Postprint: Gamma-ray Flux Distribution and RMS-Flux Relation of RGD and NLSY1

Authors: Wang Na, Yi Tingfeng, Pu Zhiyuan, Zhang Shun, Wang Liang, Chen Yutong, Yi Tingfeng

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Abstract

We studied the γ-ray flux distribution characteristics and the linear relationship between root-mean-square and flux (RMS-Flux) for radio galaxies (RDG) and narrow-line Seyfert 1 galaxies (NLSY1) in the Fermi-LAT 4th catalog. Based on the γ-ray flux data processing of these two types of active galactic nuclei, we fitted their flux distributions using Gaussian and log-normal functions. Through the K-S test (Kolmogorov-Smirnov test), S-W test (Shapiro-Wilk test), and reduced χ^2, we found that the distributions of both radio galaxies and narrow-line Seyfert 1 galaxies are more consistent with log-normal distributions rather than Gaussian distributions, indicating that their variability may have nonlinear and multiplicative properties. Additionally, we performed linear fitting on the RMS-Flux relationships for two different groupings of these two types of sources, and found that the RMS-Flux has extremely strong linear correlations with positive slopes.

Full Text

Gamma-Ray Flux Distribution and RMS-Flux Relationship of Radio Galaxies and Narrow-Line Seyfert 1 Galaxies

Abstract: This study investigates the flux distribution characteristics and RMS-flux linear relationship for radio galaxies (RDG) and narrow-line Seyfert 1 galaxies (NLSY1) in the fourth Fermi LAT catalog. Using gamma-ray flux data processing, we fit the flux distributions with both Gaussian and log-normal functions. Through Kolmogorov-Smirnov (K-S) testing, Shapiro-Wilk (S-W) testing, and reduced chi-square analysis, we find that the flux distributions of both RDG and NLSY1 are more consistent with log-normal than Gaussian distributions, indicating that their variability may have nonlinear and multiplicative properties. Additionally, we perform linear fitting on two different groupings of RMS-flux

for these source types and find that RMS-flux exhibits a strong linear correlation with positive slopes.

Keywords: radio galaxy; narrow-line Seyfert 1; gamma-ray; Fermi-LAT

Introduction

Active galactic nuclei (AGN) can be classified into quasars, Seyfert galaxies, low-ionization nuclear emission-line regions (LINERs), radio galaxies, and other categories based on luminosity and emission line properties. Different types of AGN arise from varying accretion rates and viewing angles. Seyfert galaxies represent lower-luminosity AGN compared to quasars. Narrow-line Seyfert 1 galaxies (NLSY1) typically exhibit relatively narrow emission line widths (FWHM $< 2000\,\mathrm{km\,s^{-1}}$), weak forbidden lines ([O III] 5007/H$\beta < 3$), relatively low black hole masses, and relatively high Eddington ratios. AGN include two fundamental types: radio-loud and radio-quiet, with radio galaxies being an important subclass of radio-loud AGN. The jets in these systems have large inclination angles relative to our line of sight, resulting in weaker Doppler boosting effects, making them ideal targets for studying jet formation and collimation processes near supermassive black holes. Radio galaxies are further divided into FR-I and FR-II types based on morphology, where FR-I galaxies have lower jet luminosities and edge-darkened structures, while FR-II galaxies have higher jet luminosities and edge-brightened morphologies.

The development of gamma-ray astronomy has become an important tool for studying the spectral and temporal behavior of AGN. The launch of the Fermi telescope has provided conditions for exploring gamma-ray sources in radio galaxies and Seyfert galaxies. Analysis of flux distributions in the gamma band facilitates understanding of jet and plasma acceleration mechanisms, and log-normal flux distributions have been discovered in both galactic and extragalactic sources. Long-term flux distribution studies are crucial for analyzing and characterizing variability in astrophysical sources. In recent years, observations have provided important conditions for studying long-term flux distributions. The log-normal nature of flux distributions implies that radiation is driven by multiplicative rather than additive processes. In Seyfert galaxies and X-ray binaries, the log-normal distribution of X-ray flux is widely considered a result of accretion disk fluctuations, possibly influenced by modulation within the accretion disk. The log-normal flux distribution in the gamma band may arise from jet instabilities, jet geometric changes, projection effects, or a combination thereof, rather than being dominated by a single factor such as magnetic field energy density, high-energy particle density, or seed photon density.

Data and Methods

We utilize gamma-ray light curve data from the Fermi satellite since 2008, selecting 21 radio galaxies and 16 narrow-line Seyfert 1 galaxies from the fourth Fermi Large Area Telescope (LAT) catalog (4FGL-DR3) with variability index greater than 21.67 and minimum detection significance. The high duty cycle and long-term monitoring capabilities of Fermi-LAT make it an important tool for time-domain astronomy, providing nearly continuous and uniform observations of gamma-ray sources. We analyze light curves with time spans of 10 days and 365 days as our research objects, which provide more data for studying flux distributions and RMS-flux relationships.

To characterize flux distributions, we construct flux histograms for both radio galaxies and narrow-line Seyfert 1 galaxies. To better understand the distribution properties, we perform Gaussian and log-normal fitting on these histograms. In addition to visual inspection of the histograms, we conduct K-S tests and S-W tests for normality and log-normality, and calculate reduced chi-square values. Most histograms show a prominent peak and a high-flux tail, indicating that the flux distributions are more consistent with log-normal than Gaussian distributions.

Results

[Figure 1: see original paper] shows the gamma-ray flux distribution histograms for radio galaxies and narrow-line Seyfert 1 galaxies, with red lines representing Gaussian fits and green lines representing log-normal fits. The fitting parameters are presented in , which lists the log-normal and normal distribution fitting parameters for the gamma-ray flux distributions of individual sources.

Based on the central limit theorem, flux distributions can arise from either additive or multiplicative processes. In additive models, observed flux is the sum of contributions from several regions, naturally producing normal distributions. In multiplicative models, flux is the product of many independent, isotropically distributed regional flux components, resulting in log-normal distributions. Let ϕ be the product of fluxes A from numerous regions: $\phi = \log \prod A$. If A follows a log-normal distribution, then ϕ follows a normal distribution. The variance of flux near f for a log-normal distribution is given by $\delta\phi^2 = (\partial f/\partial x)^2 \delta x^2$, showing that the linear RMS-flux relationship is equivalent to an exponential relationship between flux and the underlying variable.

We investigate the RMS-flux relationship by fitting two different groupings: bins of 10 data points and bins of one-year intervals (365 days). [Figure 2: see original paper] shows the linear fitting of RMS-flux correlation for 10-data-point bins, while [Figure 3: see original paper] shows the same for one-year bins. presents the slopes and Pearson correlation coefficients for both binning strategies.

The Pearson correlation coefficient measures the strength of the RMS-flux correlation, with values closer to 1 indicating stronger correlation. In both grouping scenarios, radio galaxies and narrow-line Seyfert 1 galaxies show strong linear RMS-flux relationships, with Pearson coefficients greater than 0.8. The slopes are all positive, with radio galaxies showing slightly steeper slopes than narrow-line Seyfert 1 galaxies in both binning schemes.

Discussion

The long-term flux distribution of quasars is significant for understanding the origin and nature of variability. The probability density functions (PDFs) of gamma-ray flux, flux histograms, and RMS-flux relationships for 21 radio galaxies and 16 narrow-line Seyfert 1 galaxies provide important clues about high-energy emission processes. These sources' histograms show typical width variations of orders of magnitude, displaying a prominent peak and an extended high-flux tail. We fit Gaussian and log-normal distributions to flux histograms spanning years of data, finding that log-normal fitting better describes the histograms for most sources at high confidence levels.

The log-normal flux distribution and strong linear RMS-flux relationship have been explained in many studies. The observed log-normal distribution in radio galaxies and narrow-line Seyfert 1 galaxies suggests that disk fluctuations in these AGN may have nonlinear and multiplicative properties. We can interpret normal and log-normal distributions as special cases of more general skewed distributions, such as Pareto distributions with varying degrees of skewness. In the context of relativistic jets, log-normal flux distributions may result from Poynting flux-dominated jets containing small, isotropically distributed "mini-jets" within the emission region.

The RMS-flux relationship is commonly observed in X-ray binaries and AGN and can be detected with high significance across various time scales. Recent studies of gamma-ray light curves in active galaxies also show RMS-flux relationships. The strong correlation can be interpreted as a consequence of log-normal flux distributions. Under the "mini-jets in a jet" model, independently and randomly oriented small jets follow a Pareto distribution, and the resulting flux distribution maintains the RMS-flux relationship. Both Gaussian and log-normal distributions can emerge from this model depending on parameters.

Our analysis of RMS-flux relationships under two binning scenarios shows strong positive correlations with slopes greater than zero for both source types. This suggests that the strong RMS-flux correlation is an intrinsic property of radio galaxies and narrow-line Seyfert 1 galaxies, though whether this property is universal requires more data support. The log-normal flux distribution may arise from complex interactions between variable magnetic fields, high-energy particle densities, photon densities, and diffusion processes under particle acceleration. The statistical characteristics expected from magnetically reconnection-driven "mini-jets in a jet" models are broadly consistent with our observed features.

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