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New cosmic-ray acceleration sites detected by the *Fermi*-LAT in our Galaxy

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Cosmic rays are mostly composed by protons accelerated to relativistic speeds. When those protons encounter interstellar material, they produce neutral pions which in turn decay into gamma rays. This offers a compelling way to identify the acceleration sites of protons. A characteristic hadronic spectrum was detected in the gamma-ray spectra of four Supernova Remnants (SNRs), IC 443, W44, W49B, and W51C, with the Fermi Large Area Telescope. This detection provided direct evidence that cosmic-ray protons are (re-)accelerated in SNRs.

In this review, we present the results from a comprehensive search for low energy spectral breaks. We use 8 years of data from the Fermi Large Area Telescope between 50 MeV and 1 GeV. This search is based on the 4FGL catalog from which we extracted the unidentified sources or those associated to SNRs with a significance above 3 sigma at low energy in both cases. Several SNRs, binaries and one star forming region as well as a handful of unidentified sources are detected with our search. We present these best candidates, focusing on the most intriguing cases such as Eta Carinae and the Cygnus star forming region, thus enlarging our view to potential new cosmic-ray acceleration sites.

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1. Introduction

The acceleration site of protons, the main components of cosmic rays, is one of the most fundamental topics of high energy astrophysics. A unique signature of the acceleration of protons is provided at gamma-ray energies. Indeed, accelerated cosmic rays interact with surrounding matter and produce π^0 mesons which quickly decay into two gamma rays, each having an energy of 67.5 MeV in the rest frame of the neutral pion. In turn, the gamma-ray number spectrum $F(E)$ is symmetric at this same energy in log-log representation [1] which then leads to a differential γ-ray spectrum in the usual $E^2F(E)$ representation rising below 200 MeV and approximately tracing the energy distribution of parent protons at energies greater than a few GeV. Leptonic γ-ray production mechanisms such as bremsstrahlung and inverse Compton (IC) emission require fine tuning to produce similar spectra. This signature of protons was detected in five SNRs interacting with molecular clouds (MCs) and detected at gamma-ray energies by *Fermi*-LAT: IC 443 and W44 [2, 3], W49B [4], W51C [5], and HB 21 [6], although in this last source both the leptonic and hadronic processes are able to reproduce the γ-ray emission. Here, we use 8 years of Pass 8 data to analyse 311 Galactic sources detected in the 4FGL catalog and search for significant spectral breaks between 50 MeV and 1 GeV. The analysis and the results are fully described in [7].

2. Analysis of the *Fermi*-LAT observations

The *Fermi*-LAT is a γ-ray telescope which detects photons with energies from 20 MeV to more than 500 GeV by conversion into electron-positron pairs, as described in [8]. For this analysis, we used exactly the same dataset as that used to derive the 4FGL catalog of sources, namely 8 years (2008 August 4 to 2016 August 2) of Pass 8 SOURCE class photons with the Instrument Response Functions P8R3_SOURCE_V3. The data reduction and exposure calculations are performed using the LAT *fermitools* version 1.2.23 and *fermipy* [9] version 0.19.0. We accounted for the effect of energy dispersion by using edisp_bins[1] = -3. We performed a summed likelihood binned analysis with three logarithmically spaced energy bins between 50 MeV and 100 MeV including only PSF3 events, and 9 energy bins between 100 MeV and 1 GeV including PSF3 and PSF2 events. The Galactic diffuse emission was modeled by the standard file gll_iem_v07.fits and the residual background and extragalactic radiation were described by an isotropic component (depending on the PSF event type) with the spectral shape in the tabulated model iso_P8R3_SOURCE_V3_PSF(3/2)_v1.txt. The normalizations of the Galactic diffuse and the isotropic components are fit.
We perform an independent analysis of the 311 candidates selected within 5° from the Galactic plane. The procedure followed is iterative; it is inspired by the *Fermi* High-Latitude Extended Sources Catalog [10]. For each source of interest, we define a $20° \times 20°$ region and include in our baseline model all 4FGL sources located in a $40° \times 40°$ region centered on our source of interest. Starting from the baseline model, we proceed to optimize the model using the optimize function provided by *fermipy*. Then, we perform a fit of the region by leaving free the normalization of all sources within 2° of the source of interest, their spectral shape if their TS value is above 16, the normalization of all sources with TS > 100 in the ROI and the spectral shape of all sources in the ROI with TS > 200. We further refine the model by identifying and adding new point source

[1] https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_edisp_usage.html

candidates. To do so, we generate a TS map for a point source that has a PL spectrum with an index $\Gamma = 2$ and we add a source at every peak in the TS map with TS > 16 that is at least 2° from a peak with higher TS due to the poor angular resolution at these low energies. In the final pass of the analysis, a second general fit of the ROI is performed.
Once the ROI is well characterized, we first test the TS value of our source of interest in our energy range (50 MeV to 1 GeV). If it is below 25, we stop the analysis for this source since it is not significantly detected in our pipeline. It is the case for 64 sources among the 311 selected. If the TS is above 25, we move on and we fix all sources located more than 5° from the source of interest and we test the spectral curvature of our source by first using a log parabola representation. If TS_{LP} is below 9, we consider that no significant curvature is detected by our pipeline, we stop the analysis of this source. This is the case for 167 sources in our sample. If the value is above 9, we then test a smoothly broken power law. This adds two degrees of freedom with respect to the power-law model (the break energy E_{br} and a second spectral index Γ_2). The improvement with respect to the power law is determined by $TS_{SBPL} = 2(\ln \mathcal{L}_{SBPL} - \ln \mathcal{L}_{PL})$. Since diffusive shock acceleration predicts $\Gamma_2 \sim 2$, we also test the improvement of the smooth broken power law with the second index fixed at 2 with respect to the power law $TS_{SBPL2} = 2(\ln \mathcal{L}_{SBPL2} - \ln \mathcal{L}_{PL})$. We require $TS_{SBPL} > 12$ or $TS_{SBPL2} > 9$ (3σ improvement for 2 and 1 additional degrees of freedom respectively) to keep the source in the significant energy break list. This procedure allowed the detection of 77 sources presenting a significant energy break in their low-energy spectrum.
To quantify the impact of systematic uncertainties (from the galactic diffuse model and the effective area), we repeated our analysis for the 77 sources using the previous Galactic diffuse model rescaled for Pass 8 Source gll_iem_v06.fits but also using IRFs which symmetrically bracket the standard effective area and flip from one extreme to the other at the measured value of the break energy. We only kept sources that always meet the criteria $TS_{SBPL} > 12$ or $TS_{SBPL2} > 9$. Overall, 56 sources among the 77 sources detected with the standard IEM and IRFs are confirmed with our systematic studies. In addition to performing a spectral fit over the entire energy range, we computed an SED for each of these 56 sources by fitting the flux of the source independently in 10 logarithmically spaced energy bins from 50 MeV to 1 GeV. All SEDs and spectral fits are published in [7].

3. Discussion

The association summary is illustrated by the pie charts in Figure 1. Out of 311 candidates, 210 are unidentified, representing 67.5% of the sources analyzed. It is striking to see that only 26 unidentified sources show a spectral break confirmed with our systematic studies (which represents 46.4% of the sources with significant breaks). The 30 remaining candidates out of 56 confirmed cases present an association reported by the 4FGL Catalog. On the other hand, the fraction of sources associated with supernova remnants (SNRs) increases from 7.4% (23 out of 311 sources) to 23.2% (13 out of 56 sources). This makes SNRs the dominant class of sources with significant low-energy spectral break. Similarly, the fraction of sources associated with binaries increases from 1.6% (5 out of 311) to 7.1% (4 out of 56), showing that almost all binaries except 4FGL J1826.2−1450 (also known as LS 5039), show a significant spectral break. Despite their small fractions, binaries could contribute significantly to our population of sources with low-energy spectral breaks. Finally, only one star-forming region is analyzed (and confirmed) which prevents us from

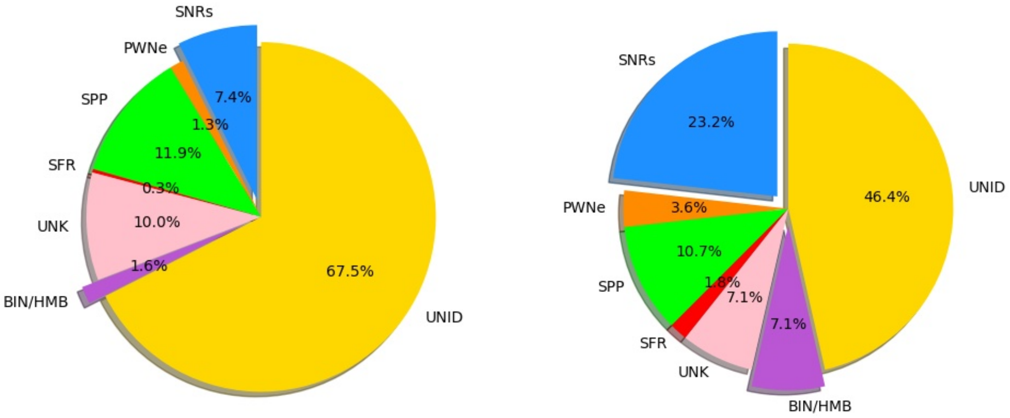

Figure 1: Pie charts showing the classes of sources analyzed (Left) and those for which a significant break is detected (Right). The class names are those used in the 4FGL catalog: SNR stands for Supernova remnant, PWN for pulsar wind nebula, SFR for star-forming region, BIN for binary, HMB for high-mass binary. The designation SPP indicates potential association with SNR or PWN. UNK includes low-latitude blazar candidates of uncertain type associated via the Likelihood-Ratio method. UNID refer to unidentified sources.

drawing a firm conclusion on this source class.
Among the 56 sources with significant breaks, the 4FGL Catalog lists ten sources as firm SNR identifications and three as associated with SNRs, including 4FGL J1911.0+0905 which is associated to W49B and thus can be safely identified as a SNR. Figure 2 (left) presents the spectral energy distributions of these 13 SNRs together with their names. One can note that most of them are interacting with molecular clouds (MCs). These molecular clouds are excellent targets for cosmic-ray interactions and subsequent pion-decay. Figure 2 (right) presents the same SEDs but rescaled at 500 MeV, together with the gamma-ray emission expected for π^0-decay emission for a primary proton spectrum n(p) $\propto$ p$^{-2.4}$, where p is the proton momentum. One can see that all SNRs follow the gamma-ray emission expected for proton-proton interaction except one: the gamma Cygni SNR (also known as 4FGL J2021.0+4031e). For this case, the bright γ-ray emission from the pulsar PSR J2021+4026, lying near the center of the remnant, is very difficult to disentangle from the signal of the SNR at these low energies which could lead to some contamination in the SNR spectrum. A follow-up study in the off-pulse of the pulsar would therefore be needed. This applies not only to supernova remnants but also to all sources close to a bright gamma-ray pulsar.
In addition to SNRs, other sources could play a significant role in the acceleration of Galactic cosmic rays. The shocks generated by the stellar winds of massive stars or star-forming regions are among these cosmic-ray accelerators. In this respect, the detection of a significant break by our analysis for 4FGL J2028.6+4110e associated with the Cygnus cocoon tends to favour the hadronic scenario, thus reinforcing the long-standing hypothesis that massive-star-forming regions house particle accelerators. Gamma-ray binaries, microquasars, and colliding wind binaries could also contribute to the sea of Galactic cosmic rays or, at least contribute significantly to the population of sources with significant breaks. And indeed our analysis revealed significant spectral breaks for

these three types of sources with 4FGL J0240.5+6113 associated with the high-mass γ-ray binary (HMB) LS I +61 303, the HMB 4FGL J1018.9−5856, 4FGL J1045.1-5940 associated with the colliding wind binary η Carinae, 4FGL J2032.6+4053 associated with the microquasar Cyg X-3 and 4FGL J1405.1−6119 recently identified as a HMB using *Fermi*-LAT observations [11].
Finally, unidentified sources represent 29.7% of the 4FGL sources: revealing the mystery of the nature of these gamma-ray sources might shed new light on the problem of the origin of galactic CRs. In this respect, three unidentified sources detected by our pipeline are of real interest since they are coincident with SNRs and/or dense molecular clouds. This is the case for 4FGL J1601.3−5224 coincident with SNR G329.7+00.4, for 4FGL J1934.3+1859 coincident with SNR G054.4−00.3 and for 4FGL J1931.1+1656 coincident with the SNR candidate G52.37−0.70 detected in a THOR+VGPS analysis [12]. These three regions are extremely complex and would deserve a dedicated analysis with *Fermi*. Even more care should be taken for the extended sources 4FGL J1633.0−4746e and 4FGL J1813.1−1737e for which significant spectral breaks are detected in our analysis but their location in confused Galactic plane regions adds to the complexity of such analysis at low energy.
Current and future observations of the LAT are thus crucial to probe the spectral characteristics of a source at low energy, providing excellent targets of proton acceleration for current and future Cherenkov telescopes such as CTA.

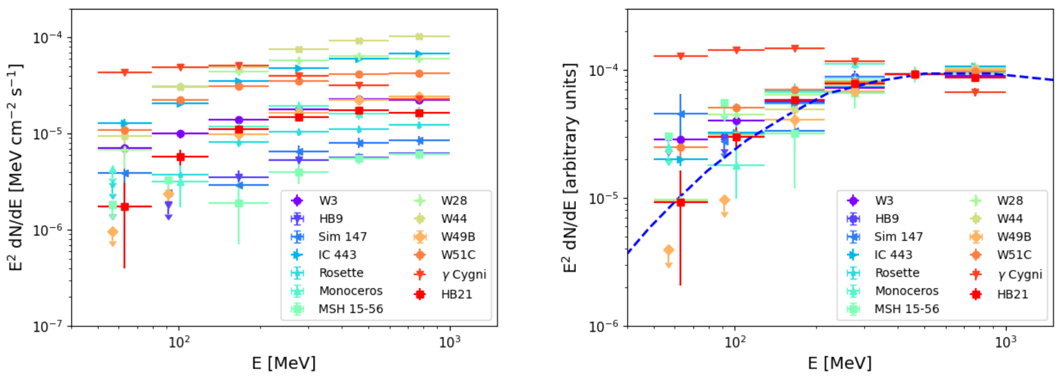

Figure 2: Left: Spectral energy distributions of the 13 sources associated with SNRs. Right: Same SEDs rescaled at 500 MeV. The blue dashed line indicates π^0-decay emission for a primary proton spectrum n(p) $\propto$ $p^{-2.4}$, where p is the proton momentum. Upper limits are shifted for visualization purposes.

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