Gamma-ray Emission Properties of Four Bright *Fermi*-LAT AGNs: Implications on Emission Processes

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Abstract. The X-ray/Ultraviolet/Optical emission from radio-quiet AGNs, black hole binaries, and other compact sources, in general, follow a lognormal flux distribution, a linear rms-flux relation, and a (broken) power-law power spectral densities (PSDs). These characteristics are normally attributed to the multiplicative combination of fluctuations in the accretion disk. Similar features have been inferred for some well-observed blazars in different energy bands, but a systematic study over a long duration is still missing. Using a continuous gamma-ray light curves over 3-days cadence from August 2008 – October 2015, we present the first systematic study of these features in four sources: the FR I radio galaxy NGC 1275 and three blazars- Mrk 421, B2 1520+31 and PKS 1510-089. For all, except Mrk 421, the flux spans 2 orders of magnitude. For blazars, a log-normal profile describes the flux histograms better compared to a Gaussian, while none is favored for NGC 1275, the only non blazar source, suggesting a complex distribution. Regardless of flux histogram profile, the rms-flux relation is linear for all with PSDs being consistent with a power-law shot noise spectrum despite hints of breaks. The inferred results are consistent with the properties of unresolved magnetic reconnection sites, as inferred in the X-ray emission from the whole Solar disk and the statistical characteristics of magnetic reconnection based minijets-in-a-jet model. The results, thus, suggest a strong jet-accretion-disk coupling with energy input from the central source being distributed over a wide range in time and energy by the reconnection process depending on the geometry and local physical conditions.

Resumo. A emissão de raios-X/Ultravioleta/Óptica de AGNs radio-silenciosas, binários de buracos negros e outras fontes compactas, em geral, seguem uma distribuição de fluxo lognormal, uma relação linear rms-fluxo e um poder de lei de poder (quebrado) densidades espectrales (PSDs). Essas características são normalmente atribuídas à combinação multiplicativa de flutuações no disco de acreção. Características semelhantes foram inferidas para alguns blazers bem observados em diferentes faixas de energia, mas um estudo sistemático durante uma longa duração ainda está faltando. Usando curvas de luz de raios-gama contínuas ao longo de 3 dias cadência de agosto de 2008 - outubro de 2015, apresentamos o primeiro estudo sistemático dessas características em quatro fontes: a FR I radio galáxia NGC 1275 e três blazars - Mrk 421, B2 1520+31 e PKS 1510-089. Para todos, exceto Mrk 421, o fluxo abrange 2 ordens de grandeza. Para blazars, um perfil log-normal descreve os histogramas de fluxo melhor em comparação com um gaussiano, enquanto nenhum é favorecido para o NGC 1275, a única fonte não é blazar, sugerindo um distribuição complexa. Independentemente do perfil do histograma do fluxo, a relação rms-flux é linear para todos com PSDs consistentes com um espectro de barulho de tiro de lei de poder, apesar das dicas de quebras. Os resultados inferidos são consistentes com as propriedades das regiões de reconexão magnética não resolvidos, como inferido na emissão de raios-X de todo o disco solar e Características estatísticas do modelo minijets-in-a-jet baseado na reconexão magnética. Os resultados, portanto, sugerem um forte acoplamento de disco de acúmulo de jato com entrada de energia da fonte central sendo distribuída em uma ampla gama de tempo e energia pelo processo de reconexão dependendo da geometria e das condições físicas locais.

Keywords. gamma rays: galaxies – radiation mechanisms: non-thermal – galaxies: active – galaxies: jets – acceleration of particles

1. Introduction

Active Galactic Nuclei (AGNs) represent the class of astrophysical galaxies powered by accretion onto a super massive black hole (SMBH). Historically divided empirically based on observational properties, primarily on features in the radio and optical bands, they exhibit a huge and wide range of characteristics in different energy bands spectrally, temporally, and spatially (Tadhunter 2008). They emit high and rapidly variable emission across the entire observable electromagnetic spectrum and constitute the largest fraction of sources in any extra-galactic surveys. At γ-ray energies covered by the Fermi-LAT (Large Area Telescope), they constitute $\gtrsim$ 50% of the total population in the latest LAT source catalog (3FGL; Acero et al. 2015) and > 75% above 10 GeV (3FHL; Ajello et al. 2017).

One of the defining characteristics of accretion-powered sources is the high, rapid, and energy-dependent brightness variability (Scaringi et al. 2015; Uttley et al. 2005; Vaughan et al.

2003). Extensive investigation of X-rays emission from compact sources such as luminous AGNs (most being radio-quiet), galactic black hole binaries (GXBs) and micro quasars show remarkable phenomenology in statistical properties of emission, characterized by a log-normal flux distribution, a linear scaling of intrinsic variability with flux (rms-flux), and a (broken) power-law power spectral density (PSD; Uttley et al. 2005; Vaughan et al. 2003, and references therein). Similar characteristics have been found in (optical/Ultraviolet/X-ray) emission from other non-compact accreting sources like young stellar objects, white dwarfs, and cataclysmic variables (Scaringi et al. 2015, and references therein). These remarkable similarities of emission features across the mass scale have been used to claim that the physics of accretion is universal and is independent of the accretor physical attributes. The most accepted explanation of such scale-free features is the multiplicative combination of fluctuations in the accretion disk (Uttley et al. 2005; Lyubarskii 1997).
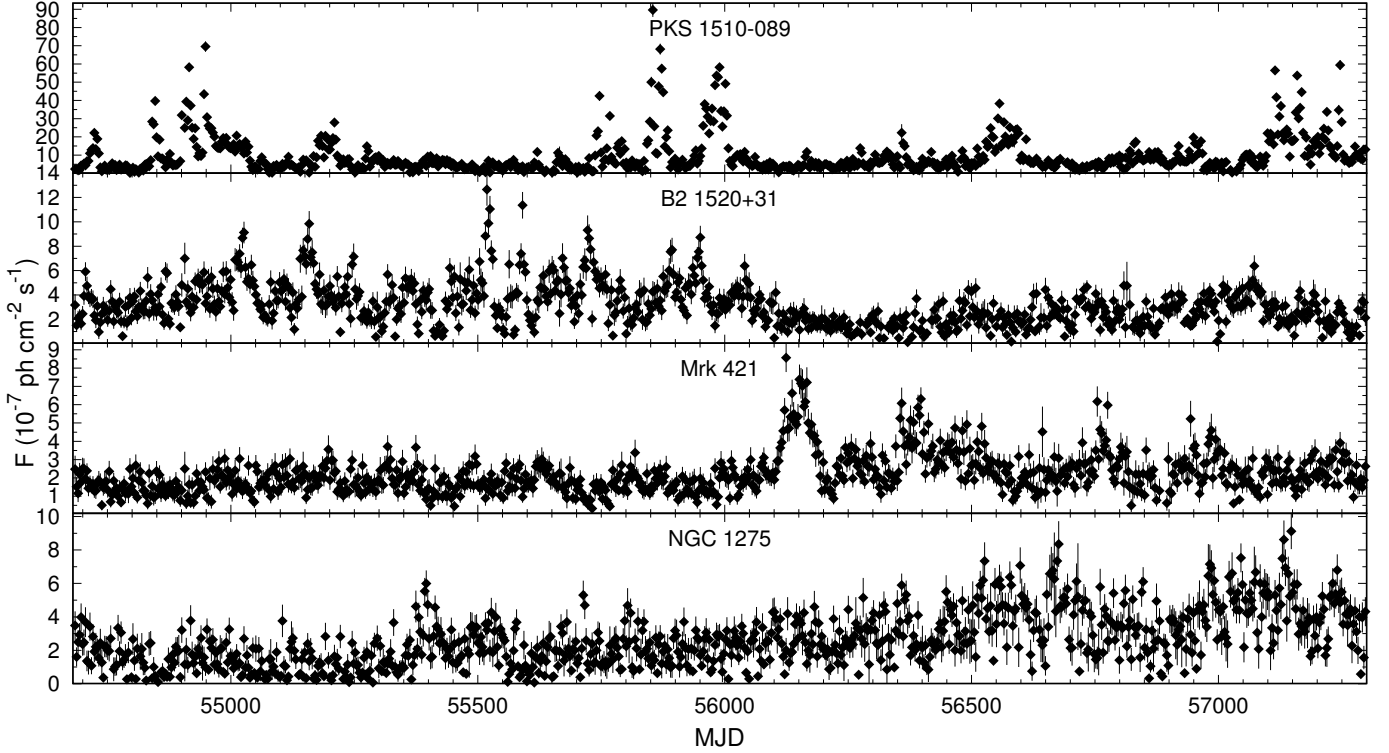
FIGURE 1. 3-days binned, 0.1-300 GeV *Fermi*-LAT γ-ray light curve of radio-galaxy NGC 1275 and three blazars: PKS 1510-089, B2 1520+32 and Mrk 421 from August 5, 2008 to October 5, 2015.

Presence of magnetic field, even sub-dominant, can substantially modify the characteristics of a system by introducing multiple scales of coupling and directions. In fact, the X-ray emission from the whole Solar disk exhibits all the above mentioned statistical features (Zhang 2007) but the variability here is the result of magnetic reconnection process (Aschwanden et al. 2017). This makes the uniqueness claim ambiguous in the magnetized accretion-powered sources like blazars and radio galaxies, the sources considered in this study (e.g. Kadowaki et al. 2015; de Gouveia dal Pino & Lazarian 2005, magnetic reconnection scenario for non-blazars sources). In these sources, the dominant emission is non-thermal and is believed be produced within the relativistic jets. But, being accretion-powered and magnetized, study of these systems offer a potential way to explore the accretion-disk-jet connection and relative roles of particles and magnetic field. In addition, a comparative study of physical process in other astrophysical sources which exhibit similar statistical features may further provide a broader insights into the jet processes. Here, we present some of the main results and summary of our work published in Kushwaha et al. (2017).

2. Data

We have used 7 years of LAT γ-ray data from August 5, 2008, to October 5, 2015, of four bright AGNs: radio-galaxy NGC 1275, and three blazars Mrk 421, B2 1520+31 and PKS 1510-089 to investigate the statistical features at γ-rays. These are the only AGNs which have a near continuous detection in the LAT on a shortest possible, uniformly binned timescale of 3-days. The choice of bin-duration is a compromise between maximizing the data length for PSDs and rms-flux estimation while, at the same time, avoiding significant non-detections which can bias the histograms. The extracted light curve is shown in Figure 1 and the

details of work and data reduction method are published in the Kushwaha et al. (2017).

3. Analysis and Results

We have investigated the statistical properties: flux distribution, PSDs and the rms-flux relation which are used to study the accretion-powered sources, for the first time at γ-ray energies. For highly variable source, a histogram is a unique tool to search for the presence of scales in the data domain while PSD in the temporal domain. Figure 2 shows the γ-ray flux histograms generated following Knuth method (Knuth 2006). We have fitted the histograms with a log-normal and a Gaussian profile and the fit statistics is reported in the Figure label, favoring a log-normal for blazars and a Gaussian for NGC 1275.

Figure 3 shows the PSD of the two sources and the best fit power-law and broken power-law curve to the data with the fit statistics in the respective labels. The PSDs are estimated following the method of Gilfanov & Arefiev (2005) while the error bars are estimated via simulating 1000 light curves using the method of Timmer & Koenig (1995). The fit favors a broken power-law over power-law interpretation with similar inferences for the other two sources: Mrk 421 and B2 1520+31 (but see §4)

In figure 4, we present the shows intrinsic variability as the function of source flux for NGC 1275 and PKS 1510-089, estimated using a sequence of 50 data per rms point from the observed light curve. The error on the rms is calculated via simulating 1000 light curves as done for the PSD followed by their sampling as per the observed light curve and then estimating the variance (Vaughan et al. 2003). The best fitted linear curves with slope values are given in the figure labels. Similar linear relation holds for the other two sources with slope consistent with the NGC 1275 value.
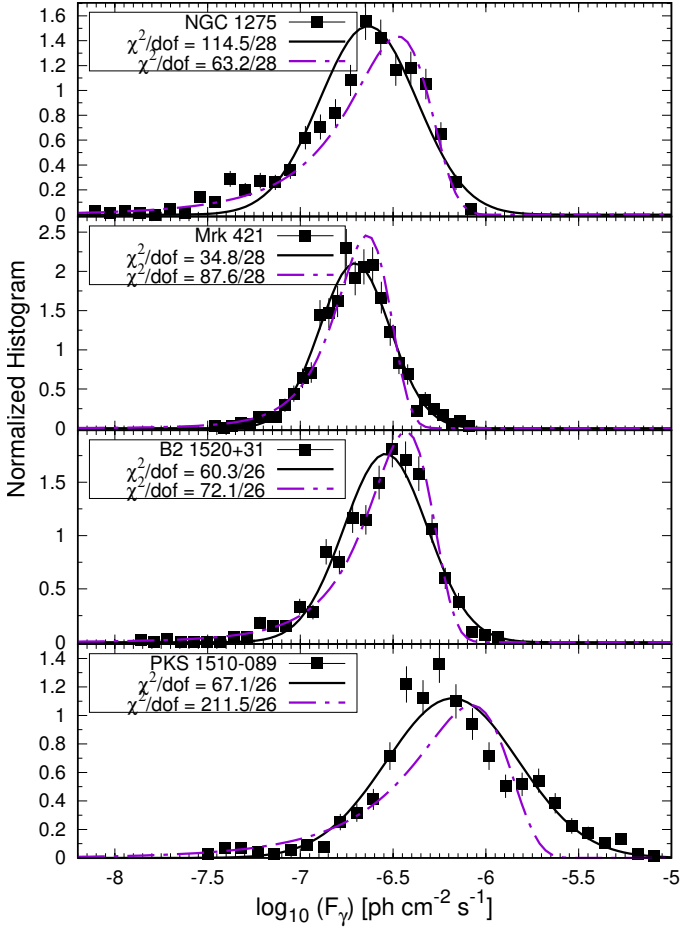
FIGURE 2. Flux histogram estimated using the Knuth method. The solid and the dashed-dotted curves are, respectively, the best fit log-normal and Gaussian to the histograms (dof = degree of freedom, see §3)

FIGURE 3. Gamma-ray PSD of radio-galaxy NGC 1275 and blazar PKS 1510-089. The dashed and solid curves are, respectively, the best fit power-law and broken power-law fit to the data (see §3).

4. Discussion

Variability, spectrally and temporally, is one of the few potential tools available to study rapidly variable sources which are beyond the resolution limit of any of the modern observing facilities. Among highly variable astrophysical sources, accretion-powered sources are the most prominent and have been explored extensively in different energy bands, especially at X-rays energies (Scaringi et al. 2015; Uttley et al. 2005; Gilfanov & Arefiev 2005; Vaughan et al. 2003). The temporal investigations have found some hallmark statistical features exhibited by these sources: a log-normal flux distribution with a linear relation with intrinsic variation (rms) and a shot nose PSD. These features have been claimed to be an imprint of a multiplicative combination of fluctuations in the accretion-disk. Here, we investigate these features, for the first time at γ-ray energies to gain insights into jet-disk connection and jet processes.

The systematic investigation reveals many interesting results with broad implications on the jet processes. In the flux domain, all the histogram show a prominent peak with extremes separated by ≳ 2 order of magnitudes except for Mrk 421. The width of the distribution around the peak is similar for all though there is a huge tail at the lower energy end (Kushwaha et al. 2017). The fit results for histograms, mentioned in labels of Fig. 2 show that a log-normal profile is favored for blazars while a Gaussian is favored for the sole non-blazar source NGC 1275. However, an in-depth statistical analysis by Kushwaha et al. (2017) has shown that neither of the distributions adequately describes the
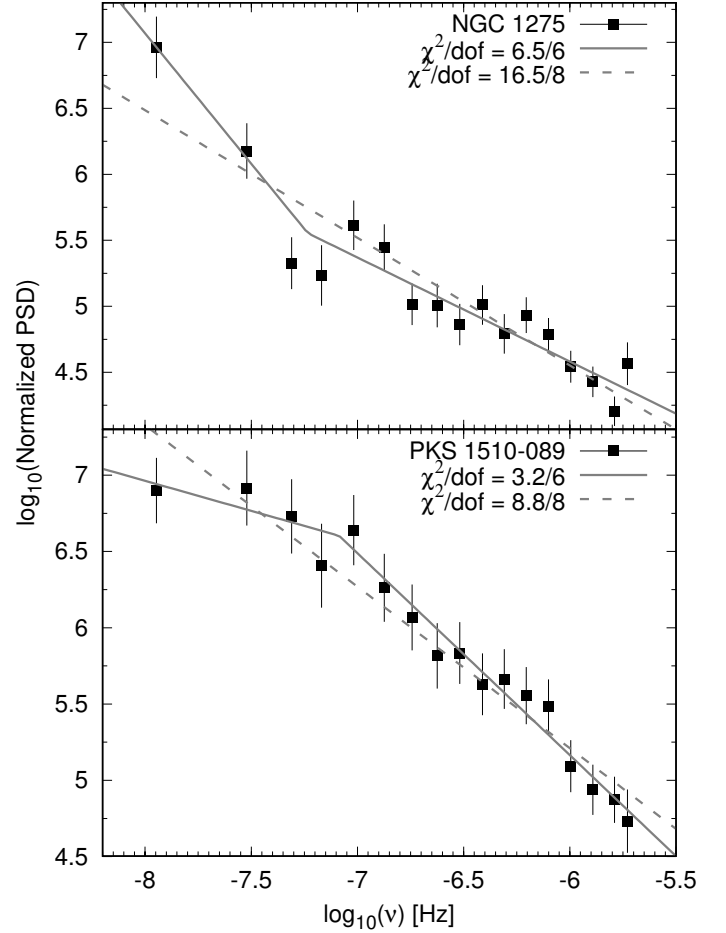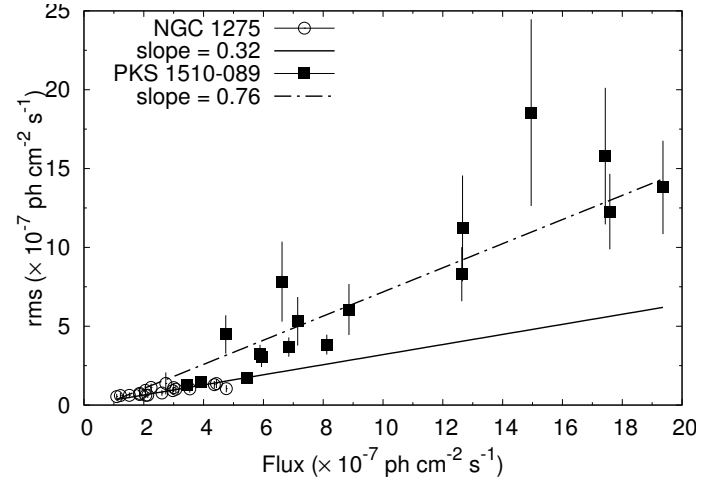

FIGURE 4. Intrinsic variability (RMS) as a function of source flux. The dashed-dotted solid line represents the best linear fit to the radio-galaxy NGC 1275 and blazar PKS 1510-089 with best file slope in the label (see §3).

NGC 1275 histogram. Surprisingly, the rms-flux relation is linear for all and so is the variance with respect to source flux state except for PKS 1510-089 (see Fig. 4). The linearity of rms-flux relation is contrary to the inferences from other accretion powered sources e.g. radio-quiet AGNs, BXBs, YSOs, CV etc. where lognormality is argued for the linear rms-flux relation and

is attributed to the multiplicative combination of the fluctuations in the accretion disk. In the Fourier domain, the PSDs exhibit a shot noise spectra (see Fig. 3), typical of accretion powered sources. Though a broken power-law fit seems to provide a better description of the PSD, the quality of data suggests breaks at many frequencies for the single broken power-law, while we have reported only the one which resulted in lowest χ^2 statistics. Thus, the nature of the best fit suggests that a more in-depth analysis is needed to statistically claim the presence of breaks within the considered duration if any.

The inferred results are broadly consistent with the statistical properties of the magnetic reconnection powered minijets-in-a-jet model (Giannios et al. 2009; Biteau & Giebels 2012; Clausen-Brown & Lyutikov 2012). In this model, emission from identical but randomly oriented emission regions follows Pareto distribution (Zaliapin et al. 2005). It predicts a huge range of histogram profiles, from a power-law in case of a single emission region to one that can be interpreted as the log-normal in case of contribution from large number of emission regions with a linear rms-flux relation for all (Biteau & Giebels 2012), as inferred for the γ-ray emission here (skewed or log-normal). The inferences are also consistent with the statistics of some of the physical quantities associated with the X-ray emission from the whole Solar disk and coronal mass ejections (CMEs) (Zhang 2007), both of which are known to be the result of magnetic reconnection. The results, combined with the highly magnetized nature of these sources suggest that magnetic reconnection is the dominant process responsible for powering the jet emission. Within this, the skewed distribution of NGC 1275 suggests that fewer regions are contributing to the emission in comparison with blazars. Since the central compact source is the main source of power, the inferences suggest that the magnetic reconnection may be a result of fluctuations in the accretion disk and/or it could be intrinsic to the jet as a result of non-linear dissipative processes within it. Another possibility could be that it is an imprint of magnetic reconnection in the corona, the likely location of the jet base, as argued in de Gouveia dal Pino & Lazarian (2005) for sources having non-boosted emission (Kadowaki et al. 2015). The latter scenario is interesting in the sense that if these imprints flow down the relativistic jet, the overall radiative output will be boosted and the boosting will also makes it appear as if more regions are contributing to the emission, thereby shifting the histogram profile closer to the log-normal, as is the case with blazars. It should be noted that a boosting factor of $\sim$ 10 can produce flux similar to the blazars.

5. Summary

Investigation of characteristics like flux distribution, rms-flux relation, and PSD at γ-ray energies which are used to characterize accretion-powered source show broadly similar yet interesting results. We find that the flux distribution exhibit complex shape with log-normal being favored over Gaussian for blazars but none for NGC 1275. Irrespective of the flux distribution, the rms-flux relation is linear for all and the PSDs are typical of accretion-powered sources i.e. shot noise profile. The linearity of rms-flux relation irrespective of the histogram profile disfavors a strong accretion disk contribution as generally claimed for accretion-powered sources, though there may be contributions. Instead, the features are consistent with the statistical properties of magnetic reconnection powered minijets-in-a-jet model and some characteristics of the quantities associated with the Sun like X-ray emission from whole Solar disk and CMEs, thereby favoring magnetic reconnection as the source powering relativistic jets. This is also consistent with the general emission charac-

teristics of these sources such as a non-thermal broadband spectrum and the rapid variability. The analysis suggests that magnetic reconnection may be an imprint of accretion disk fluctuations on the jet or effect of dynamics within the jet and/or could be an imprint of the corona.

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