Quasi–periodic Oscillation and Evidence of a Curved Jet in the Blazar 3C 454.3

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ABSTRACT

We report the detection of a quasi-periodic oscillation (QPO) in light curves of the blazar 3C 454.3. Periodic flux modulation was detected simultaneously in both γ–ray and optical wavebands with a dominant period of ∼47 days. This period has a significance of over 4.2σ in the Fermi γ–ray waveband and around 2.4σ in the optical V band. This QPO lasted for over 450 days (from MJD 56800 to 57250) resulting in over nine observed periods which is among the highest number of periods ever detected in a blazar light curve. The lower significance of the dominant period in optical wavebands is attributed to the absence of optical data for a number of QPO cycles due to the daytime transit of the source. We explore several physical models to explain the origin of this transient quasi-periodic modulation in the observed flux with a month-like period. These scenarios include a binary black hole system, a hotspot orbiting close to the innermost stable circular orbit of the supermassive black hole, and precessing jets. We conclude that the most likely scenario involves a region of enhanced emission moving helically inside a jet. Also, a curvature of ∼0.05° pc−1 in the jet fits the emission much better than does a straight blazar jet.

Keywords: galaxies: active — galaxies :jet — methods: observational — quasars: individual (3C 454.3) — techniques: photometric

1. INTRODUCTION

Blazars are the class of active galactic nuclei (AGN) that show the most substantial variability across all bands of the electromagnetic spectrum. All active galaxies are understood to derive their ultimate power from accretion onto a supermassive black hole (SMBH) with a mass in the range of 10^6 – 10^10 M_☉. Blazars also possess relativistic jets pointing toward us that dominate the observed emission in most bands (Urry & Padovani 1995; Wagner & Witzel 1995). There are quite a few similarities in the nature of the time series data (light curves) between X-ray emission from AGN and X-ray emitting binaries in our and nearby galaxies, where gas flows from a star through an accretion disc onto a neutron star or black hole of several solar masses. In fact, AGNs can be considered as scaled up galactic BH binaries wherein the location of a break from shallower to steeper slopes in the red-noise power-spectrum of the light curve is proportional to the BH mass (Abramowicz et al. 2004). Although QPOs are rather common in the light curves of X-ray emitting binaries (Remillard & McClintock 2006), they appear to be quite rare for AGNs (Gupta 2014, 2018).

There have been rather strong claims of AGN QPOs in different bands of the electromagnetic spectrum, ranging from minutes through days through months and years (e.g., Gierliński et al. 2008; Lachowicz et al. 2009; Gupta et al. 2009, 2019; Gupta 2014, 2018; Zhou et al. 2018; Bhatta 2019, and references therein). However, many of the claimed QPOs, particularly those made earlier (Gupta 2014) are marginal detections, lasting only a few cycles, and the originally quoted statistical significances are probably overestimates (Gupta 2014; Covino et al. 2019). Among the better recent claims of QPOs in the γ–ray band are ∼34.5 days in the blazar PKS 2247–131 (Zhou et al. 2018) and one of ∼71 days was found in the blazar B2 1520+31 (Gupta et al. 2019) as part of a continuing analysis of blazar Fermi–LAT observations. Some possibly related QPOs of a few hundred days in two widely separated bands have been reported (Sandrinelli et al. 2016a,b, 2017). However, it was recently
found that multiwaveband QPOs, along with most earlier claims of γ-ray QPOs, are not significant (Covino et al. 2019) when a uniform and more careful power spectral density (PSD) analysis was performed. In no case has there been a claim that a QPO with a period of few tens of days has recurred at the same central frequency in the same AGN during observations well separated in frequency.

Here we detect in 3C 454.3, for the first time, a QPO with a month-like period of around 47 days simultaneously in both archival γ-ray measurements and optical V band observations. 3C 454.3 is among the brightest and most well studied (e.g., Jorstad et al. 2005, 2013; Hovatta et al. 2009; Bonning et al. 2009; Gaur et al. 2012; Kushwaha et al. 2017; Gupta et al. 2017; Sarkar et al. 2019, and reference therein) of the flat spectrum radio quasar (FSRQ) subclass of blazars. We examine several
possible explanations for this periodicity and conclude that a geometrical model with blobs moving helically in a curved jet best explains this QPO aspect of the variability, and where the curvature of the relativistic jet of 3C 454.3 is estimated from the flux modulation during the QPO.

The mass of the SMBH at the center of 3C 454.3 (B2251+158; z = 0.859) is estimated by optical spectroscopy methods to be in the range of \((0.5 - 2.3) \times 10^8 M_\odot\) (Gupta et al. 2017). The flow speed down the approaching relativistic jet is in the range of 0.97c to 0.999c (Jorstad et al. 2005; Hovatta et al. 2009) and the angle to the observer’s line of sight is between 1° and 6° (Sarkar et al. 2019). 3C 454.3 has shown a variety of observational patterns in multi-band observations made at different epochs, ranging from correlated multiwaveband emission (except for X-rays) (Bonning et al. 2009; Gaur et al. 2012; Kushwaha et al. 2017) to strong \(\gamma\)-ray flaring events in 2009–2010 which were modeled using a combination of standing conical shocks and magnetic reconnection events in the core of the jet (Jorstad et al. 2013).

A strong, correlated multiwaveband flare occurred in 2009 December 3–12 where dramatic changes (\(\sim 170^\circ\)) in optical polarization were observed along with strong anti-correlation between optical flux and degree of polarization (Gupta et al. 2017). It is a peculiar blazar, and various sets of possible correlations between multiwavelength observations at different epochs have been noted (e.g., Gupta et al. 2017; Sarkar et al. 2019, and references therein).

The subsequent sections of this work deal with the detection and physical interpretation of the observed QPO. Section 2 provides the data reduction procedures, and Section 3 deals with the analyses involved in searching for QPOs in the emitted flux. The results are elaborated in Section 4 and our physical interpretation is given in Section 5.

2. DATA ACQUISITION

The \(\gamma\)-ray observations were made using the large area telescope onboard the Fermi satellite (Fermi–LAT). It is a pair conversion detector having a field of view of 2.4 sr (Atwood et al. 2009) and provides near constant monitoring of the \(\gamma\)-ray sky. For our analysis, we consider a region of interest of 15° centered around the source (RA: 343.491, DEC: +16.1482). The data in the energy range 100 MeV to 300 GeV from MJD 56800 to MJD 58000 were examined using a zenith angle cut of 90° to prevent source contamination from the earth’s limb. The filter (\texttt{DATQUAL} \(> 0\) \texttt{&& LAT_CONFIG} \(= 1\)) was applied to select the good time intervals. The data were analysed using Fermi tools and enrico software (Sanchez & Deil 2013). During the likelihood analysis, the galactic diffuse emission was modeled using \texttt{gll_iem.v06.fit} and the isotropic background was modeled using \texttt{iso_P8R2_SOURCE_V6.v06.txt}. The unbinned likelihood analysis was performed using the \texttt{gtlike} tool (Cash 1979; Mattox et al. 1996). There were 53 point sources from the 3FGL catalog in our region of interest. The parameters of the sources that were within a 5° region around 3C 454.3 were allowed to vary. The parameters of a bright source, J2232.4+1143 (CTA 102) at about 12° from the source were also kept free. During the likelihood analysis, the sources having significances of \(< 1\sigma\) were removed after every fit. The light curve was obtained by integrating the source fluxes with an integration time of 1 day for the intervals where the test statistic (Mattox et al. 1996) exceeded 25 (\(\geq 5\sigma\) significance). For the light curve generation, the source spectrum was modeled using a power law, whose index was kept free during the fit.

Because of the relative brightness of the blazar 3C 454.3, several long-term ground-based optical monitoring programs have tracked its variability for many years, albeit with unavoidable annual gaps when it is not visible at night. We obtained magnitudes of 3C 454.3 for the same interval as the Fermi data were available from the public archive of the Small and Medium Aperture Research Telescope System (SMARTS). These observations were taken at the Cerro Tololo Inter–American Observatory in Chile using CCD imaging and photometry on the 1.3-m telescope. Details about the instrument, observation, and data reduction and analysis of SMARTS data are described in Bonning et al. (2012). We also employed optical photometric observations that were carried out at Steward Observatory, University of Arizona, using SPOI (a CCD Imaging/Spectropolarimeter). Details of this instrument, observations, and data analysis are provided in Smith et al. (2009). The V magnitudes of 3C 454.3 obtained from SMARTS and Steward Observatory observations were combined into 1-day bins after converting the magnitude values into flux densities.

The light curves are given in Figure 1a & b. The light curves were divided into segments A (MJD 55000 to 55700) and B (MJD 56750 to 57700) during the search for QPOs. A visual inspection of Figure 1 indicated a presence of quasi-periodic flux modulation during segment B in both wavebands. More stringent tests are performed in the next section.

3. ANALYSIS

To begin a search for the presence of periodicity, we used a periodogram, or PSD, which gives the power
emitted in each frequency for a regularly sampled time series. A periodogram is constructed by taking the modulusquare of the discrete Fourier transform (DFT) of the astrophysical light curve. DFT needs the data points to be regularly sampled (i.e., no gaps in the data). However, astrophysical light curves are rarely regularly sampled. To account for irregular sampling, we use the Lomb-Scargle periodogram (LSP, Lomb 1976; Scargle 1982) algorithm. It fits sinusoids with different frequencies to the data and constructs a periodogram from the goodness of fit. We limit our analysis to a period of 10 to 100 days; as our data range consists of 950 days binned into 1-day bins, searching beyond this range would not be reasonable. Considering the periodogram power at $N$ different frequencies are independent and normally distributed (white-noise spectrum), the probability ($p$) that the maximum power of any of the frequencies crossing a threshold ($z$) can be calculated using $p(> z) \approx N \ e^{-z^2}$. This is the false alarm probability (FAP) of the period peak (Scargle 1982; Hong et al. 2018) considering a white-noise spectrum. Most astrophysical processes, however, have a red-noise power spectrum, with more power emitted at lower frequencies. The FAP thus is not a good metric to judge the significance of periodogram peaks.

The underlying red noise spectrum needs to be modeled properly to get the correct significances of the periodogram peaks. A rudimentary model of the red noise spectra is a power-law fit to the observed periodogram (Vaughan 2005). However, this model underestimates the peak significances, especially at lower frequencies. Since the time series of a red-noise process can be approximated by a discrete auto-regressive (AR) process (current emission is dependent on past emissions, thereby yielding fewer dramatic jumps as compared to white-noise), a better model can be obtained by considering the spectrum due to an AR(1) process, where the present emission depends only on the emission that preceded it. Mathematically, $F(t_i) = A_i \ F(t_{i-1}) + \sqrt{1-A_i^2} \ \epsilon(t_i)$ (Robinson 1977). Here $F(t_i)$ is the flux value at time $t_i$. $A_i = \exp((t_{i-1} - t_i)/\tau) \in [0,1]$ is the auto-regression coefficient where $\tau$ is the characteristic timescale of the AR1 process and $\epsilon$ is a Gaussian noise. The spectrum of the AR(1) process is given by (Percival & Walden 1993)
Figure 3. Periodograms (black) for (a) γ-ray and (b) optical light curves, generated using REDFIT. The red curves give the theoretical AR(1) models and the blue curves are the nominal 99% significance levels. Folded light curves (black) (c) for γ-rays and (d) for optical emission fitted using models (red) with two Lorentzian components (purple and blue). The time range considered is at the top of the figure.

\[ G_{rr}(f_j) = G_0 \frac{1 - A^2}{1 - 2A \cos(\pi f_j / f_{Nyq}) + A^2} \]  

where \( f_j \) is the discrete frequency up to the Nyquist frequency \( f_{Nyq} \), \( G_0 \) is the average spectral amplitude, and \( A = \exp(\Delta t / \tau) \) is obtained by averaging over the sampling interval while \( \tau \) is obtained from Welch-overlapped-segment-averaging (WOSA, Welch 1967) of the LSP. This entire analysis was performed using a computer code (REDFIT\(^1\), Schulz & Mudelsee 2002).

To look for transient periodicities, we use a wavelet method (WWZ) to decompose the data into time and frequency domains (WWZ maps, Foster 1996), by convolving the light curve with a time and frequency dependent kernel. The wavelet kernel used is the abbreviated Morlet kernel (Grossmann & Morlet 1984) which has the following functional form: \( f(\omega | t - \tau) = \exp(\im \omega (t - \tau) - c \omega^2 (t - \tau)^2) \). The WWZ map is then given by

\[ W(\omega, \tau; x(t)) = \omega^{1/2} \int x(t) f^*(\omega(t - \tau)) dt \]  

Here \( f^* \) is the complex conjugate of the wavelet kernel \( f \), \( \omega \) is the scale factor (frequency) and \( \tau \) is the time-shift. This kernel is like a windowed discrete fourier transform (DFT) with the window \( \exp(-c \omega^2 (t - \tau)^2) \), so where the window size depends on \( \omega \). A WWZ map has the advantage of locating both, any dominant periods and their spans in time.

It can be seen (Fig. 1) that the sampling of V-band is worse than γ-rays in segments A and B. This is caused by the source transiting during day. Due to this poorer sampling, the significance of the dominant period in the V-band can be underestimated as compared to the γ-ray band. To mediate this issue, we use a discrete correlation function (DCF, Edelson & Krolik 1988) to understand the temporal correlation between the emissions in the two wavebands. If emissions in different wavebands show high correlation, then even if the dominant period in one band is less significant, we can attribute it to poorer sampling (not on something intrinsic). The DCF is calculated by first computing the unbinned DCF

\[ UDCF_{ij} = \frac{(F_{\gamma}(t_i) - \overline{F}_{\gamma} \right) (F_{V}(t_j) - \overline{F}_{V})}{\sqrt{\sigma^2(F_{\gamma}) \sigma^2(F_{V})}} \]  

Here \( F_{A}(t_i) \) is the A band flux at time \( t_i \) and \( \overline{F} \) and \( \sigma^2(F) \) are the flux mean and variance respectively. To

\(^1\) https://www.manfredmudelsee.com/soft/redfit/index.htm
obtain the DCF, we bin the UDCF by averaging the points with a delay ($\Delta t_{ij} = t_i - t_j$) in the range $\tau - \Delta \tau/2 \leq \Delta t_{ij} \leq \tau + \Delta \tau/2$. Here $\tau$ is the time lag and $\Delta \tau$ is the bin width. The DCF is then

$$ DCF(\tau) = \frac{1}{n} \sum UDCF_{ij}(\tau) $$

Since the blazar emissions arise from a non-stationary statistical process, the mean and standard deviation were calculated using only the points that fall within a given time-lag bin (White & Peterson 1994). The DCF bin error is given by

$$ \sigma_{DCF}(\tau) = \frac{1}{M-1} \sqrt{\sum_{k=1}^{M} (UDCF_k - DCF(\tau))^2} $$

Both the light curves were de-trended by subtracting a linear baseline prior to the DCF analysis following Welsh (1999).

The significance of the periodogram peak was obtained both analytically and by using a Monte-Carlo (MC) method. Analytically, the significance is obtained by the distribution of a $\chi^2$ variable about the red noise model (since DFT consists of real and imaginary parts which are normally distributed and mod-squaring them gives a $\chi^2$ random variable). For the MC method, a thousand light curves were generated following the same PSD and flux distribution of the original light curves (Emmanoulopoulos et al. 2013). The PSD of each original light curve was approximated using a smooth bending power-law approximation of Equation 1 and the flux distribution were approximated using lognormal distributions. The flux errors were sampled from a Gamma

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Figure 4. $\gamma$-ray emission (black) modeled by a blob moving on a helical helical path within (a) a straight jet (green) or by one moving within (b) a curved jet (red). (c) Viewing angle of the jet as a function of time (which can also be interpreted as the change in viewing angle as a function of distance from the base of the jet) for these models. (d) Average flux in each period modeled using straight and curved jets, with the Akaike Information Criterion (AIC) values given in the inset. Lower AIC values indicate a better model, so the curved jet is a more likely scenario. (e) A cartoon of a blob moving helically inside a curved jet.
distribution. Every analysis that was performed on the real light curve was also performed on the thousand simulated light curves. The significances were obtained using the mean and standard deviation of the results in the simulated light curves. The significances of the DCF was calculated exclusively using the MC method.

4. RESULTS

Our search for quasi-periodicity in the intervals A and B revealed highly significant QPO during interval B in the $\gamma$-ray light curve of 3C 454.3 (Fig. 2). Because the DCF for interval B shows that the $\gamma$-ray and optical emissions are significantly ($>3\sigma$) correlated at zero lag (Fig. 1c), if a significant quasi-periodicity is observed in one wave-band, it is expected that the other wave-band would also demonstrate quasi-periodicity. The WWZ maps for both bands in interval B are shown in Figure 2 which shows a significant QPO at $\sim 47$ days in both the wave-bands in the time range MJD 56800 to 57050. The QPO remains visible in the Fermi–LAT data through MJD 57250; unfortunately, optical data are not available after MJD 57050. We obtained the dominant periods by fitting the LSP peak, also shown in Figure 2, using a log-normal function. The centre of the quasi-period of oscillation is $47.4^{+0.97}_{-0.51}$ days (4.1σ significance) for the $\gamma$-ray and $47.3^{+1.08}_{-0.63}$ days (2.4σ significance) for the optical. The FAP (considering white noise) for the $\gamma$-ray period is $10^{-5}$ and for optical it is $\sim 10^{-5}$. Using an AR(1) model (REDFIT), both the peaks turned out to be of $>99\%$ significance (Fig. 3). It can be noted that for the $\gamma$-ray emission, along with the most significant period at $47.4^{+0.97}_{-0.51}$ days, the source also shows evidence of periodicity at $\sim 95$ days, which, at twice the dominant period, is almost certainly a harmonic. Since it is not strongly significant, is very close to the upper limit of the periods that can be considered, and is not seen in the optical band, we do not consider it further.

5. DISCUSSION

The apparent QPO in the $\gamma$-ray light curve of the blazar 3C 454.3 extends for over 9 cycles and is therefore among the strongest claims made for one in an AGN. Even though the significance of the optical quasi-period is formally $<3\sigma$, we consider this period significant because the optical and $\gamma$-ray QPOs have the same periods and occur simultaneously. It is thus extremely likely that the periodicity in both the wave-bands are caused due to closely related intrinsic physical processes and the significance of the optical QPO is lower because of the poorer sampling in that band.

Several different physical models might explain the origin of periodicity or quasi-periodicity in a blazar emission. One possible explanation could be a binary supermassive black hole (SMBH) AGN system (Ackermann et al. 2015; Sandrinelli et al. 2016a,b) where the orbital period provides the flux modulation. The total mass of the BH system in those cases is $\sim 10^8 M_\odot$, while 3C 454.3 is almost certainly more massive. So the secondary BH’s orbital period would be of the scale of a few years considering the distance between them to be of the order of milli-parsec. Explicitly, periodicity can be induced by the secondary BH by piercing the accretion disc of the primary BH during the orbit (Valtonen et al. 2008) and for the blazar OJ 287 where the mass is greater, the period is $\sim 12$ y. Also, a binary SMBH model cannot naturally explain the fading of the oscillation in 3C 454.3 after $\sim 500$ days. A second possibility involves an accretion disc hotspot orbiting close to the innermost stable circular orbit of the SMBH (Gupta et al. 2019). Hotspot emissions are quasi-thermal and could directly explain the optical flux modulation. The optical emission could produce variations in the seed photon field for external Compton interactions which gives rise to the flux modulation in the $\gamma$-ray light curve (Gupta et al. 2017). However, the expected period would be much shorter than 47 days for any reasonable SMBH mass and spin. It would not be same as the $\gamma$-ray period, which would be Doppler boosted. While jet precession models could give rise to QPOs in the light curve of a blazar, the expected period is $>1$ year (Rieger 2004) which does not agree with the present observations.

We find that the most likely scenario for the observed QPO is for it to arise from a region of enhanced emission, or blob, moving helically within the jet. The Doppler factor is related to the viewing angle to the emission region and so such a motion of the blob changes the special relativistic boosting and can result in a signifi-

\[ F(\text{ph cm}^{-2} \text{s}^{-1}) \]

\[ 1 \times 10^{-6} \]

\[ 3.5 \]

\[ 2.5 \]

\[ 2.0 \]

\[ 1.5 \]

\[ 1.0 \]

\[ 0 \]

\[ 10 \]

\[ 20 \]

\[ 30 \]

\[ 40 \]

\[ \text{Phase (days)} \]

\[ \text{F (ph cm}^{-2} \text{s}^{-1}) \]

\[ 1 \times 10^{-6} \]

\[ 3.5 \]

\[ 2.5 \]

\[ 2.0 \]

\[ 1.5 \]

\[ 1.0 \]

\[ 0 \]

\[ 10 \]

\[ 20 \]

\[ 30 \]

\[ 40 \]

\[ \text{Phase (days)} \]

\[ \text{F (ph cm}^{-2} \text{s}^{-1}) \]
icant change in the observed flux. For a blob moving helically, the changing viewing angle of the blob with respect to our line of sight, $\theta_{\text{obs}}(t)$, is given by (Sobacchi et al. 2017)

$$\cos \theta_{\text{obs}}(t) = \sin \phi \sin \psi \cos(2\pi t/P_{\text{obs}}) + \cos \phi \cos \psi$$

where $P_{\text{obs}}$ is the observed period, $\phi$ is the pitch angle of the helix and $\psi$ is the angle of the axis of the jet with respect to our line of sight (Fig. 4c). The Doppler factor dependence on viewing angle is $\delta = 1/\Gamma(1 - \beta \cos \theta_{\text{obs}})$, where $\Gamma = 1/(1 - \beta^{-2})^{1/2}$ is the bulk Lorentz factor and $\beta = v_{\text{jet}}/c$. Any emission in the comoving frame of the blob will be Doppler boosted and the observed emission will be $F_\nu \propto \delta^3 F'_\nu$ (primed coordinates are in the rest frame of the blob). Substituting the value of $\cos \theta_{\text{obs}}(t)$ in the expression for $\delta$ and subsequently in the expression for $F_\nu$, we get

$$F'_\nu \propto \frac{F'_\nu}{\Gamma^3(1+S)^3} \left(1 - \frac{\beta C}{1+S} \cos(2\pi t/P_{\text{obs}})\right)^{-3}$$

where $F'_\nu$ is the rest frame emission, $P_{\text{obs}}$ is the observed period, $C = \cos \phi \cos \psi$ and $S = \sin \phi \sin \psi$. The boosted emission was modeled in the observed frame by considering a straight jet (Fig. 4a) and a curved jet (Fig. 4b) with the viewing angle to the jet (at the position of the blob as a function of time) given in Figure 4c. A curvature in the jet can easily be accounted for by considering $\psi \equiv \psi(t)$, which implies spatial jet curvature due to the longitudinal motion of the blob.

We compare the straight jet model with the curved jet model using the Akaike Information Criterion (AIC). That is defined as $AIC = -2 \ln L + 2k$, where $L$ is the likelihood of obtaining the data given the model and $k$ is the number of free parameters in the model. Judging by the AIC, the observed flux and flux per period is better modeled by a curved jet (Fig. 4d). Due to Doppler boosting, the periods in the observed and rest frame of the blob are related by $P_{\text{obs}} = P_{\text{rest}}(1 - \beta \cos \psi(t) \cos \phi)$, implying either $P_{\text{obs}}$ or $P_{\text{rest}}$ is a function of time if the other one is constant and the jet is curved. We assume that the period in the rest frame of the blob is constant, at $P_{\text{rest}} = P_{\text{obs}}/(1 - \beta \cos(\psi(t)) \cos \phi) \approx 27.6$ years which translates to a change in the observed period from 40 to 48 days. Since nearly 70% of the observed stretch is dominated by near–constant viewing angles, the resultant dominant quasi-period is closer to 47 days.

Light curves folded with a period of 47 days (Fig. 3) were fitted using a Lorentzian approximation of Equation 7. Both $\gamma$-rays and V-band required two Lorentzian components, $L_1$ and $L_2$, to properly fit the folded light curve. The peak positions of the two Lorentzian components are the same in both the $\gamma$ and V–bands, but the relative amplitudes of the two components are different. This is similar to recent observations of the blazar PKS 2247–131, where the two features were explained as a signature of two discrete emission regions, perhaps corresponding to forward and backward shocks (Zhou et al. 2018).

Another plausible explanation is the variable period of oscillation due to the jet curvature so that, $L_1$, is contributed by aggregating the flux from most of the cycles (3 onwards), whereas the component $L_2$ is due to fluxes from cycles 1–3 where the greater differences in period translates to a difference in phase in the folded $\gamma$-ray light curve. Since the observed fluxes in the first three cycles are significantly higher than the rest, their contribution does not wash out even after averaging over 10 periods (see Fig. 5). However, the V-band light curve was observed for fewer cycles (< 5), so the folded light curve is dominated by fluxes from cycles 1–3. Hence $L_2$ has a higher relative amplitude for the V–band. We also note that the optical electric vector polarization angle (EVPA) varied substantially, from 0° to 180° during this period (see Fig. 1d). Such variations are another signature of blobs moving helically in the jet (Marscher et al. 2008), but in the present case, the polarimetric sampling is not good enough to adequately define the evolution of the EVPA with time.

Our analysis strongly suggests that the observed modulation of the flux from 3C 454.3 over more than a year is due to an enhanced emission region moving helically within a curved jet or conceivably a curved-helical jet itself. But since blazar emission mechanisms are complicated, it is possible that the observed flux modulation is due to some other effect (intrinsic or otherwise) or a combination of such effects. Considering the model to be correct with parameter values $\phi \approx 2^\circ$ and $\Gamma = 15$, we can best model the viewing angle as changing from 2.6° at MJD 56850 to 3.6° over three QPO cycles (after the first, partial one, which corresponds to an initial $\psi$(MJD 56800) = 1.6° (Fig. 4c). The distance travelled by the blob in one period is $D_{1P} = c\beta P_{\text{rest}} \cos \phi \approx 8.4$ pc. Thus the viewing angle changes by $1^\circ$ at a distance of 3$D_{1P}$ resulting in the jet curvature to be $\approx 0.05^\circ$ pc$^{-1}$.

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