Investigating Unassociated Fermi-LAT sources for the search of Gamma ray pulsars including Millisecond pulsars using semicoherent approch.

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Abstract. The search for gamma-ray pulsars including millisecond pulsars (MSPs) among unassociated Fermi-Large Area Telescope (LAT) sources offers an opportunity to study these rapidly rotating, highly magnetized neutron stars. This work uses semi-coherent data analysis method adapted from gravitational wave (GW) searches to detect periodic signals indicative of pulsar activity. Identified candidates are to be submitted to the LIGO-VIRGO-KAGRA (LVK) collaboration for further analysis, linking electromagnetic and GW observations for potential multimessenger insights. This research expands the pulsar catalog, providing insights to the GeV excess issue and enhancing the detection prospects of GW from isolated pulsars.

1 Introduction

The Fermi-LAT's fourth source catalog (4FGL-DR3) [1] [2] provides an updated view of gamma-ray sources based on over a decade of observations (2008–2020). Covering an energy range of 50 MeV to 1 TeV, it includes 6658 sources, featuring newly classified pulsars and blazars. Significant updates in the release include improved spectral parameterization and extended energy range analyses, offering a more refined perspective on the gamma-ray sky. A key feature of the DR3 catalog is its emphasis on unassociated sources, which remain enigmatic and present opportunities for the discovery of new astrophysical phenomena.

Unassociated gamma-ray sources [2] represent a significant portion of the catalog. These objects emit detectable gamma radiation but lack clear counterparts at other wavelengths, such as optical, radio, or X-ray. Their mysterious nature and unknown origin make it difficult to link gamma-ray detections to known astrophysical objects, highlighting the challenges in understanding them. However, these unexplained sources also offer exciting opportunities for groundbreaking discoveries in astrophysics.

One notable discovery from observations of the Milky Way's Galactic Center using the Fermi-LAT is the detection of the GeV excess [3]. This refers to an unexpected surplus of gamma rays with energies between 1-3 GeV that cannot be entirely accounted for by known astrophysical sources like pulsars or supernova remnants. Studies of the GeV gamma-ray excess focus on detecting gamma rays that could result from the annihilation of dark

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matter particles, such as Weakly interacting massive particles (WIMPs) [4]. These analyses constrain the properties of dark matter by determining upper limits on their annihilation cross-section. Alternatively, the excess may arise from an unresolved population of Millisecond pulsars (MSPs) [5]. Studies using wavelet decomposition and photon clustering techniques provide evidence supporting this hypothesis, suggesting that these pulsars could account for the excess.

2 Analysis of Unassociated gamma ray sources using Direct Search Data Analysis (DSDA) method

The Direct Search Data Analysis (DSDA) method is an extension of a semicoherent search method used in the context of interferometric detectors to Fermi data. It is based on the resampling method [6]. A semi-coherent search is used when one or more parameters of a source are not known, or in the case of all-sky searches, when searching for completely unknown sources. In this research, the frequency of the source and its temporal evolution are completely unknown, while we have information on the region of the sky from which the emission comes. Due to the Doppler effect caused by the motion of the Fermi satellite, an angular uncertainty (ε) arises. To account for the uncertainty in sky position, a grid is constructed over the parameter space, dividing the sky into small regions. The search involves a grid in three dimensions: frequency (f), spin-down ($\dot{f}$), and position ($\boldsymbol{r}$). Since the pulsar's rotational and positional parameters are unknown, this grid provides a structure over which the parameter space is explored. Each grid point represents a potential source, and the search is performed individually for each point.

The photon arrival time is corrected for Doppler effect, Einstein delay and Shapiro delay. Pulsars gradually lose rotational energy over time, resulting in a slow decrease in their rotational frequency, a process known as "spin-down". A new time variable t' is introduced, shifted as compared to t by an amount depending on the frequency evolution of the pulsar itself:

$$t' = t + \frac{1}{2}\frac{\dot{f}_0}{f_0}(t - t_0)^2 + \frac{1}{6}\frac{\ddot{f}_0}{f_0}(t - t_0)^3 + \dots \quad (1)$$

Considering terms up to the second-order expansion $\lambda(t_0) = \frac{\dot{f}_0}{2f_0}$, equation (1) becomes $t' = t + \frac{1}{2}\lambda(t_0)(t - t_0)^2$. For this work DSDA was applied to the Fermi data. The analysis of 4FGL J1801.6-2326 is discussed in this section. The energy flux for the source, derived from spectral fitting in the range of 100 MeV to 100 GeV, is $1.2782783 \times 10^{-10}$ erg cm^{-2} s^{-1}.

2.1 Source parameters

The source parameters of the source 4FGL J1801.6-2326, as mentioned in the Fermi catalog, are tabulated in table 1. The time resolution was selected to be 1/64 s, as this is suitable for searching gamma-ray pulsars, which can have maximum frequencies of up to 32 Hz. We began the analysis by setting the value of the time analysis window to 7 days, with the analysis running through the data from 4 August 2008 to 7 December 2023. The λ range was selected to encompass the typical gamma-ray population ($-8\times10^{-13} Hz$ to $-8\times10^{-18} Hz$) [7]. The range of spindown covered is $-1.11 \times 10^{-17} s^{-2}$ to $-1.024 \times 10^{-11} s^{-2}$.

2.2 Candidate Selection and follow up analysis

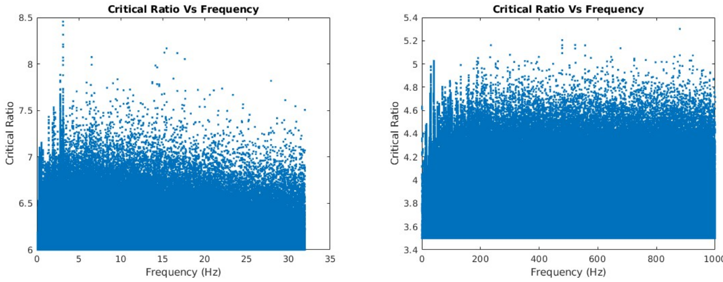
Each candidate is associated to a statistical significance, via the so called Critical Ratio (CR), a measure to distinguish signal from noise. It is defined as follows:

$$\mathrm{CR} = \frac{y_{\max} - \bar{y}_{\mathrm{noise}}}{\sigma_{y_{\mathrm{noise}}}} \quad (2)$$

$y_{\max}$ is the maximum value in the power spectrum for a candidate signal, $\bar{y}_{\mathrm{noise}}$ represents the mean of the noise spectrum, $\sigma_{y_{\mathrm{noise}}}$ is the standard deviation of the noise spectrum.

Table 1. Parameters used to analyze the source 4FGL J1801.6-2326

Name of the parameter	Value
Right ascension (hh:mm:ss)	18:01:41.7359
Declination (hh:mm:ss)	-23:26:04.1999
Region of interest (deg)	0.0389



(a) (b)

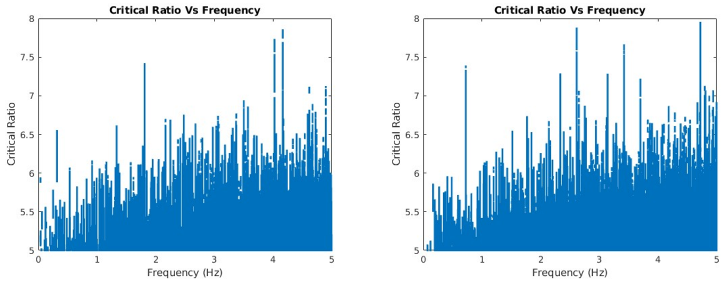
Figure 1. (a) Critical Ratio vs Frequency for the analysis in the λ range of gamma-ray pulsars for the source 4FGL J1801.6-2326. (b) Critical Ratio vs Frequency for the analysis in the λ range of MSPs for the source 4FGL J1801.6-2326

2.3 Follow-up analysis

Based on the CR, the most significant candidates are selected for further analysis. A more sensitive investigation is then conducted to either confirm or rule out the hypothesis of a potential source. The CR threshold (c') for this selection is determined by the available computational power and other constraints. To enhance sensitivity, follow-up is performed increasing the coherence time to 30-days. Sensitivity depends on the time analysis window as $Sensitivity \propto \frac{1}{T_w^{\frac{1}{4}}}$ and $CR \propto \frac{1}{T_w^{\frac{1}{2}}}$ [8]. For the source 4FGL J1801.6-2326, c' was evaluated to be 7.5 and 174 frequency candidates were found above this value (Figure 1(a)). Upon further analysis with 30 days time analysis window, no significant peaks were observed (Figure 2 (a) and (b)). The analysis was also performed in the λ range of MSPs ($-8 \times 10^{-16} Hz$ to $-8 \times 10^{-20} Hz$). The time resolution was set to be 1/2000 s because the maximum frequency for MSPs is 1000 Hz. The c' was evaluated to be 6.4 and no candidates were found above this threshold (Figure 1(b)). Therefore, no further analysis was performed.

3 Conclusion

The DSDA method was used to analyze unassociated sources. For the source 4FGL J1801.6-2326, using the input parameters provided and the available computational resources, no pulsar-like characteristics were detected. Although no pulsar-like characteristics were detected, the study highlights the potential of semi-coherent search techniques by applying the DSDA pipeline to unassociated gamma-ray sources in the 4th Fermi-LAT catalog. By dividing the data into 7-day segments and combining them incoherently, the method efficiently explored the parameter space, balancing sensitivity and computational efficiency for investigating faint signals. Future enhancements in sensitivity and computational tools could improve detection rates, contributing to a better understanding of pulsar populations and their astrophysical significance. This work provides a foundation for further studies linking gamma-ray data with GW observations.



(a) (b)

Figure 2. (a) Critical Ratio vs Frequency for the follow up of frequency candidate f1 = 2.7964 Hz for the source 4FGL J1801.6-2326. (b) Critical Ratio vs Frequency for the follow up of frequency candidate f2 = 3.1399 Hz for the source 4FGL J1801.6-2326.

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