A blind search for isolated millisecond pulsars in the Fermi LAT data

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The Large Area Telescope (LAT) on the *Fermi* satellite has opened a new era in the study of pulsars by detecting nearly a hundred of these objects in gamma rays, by detecting high-energy pulsations from millisecond pulsars (MSPs) for the first time, and by being the first gamma-ray telescope to discover new pulsars. Nevertheless, none of the pulsars discovered so far in blind searches of the data recorded by the LAT are MSPs. Most MSPs have binary orbits, which makes the parameter space to be searched overwhelmingly vast. For isolated MSPs, the number of trial sky positions, frequencies and frequency derivatives needed to detect a pulsed signal still makes searches very challenging. We present a semi-coherent search technique that, coupled with large computational power, will be used to search for unknown isolated MSPs. The discovery of a new population of radio-quiet MSPs would open a completely new window on the study of pulsars.

Introduction

Blind searches for gamma-ray pulsars in the *Fermi* LAT data have been very successful, with nearly a third of the currently known gamma-ray pulsars detected with these techniques (see e.g. [1]). Subsequent radio observations have failed to find pulsations from most of these newly discovered pulsars, suggesting that they are "radio-quiet", in contrast with most other known pulsars. However, none of them are "millisecond pulsars" (MSPs), pulsars with large rotational frequencies (typically greater than 50 Hz) that were spun up by accretion of matter from a binary companion [2].

Fermi has detected more than 30 radio-loud MSPs, establishing them as a prominent class of gamma-ray sources [3]. Pre-launch estimates of the number of radio-quiet MSPs visible by *Fermi* based on limited radio survey sky coverage and sensitivity were optimistic (see e.g. [4]). However, it has been shown recently that radio emission from MSPs may occur at higher altitudes in the magnetosphere than previously thought, leading to larger portions of the sky illuminated and therefore fewer radio-quiet pulsars. The very successful surveys for MSPs in *Fermi* sources (see e.g. [5,6]) should also be taken into account in population synthesis models. Finally, *Fermi* has detected several gamma-ray MSPs with co-located radio and gamma-ray emission regions [7,8]. Under these geometries, very few radio-quiet MSPs are to be expected. In all cases, a blind search for MSPs will help place constraints on the ratio of radio-loud to radio-quiet gamma-ray MSPs.

Blind searches for MSPs are technically more difficult than for "normal" pulsars. MSPs have much larger rotational frequencies, so that many more sky position trials are needed to properly correct for the Doppler shift induced by the Earth's motion. Additionally, 80% of MSPs have binary orbits, while fewer than 1% of normal pulsars do. The binary motion introduces several other search parameters, making searches for binary MSPs in gamma rays currently intractable due to the sparsity of the data.

We describe a new blind search technique that enables searches for isolated gamma-ray MSPs in the data recorded by the *Fermi* LAT. This analysis technique will be applied to unassociated *Fermi* sources, with an aim at uncovering the unseen population of radio-quiet MSPs.

A sliding coherence window technique for searching isolated MSPs in LAT data

MSPs are very stable rotators. The rotational phase of isolated MSPs is well-reproduced by a simple model involving the spin frequency f_0, its time derivative f_1, and the sky coordinates. Fully-coherent searches of year-long data sets over these four parameters are however computationally impractical. We have therefore developed a novel hierarchical search technique for searching isolated gamma-ray MSPs, in which short data segments are analyzed coherently and the results for each segment are then incoherently combined [9,10].

This "sliding coherence window method" has similarities with the "time-differencing technique" [11] and employs tools developed for gravitational-wave pulsar searches [12]. In short, the coherent search results (Fourier power) from the analysis of data segments of duration the coherence window size are incoherently combined while "sliding" the window over the entire data set. As a consequence, photon timestamps separated by less than the coherence window size are combined coherently, otherwise they are combined incoherently.

Previous searches for normal pulsars probed frequencies up to 64 Hz, so that the usage of single Fast Fourier Transforms (FFTs) with 64 Hz of bandwidth was sufficient. For MSP searches, analyzing with a single FFT up to 1.4 kHz is not feasible because of memory limitations on modern computers. In our method the frequency range is therefore split into sub-bands, and each sub-band is analyzed separately. The number of sky positions to be searched, increasing quadratically with frequency, can therefore be adjusted to the maximum frequency in each band, thereby reducing the computational burden dramatically. Additionally, the sky gridding is optimized by imposing that the Doppler shift due to the Earth's motion is constant between grid points. The number of points is then determined by the maximum loss in signal-to-noise ratio allowed.

Promising candidates identified via the sliding coherence window technique will be followed-up using more sensitive methods covering smaller parameter ranges. Such follow-up methods include the usage of a larger coherence window size or a fully-coherent search around the candidate parameters.

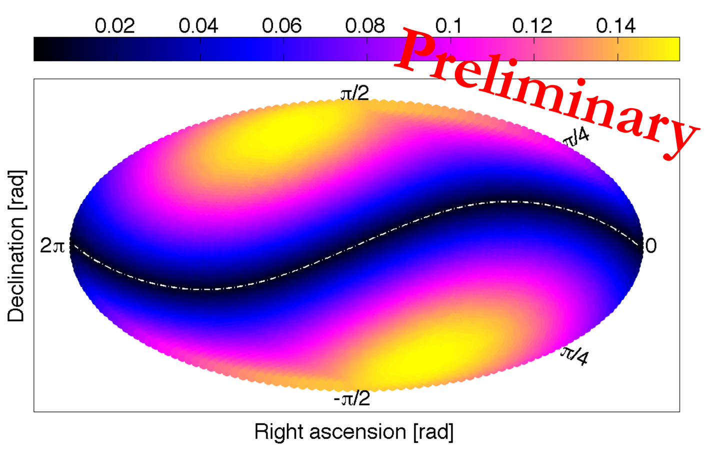


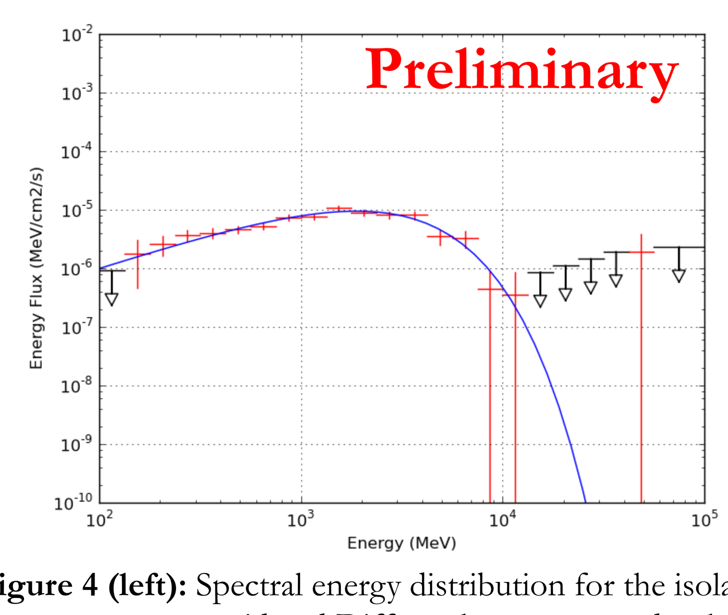
Figure 1: Estimated time (in days) needed to search 8000 gamma-ray photons for pulsations up to 1.4 kHz with the new search technique, using 6000 CPU cores and assuming a search radius of 2.5'.

Which sources will be searched?

Searches for radio pulsars in unassociated *Fermi* LAT sources have been very successful, with the discovery of more than 30 previously unknown MSPs in the Galactic disk (see e.g. [5,6]). One of the keys to the success of these searches was the LAT's ability to distinguish pulsars among unassociated sources, by checking their spectral and variability properties. In contrast with most other gamma-ray sources, pulsars are characterized by spectra exhibiting sharp cutoffs (an example is shown in Figure 4) and lack of variability. Likewise, we will concentrate our search efforts on sources exhibiting pulsar-like spectra.

Sources from the forthcoming Fermi LAT Second Year Catalog with no known associations will be analyzed, to determine their spectral properties and compare them to those of known pulsars, in order to find ~10-100 good candidates.

Finally, it must be noted that a number of sources of the 3-month and 1-year catalogs [15,16] that have clear pulsar-like spectra still remain unassociated, in spite of deep radio pointings at several large radio telescopes. These sources will be analyzed as a priority, with the hope of discovering radio-quiet isolated MSPs.



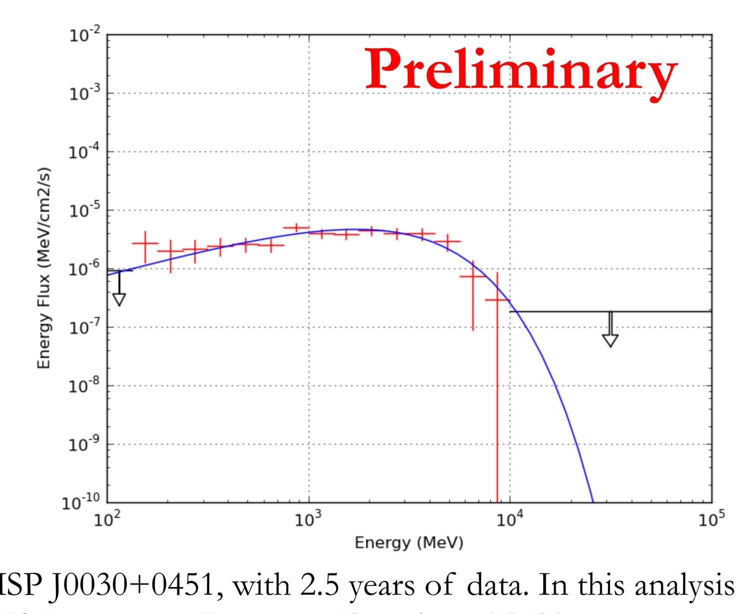
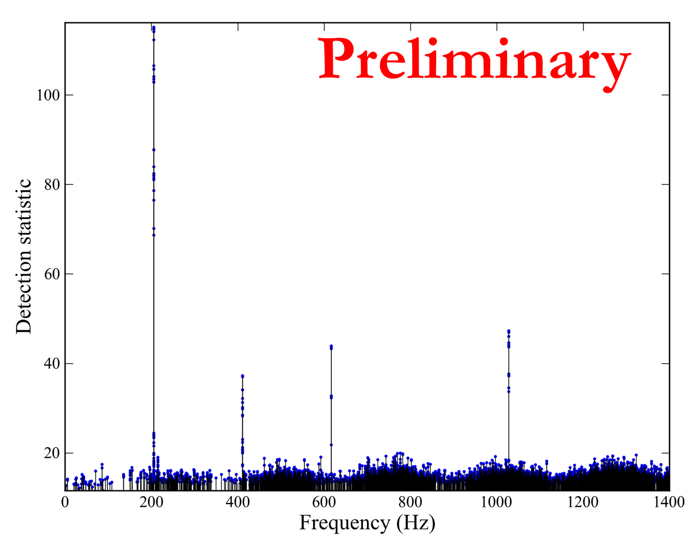


Figure 4 (left): Spectral energy distribution for the isolated MSP J0030+0451, with 2.5 years of data. In this analysis we considered Diffuse class events under the P6_V3 Instrument Response Functions (IRFs).
Figure 5 (right): Same, for a *Fermi* source with no known associations.

Application to isolated MSPs seen with *Fermi*

We carried out initial tests of the new search technique using known isolated MSPs detected by Fermi, and in particular the bright MSPs J0030+0451 and J2124-3358 [13]. For each of these pulsars, we performed a spectral analysis of 2.5 years of Fermi LAT data in order to determine the probabilities that the different photons originate from them. The photon arrival times, weighted using these probabilities, were then searched for pulsations.

Figures 2 and 3 show that J0030+0451 and J2124-3358 are clearly detected with coherence window lengths of 2^{19} s (6 days), and search radii of 2.5' and 1.5' around the pulsars. The assessment of the search sensitivity is in progress. It will be interesting to apply the technique to the fainter MSPs J0340+4130, J1744-1134, and J1939+2134 [8,13,14]. To fully assess the sensitivity, we will simulate LAT data using *gtobssim* and different pulsar fluxes, background fluxes and light curve shapes.



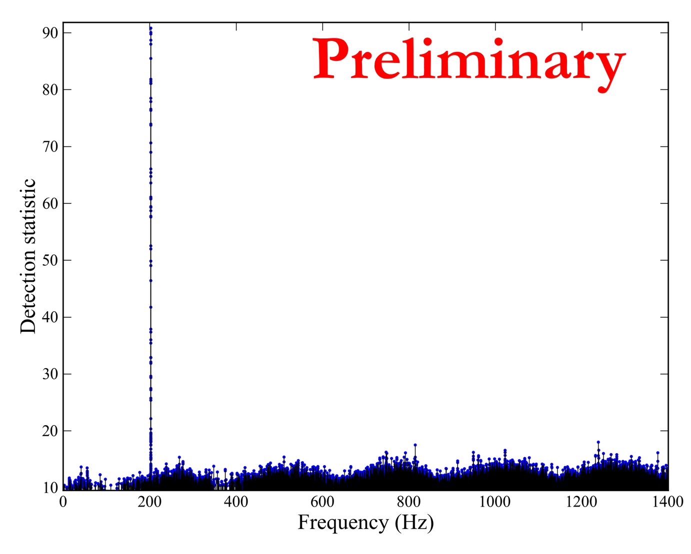


Figure 2 (left): Example spectrum for PSR J0030+0451. A region of 2.5' around the pulsar was searched with a coherence window length of 2^{19} s. A maximum is observed at the pulsar's rotational frequency (f_0 = 205.53 Hz).
Figure 3 (right): Same, for PSR J2124-3358 and for a search radius of 1.5' (f_0 = 202.79 Hz).

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Conclusions and Prospects

We have developed a semi-coherent hierarchical search technique that enables searches for isolated gamma-ray MSPs in the data recorded by the *Fermi* LAT by reducing the number of trials in sky position, frequency and frequency derivatives dramatically over fully-coherent searches. This technique will be used for searching *Fermi* LAT sources with no known associations with the ATLAS cluster in Hannover, a 7100-CPU-core and 264-GPU cluster designed for searching for gravitational wave signals in LIGO data [17,18]. The large computing power provided by the ATLAS cluster allows to search for sources in short times (see Figure 1), which in turn allows us to process many unassociated gamma-ray sources quickly.

We will search unassociated *Fermi* sources from the Second Year Catalog with pulsar-like spectra for isolated MSPs, hoping to uncover the currently unconstrained population of radio-quiet MSPs.

In the future, we may also make use of some the resources of the volunteer computing project Einstein@Home.