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The potential of LHAASO for detecting QPOs in BL Lacs

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ABSTRACT

Quasi-periodic Oscillation(QPO) is a special phonomenon appearing in the X-ray light curves of AGNs. By now, no study investigates whether it is possible to detect QPOs in TeV band. In this work, we utilize the Fermi 4FGL-DR4 catalog to test the potential of the Large High Altitude Air Shower Observatory(LHAASO) for detecting QPOs. We use the fitting parameters o in the catalog to generate mock PSDs and compare them with the sensivity of LHAASO. Among 7194 sources, 598 sources have completeness more than 30% while 351 sources have completeness more than 50%, and most of the latter are BL Lacs. Our study verifies the LHAASO has great potential to detect QPOs.

Keywords: jets — QPO — Time domain — BL Lac

1. INTRODUCTION

Active Galactic Nuclei(AGNs) are supermassive black holes located at the centers of galaxies, which are on remarkable accretion state. Since the discovery of AGNs, astronomers have observed different types of AGNs, some of which launch highly-collimated jets. Accordding to the unified model of AGN(Antonucci 1993), we can observe jet just because the propagation direction of jet of certain AGN is properly towards us. And one of these types of AGNs is BL Lac, which is characterized by rapid and large-amplitude flux variability and significant optical polarization.

quasi-periodic Oscillation(QPO) is one of the most mysterious phonomenon in accreting black holes and neutron stars, characterized by rapid quasi-periodic variability in X-ray light curves. In black holes these features are identified by relatively broad peaks in the power spectrum, where the broadening may result from the modulation of the oscillation frequency itself, or the finite lifetime of the oscillation. The origins of QPO are still up for debate. Some contribute it to kink instability in jet(Jorstad et al. 2022) while others involve the accretion disk, considering Lense-Thirring Precession(Bollimpalli et al. 2024) or oscillations of spiral density waves(Rodriguez et al. 2002).

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Usually the QPOs are caught by Fermi(Atwood et al. 2009; Chen et al. 2022) or Insight-HXMT(Zhang et al. 2020; Yu et al. 2023). In this work, however, we explore the possibility to utilze the Large High Altitude Air Shower Observatory(LHAAASO) to detect QPOs. LHAASO(Cao et al. 2019) is a new generation multi-component facility located in Daocheng, Sichuan province of China, at an altitude of 4410 meters. It aims at measuring with unprecedented sensitivity the spectrum, composition, and anisotropy of cosmic rays in the energy range between 1 and 10^6 TeV, and acting simultaneously as a wide aperture (one stereoradiant) continuosly-operating gamma-ray telescope in the energy range between 0.1 and 10^3 eV with the designed sensitivity of 1.3% of the Crab Unit (CU) above 100 TeV. Although LHAASO only achieves a poor angular resolution: 0.4° at 30 TeV and 0.2° at 1 PeV, we can still seize potential QPOs from the gamma-ray light curves, following Chen et al. (2022)'s steps.

In this work, we untilize 4FGL-DR4 catalog of Fermi(Ballet et al. 2023), screening the sources that might be observed by LHAASO. Then we discuss the properties of these sources simply.

In Section 2, we demonsrate how to clean the 4FGL-DR4 catalog. In Section 3, we use the fitting spectral to verify whether LHAASO can observe these sources. In Section 4, we obtain a catalog that shows the completeness of the observed energy interval for each source. In Section 5, we summarize our result.

2. DATA

Fermi Large Area Telescope Fourth Source Catalog Data Release 4 (4FGL-DR4,(Ballet et al. 2023))[1] contains 7194 γ-ray sources, including data from DR1 to DR4. Based on the first 14 years of science data in the energy range from 50 MeV to 1 TeV, it also recognizes the types and spectral types of the gamma sources.

For data selection, we selected LAT events with $-10° < \mathrm{Dec} < 70°$. And we only selected events with **Source_type** belonging to *agn, bcu, bll, css, nlsy1, sey, ssrq, fsrq*. It makes sure that we only kept AGN sources. After data exclusion, there were 2211 sources, including 5 other non-blazar active galaxies(*agn*), 787 active galaxies of uncertain type(*bcu*), 936 BL Lac type of blazars(*bll*), 4 compact steep spectrum quasars(*css*), 473 FSRQ type of blazars, 3 narrow line Seyfert 1 galaxies(*nlsy1*), 1 Seyfert galaxy(*sey*) and 2 soft spectrum radio quasar(*ssrq*).

3. METHOD

In order to test whether LHAASO can observe these sources, we applied a simple approach: calculate the power spectrum distribution(PSDs) in TeV band, and compare them with the detection limit of the LHAASO. At first, we generated mock PSDs of these sources.

3.1. *generation of mock PSDs*

The 4FGL-DR4 catalog contains the spectral fitting parameters for each source. In our catalog, there are two spectral types[2]. One is **PowerLaw**:

$$\frac{dN}{dE} = N_0 \frac{E}{E_0}^{-\gamma} \tag{1}$$

The other is **LogParabola**:

$$\frac{dN}{dE} = N_0 (\frac{E}{E_0})^{-(\alpha+\beta \ln(E/E_0))} \tag{2}$$

We untilized the fitting spectrum to generate mock PSDs between $0.3 \sim 10^3$ TeV. Fig 1 shows the mock PSDs of two sources, which are consistent with the fit plots in Fermi website[3]

3.2. *Sensitivity of LHAASO*

The left panel of Fig 2 shows the detection limit of LHAASO between 0.3 and 10^3 TeV. Since we cannot acquire the exact data, we use two polynomial functions to approximate this profile:

$$\lg g(E) = \begin{cases} -0.29(\lg E)^3 + 0.89(\lg E)^2 & \\ -1.06 \lg E - 11.89 & 0.3 < E < 20\mathrm{TeV} \\ 1.09(\lg E)^5 - 11.48(\lg E)^4 & \\ +47.52(\lg E)^3 - 95.54(\lg E)^2 & \\ +91.61 \lg E - 45.68 & 20 \le E < 10^3\mathrm{TeV} \end{cases} \tag{3}$$

Here $g(E)$ is the sensitivity. The red line in the right panel of fig 2 shows the polynomial approximation is quite similar to true sensitivity.

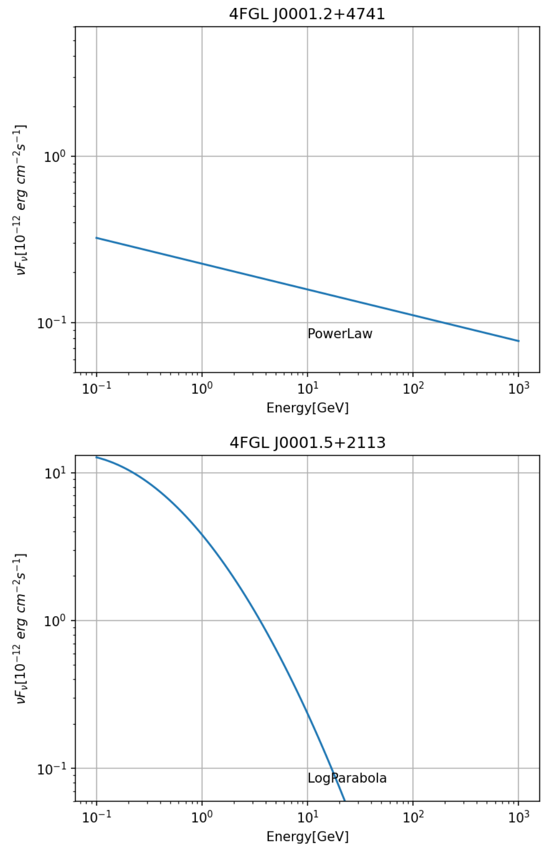

Figure 1. The two spectrum types in our catalog.

4. RESULT

Finally we compare the mock spectrums with the sensivity of LHAASO. We define a parameter "**completeness**", which describes the proportion of spectrum above the detection limit in logarithmic space between 0.3 and 10^3 TeV. For example, the completeness of *4FGL J0001.2-0747* is 73.4%. So the 73.4 percent of

[1] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/14yr_catalog/

[2] https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source_models.html

[3] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/14yr_catalog/4FGL-DR4_SpecPlots_v32.tgz

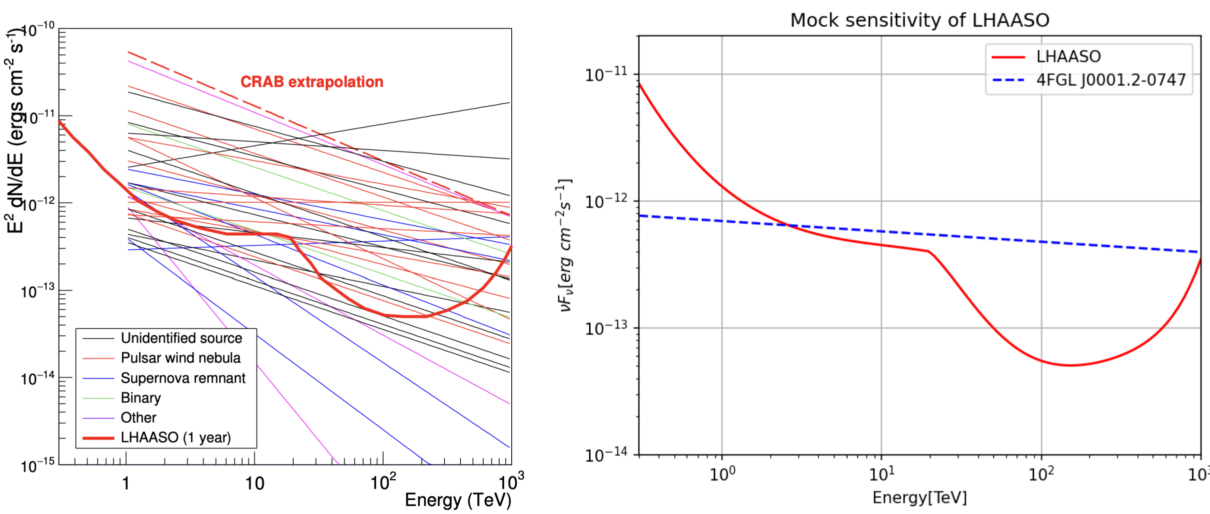

Figure 2. The left panel: the sensitivity of LHAASO. The right panel: the red lines marks the sensitivity fitted by two polynomial functions and the blue dashed lines represents the mock spectrum of the source *4FGL J0001.2-0747*.

its spectrum(blue dashed line) in the right panel in fig 2 is above the limit(red line).

For the remaining 2211 sources, 598 of them have completeness more than 30% while 351 of them have completeness more than 50%. We make a catalog of these sources and upload it on Github[4]. The organization of the catalog is shown in Table 1.

We also analyzed that the distribution of completeness. As is shown in Fig 3, most of the sources with large completeness are BL Lac. It implies the radiation we observe is emitted by jet, which is an important origin of QPOs.

We also plot the spatial distribution of the total samples and the samples with compeleteness> 50%(Fig4). But it does not exhibit any inhomogeneity.

5. DISCUSSION AND CONCLUSION

In this work, we explore the potential of LHAASO for detecting QPOs in AGNs and the key challenge is to test whether LHAASO can observe these sources. At first, we select 2211 sources which in the observation sky area of LHAASO from 7194 γ-ray sources in 4FGL-DR4 catalog. Then we use the fitting parameters to generate mock spectrums between 0.3 and 10^3 TeV and compare them with the sensivity of the LHAASO, which is approximated by two polynomial functions. We find 598 sources have completeness more than 30% while 351 sources have completeness more than 50% so the LHAASO does have great potential to detect QPOs. Going further, we recognize that most of sources with large completeness are BL Lacs.

We have to assume the spectrum shapes of the sources, but the true spectrums may be diffent. In particular, we are concerned that the radiation regime of particles at higher frequencies will change. Besides, the light curves will be polluted by background due to the poor angular resolution of LHAASO. The development of cleaning algorithm is necessary. To compute a stable PSD, we need a long enough light curve with good cadence. For example, to detect a QPO period about 30 d, the baseline may be 10 times longer than the variability timescale(Kozłowski 2017; Hu et al. 2024). Fortunately, LHAASO can observe the sky every day so our light curves will have a great cadence.

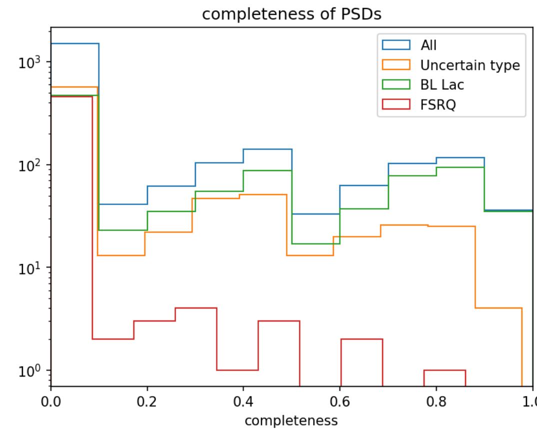

Figure 3. The distributin of completeness. The blue line is the total sample. The green line is BL Lac sample.The organge line is the active galaxy of uncertain type. The red line is the FSRQ sample.

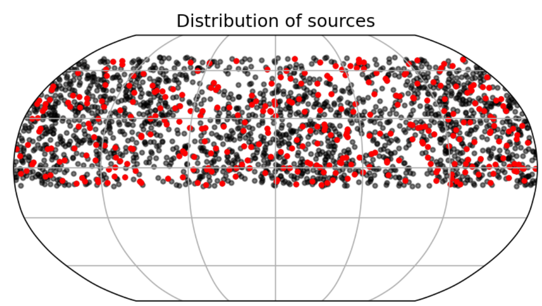

Figure 4. The spatial distributin of sources. The grey points are the total sample and the red points are the sample with compeleteness> 50%.

Facilities: Fermi,LHAASO

Software: astropy (Astropy Collaboration et al. 2013, 2018)

[4] https://github.com/Lace-t/QPO-LHAASO

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index	column number in 4FGL-DR catalog	item
0	0	name
1	-	index in 4FGL-DR4 catalog
2	2	RA
3	3	Dec
4	4	LII
5	5	BII
6	15	Pivot_Energy(MeV)
7	20	Spectrum_Type
8	21	PL_Flux_Density
9	23	PL_Index
10	25	LP_Flux_Density
11	27	LP_Index
12	29	LP_Beta
13	34	PLEC_Flux_Density
14	36	PLEC_Index_S
15	38	PLEC_Exp_Factor_S
16	40	PLEC_Exp_Index
17	69	Source_Type
18	-	completeness

Table 1. The organizatins of our catalog.The first column is the index. The second column records the location of the column where the data would be in the 4FGL-DR4 catalog(if it is from the 4GL-DR4 catalog).The third column is the parameter in the catalog.

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