting site of outburst. Thus, the average velocity of the primary components rather than the trailing features will be a good proxy of the global velocity of the component emitting outburst. The viewing angle is the same case as for the velocity. A similar choice is accepted for the jet parameters for 3C 273 (see Paper I). There are positive and negative time lags between radio variations and those of broad-line Hα, Hβ, and Hγ due to the relatively short coverage of these line light curves in 3C 273. The longer ultraviolet line light curves show that these broad-line variations lag the radio variations (see Paper II). Thus, the broad-line variations lag the radio variations. A constraint of $R_p \lesssim 0.40–2.62$ pc is set by the negative time lags (see Paper I). The gamma-ray flares detected with Fermi/LAT set a limit of $R_p < 1.6$ pc for 3C 273 (Rani et al. 2013). The limit is marginally consistent with the constraint of $R_p \lesssim 0.40–2.62$ pc. The acceptance of the average parameters of the inner jet is reasonable.

In this paper, we find a correlation between the broad-line and radio variations with the ZDCF method and the FR/RSS method, and obtain a positive lag for the broad-line radio galaxy 3C 120. The positive lag means that the 15 GHz variations lag the Hβ line variations. We derive $t_{0,\beta} = 0.34 \pm 0.01$ yr from the FR/RSS method. This time lag is consistent with that estimated from the ZDCF method. Monte Carlo simulations give the radio emitting location $R_{\text{radio}} = 5.24 \pm 0.16$ lt-yr from this time lag, the average parameters of inner jet, and Equation (4). It is reasonable to use the average parameters of the inner jet in Equations (1)–(4). This is supported by the marginal agreement of our previous constraint of $R_p \lesssim 0.40–2.62$ pc with the limit of $R_p < 1.6$ pc from Fermi/LAT observations of gamma-ray flares in 3C 273. The underlying baseline of the 15 GHz light curve significantly influences the correlation between broad Hβ line and 15 GHz variations. The subtraction of this baseline from the 15 GHz light curve can improve the correlation. A well-sampled, longer Hβ line light curve may be used to test the correlation. The existence of this correlation is a key to connecting the BLR size with the emitting location of jet, and it is important to the gamma-ray emission of AGNs.

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