A Large Population of Sub-Threshold Gamma-ray Pulsars

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ABSTRACT

We report on a likelihood stacking search for gamma-ray pulsars at 525 high latitude locations that coincide with known radio pulsar positions. We report 8 newly detected or associated pulsar candidates and 36 sub-threshold pulsar candidates. Stacking their likelihood profiles in spectral parameter space implies a pulsar-like spectral index and a flux one order of magnitude below the Fermi sensitivity. The same procedures performed on empty control fields imply a high false detection rate (20-50%) although the stacked spectra are distinctly softer than the pulsars. This study also probes a unique region of parameter space populated by older, transitional, and recycled (millisecond) pulsars. Many of these sources have lower rotational energy loss rates implying that the empirical $\gamma$-ray “death line” could be predominantly a sensitivity limit. Their luminosities, however, are consistent with the heuristic relation between spin-down power and $\gamma$-ray luminosity. If their pulsar nature can be confirmed, these results will expand the number of $\gamma$-ray pulsars by 16%. Furthermore, the improved millisecond pulsar luminosity function with these new sources can help characterize their possible contribution to the Galactic center GeV excess.

Keywords: Pulsars; Gamma-rays

1. INTRODUCTION

Identifying astrophysical $\gamma$-ray sources is one of the main goals of the Fermi Gamma-ray Space Telescope, and the updated 10-year source catalog, 4FGL-DR2, identifies 279 sources as pulsars (Ajello et al. 2020). However, the Australia National Telescope Facility (ATNF) pulsar catalog lists over 2800 pulsars discovered as of November 2020 (Manchester et al. 2005). Gamma-ray flux from these undetected pulsars is almost certainly present in data from the Fermi Large Area Telescope (LAT) and should be discoverable using stacking techniques (Huber et al. 2012). The characteristics of such stacked signals can provide insight into pulsar $\gamma$-ray emission properties and potentially serve as a means to determine whether and how pulsars may contribute to the diffuse $\gamma$-ray background, the $\gamma$-ray excess observed at the Galactic center, and $\gamma$-ray flux from globular clusters.

Stacking analyses using Fermi data were proposed as useful techniques by Huber et al. (2012) to extend the detection threshold for $\gamma$-ray sources. This work has since been expanded in surveys towards galaxy clusters (Dutson et al. 2013; Griffin et al. 2014; Prokhorov & Churazov 2014; Reiss & Keshet 2018), providing strong upper limits or detections. An aperture photometry counts stacking analysis of the high energy emission from pulsars in the third Fermi catalog was done by McCann (2015) with a null result. However, more recently, an improved likelihood stacking technique

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was developed and successfully used to characterize the faint blazar and starburst galaxy populations at GeV energies (Ajello et al. 2020; Paliya et al. 2019), pushing well beyond the point source detection limit of the LAT.

With over twelve years of almost continual all-sky survey data, Fermi offers the opportunity to probe below the γ-ray pulsar “death line” in spindown luminosity $E$ (Smith et al. 2019) where the vast majority of rotationally-powered pulsars reside. A study of several faint γ-ray pulsars by Hou et al. (2014) illustrated both the difficulties and benefits of pushing the limits of sensitivity. They cite issues of bright backgrounds, steep source spectra with low energy cutoffs, and broad, hard to discern pulses. Challenging as they are to identify and confirm, this faint population is a window into an anticipated corner of pulsar parameter space that probes rare alignment geometries and potentially novel emission mechanisms. Despite their faintness, Bruel (2019) demonstrated techniques that manage to extract a pulse signature and spectral information even from sub-threshold sources.

With this project we aim to utilize stacking techniques to create a catalog of sub-threshold γ-ray pulsars to establish their existence and enable investigation of this elusive population. The organization of this paper is as follows: In § 2 we describe our list of targets, the observational methods and results. We summarize the new candidate detections and associations made in this study along with the population of sub-threshold pulsars. We also analyze control fields to verify the results. In § 3, the new candidates are described, including their spectral properties. The sub-threshold population of pulsars is analyzed in § 4. The overall properties of these sources are placed in context with the known pulsar population in § 5.

2. OBSERVATIONS AND RESULTS

2.1. Data Selection

The target pulsars were chosen from the ATNF pulsar catalogue version 1.64, November 2020. Data were chosen between Mission Elapsed Time (MET) 239560000s and 641950000s. Each region of interest (ROI) is a 21.2° × 21.2° square, which corresponds to a 15° radius ROI. The data were also filtered using a zenith angle cut of 90° to avoid bright emission from the Earth. Good time intervals were chosen with conditions DATA_QUAL==1 && LAT_CONFIG==1. The data were binned in 30 logarithmically spaced energy bins. An all-sky livetime cube and all-sky exposure cube within the specified time range from above were created and utilized for all ROIs.

Some previous studies have uncovered potential systematic effects studying faint populations at low energies (Paliya et al. 2020; Principe et al. 2021). We took a data-based approach to quantify this effect by conducting the likelihood analysis in two different energy ranges. We used data between 100 MeV and 100 GeV to constrain the spectral energy distributions (SEDs) and for initial candidate detection, and data between 300 MeV and 100 GeV to calculate final fluxes, confirm candidate associations, and for the stacking analyses.

Finally, we examined 808 control fields to validate the likelihood results, identify any systematic effects, and estimate the rate of false associations. The control fields have the same radius of 15°, and are centered at random locations in the sky within the same Galactic latitude and longitude ranges and other exclusions described in § 2.1. The center of each control field is chosen to be at least 1° away from any known 4FGL source to be more certain that any measured signal can be attributed solely to fluctuations in the background noise.

2.2. Fermi-LAT Data Analysis

1 https://www.atnf.csiro.au/research/pulsar/psrcat/
2 https://psrqpy.readthedocs.io/en/latest/
3 https://fermipy.readthedocs.io/en/latest/
4 https://fermi.gsfc.nasa.gov/ssc/data/analysis/
Fermipy automatically reads the currently available version of the 4FGL catalog and creates a model file for each ROI, along with the Galactic diffuse background emission and the isotropic background. An additional source was modeled at the center of each ROI as a power law with super exponential cutoff (PLEC). The spectral parameters of all sources within 7.5° from the ROI center, and the backgrounds, were set free. This process yields the Test Statistic value of each pulsar, defined as TS = 2 log $L/L_0$, a comparison of the log likelihoods of the source model and the null hypothesis (no source, $L_0$). Usually, $\sqrt{TS}$ is used as a rough estimate of the source significance.

Additional unmodeled sources with TS $> 25$ were identified using the find_sources function in Fermipy, assuming they are power law sources. Localization of the central source was carried out with the localization function in Fermipy. Some of these sources were localized far from the ROI center (> 1°), in which case a new PLEC source was placed at that location in addition to the central source. Signal contamination from nearby sources, if not very bright and/or highly variable, has been shown to be rather minimal (Song & Paglione 2020). TS maps of each ROI are generated by the tsmap function in Fermipy, which excludes each putative pulsar from the model and should result in an excess likelihood at the map center if a $\gamma$-ray source is there.

2.3. Initial Results

Fig. 1 shows the TS distributions of the central sources in the target ROIs above 300 MeV. For comparison, the TS values for test sources at the centers of the control fields are also shown. Any negative TS values are omitted in making these plots. The $\chi^2/2$ distribution for three degrees of freedom is also shown, which should be equivalent to the theoretical null (Mattox et al. 1996).

Initial detection significance was determined using the TS value from the 100 MeV to 100 GeV likelihood analysis (TS$_{100}$), and confirmed using the 300 MeV to 100 GeV data (noted simply as TS). Choosing TS$_{100} > 25$ (which corresponds to about a $4\sigma$ detection for 3 degrees of freedom), and TS$ > 9$ (which corresponds to about a $2\sigma$ detection), as the detection thresholds, we find eight new candidate associations with ATNF pulsars, described below in § 3. There also are numerous sources above the theoretical noise level delimited by $\chi^2/2$. There are 36 ROIs that satisfy the sub-threshold inclusion criteria we use, namely 12 < TS$_{100}$ < 25, or 12 < TS < 25 with $|TS_{100} - TS| < 9$. These putative sources could signify a substantial increase in the known population of $\gamma$-ray pulsars. Hereafter, we will refer to these 36 pulsars as “sub-threshold sources.”

We adapted the method used in Huber et al. (2012) to add up the TS values of all 410 ROIs with TS $\geq 0$. We added up the TS values ROI by ROI for the pulsars and control fields, respectively, to investigate if there is any difference in their cumulative TS distributions. To evaluate the significance/uncertainty of these stacks, we did a bootstrap resampling of the ROIs 100 times. The averaged cumulative TS values are shown in Fig. 1 along with their standard
deviations. For each resampling, 410 control fields are randomly selected from the entire control field sample with TS > 0. The results, as shown in the right panel of Fig. 1 show a statistically significant difference between the cumulative TS values of the pulsars and the test sources in the control fields, confirming the detection of an underlying population.

The new $\gamma$-ray pulsar candidates – along with the full ATNF catalog, our target ATNF pulsars, and 4FGL pulsars – are plotted in Fig. 2. This high latitude study, while aimed primarily at reducing the background systematics, also probes a unique region of parameter space populated by older, transitional, and recycled (millisecond) pulsars (MSPs). Many of these sources also have lower rotational energy loss rates, $\dot{E}$. The $\gamma$-ray “death line” around $10^{33}$ erg s$^{-1}$ appears to be a sensitivity limit more than anything else. The surveyed and detected source distributions also more closely reflect the overall distribution of objects in the ATNF compared to those in the 4FGL. The implications of these results are explored in § 5.

2.4. Parameter Space Stacking

Figure 2. $P$-$\dot{P}$ diagram of the pulsars surveyed here (red dots), sub-threshold sources that were stacked (green diamonds), and new candidate detections (white dots with black circles) along with Fermi catalog pulsars (blue dots) and ATNF pulsars (gray dots). The right side histogram shows the distribution of $\dot{P}$ for all the pulsars; the top panel histogram shows the distribution of $P$ for all the pulsars. The histograms have the same color coding as the symbols. Lines of constant characteristic age and $\dot{E}$ are indicated.
To investigate the spectral properties of the pulsar population, we performed a parameter space likelihood stack similar to Paliya et al. (2019). A point source with a PLEC spectrum is placed at the center of each ROI fixing flux, spectral index, and cutoff energy. Only the background isotropic and Galactic diffuse normalizations are free to be fit by Fermipy’s fit function. This process returns a log likelihood for the ROI given these spectral parameters for the central source. We repeat this process over a grid of flux and index values, keeping the cutoff energy fixed at 823.3 MeV to lower the degrees of freedom to 2. A detailed justification is given in Appendix C. TS maps in flux-index parameter space for each ROI are made by subtracting the log likelihood of the grid point representing the null, which is chosen to be at the lowest flux ($1.5 \times 10^{-13}$ ph cm$^{-2}$ s$^{-1}$) and spectral index of $-4$. The stacked TS map is then made by summing the individual TS maps. A similar analysis of 410 control fields with central test sources with $0 < \text{TS} < 25$ is done for comparison.

The spectral parameter stacks for pulsar ROIs and control fields are shown in Fig. 3. For the pulsar ROIs, the maximum likelihood occurs for a flux of $1.93 \times 10^{-10}$ ph cm$^{-2}$ s$^{-1}$, and a spectral index of $-1$. The sensitivity of the LAT for these latitude ranges is $1.2 \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$, one order of magnitude higher than the fluxes we are able to probe here. The spectral index is typical for 4FGL pulsars.

We note that a peak occurs in the parameter space stack for the test sources as well. However, that peak corresponds to a significantly softer spectral index than for a typical pulsar. Subtracting the pulsar and control field TS maps confirms that these populations have significantly different spectral properties, and that the diffuse background may introduce a systematic effect leading to false association/detection. Very soft sources in particular should be treated with suspicion.

### 3. NEW CANDIDATE DETECTIONS

We detect γ-ray sources in the direction of eight ATNF pulsars in this survey (Table 1). Only one of these, PSR J2336-01, a newly discovered pulsar by the LOFAR Tied-Array Allsky Survey (LOTASS) (Sanidas et al. 2019), has been reported as a possible γ-ray source with upper limits of its Fermi gamma-ray flux placed by Lu et al. (2021) of $1.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. Of the remaining pulsars, PSR J1517-4356 has no particularly distinguishing characteristics (Edwards et al. 2001), but we note unique phenomenology for the remaining candidates. PSR J0048+3412 (Herfindal & Rankin 2009), PSR J1926-0652 (Zhang et al. 2019), and PSR J2048-1616 (Ritchings 1976) are mulling pulsars while PSR J1705-04 is a Rotating RAdio Transient (RRAT) (Karako-Argaman et al. 2015). PSR J1405-4656 is a binary millisecond pulsar (Bates et al. 2015). Finally, while we believe the association may be spurious (see § 5.1), PSR J1239+2453 famously exhibits giant pulses (Hankins & Wright 1980).

Spectral energy distributions (SEDs) of all new detections are displayed in Fig. 9 which can be found in Appendix A. We include the PLEC model results from the likelihood analysis over the full energy range (Table 1) for each source, along with the energy flux in energy bins [0.1 GeV, 0.3 GeV], [0.3 GeV, 0.79 GeV], [0.79 GeV, 2.08 GeV], [2.08 GeV, 5.48 GeV], [5.48 GeV, 14.42 GeV], [14.42 GeV, 37.98 GeV] and [37.98 GeV, 300 GeV].

While phase-folded pulse detection would confirm the pulsar nature of these sources, attempting to establish γ-ray timing solutions is reserved for future work.
The control fields effectively probe the false detection or false associate rate in this study. Four control fields returned detected central test sources according to the same detection criteria used for the pulsar ROIs. The test sources in 29 control fields satisfy the sub-threshold source classification.

4. SUB-THRESHOLD SOURCES

All of the sub-threshold pulsars that are described in § 2.3 can be found in Table 2. In this section we describe the parameter space stacking results focused on this group of pulsars in our target list. These 36 pulsars are plotted on the $P$-$\dot{P}$ diagram (Fig. 2) and include various types of pulsars, from MSPs to a magnetar, and most of them are below the $\sim 3 \times 10^{33}$ erg s$^{-1}$ $\gamma$-ray “deathline.”

The spectral parameter stack of just the sub-threshold sources is shown in Fig. 4. Again their most likely spectral parameters differ significantly from the stack of the control field ROIs with test source TS values in the sub-threshold range. However, since it is unreasonable to assume that all these pulsars emit at a similar flux, we explored different parameters differ significantly from the stack of the control field ROIs with test source TS values in the sub-threshold range.

| RA        | Dec       | Photon Flux ($\times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$) | Index | Cutoff Energy GeV | $\text{T_S}_{\text{rel}}$ | TS | Luminosity$_{\text{rel}}$ ($\times 10^{32}$ ergs s$^{-1}$) | $\dot{E}$ | Dist (kpc) |
|-----------|-----------|-------------------------------------------------|-------|------------------|------------------------|----|---------------------------------|---------|-----------|
| J0048+3412 | 12.4176 ± 0.2587 | 34.076 ± 0.243 | 4.82 ± 4.68 | $-2.16 \pm 2.28$ | 1.0 ± 0.23 | 30.90 | 22.55 | 0.22 ± 0.38 | 0.0516 | 4.5 |
| J1239+2453 | 189.914 ± 0.003 | 24.947 ± 0.003 | 7.40 ± 0.55 | $-4.41 \pm 0.5^{***}$ | 2.431 ± 2.563 | 29.36 | 9.15 | 0.038 ± 0.023 | 0.0143 | 0.84 |
| J1405-4656 | 211.339 ± 0.001 | -46.934 ± 0.001 | 6.71 ± 4.777 | $-0.050 \pm 0.5^{***}$ | 0.156 ± 0.00047 | 47.87 | 21.46 | 0.000 ± 0.028 | 2.51 | 0.609 |
| J1517-4356 | 229.364 ± 0.001 | -43.938 ± 0.0004 | 2.24 ± 0.43 | $1.16 \pm 2.19$ | 0.016 ± 0.0018 | 28.41 | 14.84 | 2.48 ± 1.63 | 0.031 | 4.473 |
| J1705-04  | 256.156 ± 0.145 | -4.661 ± 0.134 | 5.86 ± 2.33 | $1.28 \pm 0.74$ | 0.135 ± 0.011 | 56.94 | 29.08 | 0.010 ± 0.006 | ... | 0.21 |
| J1926-0652 | 291.654 ± 0.003 | -6.878 ± 0.003 | 6.17 ± 14.321 | $1.50 \pm 0.5^{***}$ | 0.009 ± 0.005 | 32.51 | 18.21 | 4.82 ± 3.11 | 0.0037 | 5.286 |
| J2048-1616 | 312.212 ± 0.102 | -16.207 ± 0.096 | 5.23 ± 2.20 | $-2.59 \pm 0.34$ | 9.934 ± 16.348 | 31.48 | 22.53 | 0.104 ± 0.068 | 0.0573 | 0.95 |
| J2236-01  | 354.081 ± 0.123 | -1.935 ± 0.198 | 1.24 ± 3.49 | $-1.80 \pm 1.64$ | 4.339 ± 7.452 | 11.67 | 30.59 | 0.062 ± 0.560 | ... | 2.393 |

* $\text{T_{S_{rel}}}$ and TS are the TS values calculated using data between 100 MeV to 10 GeV and between 300 MeV to 100 GeV, respectively. 
** No data  
*** The uncertainty in index was extremely low indicating a possible convergence issue. We use 0.5 instead.
Figure 4. Top left: Parameter space stack of 36 ROIs with sub-threshold pulsars. This is stacked assuming these pulsars have a similar average flux. The white X marks the optimal parameters with largest TS value of 164.9, and the contour indicates 3σ from the maximum. Top middle: Parameter space stack for 29 control fields that satisfy the sub-threshold criteria as described in § 2.3. Top right: Parameter space stack of 36 ROIs with sub-threshold pulsars with well calibrated distances. This is stacked assuming these pulsars have a similar average luminosity. The white X marks the optimal parameters with largest TS value of 98.5. Bottom left: Parameter space stack of 30 ROIs with sub-threshold pulsars that have a measured $\dot{E}$. This is stacked assuming the $\gamma$-ray flux of these pulsars scales with $\dot{E}$. Bottom middle: Parameter space stack of the same 30 ROIs assuming the $\gamma$-ray flux scales with $\sqrt{\dot{E}}$. Bottom right: Parameter space stack of 30 ROIs with sub-threshold pulsars assuming the $\gamma$-ray luminosity of these pulsars scales as $\dot{E}/d^2$.

We also examined simulated data to understand if the control fields with high TS could be caused by uncertainties in modeling the background and/or other sources. The simulated observations were generated by the `simulate_roi` function in `Fermipy`. The central source is left out of the model when creating the simulated observation, and the normalization of the isotropic background is adjusted to test the effects of varying counts noise. The simulated observations of each of the 808 control field ROIs is then fed through the analysis pipeline with the central source added back to the model, and the TS value of the central source is measured. Without altering the background normalization, the resulting TS distribution is indistinguishable from the null, $\chi^2/2$, which is inconsistent with the control field results in Fig. 1, and indicates that systematic observational effects are causing a high false detection rate. Source detection is apparently highly sensitive to background modeling, however. An increase of only 0.1% in the isotropic background normalization yields test source TS values that stack in a similar way as the control fields (Fig. 6). The resulting simulated TS distribution exceeds the null, but still produces fewer sub-threshold sources and no detections (TS > 25). Thus, while spurious counts noise or background modeling systematics can account for much of the relatively high rate of false association we find, it seems likely that emission from unrelated sources along the line of sight contributes as well. The control field parameter stacking results indicate that these contaminating or spurious sources should have notably softer spectra, however, and are distinguishable at least from pulsars. Despite a false detection rate nominally as high as 50%, only one candidate pulsar has a very soft spectral index, J1239+2453. This one is also poorly localized and the TS value above 300 MeV is quite low. In addition this pulsar is $5^\circ$ away from a relatively bright flat-spectrum radio quasar, 4FGL 1224.8+2122 with a detection significance of 215 in the 4FGL catalog. Although unlikely, some signal leakage from that source could be possible. The remaining candidate detections are well localized and exhibit an associated likelihood excess in their TS maps (Appendix A). In contrast, of
Figure 5. Stacked SED of 36 sub-threshold pulsars with well calibrated distances. The data points represent the best fit power law model in each energy bin, and the gray butterflies represent the 3σ uncertainties on the spectral parameters. The red dashed curve represents the model fitting result using inverse Compton scattering using naima as described in § 5.2.

Figure 6. Results of ROI simulation.

The control field ROIs that satisfy the detection criteria, only one shows a well-localized likelihood excess. We therefore estimate the false associate rate at 20-50%.

5.2. Luminosities

The Fermi detected pulsars show a correlation between their $\gamma$-ray luminosities and $\dot{E}$ (Abdo et al. 2013). Depending on the beaming geometry, their efficiencies can be rather high as well. There has been some suggestion that at low $\dot{E}$ the heuristic relation of $L_\gamma \propto \sqrt{\dot{E}}$ may change to an even stronger dependence and a very high efficiency (Smith et al. 2019). This study allows us the opportunity to probe these low rotation power sources for the first time.
We extracted the spectral parameters of all 4FGL pulsars and converted them to luminosity within the photon energy range of 300 MeV to 100 GeV using the default ATNF distance modeled with YMW2016 (Yao et al. 2017) and assuming a 30% uncertainty. For the newly detected pulsars, the luminosity is calculated from their best-fit PLEC parameters, integrating from 300 MeV to 100 GeV to be comparable with the 4FGL values. In both cases, we consider a beaming factor $f_{\Omega} = 1$, where the luminosity is the energy flux multiplied by $4\pi d^2 f_{\Omega}$. We estimated the luminosity of sub-threshold pulsars based on the results from the parameter space stacking in § 4. The flux and photon index spread is quite large. Their luminosity distribution is consistent with the low tail of the 4FGL pulsars.

Several pulsars, most of those from the 4FGL, have luminosities orders of magnitude higher than the maximum efficiency given the assumed beaming factor. While various factors such as extreme beaming geometries, different spectral models, and distance uncertainties can account for some of this discrepancy, the seeming connection with low $\dot{E}$ is unclear. These objects of course could be unassociated with their presumed ATNF counterpart, but the number exceeds even our conservative false association rate. The SEDs are also quite pulsar-like and the 4FGL sources all have fairly significant spectral curvature, low variability, and a pulsar type association (though no phased pulse identification yet).

Another issue is that many models of $\gamma$-ray emission from pulsars indicate that the emission mechanism may simply turn off at low $\dot{E}$. Their low $\dot{E}$ also precludes them from being pulsar wind nebula candidates. This survey was designed specifically to have clean backgrounds so the $\gamma$-ray source should be the neutron star itself, similar perhaps to the presumed magnetospheric off-peak emission seen in some pulsars (Abdo et al. 2013). We investigate a simple scenario where the $\gamma$-ray emission is from an inverse Compton halo located near the light cylinder. Using the \texttt{naima} code (Zabala 2015; Khangulyan et al. 2014), we assume a seed photon field from photospheric thermal emission at $10^6$ K. We also assumed a population of relativistic electrons described by a range of power law indices between $-1$ and $-5$, and cutoff energies between 500 and 1000 MeV. Integrating over all scattering angles, inverse Compton scattering generates a spectrum that matches the fluxes and SEDs of the detected and sub-threshold sources, as shown in Fig. 5. To achieve this result requires an electron distribution with a power law index of $-1.8$, and cutoff energy of 3871.1 MeV, though their uncertainties are very large. The required normalization depends on the product of the non-thermal electron density and photon density (which depends on the characteristic scattering distance from the stellar photosphere). If this distance is comparable to the light cylinder radius, $\gtrsim 10$ neutron star radii, then the lepton densities required to create such a spectrum are orders of magnitude below the Goldreich-Julian density (Goldreich \\& Julian 1969).

5.3. Sub-threshold Pulsars and the Galactic Center Excess

An excess of GeV $\gamma$-ray emission around the Galactic center (Galactic center excess, or GCE) has been identified by many groups (e. g., Atwood et al. 2009; Goodenough \\& Hooper 2009; Abazajian 2011). Some studies argue that this emission may be evidence of a dark matter signal (Cholis et al. 2015; Calore et al. 2015). Others argue that unresolved point sources in the Galactic bulge contribute to this emission (Bartels et al. 2018; Calore et al. 2014; Chang et al. 2020). As an example, Abazajian (2011) concluded that the GCE had a spectrum consistent with the spectra of four Fermi-detected globular clusters, whose signal is attributed to MSPs. Subsequently, some studies indicate that MSPs may perhaps explain the entire $\gamma$-ray excess (e. g., Ploeg et al. 2017). These analyses are mostly limited by the uncertainties in the luminosity function for MSPs due to incompleteness (Hooper \\& Mohlabeng 2016; Eckner et al. 2018, and references therein). The Fermi-LAT Collaboration (2017) concluded that 800-3600 MSPs would be required to explain the entire excess, depending on the luminosity function.

Here we examine the luminosity function of the entire $\gamma$-ray pulsar population combining the 4FGL pulsars, 8 newly detected ones and the sub-threshold pulsars with their estimated luminosity as described in § 5.2. The luminosity function, $dN/dL$, and the cumulative luminosity distributions are shown in Fig. 8 for both the entire pulsar population and only MSPs ($P < 15$ ms). The MSP luminosity function is well fit with a broken power law. This fit also describes...
Figure 7. Gamma-ray luminosity versus $\dot{E}$, along with their distributions, for 4FGL pulsars (blue), newly detected sources (orange), plus the two confirmed pulsars and the likely 4FGL association (hollow black circles). The stacking results for the sub-threshold sources are indicated in green with $3\sigma$ error bars. The red dashed line indicates the maximum efficiency limit for a beaming factor $f_B = 1$. The heuristic dependence of $L$ on $\sqrt{\dot{E}}$ is noted by the purple dashed line.

Top and Right: $\dot{E}$ and luminosity distributions of 4FGL pulsars (blue), all targeted ATNF pulsars (red), newly detected pulsar candidates (orange) and sub-threshold pulsars (green).

The cumulative distribution very well and is consistent with previous work (Ploeg et al. 2017; Bartels et al. 2018b; Hooper & Mohlabeng 2016). Using the best fit MSP luminosity function of the 106 MSPs in our study, we calculate their total luminosity to be $1.68 \times 10^{36}$ erg s$^{-1}$. Bartels et al. (2018b) determined the GCE intensity to be $2.3 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$, which yields a total luminosity of $1.76 \times 10^{37}$ erg s$^{-1}$ for a distance of 8.0 kpc. If bulge MSPs are to explain the entire GCE, then about 1110 are required, which is consistent (if on the low end) with the Fermi estimation. We note that the SED of the primarily low $\dot{E}$ sub-threshold pulsars does not peak around a GeV like the GCE, so higher spin down pulsars are the more likely contributors.

6. CONCLUSIONS
In this work we examined the γ-ray emission from 525 locations that coincide with ATNF pulsars using Fermi-LAT data. Our sample ranges widely from young to old pulsars, magnetars, MSPs, and low \( \dot{E} \) pulsars. We report 8 new pulsar candidate detections. Their TS maps and SEDs indicate their plausibility as pulsar candidates, yet γ-ray timing analysis, if possible, should confirm their pulsar nature.

We also report a population of sub-threshold pulsars. Stacking their TS profiles in spectral parameter space (flux and photon spectral index) indicates a pulsar-like spectrum assuming a cutoff energy at 823 MeV, with an index of −1.0, which is consistent with known pulsar SEDs. The characteristic γ-ray flux of \( 1.93 \times 10^{-10} \text{ ph cm}^{-2} \text{ s}^{-1} \) is about an order of magnitude lower than the Fermi-LAT detection sensitivity. We are also constructed the stacked SED of these sub-threshold pulsars.

The dozens of reported sub-threshold pulsars follow the heuristic dependence of \( L_\gamma \) on \( \sqrt{\dot{E}} \). Other low \( \dot{E} \) pulsars, both newly detected and listed in the 4FGL, seemingly exceed the 100% efficiency. Our analysis of control fields and modeling the population indicates that while some of these might be mis-associations, the SEDs are consistent with a simple model of inverse Compton scattering of thermal photospheric emission.

The total luminosity of the 107 MSPs in our survey can account for \( \sim 11\% \) of the GCE. This result supports the hypothesis that a population of 1120 MSPs in the Galactic bulge could be responsible for the GCE.

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APPENDIX

A. SUPPORTING DATA FOR CANDIDATE DETECTIONS

The SEDs and TS maps of the 8 detected pulsar candidates are shown in Fig. 9. For comparison, the SEDs and TS maps of the 4 control field test sources that satisfy the detection criteria are shown in Fig. 10, and their spectral parameters are listed in Table 3. All of the control field test sources satisfying the detection criteria were fit with extremely small uncertainties in either the index, the cutoff energy, or both. This is often a sign of a poor convergence, bad fit, and/or improper spectral model. While the nominal false detection rate implied by four control field detections versus eight pulsar ROI detections is \( \sim 50\% \), we note that only three detected pulsar candidates had poor convergence and three out of four control field ROIs exhibit no excess likelihood in the 95% localization uncertainty in their TS maps.
Recent work has revealed that due to the worse resolution and contamination from the backgrounds, parameter stacking that includes photons below 300 MeV may introduce a spurious population of extremely soft sources (Paliya et al. 2020). Here, we test this claim by repeating the stacking analyses with both the 100 MeV to 100 GeV and the

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**Table 3.** “Detected” Control Field Sources

| name   | R.A(°) | Dec(°) | TS    | Index       | Cutoff (MeV) |
|--------|--------|--------|-------|-------------|--------------|
| CF497  | 4.30   | 80.78  | 24.68 | 1.499 ± 0.5* | 137.72 ± 26.02 |
| CF488  | 133.46 | -24.01 | 21.27 | 1.499 ± 0.5* | 138.03 ± 26.94 |
| CF416  | 136.90 | -27.14 | 27.82 | -0.0054 ± 0.5* | 202.36 ± 6.83 |
| CF412  | 230.60 | -43.36 | 24.82 | -0.30 ± 0.5* | 387.3658 ± 0.0027 |

* The uncertainty in index is extremely low indicating possible convergence issue. We use 0.5 instead.

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**B. STACKING RESULTS FROM 100 MEV**

Recent work has revealed that due to the worse resolution and contamination from the backgrounds, parameter stacking that includes photons below 300 MeV may introduce a spurious population of extremely soft sources (Paliya et al. 2020). Here, we test this claim by repeating the stacking analyses with both the 100 MeV to 100 GeV and the
Figure 10. Columns 1 and 3: Spectral energy distributions of the “detected” test sources. Fluxes with errorbars are shown in each energy bin with a detection (TS > 4), and the rest are shown with 95% upper limits. We also plot the best-fit PLEC (black solid line) spectral models from the likelihood analysis over the full energy range along with the uncertainties (gray shaded area), with the parameters given in Table 3. Columns 2 and 4: TS maps of the “detected” control fields with 300 MeV to 100 GeV data. The red + at the center of the map indicates the original center of the control field the white X and circle represent the optimized location and 95% uncertainty of the test source.

300 MeV to 100 GeV data sets, following the prescription outlined in § 2. In Fig. 11, we plot the TS$_{100}$ distribution and the cumulative TS$_{100}$ distribution of both the pulsar ROIs and control field ROIs. The similarities between the TS$_{100}$ distributions indicates that there is likely both a high rate of false detection and a spuriously large sub-threshold population. However, the stacked signal still persists when examining the cumulative TS$_{100}$ distribution, though it is less significant.

We also investigated both the pulsar and control field ROIs using the parameter space stacking technique. However, about $\sim 1/4$ of the pulsar ROIs did not converge at all points in parameter space using this method. In Fig. 11, we show the parameter stacking results of 370 pulsar ROIs with $0 < $ TS$_{100} < 25$ that converged in parameter space, as well as 370 control fields. The parameter space stacking shows no significant difference when compared to the results using 300 MeV to 100 GeV data. In both cases, the pulsars collectively have a harder spectral index than the control fields. The flux in the control fields also appears to be an upper limit.

Overall, we do not see a dramatic improvement to the stacking results using only photon energies $\geq$ 300 MeV. However, we still recommend using the higher energy range due to the following considerations: 1) In our analysis, we used a curved PLEC spectrum for our sources instead of a simple power law. A larger systematic effect could occur for power law sources. 2) Above 300 MeV, the improved resolution of Fermi-LAT can greatly aid in localizing faint signals and make less ambiguous source associations. 3) We also saw a decrease in the false association rate when excluding the lower energies.

C. THREE-DIMENSIONAL PARAMETER SPACE STACK

With three parameters for PLEC fitting, a complete parameter-space stack could include, in addition to the flux and index, the cutoff energy. However, in the final analysis of the detected pulsar candidates, the cutoff energy uncertainty was always quite large. To test the dependence on cutoff energy, we calculated the same parameter stack at 4 different cutoff energies with a sample selection of 301 pulsars from the target list. For cutoff energies of 655 MeV, 823 MeV, 1034 MeV and 1300 MeV, as shown in Fig. 12, the stacks indicate a negligible dependence between spectral index and cutoff energy. There is a slight softening of the spectrum with increasing cutoff energy, which is consistent with the trends for 4FGL pulsars and the analytical relation between the two quantities derivable directly from the PLEC model. However, the 3$\sigma$ range is large compared with the trend. We therefore chose to fix the cutoff energy at the median value of all the PLEC 4FGL pulsars for the analysis presented in § 2.4.
Figure 11. Top left: TS\textsubscript{100} values of target pulsars from analysis with 100 MeV to 100 GeV data. Bottom left: TS values of target pulsars from analysis with 300 MeV to 100 GeV data. The orange histogram represents the $\chi^2$/2 distribution for 3 degrees of freedom. The red dashed vertical line represents TS = 25, the presumed detection threshold. Right: Cumulative TS\textsubscript{100} values of the target pulsars (blue) and control field test sources (green). Shaded areas represent uncertainties estimated from bootstrap resampling of the stacks. Bottom left: Parameter space stack of 370 pulsar ROIs with TS\textsubscript{100} between 0 and 25. The white X marks the optimal parameters with largest TS value of 603.9, and the contour shows the 5-σ range. Bottom right: Parameter stack of 370 control fields.

Figure 12. Parameter space stacking of 301 randomly sampled pulsar ROIs with 4 different cutoff energies of 655 MeV, 823 MeV, 1034 MeV and 1300 MeV, from left to right respectively.
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