Optical and Gamma-Ray Variability Behaviors of 3C 454.3 from 2006 to 2011

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Abstract

We present our photometric monitoring of a flat spectrum radio quasar 3C 454.3 at Yunnan observatories from 2006 to 2011. We find that the optical color of 3C 454.3 shows an obvious redder-when-brighter trend, which reaches a saturation stage when the source is brighter than 15.15 mag at V band. We perform a simulation with multiple values of disk luminosity and spectral index to reproduce the magnitude–color diagram. The results show that the contamination caused by the disk radiation alone is difficult to produce the observed color variability. The variability properties during the outburst in 2009 December are also compared with γ-ray data derived from the Fermi γ-ray space telescope. The flux variation of these two bands follows a linear relation with $F_{\gamma} \propto F_{\text{lat}}^{1.14 \pm 0.07}$, which provides observational evidence for the external Compton process in 3C 454.3. Meanwhile, this flux correlation indicates that electron injection is the main mechanism for the variability origin. We also explore the variation of the flux ratio $F_{\gamma}/F_{\text{lat}}$ and the detailed structures in the light curves, and discuss some possible origins for the detailed variability behaviors.

Key words: galaxies: jets – quasars: individual (3C 454.3)

Supporting material: machine-readable table

1. Introduction

Blazars are the most extreme subclass of active galactic nuclei. They show dramatic variability throughout the entire electromagnetic spectrum. Although the mechanisms producing variability remain unclear, multi-wavelength variability is frequently used to constrain the radiation mechanisms and emission regions of blazars (Agudo et al. 2011; Liu et al. 2011; Liao et al. 2014). Recently, several attempts were performed to explore common characteristics in variability itself (Finke & Becker 2014; Wu et al. 2016; Li et al. 2017; O’Riordan et al. 2017).

3C 454.3 (2251+168) at $z = 0.859$ is a typical flat spectrum radio quasar (FSRQ). FSRQ is a subclass of blazar that shows prominent emission lines and thermal radiation from the accretion disk. Their γ-ray emission is usually explained as external Compton (EC) radiation of the relativistic electrons, which also produce the synchrotron radiation at the low energy band. However, this view still lacks direct observational evidence (Chen & Bai 2011; Meyer et al. 2012; Fan et al. 2016). 3C 454.3 started an extreme activity in 2005 (Villata et al. 2006). Then it remained active and generated several violent outbursts in the last decade throughout the multi-wavelength (Raiteri et al. 2008, 2011; Abdou et al. 2009, 2011; Ackermann et al. 2010; Pacciani et al. 2010; Sasada et al. 2012; Wehrle et al. 2012; Jorstad et al. 2013; León-Tavares et al. 2013; Kushwaha et al. 2017, also see the γ-ray light curve of the Fermi Gamma-ray Space Telescope at the website of Fermi/LAT monitored sources). The IR, optical, UV, and γ-ray outbursts occur almost simultaneously while the variation of millimeter radio flux generally lags the high frequencies (Raiteri et al. 2008, 2011; Jorstad et al. 2013, simultaneous millimeter-wave flares were also observed by Wehrle et al. 2012). The X-ray variability is more complicated. In the 2008 outburst, no corresponding X-ray variability was observed by Swift (Bonning et al. 2009), while a slightly decayed X-ray flare was observed during the 2009 outburst (Pacciani et al. 2010; Raiteri et al. 2011). In the 2010 outburst, the X-ray flare seemed simultaneous with the optical (Wehrle et al. 2012; Jorstad et al. 2013). In addition, the low-frequency radio emission (lower than 8 GHz) turned into a low activity stage when the high frequencies became active (Villata et al. 2006; Raiteri et al. 2008).

The outburst of 3C 454.3 in 2009 December had been extensively explored by many authors at various wavelengths (Pacciani et al. 2010; Bonnoli et al. 2011; Raiteri et al. 2011; Sasada et al. 2012; Jorstad et al. 2013). However, there are still some observations that have not been clearly understood, especially about the radiation mechanism of γ-ray emission and the variability origins. Bonnoli et al. (2011) found that the γ-ray flux varied quadratically with the optical flux, which is inconsistent with the prediction of the commonly assumed EC process in FSRQs. Raiteri et al. (2011) found that the major optical flare corresponded to the minor flare at the γ-ray band, which is difficult to understand under the one-zone leptonic model. Jorstad et al. (2013) performed detailed analyses on the multi-wavelength variability and the polarization variation of 3C 454.3, including the outburst in 2009. They presented several theoretical models beyond the one-zone leptonic model to interpret the multi-wavelength behaviors, while it is still unclear which model is better.
The obvious redder-when-brighter trend at a relatively faint state, following a saturation effect at a bright state, is the typical feature for the optical color variability of 3C 454.3 (Raiteri et al. 2008; Zhou et al. 2015). The redder-when-brighter trend, which is often observed in FSRQs (Gu et al. 2006; Bonning et al. 2012), is usually explained as the contribution from a less variable, bluer accretion disk to the strongly variable, redder jet emission. In addition, more complicated color behaviors of 3C 454.3 have also been observed at short timescales, which may indicate multiple emission components in this source (Zhai et al. 2011).

In this paper, we present our optical monitoring data of 3C 454.3 from 2006 to 2011. Combined with the data from the Whole Earth Blazar Telescope (WEBT) campaign, we investigate the origin of the optical color variability of 3C 454.3, and reanalyze its optical and γ-ray variability during the 2009 December outburst. This paper is organized as follows. In Section 2, we present our optical multi-color monitoring of 3C 454.3 and the data reduction for optical and Fermi/LAT γ-ray data. Section 3.1 presents the explorations for optical color variability. In Section 3.2, we investigate the correlation between optical and γ-ray flux. The variation of the flux ratio between γ-ray and optical is discussed in Section 3.3. In Section 3.4, we compare the detailed light curve between optical and γ-ray. Our main conclusions are summarized in Section 4.

2. Observations and Data Reduction

2.1. Optical Monitoring

Our photometric monitoring of 3C 454.3 was performed with the Lijiang 2.4 m telescope\(^8\) and the Kunming 1 m telescope at Yunnan observatories from 2006 September to 2011 November. A PIVersArray 1300B CCD with 1340 × 1300 pixels was used on the Lijiang 2.4 m telescope before 2011 that covered a field of view of 4′48″ × 4′40″. After 2011, the Yunnan Faint Object Spectrograph and Camera (YFOSC) began to apply for most photometric and spectroscopy observations on the Lijiang 2.4 m telescope. YFOSC has a field of view of about 10′ × 10′ and 2148 × 2200 pixels for photometric observation. Each pixel corresponds to a sky angle of 0″/283. Before 2008 July 30, a PI 1024TKB CCD with 1024 × 1024 pixels was equipped at Kunming 1.02 m telescope. The field of view is 6′5″ × 6′5″. After that, it was updated to an Andor DW436 CCD with 2048 × 2048 pixels. The field of view is 7′8″ × 7′8″. The photometric observations were performed with the standard Johnson/Cousins BVRI filters. Different exposure times were applied to match various seeing and weather conditions.

The photometric data are reduced with the standard IRAF procedure, including the bias subtraction and the flat-field correction. Then the aperture photometry is performed with the APPHOT package. The differential photometry is applied with the comparison star D in the finding chart.\(^9\) The observational uncertainty of each night is estimated by the standard deviation of the magnitude difference between comparison stars D and E. For the B-band data, the magnitude differences between comparison stars D and E have large deviations. Bonning et al. (2012) also mentioned the same problem. They obtained the new B-band magnitudes of the comparison stars based on the SMARTS data sets. Thus, in our work, the differential photometry for the B band is based on the finding chart of SMARTS.\(^10\) For multiple exposures during individual nights, we average their magnitudes. The daily averaged magnitudes are presented in Table 1. Multi-band light curves are presented in Figure 1. For the analyses in this paper, the galactic extinction is corrected according to the values from NED ($A_B = 0.462$, $A_V = 0.355$, $A_R = 0.286$, $A_I = 0.208$), which are based on the dust map of Schlegel et al. (1998). For the 2009 December outburst (from MJD 55120 to 55220), our observations get nearly one data point per night at the R band, which provides a good opportunity to study the correlated variability between optical and γ-ray bands. In order to construct more continuous multi-band light curves between 2006 and 2011, we also include the data from WEBT during the same period (from MJD 54000 to 56000) in our analyses (Raiteri et al. 2011; Vercellone et al. 2011).

2.2. Fermi/LAT Gamma-Ray Data Reduction

The γ-ray data of Fermi/LAT for 3C 454.3 are reduced with the Fermi ScienceTools v10r0p5 (more details about the Fermi/LAT data reduction can be found in Liao et al. 2016). The newest Pass 8 data of 3C 454.3 are downloaded from the Fermi data server. The data from 2009 September 1 (MET 273456002) to 2010 February 1 (MET 286675202) in the energy range 0.1–300 GeV, and in the region of interest (ROI) 10° are selected with gtselect. After the standard preprocess threads, the unbinned likelihood analysis is applied to extract the flux and spectrum with gtlike. All 3FGL sources within 20° around the target are included in the likelihood analysis. Considering the rare photons on a daily timescale, a simple power-law model is used to construct the 1 day bin light curve. An overall fit is performed first for the whole time range. Then the spectral parameters of the background sources are fixed to the values of the overall fitting. The 1 day bin light curves of the integral flux and spectral index are plotted in Figures 2(e) and (f), respectively.

3. Results and Discussions

3.1. Optical Color Variability

The color index $V − I$ shows a similar variation trend with the optical and γ-ray brightness (Figure 2, panel g), which means that the source gets redder when the source brightens. The color indices $V − I$ versus the $V$-band magnitudes are plotted in Figure 3. An obvious redder-when-brighter trend is also shown, where the slope gets flatter when the object is brighter than a critical magnitude. We fit the data with a piecewise function with two linear slopes. The fitting result is overplotted in Figure 3, with the transition point at $V_{mag} = 15.15$. When the source is fainter than 15.15 mag, it shows a clear redder-when-brighter trend with

$$ci = -0.55 V_{mag} + 9.38.$$  \hspace{1cm} (1)

When the source is brighter than 15.15 mag, it reaches a saturation stage with

$$ci = -0.06 V_{mag} + 1.86.$$  \hspace{1cm} (2)

\(^8\) http://www.gmg.org.cn/english/

\(^9\) https://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/2251+158.html

\(^10\) http://www.astro.yale.edu/smarts/glast/fc3C454.3.php
The similar trends have also been found by Raiteri et al. (2008) and Zhou et al. (2015). This two-stage trend is usually explained as the existence of the thermal component from the accretion disk (Raiteri et al. 2008; Isler et al. 2017). The saturation effect implies that the optical emission is dominated by jet radiation. Thus the transition magnitude gives an upper limit of the disk luminosity of $3 \times 10^{46}$ erg s$^{-1}$ at 2931.7 Å. This value is much larger than the results derived from the GALEX observation at 1350 Å (Bonnoli et al. 2011, $4 \times 10^{46}$ erg s$^{-1}$, which corresponds to 16.73 mag at V band if the power-law slope $\alpha = 0.5$ is assumed) and the value estimated from the BLR luminosity (Sbarrato et al. 2012, $3.33 \times 10^{46}$ erg s$^{-1}$).

In order to verify whether such a low contribution from the disk can produce the observed color variability, we attempt to reproduce the magnitude–color relation for the first time. First, the color indices of the jet emission between 0.5 and 1.5 (spectral index between 0.14 and 2.55) are inputted. The $V$-band magnitudes of jet emission are calculated from the dependent trend between the magnitude and the color index at the saturation stage (Equation (2)). The $I$-band magnitudes are calculated with the corresponding color indices. Then the magnitudes of $V$ band and $I$ band are converted into fluxes, and add the fluxes of the disk emission of $V$ band and $I$ band, respectively. Finally, we calculate the magnitudes and the color indices with the combined flux. The disk fluxes of $V$ and $I$ bands are extrapolated from the luminosity at 1350 Å with a power-law index. In order to take into account the uncertain disk features of 3C 454.3, we consider multiple values of disk luminosity and spectral index. The disk luminosities at 1350 Å and the spectral indices are varied from 0.5 to $4.0 \times 10^{46}$ (with step 0.1 less than 1.0 and step 1.0 for larger than 1.0) and $-1.0$ to 1.0 (with step 0.1), respectively. The simulated magnitudes and color indices for the mixture of the disk and jet emission are plotted in the left panel of Figure 3 (different dotted lines correspond to different values of disk luminosity and spectral index).

For disk luminosities fainter than $10^{46}$ erg s$^{-1}$ (black dotted lines in Figure 3), the influence of the disk radiation is hardly observed when the source is brighter than about 17 mag. For disk luminosities brighter than $10^{46}$ erg s$^{-1}$ and spectral indices larger than 0.3 (the magenta dotted lines), the predicted colors are much redder than the observed ones. The results for disk luminosities brighter than $10^{46}$ erg s$^{-1}$ and spectral indices less than 0.3 (the green dotted lines) also have large deviations from the observations. We also consider the condition that the color index of the jet emission is constant (Jorstad et al. 2013, $\alpha = 1.5$, $ci = 1.06$). The results are plotted in the right panel of Figure 3. With such low disk luminosity, the redder-when-brighter trend is hardly observed at the brightness less than about 16 mag. More importantly, the predicted colors are much redder than the observed ones.

According to the results of the simulations, it seems difficult to produce the observed color variability only considering the contamination of the disk radiation. The combined emission of jet and disk can produce a redder-when-brighter trend, but this trend should be obvious at the fainter state for the observed disk luminosity of 3C 454.3 (Figure 3). Thus, despite of the contamination of the disk radiation, the two-stage trend of 3C 454.3 requires that the jet emission contains more than one trend between brightness and color index. Considering a similar trend (redder-when-brighter for faint state and saturation effect for bright state) at the long-term light curve (Raiteri et al. 2008; Zhou et al. 2015), it can be expected that high and low states have different dependent trends between brightness and spectral slope, which may indicate two distinct variability origins, or different components (Jorstad et al. 2013). During the outburst, the variability origin is mainly related to the knot ejection (Jorstad et al. 2013). For the other relatively small flares without corresponding knot ejections, the flux variability may originate from the variation of other factors (see the discussion in Section 3.4).

Bonning et al. (2012) built a magnitude–color diagram of 3C 454.3 with $J$-band magnitudes and $B – J$ colors. Their results only showed a redder-when-brighter trend without the saturation stage. For the entire data set of SMARTS monitoring, it shows a slight saturation effect. The transition magnitude is close to 12.0 mag at the $J$ band (there are few data points brighter than 12.0 mag in Bonning et al. 2012). The disk brightness is 15.40 mag at $J$ band (for disk luminosity $4 \times 10^{46}$ erg s$^{-1}$ at 1350 Å and $\alpha = 0.5$). The difference is much larger than that of $V$ band (15.15 mag compared with 16.73 mag). If the contamination of disk emission is the unique reason for the redder-when-brighter trend of 3C 454.3, this trend would get flatter at a much fainter state than 12.0 mag for the $J$ band. The deviation with observation also supports our conclusion from the simulations. Isler et al. (2017) analyzed the color variability of 3C 279 over a long-term timescale. They concluded that a FSRQ can go through three stages of color variability for combined jet and disk radiation generally, redder-when-brighter, constant color, and bluer-when-brighter. For 3C 454.3, the former two stages are obvious for long timescales (Raiteri et al. 2008; Zhou et al. 2015). The bluer-when-brighter trend is slightly observed at the bright state in 2007 (Raiteri et al. 2008; Zhai et al. 2011). However, our results show no evidence for the bluer-when-brighter trend during the 2009 December outburst of 3C 454.3 (although the color during the brightest flare seems slightly bluer than other small flares; Figure 2, panel g). On the contrary, $\gamma$-ray variability shows a slightly harder-when-brighter trend during the outburst (Figure 2, panel f; also see Ackermann et al. 2010; Abdo et al. 2011). The different spectral behaviors at the bright days of 3C 454.3 may be related to different electron acceleration mechanisms (also see the discussion in Section 3.4).

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11 $F \propto \nu^{-\alpha}$. 

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http://www.astro.yale.edu/smarts/glast/tables/3C454.tab
manifest the data observed by the Lijiang 2.4 m telescope. The black points represent the data observed by the Kunming 1 m telescope. The orange points represent

\[ \gamma \text{electron number density varies during the} \]

\[ \text{obvious disk radiation at the UV band} \]

Figure 1.

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3.2. The Flux Correlation between Optical and Gamma-Ray

Figure 4 presents the flux correlation between optical $R$-band flux ($R$-band magnitude is converted to flux with the zero point 3064 Jy, Bessell et al. 1998) and the integral $\gamma$-ray flux from 0.1 to 300 GeV during the 2009 December outburst. The solid line gives the best linear fit with

\[ \log F_\gamma = (1.14 \pm 0.07) \log F_R - (6.25 \pm 0.05). \]  (3)

The flux of synchrotron radiation is dependent on the number of the emitting electrons. For $\gamma$-ray emission produced by the synchrotron self-Compton (SSC) process, if only the electron number density varies during the flux variability, the $\gamma$-ray emission would vary quadratically with optical emission (mainly dominated by synchrotron radiation at the high state) $F_\gamma \propto F_R^2$. For the EC process, this relation has the form $F_\gamma \propto F_R^\delta$ (Bonnoli et al. 2011).\(^\text{13}\) Our result is consistent with the prediction of the EC process. Moreover, this relation indicates that the variation of electron number density (e.g., electron injection) is important for generating the outburst. This is also supported by the VLBI observations, where new knots emerge during the $\gamma$-ray outbursts (Jorstad et al. 2001, 2013).

Bonnoli et al. (2011) used the Swift UVOT data and found $F_\gamma \propto F_{\text{UV}}^{1.57}$ for 3C 454.3. The deviation is caused by the obvious disk radiation at the UV band (Raiteri et al. 2007), especially at the low state. Only when the jet is bright and the jet emission is dominant (such as the $R$ band in our case), the relation predicted by the EC process could be obvious.

\[^{13}\] There are two main processes to generate the high energy emission from the hadronic process, synchrotron radiation of relativistic protons, and the $p\gamma$ process (Böttcher et al. 2013). Both processes are difficult to fit the break spectra at GeV of some FSRQs and require extreme power of protons (Böttcher et al. 2013). Thus we do not consider the hadronic model in this work.

3.3. The Flux Ratio between Gamma-Ray and Optical

The brightest fluxes of optical and $\gamma$-ray occurred on the same day (MJD 55167, hereafter the flare around MJD 55167 is called major flare) during the 2009 outburst. Figure 2(b) shows the flux ratio between $\gamma$-ray and optical $F_\gamma/F_R$ of this outburst. As expected from the flux correlation $F_\gamma \propto F_R$ derived above, $F_\gamma/F_R$ is generally a constant. However, there are also several small variations. An increase of $F_\gamma/F_R$ is shown at the beginning of the major flare. Then it declines when the flux falls during the major flare. At the end of our observation of this outburst, $F_\gamma/F_R$ also shows a declining trend along with the flux falling.

The flux ratio $F_\gamma/F_R$ can be taken as the Compton dominance if the slope of SED is invariant over time. Thus $F_\gamma/F_R \sim CD \propto \delta^2 u_{\text{ext}}/u_B$ for EC process (where $CD$ is Compton dominance, $u_{\text{ext}}$ is the energy density of the external photon field, $u_B = B^2/8\pi$ is the energy density of the magnetic field, and $\delta$ is the Doppler factor, see, e.g., Finke 2013). That means $F_\gamma/F_R$ would be constant if no other parameter changes, except for the electron number density during the flux variability. Obviously, this is not the case in the observation. Therefore, it can be expected that there are some other parameters varying during the outburst (changed spectra or others, see the discussion in the next section).

The general variability profile can be a result of changing Doppler factors. If this is the case, it would result in the same trend between the light curve and $F_\gamma/F_R$ under the EC process for homogeneous jet (as $F_\gamma/F_R \sim CD \propto \delta^2$), which is not seen in our results. This indicates that the variation of the Doppler factor is not the main reason for the variability, which is also consistent with the scenario indicated by the flux correlation. Jorstad et al. (2013) compared the SEDs for three different outbursts and the quiescent state. They found that for the outburst with a larger variability amplitude, the Doppler factor was also larger than that in others. Thus the variation of the
Doppler factor is still important for different variability amplitude of various outbursts.

3.4. The Detailed Structures in Optical and Gamma-Ray Light Curves

There are some differences in the detailed variability behaviors between optical and γ-ray bands. In particular, the R-band flux declines slower than the γ-ray flux. After the major flare at MJD 55167, it seems that there are several minor flares following at the R band, which have no direct counterparts at the γ-ray band (Figure 2). In order to study these differences in detail, we perform a decomposition for the light curves with multiple exponents. Each component has the form

\[ F = 2F_0(e^{(h-o)/T_r} + e^{(o-h)/T_f})^{-1}, \]

where \( T_r \) and \( T_f \) are the timescales for rising and falling, respectively, \( F_0 \) is the flux at \( t_0 \) (Abdo et al. 2011). The R-band light curve is linearly interpolated first to match the daily time resolution of the γ-ray data. Then the light curves are smoothed to reduce the random variations. Before fitting, the minimum values of optical and γ-ray flux are subtracted from the data, respectively. Each light curve requires 11 components of Equation (4). The results are plotted in Figure 5. The fitting parameters of each component are listed in Table 2.

The subflares of the γ-ray generally correspond to those of the optical. The biggest difference between the structures of two light curves occurs after the major flare. Two minor flares (\( t_0 = \text{MJD} \ 55178.1 \) and 55188.4, Table 2) follow the major flare at optical without γ-ray counterparts. On the other hand, the γ-ray flux drops rapidly with two plateaus (\( t_0 = 55174.2 \) and 55179.1, Table 2). The first plateau starts approximately 4 days after the brightest flux (the black points in Figure 5). The second plateau seems to be corresponding to the two minor flares at the optical. These different structures on the light curves are difficult to explain by simple electron injection in the emission region(s).

There are some possible explanations for the orphan flare at the optical band. A natural one is that it comes from another component, e.g., thermal radiation from the accretion disk. However, the emission lines show rare variability except for two flares corresponding to the γ-ray flare, which indicates that disk radiation is slowly varying (Isler et al. 2013). The increase of magnetic field strength would only increase the flux of synchrotron and SSC components, but not increase that of the EC component. Meanwhile, the increase of magnetic field strength leads to a decrease of the Compton dominance, which is actually seen from the variation of \( F_\gamma/F_\gamma \) (Figure 2, panel h). However, after the minor flares, \( F_\gamma/F_\gamma \) still remains low, which seems contradictory to the variations of magnetic field strength.

Increasing the energy density of the external field can result in the increase of \( F_\gamma/F_\gamma \). A flare of the emission line has been observed during the 2009 outburst (Isler et al. 2013). But this flare is more likely to be associated with the excitation of the jet rather than the disk (Isler et al. 2013; León-Tavares et al. 2013, but see Paggi et al. 2011 for the indirect evidence of increasing accretion rate). There is also a possibility that the emission region gets closer to the external photon field, which makes the energy density of the external field increase. But it is difficult to explain the orphan flare at optical band by changing the external fields. We note that the variation of the external field strength can be important on a long-term timescale, such as that for different outbursts. Because the variability amplitude of the γ-ray can be much larger than that of the optical (Raiteri et al. 2011).

Another possibility is related to the helical movement of the emission region. As the electron cooling for the optical and γ-ray could be non-simultaneous in the emission region, the observed emission of these two bands may generate at different locations, which correspond to different viewing angles in the helical jet. Then the Doppler factors are different for different wavelengths, which could result in different fluxes for the optical and γ-ray. Moreover, the variation of the Doppler factor can also explain the variation of \( F_\gamma/F_\gamma \).

In addition, if the injected electron energy distribution (break energy or spectral index) changes for different flares, the SEDs would change accordingly. As the γ-ray flux is integral between 0.1 and 300 GeV, if spectral index of the minor flare is steeper than that of the major flare, the γ-ray flux of the former may vary less than the latter. The optical flux is little affected by this effect. This effect also affects the flux ratio \( F_\gamma/F_\gamma \), which indicates that \( F_\gamma/F_\gamma \) cannot represent Compton dominance simply (see Fan et al. 2012 for the similar behavior of the ratio between γ-ray and...
Figure 3. Color index $V-I$ vs. $V$-band magnitude. The blue solid line shows the best fit of two linear slopes. The black dotted lines are the simulated results for disk luminosity fainter than $10^{46}$ erg s$^{-1}$. The green dotted lines show the results for disk luminosity brighter than $10^{46}$ erg s$^{-1}$ and the spectral index less than 0.3. The magenta dotted lines show the results for disk luminosity brighter than $10^{46}$ erg s$^{-1}$ and the spectral index larger than 0.3. The left panel displays the results based on the relation between magnitude and color index from Equation (2), the right panel displays the results based on a constant color index. See the text for details.

Figure 4. Correlation between optical and $\gamma$-ray flux. The solid line shows the best fit.

radio luminosity). Meanwhile, this would predict a softer spectrum for the minor flare. Actually, the optical color during the major flare appears to be bluer (smaller color index) than the minor flare (Figure 2, panel g), which may indicate the possible steeper electron spectrum for the minor flare. However, we do not find obvious differences on the $\gamma$-ray spectral index between major and minor flares (Figure 2, panel f).

As the blob moves downstream, it collides with the previously ejected blobs. This process generates internal shock and accelerates the electrons. The collision can occur more than once, then produce the multiple flares in the observations. In addition, the magnetic reconnection process can also accelerate electrons and produce the flares. The electron spectrum accelerated by the magnetic reconnection process can be much harder than by shocks (Guo et al. 2014; Sironi & Spitkovsky 2014). Different flares coupled with different spectral behaviors during the outburst may be produced by different acceleration mechanisms. Some of the brightest flares might be related to magnetic reconnection events (Zhang & Yan 2011; Sikora 2016), which lead to harder electron spectra (also bluer-when-brighter trends at optical). Other flares with relatively steeper spectra (corresponding to redder-when-brighter trends), on the other hand, may be produced by shocks.

The discussions above are mainly based on the one-zone leptonic model, which is widely applied to 3C 454.3 (e.g., Pacciani et al. 2010; Bonnoli et al. 2011). In addition, Raiteri et al. (2011) explained the variability of 3C 454.3 as a geometrical effect of changing viewing angles under a curved inhomogeneous jet model (also see Villata & Raiteri 1999; Raiteri et al. 2017). Under this model, the emission regions are different for different bands, and the curved jet makes the viewing angles different for different bands. This effect results in different Doppler factors between the optical and $\gamma$-ray. The general profile of the light curves can be explained by the varying viewing angles over time, which do not require the electron injection. Similar to the helical movement of the emission region, this model can explain the difference on the detailed variability behaviors between optical and $\gamma$-ray, as well as the variation of the flux ratio $F_{\gamma}/F_R$.

Jorstad et al. (2013) analyzed the multi-wavelength variability, as well as the behaviors of the millimeter-wave core and optical polarization of 3C 454.3. They explained the three-peak structure during the outburst as different locations of the emission region. In addition, they presented three more complicated models beyond the one-zone leptonic model, namely the recollimation shocks and the turbulent extreme multi-zone (TEMZ) model (Marscher 2014), mini-jet model (Giannios et al. 2009), and current-driven instability (CDI, Nalewajko & Begelman 2012), to explain the flux and polarization behaviors along with the evolution of the millimeter-wave core. The TEMZ model seems difficult to fit the X-ray spectrum of 3C 454.3. The emission region of mini-jet and CDI models might be different. The CDI is most prominent at the end of the acceleration and collimation zone of the jet (Jorstad et al. 2013), while the locations of mini-jets are related to the processes that trigger the magnetic reconnection events (Giannios 2013). In addition, both models require strongly magnetized jets, while the magnetization in the dissipation region of the blazar is still under debate (Janiak et al. 2015; Sikora 2016). More data with even sampling and systematic analyses for the common characteristics (such as the spectral behaviors, the location of emission region, the
polarization variability, and the timescales) during blazar variability may be helpful to distinguish all of these models.

4. Conclusions

In this paper, we present our optical monitoring data of 3C 454.3 at Yunnan observatories from 2006 September to 2011 November. Based on the multi-color photometry, we explore the origin of the optical color variability of 3C 454.3, which is characterized by a two-stage trend. Thanks to the good cadence for the 2009 outburst of 3C 454.3, we further analyze the correlated variability behaviors of optical $R$ band along with the Fermi/LAT $\gamma$-ray data.

The optical color indices show an obvious redder-when-brighter trend when the source is fainter than 15.15 mag at $V$ band, and a clear saturation effect when the source is brighter than 15.15 mag. We perform simulations with multiple disk luminosities and spectral indices to evaluate the impact from disk radiation on the magnitude–color relation. The simulations show that the contamination of the disk radiation alone is difficult to explain the observed color variability, which indicates two distinct components or variability origins at high and low states of 3C 454.3.

We find that the variation of the optical and $\gamma$-ray fluxes follows the relation $F_\gamma \propto F_R$, which gives observational evidence for the EC process of the $\gamma$-ray emission. Meanwhile, this relation implies that the main mechanism for the variability is electron injection. We also explore the variation of the flux ratio between the $\gamma$-ray and optical, as well as the detailed structures of the light curves at both bands. The flux ratio $F_\gamma/F_R$ shows small variations during the outburst. There are two minor flares following the major flare, which are only observed at the optical band. Based on the one-zone leptonic model of the EC process, some possible mechanisms, including the variations of the slope of electron spectrum, magnetic field strength, external field, and Doppler factor are discussed. The varying Doppler factors in helical (or inhomogeneous) jets, and changed electron spectra for different flares seem feasible to interpret the observations.

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