

On the highest energy emission from millisecond pulsars

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Fermi has detected over 200 pulsars above 100 MeV. In a previous work, using 3 years of LAT data (1FHL catalog) we reported that 28 of these pulsars show emission above 10 GeV; only three of these, however, were millisecond pulsars (MSPs). The recently-released Third Catalog of Hard *Fermi*-LAT Sources (3FHL) contains over 1500 sources showing emission above 10 GeV, 17 of which are associated with gamma-ray MSPs. Using three times as much data as in our previous study (1FHL), we report on a systematic analysis of these pulsars to determine the highest energy (pulsed) emission from MSPs and discuss the best possible candidates for follow-up observations with ground-based TeV instruments (H.E.S.S., MAGIC, VERITAS, and the upcoming CTA).

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1. Introduction

Studies of the γ -ray sky above 10 GeV were limited in the past by the relatively poor sensitivity of the instruments. The Energetic Gamma Ray Experiment Telescope (EGRET) on the *Compton Gamma Ray Observatory (CGRO)* detected just over 1500 photons above 10 GeV in its 9-year lifetime, 37 of which fell within 1° of one of the 5 EGRET-detected γ -ray pulsars known at the time [1]. The *Fermi* Large Area Telescope (LAT), launched in 2008, has already exceeded EGRET's lifetime and with its larger field of view and better sensitivity, has collected about three orders of magnitude more photons than EGRET did. Based on silicon-strip detector technology, compared to the older generation gas-based spark chambers, the LAT's improved sensitivity is particularly significant at the highest energies. The First *Fermi*-LAT Catalog of sources above 10 GeV (1FHL) [2], using the first three years of LAT data above 10 GeV, contained 514 sources. Most of the 1FHL sources (76%) are associated with active galactic nuclei, but 27 are associated with pulsars, while $\sim 13\%$ of 1FHL sources are unassociated.

2. Pulsars in 1FHL and 2FHL

The 27 pulsars coincident with 1FHL sources covered every category, including the 5 EGRET-detected pulsars, roughly equal numbers of young *radio loud* and *radio quiet* pulsars, and 5 millisecond pulsars (MSPs). A likelihood ratio analysis was carried out, comparing the *low energy* (>100 MeV) light curve to the *high energy* (> 10 GeV) events, in order to determine whether significant pulsations were detected above 10 GeV and 25 GeV. A majority of the pulsars tested (20/25¹) were found to “pulse” above 10 GeV, with 12 pulsars showing significant pulsations above 25 GeV (including the MSP J0614–3329). In addition to these, 14 pulsars from the 2nd Pulsar Catalog which showed evidence for possible emission above 10 GeV were studied. Of these, eight showed significant pulsations above 10 GeV, including the MSPs J2017+0603 and J2302+4442. In short, [2] showed that at least 28 gamma-ray pulsars show pulsations above 10 GeV, 5 of which were MSPs, with one MSP (J0614–3329) showing pulsations above 25 GeV. The Second Catalog of Hard *Fermi*-LAT Sources (2FHL) [3] spanned 80 months and used the improved *Pass 8* data. However, the low energy threshold this time around was set at 50 GeV, instead of 10 GeV used for 1FHL. This resulted in far fewer sources (360), and only one of these was coincident with a pulsar (Vela). Indeed, [4] confirmed that Vela emits pulsations above 50 GeV, something also confirmed now by H.E.S.S. [5].

3. The 3FHL Catalog

The Third Catalog of Hard *Fermi*-LAT Sources (3FHL) [6] uses 7 years of *Pass 8* data above 10 GeV and contains 1556 sources. It's interesting to note that the number of γ -ray sources above 10 GeV now slightly exceeds the number of >10 GeV photons detected by EGRET in its 9-year lifetime. Like the 1FHL before it, the 3FHL contains mainly (79%) sources associated with active galactic nuclei, with $\sim 13\%$ of its sources being unassociated.

¹PSR J1536–4948 and J2339–0533 were not part of the Second Fermi LAT Catalog of Gamma-ray Pulsars (2PC, [7]), so these were left out of the analysis.

4. MSPs in 3FHL

Compared to 1FHL, there are approximately three times the number of pulsars associated with 3FHL sources, including 17 γ -ray MSPs. Note that only 5 MSPs were previously coincident with 1FHL sources. We have undertaken a similar analysis to that carried out in 1FHL, but this time focussed only on the MSPs associated with 3FHL sources.

The 17 MSPs coincident with 3FHL sources span a range of different categories of MSPs: *isolated MSPs* such as J0340+4130 and J0533+6759, the *Black Widow* pulsar J1311–3430, *Redback* MSPs, such as J2215+5135 and J2339–0533, and even the *transitional* MSP J1227–4853. We carried out a dedicated analysis using 9 years of LAT data (three times the amount of data used in 1FHL). The improved statistics enabled us to generate the *low energy* pulse profile of each pulsar using events above 1 GeV. Because the pulse profile of most pulsars is known to change with energy (with pulses typically becoming narrower), this improves the sensitivity of the pulsation search at higher energies. We performed a spectral analysis of each of the pulsars, followed by an updated timing analysis of all systems. We excluded J1227–4853 from our analysis for now, since its pulsed emission is variable and requires a more careful dedicated analysis.

We find that all 16 MSPs that we tested showed significant pulsations above 10 GeV. This includes PSRs J1536–4948 and J2339–0533 which had been found to be coincident with 1FHL sources but were not part of the previous analysis as these pulsars were not part of 2PC [7]. Of these 16 MSPs, five show significant pulsations above 25 GeV: J0218+4232, J0614–3329, J1231–1411, J1311–3430, and J1536–4948 [8].

PSR J0218+4232 was discovered over 25 years ago [9]. A tentative detection was claimed using EGRET data [11] and it was among the first MSPs to be firmly detected by the *Fermi* LAT [10]. Its spindown luminosity of 2.4×10^{35} erg s⁻¹ makes it the second most energetic *field* MSP² (after J1939+2134), of the ~ 100 gamma-ray MSPs detected so far by *Fermi*. Its non-thermal X-ray flux, as well as its radio luminosity ($L_{400} = S_{400} d_{kpc}^2 \sim 400 \text{mJy kpc}^2$) are among the highest of all MSPs [7]. **J0614–3329** and **PSR J1231–1411** were two of the first three MSPs discovered in radio searches of *pulsar-like* unassociated γ -ray sources [12] and as such are among the brightest and most energetic MSPs detected by the LAT ($\sim 2 \times 10^{34}$ erg s⁻¹). **J0614–3329** was the only MSP which was previously (in 1FHL) shown to have significant pulsations above 25 GeV; in fact, despite being due to a single photon, the maximum energy above which the pulsed emission was still found significant for this pulsar exceeded 60 GeV. Recently, [13] reported emission from this pulsar up to 60 GeV. The Black Widow pulsar **J1311–3430** was the first binary MSP discovered in blind searches of LAT data [14]. Finally, **PSR J1536–4948** was discovered by the Giant Metrewave Radio Telescope (GMRT), in its searches of *pulsar-like* LAT γ -ray sources [15].

It is indicative of the success of *Fermi*, that 4 out of the 5 γ -ray MSPs now known to be emitting above 25 GeV were not even known prior to the launch of *Fermi*³.

5. VHE Pulsars

At energies above 50 GeV, the LAT unfortunately is simply too small to collect sufficient

²i.e. **not** in a Globular Cluster.

³J0614–3329, however, is coincident with an EGRET unidentified source.

statistics. Indeed, the total exposure on each of the 16 MSPs described above, over the 9-year period of observation, ranges from $\sim 1.0\text{--}1.7\text{ m}^2\text{ yr}$, depending on the location in the sky. Fortunately, ground-based γ -ray telescopes have made tremendous advances in recent years. The MAGIC telescope led the way with the first detection of the Crab pulsar above 25 GeV [16], followed by the VERITAS detection of pulsed emission above 100 GeV [17]. Most recently, MAGIC has detected the Crab pulsar up to TeV energies [18]. Added to the H.E.S.S. detection of the Vela pulsar up to 120 GeV [5], we now have two pulsars that emit at Very High Energies (VHE, $>100\text{ GeV}$). A number of models have been developed to explain this emission (e.g. [19, 20, 21, 22]). Observationally, it remains to be seen whether any other pulsars can be found that emit at these energies. Current instruments like H.E.S.S., MAGIC, and VERITAS continue to search for such VHE pulsars, and in a few years, the much more sensitive Cherenkov Telescope Array (CTA) will join the excitement, likely detecting a number of γ -ray pulsars, starting at a few tens of GeV [23].

6. Summary

The 1FHL Catalog [2], based on 3 years of LAT data above 10 GeV showed that 28 (13) pulsars showed significant pulsations above 10 (25) GeV, including 5 (1) MSPs emitting above 10 (25) GeV. The 3FHL catalog includes 17 sources coincident with MSPs. We carried out an analysis of 16 of these (excluding the *transitional* system J1227–4853) and found that all 16 of them show significant pulsations above 10 GeV, with 5 of them showing significant pulsations above 25 GeV. Detailed results are presented in [8]. Future observations with ground-based γ -ray telescopes like H.E.S.S., MAGIC, and VERITAS, and in the near future CTA, will determine whether any of these systems are VHE pulsars, emitting above 100 GeV, like the Crab and Vela. The detection of new pulsars at these energies will be crucial to test the many models that have been developed in recent years to explain the VHE emission of the Crab and (to a lesser extent) Vela pulsars.

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