# Radio and Gamma-Ray Variability Characteristic Timescales of 4C 01.02 (Postprint)

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## Abstract

Using the celerite method, which differs from traditional Fourier-like approaches, we analyze the long-term variability characteristics of the blazar 4C 01.02 in the $\gamma$-ray and radio bands. The results demonstrate that the simplest damped random walk (DRW) model in celerite can successfully fit the long-term light curves in both radio and $\gamma$-ray bands, whereas the more complex second-order stochastic process (stochastically-driven damped harmonic oscillator, SHO) does not significantly improve the goodness of fit. The derived intrinsic characteristic timescale for $\gamma$-ray variability is approximately 3 years. Such a long timescale cannot be generated in leptonic radiation models but is permissible in hadronic models, leading us to speculate that the long-term $\gamma$-ray emission of 4C 01.02 may originate from hadronic processes. The intrinsic characteristic timescale for radio variability is approximately 10 years, which may correspond to the escape timescale of the radio emission region, indicating that radio emission is produced in the large-scale jet.

## Full Text

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## Studying Radio and (cid:13)-ray Variability Characteristic Timescales of the Blazar 4C 01.02 with Stochastic Process Method

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## Abstract

Here, we use the celerite method, which is different from the traditional Fourier-like methods, to analyze the (cid:13)-ray and radio long-term variabilities of 4C 01.02. The results show that the simplest kernel in celerite, damped random walk (DRW), can successfully fit both radio and (cid:13)-ray long-term light curves, and the more complex second-order stochastic process (stochastically-driven damped harmonic oscillator, SHO) does not significantly improve the goodness of fit.

The intrinsic characteristic timescale of (cid:13)-ray variability is about 3 a, and such a long timescale cannot be generated in the leptonic emission model, but it is allowed in the hadronic model. We therefore speculate that the long-term (cid:13)-ray emission of 4C 01.02 may originate from hadronic process. The intrinsic characteristic timescale of radio variability is about 10 a. It may correspond to the escape timescale of the radio emission region, indicating that radio emission is produced in the large-scale jet.

**Key words:** active galactic nucleus; blazar; radio variability; (cid:13)-ray variability; celerite

## 1 Introduction

Blazars are a class of active galactic nuclei with relativistic jets pointing nearly at the observer. Blazars can be divided into BL Lacertae objects (BL Lacs) and flat-spectrum radio quasars (FSRQs). Typically, BL Lacs are intrinsically low jet-power radio galaxies, while FSRQs are intrinsically high jet-power radio galaxies [1, 2]. Blazar radiation covers the entire electromagnetic spectrum, dominated by emission from relativistic jets. The typical multi-band spectral energy distribution of blazars has two distinct peaks: the low-energy peak in the infrared to X-ray band and the high-energy peak in the (cid:13)-ray band [3, 4]. Blazars are the most important extragalactic (cid:13)-ray sources.

Blazar (cid:13)-ray radiation can be produced by both leptonic and hadronic processes, with no definitive conclusion yet. In leptonic jet models, (cid:13)-rays are produced by inverse Compton scattering of low-energy photons by relativistic electrons in the jet, including synchrotron self-Compton scattering [5, 6] and external Compton scattering [7-9]. In hadronic models, (cid:13)-rays mainly originate from synchrotron radiation of high-energy protons in the jet or from proton-photon interactions [10-13].

Blazars exhibit significant variability. In the (cid:13)-ray band, variability timescales can be as short as minutes [14], while in radio and optical bands they can be as long as decades [15]. Variability analysis is an important tool for exploring the physical nature of active galactic nuclei [16, 17]. The Fermi (cid:13)-ray Space Telescope has been operating for more than a decade, and its Large Area Telescope (LAT) provides high-quality long-term light curves for bright blazars. The 40 m telescope at the Owens Valley Radio Observatory (OVRO) monitors blazar radio activity, complementing Fermi's (cid:13)-ray observations [15]. The purpose of this work is to use OVRO and LAT data to study the radio and (cid:13)-ray long-term variability characteristics of the high-redshift blazar 4C 01.02.

Stochastic process models (also called Gaussian process models) are powerful tools for analyzing active galactic nucleus variability [18]. The optical variability of active galactic nucleus accretion disks can be described by a simple stochastic process model [19], namely the damped random walk model (DRW). Recently, stochastic process methods have been used to analyze blazar (cid:13)-ray variability [20, 21]. These authors adopted the CARMA model (continuous time autoregressive moving average) developed by Kelly et al. [17], claiming that the CARMA(1,0) process (i.e., the DRW model) cannot well describe the characteristics of some blazars' (cid:13)-ray data. Celerite is a new stochastic process model [22] that has been widely applied to stellar variability studies in recent years. Yang et al. [23] used the celerite model to analyze LAT data for 27 blazars that may exhibit (cid:13)-ray quasi-periodic oscillations, finding evidence for possible quasi-periodic oscillations in only two of them. Zhang et al. [24] used celerite to find significant evidence for (cid:13)-ray quasi-periodic oscillations in PKS 0521-36. These works demonstrate that the celerite model is suitable for blazar variability studies.

Here we use the celerite model to simulate the radio and (cid:13)-ray light curves of blazar 4C 01.02. In addition to the DRW model, we also employ a higher-order damped harmonic oscillator model (SHO) to investigate whether the SHO model can better describe the variability than the DRW model. Furthermore, we explore the physical origin of radio and (cid:13)-ray variability. Section 2 briefly introduces the stochastic process models we use; Section 3 presents the fitting results in detail; finally, Section 4 discusses the results and provides a summary.

## 2 Stochastic Process Model

A stochastic process (also called a Gaussian process) is a random model composed of a mean function (x) and a covariance, or kernel function k$\sigma$(xn; xm) [22], where and $\sigma$ are parameters. Here, the log-likelihood function for data y = (y1, y2, y3, …, yN)^T at coordinates X = (x1, x2, x3, …, xN)^T is:

ln L( , $\sigma$) = ln p(y|X; , $\sigma$) = -½ r ^T K$\sigma$^-1 r - ½ ln det K$\sigma$ - N ln(2$\pi$), where p(y|X; , $\sigma$) is the likelihood function, r is the residual vector, and K$\sigma$ is the N × N covariance matrix, with N being the number of data points.

For a given dataset (y, X), the parameters and $\sigma$ can be optimized using nonlinear optimization methods to obtain optimal values that maximize the likelihood function L( , $\sigma$). The uncertainties of and $\sigma$ can be obtained by setting a prior p( , $\sigma$) and then calculating the posterior distribution of parameters through Markov chain Monte Carlo (MCMC) algorithms.

The kernel function of the DRW model is [22]:

k(t) = a e^(-t/τ_{DRW}),

where a is the amplitude parameter and τ_{DRW} is the characteristic timescale of this model.

The differential equation of the SHO model is [22]:

$d^2$y(t)/$dt^2$ + (\$ \$0/Q) dy(t)/dt + \$ 0^{2}\$ y(t) = (t),

where \$ \$0 is the angular frequency of the damped oscillator, which can be converted to a characteristic timescale τ_{SHO} = 2π/\$ \$0, Q is the quality factor of the oscillator, and (t) is white noise. The corresponding power spectral density (PSD) is [22]:

S(ω) = √(2/π) S0 \$ 0^{4}\$ / [($\omega^2$ - \$ $0^{\{2\})}${2}\$ + \$ 0^{2}\$ $\omega^2$/$Q^2$],

where S0 is the power at ω = \$ \$0.

Here, we use the celerite model to fit light curves and employ the Bayesian Deviance Information Criterion (DIC) for model selection.

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## 3 4C 01.02 Light Curve Fitting Results

4C 01.02 (PKS B0106+013) is a bright (cid:13)-ray flat-spectrum radio quasar at high redshift (z = 2.099). The LAT data analysis follows the standard point source analysis. We select data above 100 MeV and use the standard tool Fermipy [25] to generate light curves with 30-day bins. Data points with TS < 25 are excluded to ensure reliability in our analysis. The 15 GHz radio light curve of 4C 01.02 is provided by OVRO. The (cid:13)-ray data cover the period from MJD 54697 to 59377 (August 19, 2008 to June 12, 2021), while the radio data cover from MJD 54910 to 58071 (March 12, 2009 to November 14, 2017).

We fit the light curves using the DRW and SHO models in celerite and use the MCMC sampler emcee [26] to improve fitting quality. For each fit, we let the MCMC sampler use 32 parallel walkers for 10,000 steps as a burn-in phase, followed by 20,000 steps to obtain MCMC samples.

Figure 1 [Figure 1: see original paper] shows the DRW fitting results for the (cid:13)-ray light curve, and Figure 2 [Figure 2: see original paper] shows the

SHO fitting results. For each model, we present the light curve fit, the autocorrelation function (ACF) of the normalized residuals, the distribution of normalized residuals, and the power spectrum calculated from the fitting results. The red dashed line in the normalized residual distribution represents the optimal constant fit to the normalized residuals. The posterior distributions of model parameters obtained from MCMC are shown in panel e).

Figure 3 [Figure 3: see original paper] and Figure 4 [Figure 4: see original paper] show the fitting results for the radio data. Similar to the (cid:13)-ray results, both models successfully reproduce the light curves, and the model parameters are well constrained.

To quantitatively distinguish between DRW and SHO, we calculate the DIC for both models. The DIC is defined as:

DIC = p_D + D(¯),

where D(¯) is the average deviance, equal to -2 ln(L(¯)), and p_D is the effective number of parameters, used to describe model complexity. We adopt p_D = var(D( )). DIC decreases with increasing goodness of fit and increases with model complexity.

From Table 1 , we see that the DIC values for DRW and SHO differ very little, indicating that the fitting results of these two models are comparable.

In Table 2 , we list the characteristic timescales obtained from the two models. It can be seen that for the (cid:13)-ray data, $\tau$*{SHO};(cid:13) and* $\tau${DRW};(cid:13) are consistent within errors, with the characteristic timescale of (cid:13)-ray variability being about 200 to 300 days. For the radio band, $\tau$*{SHO};r is greater than* $\tau${DRW};r. The radio data coverage is slightly longer than $\tau$*{SHO}, which may introduce larger bias in determining* $\tau${SHO};r; the radio data length is about 3 times $\tau$*{DRW};r, so* $\tau${DRW};r is basically reliable [19]. $\tau$_{DRW};r is about 1000 days, significantly larger than the (cid:13)-ray timescale.

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## 4 Discussion and Summary

In this work, we use the celerite model to fit the flux variations of blazar 4C 01.02 in radio and (cid:13)-ray bands and obtain the characteristic timescales of long-term variability in each band. The results show that both the simplest stochastic model DRW and the more complex SHO model can successfully describe the radio and (cid:13)-ray light curves, with comparable fitting results. Therefore, the more complex SHO model is not necessary. This is similar to the behavior of optical variability in active galactic nucleus accretion disks [19]. Notably, the characteristic timescales we obtain from the light curves are observed values; the intrinsic timescale should be $\tau$_0 = $\tau$ / ($\delta$_D/(1 + z)), where $\delta$_D is the Doppler factor. The Doppler factor of 4C 01.02 is unknown; the average Doppler factor for flat-spectrum radio quasars is 7-15 [28-30], so we adopt a typical Doppler factor $\delta$_D = 10 for FSRQs. The corrected (cid:13)-ray characteristic timescale is about 3 years, while the radio band characteristic timescale is about 10 years.

This characteristic variability timescale is generally thought to correspond to some timescale of the radiation system, such as cooling timescale, acceleration timescale, or escape timescale [31]. (cid:13)-ray radiation in jets can be produced by both leptonic and hadronic processes, with no definitive conclusion yet [32]. 4C 01.02 is a typical flat-spectrum radio quasar; in leptonic models, its (cid:13)-rays are usually produced by external Compton processes, with corresponding cooling timescales of about 10 days [33]. This cooling timescale is much shorter than our obtained characteristic variability timescale, so we believe the (cid:13)-ray characteristic variability timescale cannot be generated by leptonic radiation effects. In hadronic models, however, the cooling timescales of relevant processes can reach years or even hundreds of years [34]. This suggests that our discovered (cid:13)-ray characteristic timescale of about 3 years can be produced by hadronic processes, meaning that the long-term (cid:13)-ray emission of 4C 01.02 may originate from hadronic processes. The specific origin of the variability needs further study within the time-dependent hadronic model framework.

Radio emission in jets is contributed by synchrotron radiation from high-energy electrons. The cooling timescale of the synchrotron radiation process is mainly determined by the magnetic field. In typical jet magnetic field parameter spaces, the synchrotron cooling timescale can reach 10 years [33], so the radio characteristic timescale suggests that radio variability may originate from disturbances in the magnetic field of the radiation region. Additionally, the radio characteristic timescale may correspond to the escape timescale of the radiation region, which can constrain the radius of the radio emission region to about $10^{18}$ cm, meaning that radio emission is produced in the large-scale jet, consistent with general understanding. It is worth emphasizing that the inference about the origin of (cid:13)-ray radiation is directed at long-term variability characteristics and may not apply to short-term rapid variability.

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*Note: Figure translations are in progress. See original paper for figures.*