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Recent detections of TeV Pulsar Wind Nebulae with the *Fermi*-Large Area Telescope

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Prior to the *Fermi* Gamma-ray Space Telescope, only six pulsars and one associated Pulsar Wind Nebula (PWN), the Crab Nebula, had been detected in γ-rays by the CGRO-EGRET experiment. Since then, the Large Area Telescope (LAT) aboard *Fermi* has significantly increased the number of detected pulsars in the 100 MeV to 300 GeV energy range. A large fraction of these pulsars, characterized by high energy loss rates ($\dot{E}$ from $\sim 3 \times 10^{33}$ to $\sim 5 \times 10^{38}$ erg/s), is associated to PWNe or candidates observed in the TeV energy range and are likely to power a PWN detectable in the *Fermi*-LAT energy range, as done for the Crab. Here, we will review the recent results obtained with the *Fermi*-LAT on TeV Pulsar Wind Nebulae, including the Crab Nebula, Vela-X and MSH 15-52, HESS J1825-137, and give a general overview of the constraints provided by *Fermi*-LAT non-detections.

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1. Introduction

High energy γ-ray observations with the *Fermi*-Large Area Telescope (LAT) revealed that pulsars are the most numerous class of identified Galactic GeV γ-ray emitting objects [1]. Up to 10% of the rotational power from pulsars is emitted in the *Fermi*-LAT energy band.

However, most of the pulsar spin-down luminosity is not observed as pulsed photon emission but is carried away as a magnetized particle wind. The deceleration of the pulsar-driven wind as it sweeps up ejecta from the supernova explosion generates a termination shock at which the particles are pitch-angle scattered and accelerated to ultra-relativistic energies. The emission from the pulsar wind nebula (PWN), resulting from processes such as synchrotron radiation and inverse Compton (IC) scattering, extends across the electromagnetic spectrum from radio to TeV energies [16]. PWNe are the major class of Galactic sources in the TeV range.

PWNe may also be detected in the high energy (HE) γ-rays. However, their study in this energy range is complex, due to : (i) the bright emission of their powering pulsars up to $\sim$ 10 GeV compared to the PWN emission, (ii) their usual faint emission in γ-rays, and (iii) their potential extension, that requires a very good sensitivity, an analysis method adapted to describe the morphology of the source as well as a good knowledge of the spatial and spectral structure of the diffuse emission (dominated by the emission from the Galactic plane).

Successfully launched on 2008 June 11, the LAT, aboard *Fermi*, succeeds to the CGRO-EGRET experiment and offers the opportunity to study a large variety of Galactic and extragalactic sources in γ-rays. Sensitive to photons from $\sim$ 20 MeV to $>$ 300 GeV, the LAT is a conversion pair telescope characterized by a large effective area, a large field of view, a very good angular resolution and an excellent timing precision [13]. Thanks to improved performance compared to its predecessor EGRET, it enables in particular the detection and study of faint sources such as PWNe. An overview of recent results on PWNe obtained with the *Fermi*-LAT is presented in the following sections.

2. The Crab Nebula

Associated to the historical supernova of A.D. 1054 and being the archetype of PWNe, the Crab Nebula is powered by the Crab Pulsar, characterized by a high energy loss rate ($\dot{E}$ = 4.6 $\times$ 10^{38} erg/s) and located at a distance of 2 kpc. The detection of the Crab Pulsar and Nebula by EGRET was reported in the 1990's. Because of the bright emission of the Crab Pulsar, the emission from the nebula had to be searched and studied using photons from the off-pulse window of the pulsar light curve, to avoid any contamination from pulsed emission. Due to the low statistics used for the study of the Crab Nebula, the derived HE γ-ray spectrum in the 70 MeV – 30 GeV energy range presents large uncertainties [20].

The improved performance of *Fermi*-LAT enables the detection and precise spectral measurements of the Crab Pulsar and Nebula using 8 months of data in survey mode. In particular, the γ-ray spectrum of the Crab Nebula in the 100 MeV – 300 GeV energy range, estimated from the off-pulse of the light curve of the Crab Pulsar and represented in Figure 1 (red points), can be described by the sum of two power-law spectra of indices Γ_{sync} = (3.99 $\pm$ 0.12_{stat} $\pm$ 0.08_{syst}) and Γ_{IC} = (1.64 $\pm$ 0.05_{stat} $\pm$ 0.07_{syst}), associated to the synchrotron and IC components respectively.

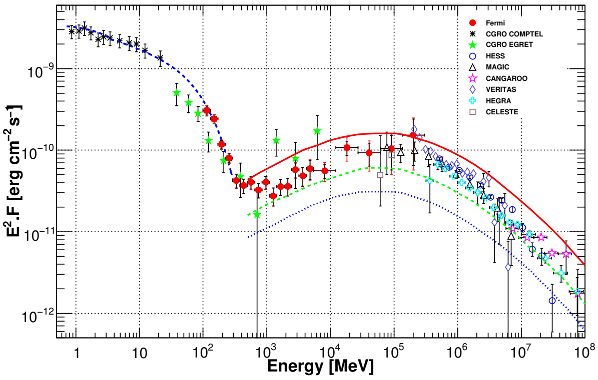

Figure 1: Spectral energy distribution of the Crab Nebula from soft to very HE γ-rays. The predicted IC spectra from [12] are overlaid for three different values of the mean magnetic field: 100 μG (solid red line), 200 μG (dashed green line) and the canonical equipartition field of the Crab Nebula 300 μG (dotted blue line).

The corresponding flux above 100 MeV is $(9.8 \pm 0.7_{stat} \pm 1.0_{syst}) \times 10^{-7}$ cm^{-2} s^{-1}, renormalized to the total phase.

The IC scattering of relativistic electrons on the synchrotron, far infrared (IR), cosmic microwave background (CMB) radiation fields is considered to be the most probable mechanism for production of γ-rays above 1 GeV. However, using a sophisticated approach done in the framework of the MHD flow of [21], Atoyan and Aharonian (1996) have commented on the apparent deficit of GeV photons in their calculations and proposed that the high γ-ray flux observed by EGRET would be due to the enhancement of the bremsstrahlung emission of electrons captured in dense filaments. Figure 1 presents the broad band energy spectrum of the Crab Nebula together with the predictions from [12] for three different values of the mean magnetic field for the nebula. The results from *Fermi* and ground-based Cherenkov telescopes are consistent with γ-ray flux predicted via simple IC scattering in a magnetic field strength between 100 μG and 200 μG (i.e. below the canonical equipartition field of the Crab Nebula of 300 μG), and do not require any additional component.

As done in [20], the synchrotron spectrum estimated from results of COMPTEL and *Fermi* observations, can be fit with a power-law with an exponential cut-off at energy $E_{c,sync} = (97 \pm 12)$ MeV. The fit is represented with a blue dashed curve in Figure 1. More details can be found in [2].

An analysis of the variability of the synchrotron component performed using a longer dataset revealed two flares lasting 16 and 4 days in February 2009 and September 2010 respectively [5].

3. The Vela-X Nebula

Located at a distance of 290 pc, the Vela-X Nebula is associated to the Vela Pulsar, which is the brightest Galactic steady source in HE γ-rays. Located south of the pulsar, Vela-X presents a complex morphology and is detected in radio (emission referred to as the "halo", extension of 2° × 3°), X-rays and TeV γ-rays (referred to as the "cocoon", extension of 0.5° × 1.5°).

The γ-ray emission detected by *Fermi* in the off-pulse of the light curve of the Vela Pulsar is significantly extended (radius of $0.88^\circ \pm 0.12^\circ$ for an assumed radially symmetric uniform disk).

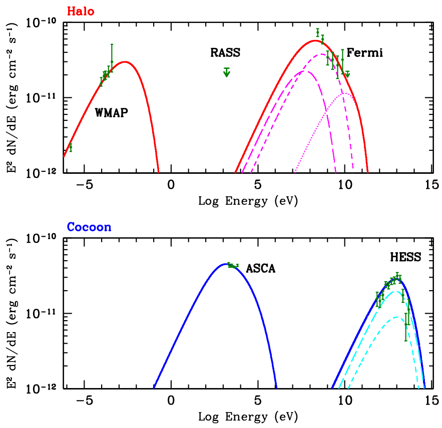

Figure 2: Spectral energy distribution of the regions within Vela-X. **Upper panel:** Emission from the low energy electron population (halo). IC components from scattering on the CMB (magenta long dashed line), dust emission (magenta dashed line) and starlight (magenta dotted line) are shown. **Lower panel:** Synchrotron and IC emission from the high energy electron population (cocoon). Only CMB (cyan long dashed line) and dust (cyan dashed line) scattered flux is shown (the starlight being Klein-Nishina suppressed).

Morphological studies show that the emission seen by *Fermi* is better correlated with the halo seen in radio than with the cocoon seen in X-rays and TeV γ-rays. Assuming a uniform disk morphology, the 200 MeV to 20 GeV LAT spectrum of the Vela-X Nebula is well described by a power-law with a spectral index of $2.41 \pm 0.09_{stat} \pm 0.15_{syst}$ and integral flux above 100 MeV of $(4.73 \pm 0.63_{stat} \pm 1.32_{syst}) \times 10^{-7}$ cm^{-2} s^{-1}.

Different scenarios have been proposed to interpret the multi-wavelength observations of Vela-X. In particular, De Jager et al (1996) proposed a leptonic model with radio and X-ray/TeV emissions resulting from synchrotron radiation and γ-ray emission arising from IC scattering from two leptonic populations. In this case, the morphology of the γ-ray emission observed by *Fermi* should be correlated to that in the radio (produced by the same electron population), as observationally seen. The modeling of the multi-wavelength spectrum also favors a scenario with two distinct electron populations, as can be seen from Figure 2. Our new LAT detection and improved low energy measurements allow us to test the plausible injection spectrum for the Vela-X PWN. In this model, the cocoon emission is produced by relatively recent injection of high energy electrons from the pulsar and its termination shock. A relic leptonic population is responsible from the halo component seen in radio and by *Fermi*. These electrons are produced over the lifetime of the pulsar for any initial spin period ≤ 60 ms. More details can be found in [3].

4. The PWN in MSH 15-52

The composite supernova remnant MSH 15−52 (SNR G320.4−1.2 [14]) is usually associated to the radio pulsar PSR B1509−58. *Einstein* X-ray observations of MSH 15−52 revealed the existence of an elongated non-thermal PWN centered on the pulsar [24]. This PWN, composed of

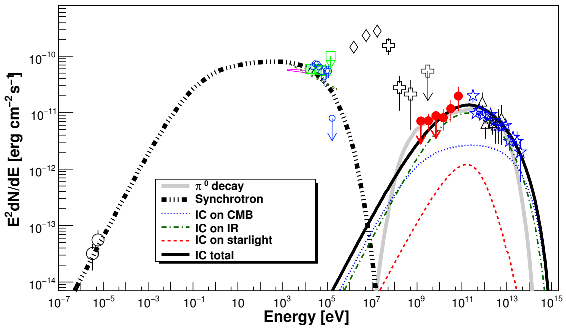

Figure 3: Spectral energy distribution of the pulsar wind nebula powered by PSR B1509−58. The total IC spectrum is shown with a solid line while thinner lines denote the individual IC components: CMB (dotted), infrared (dot-dashed) and optical (dashed). The dot-dot-dot-dashed line indicates the corresponding synchrotron emission. A hadronic γ-ray model is overlaid by a thick gray curve.

a torus and bipolar jets, is especially bright in X-rays [15, 17, 26] and at very high energy (VHE) [11, 22].

Fermi-LAT enabled the detection of an extended γ-ray emission above 1 GeV spatially coincident with the PWN in MSH 15-52 using 1 year of survey data. The spectrum of the nebula in the 1 – 100 GeV energy range is well described by a power-law with a spectral index of (1.57 $\pm$ 0.17$_{stat}$ $\pm$ 0.13$_{syst}$) and a flux above 1 GeV of (2.91 $\pm$ 0.79$_{stat}$ $\pm$ 1.35$_{syst}$) $\times 10^{-9}$ cm^{-2} s^{-1}. The LAT spectrum connects nicely with Cherenkov observations, as can be seen from Figure 3. The spectral modeling of the multi-wavelength spectrum brings new elements to the discussion on the emission models responsible for the high to very high emission from this source and favors IC processes, assuming a broken power-law spectrum for the electrons. In this model, the γ-ray emission from the PWN is dominated by the IC scattering off the IR photons from interstellar dust grains. More details can be found in [4].

5. The PWN HESS J1825-137

The VHE emission of the PWN HESS J1825-137 was revealed during the first H.E.S.S. Galactic plane survey [9]. Significantly extended (radius of $\sim 0.23^\circ$), this nebula is powered by the radio pulsar PSR J1826-1334 and presents in the VHE domain an energy-dependent morphology, that may be explained by cooling mechanisms [8].

Using 20 months of data with the *Fermi*-LAT, we detected a significantly extended (radius of $\sim 0.57^\circ$) emission above 1 GeV, spatially correlated with the TeV emission known as the PWN HESS J1825-137. The *Fermi*-LAT spectrum in the 1 – 100 GeV energy range is well described by a power-law with a spectral index of $\sim$ 1.38 and a flux above 1 GeV of$\sim$ 6.5 $\times 10^{-9}$ cm^{-2} s^{-1}. The LAT spectrum connects nicely with Cherenkov observations, as can be seen from Figure 4. The spectral modeling of the multi-wavelength spectrum favors the IC process as responsible for the γ-ray emission seen by *Fermi* and H.E.S.S., assuming a leptonic injection with a power-law with an exponential cut-off and a low value of the magnetic field (B $\sim$ 4 μG). The decrease of the

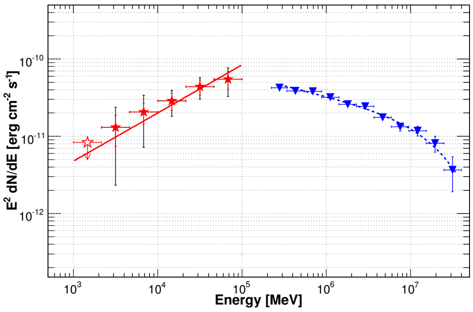

Figure 4: Gamma-ray spectral energy distributions of the PWN HESS J1825-137. *Fermi*-LAT results are presented in red. A 95 % C.L. upper limit is computed when the statistical significance is lower than 3 σ. The blue triangles present the H.E.S.S. spectral points [8].

PWN size with the energy in the *Fermi* to H.E.S.S. energy range strongly supports the existence of cooling mechanisms in the nebula. More details can be found in [18].

6. A PWN candidate associated to the γ-ray pulsar PSR J1023-5746

In 2007, the VHE emission from an extended source, HESS J1023-575, located close to the young stellar cluster Westerlund 2 was reported [7]. Several scenarios were proposed to explain the TeV emission among which colliding stellar winds in the WR 20a binary system (although it can hardly reproduce a source extension of $\sim 0.18°$) collective effects of stellar winds in the Westerlund 2 cluster (although the cluster appears too narrow to account for the VHE γ-ray emission). The recent *Fermi*-LAT detection of the very young and energetic pulsar PSR J1023-5746, coincident with the TeV source HESS J1023-575 [23] motivated another scenario.

Recent analyses of the off-pulse window of the light curve of PSR J1023-5746 shows an emission above 10 GeV significant at more than 3σ level. The results of the spectral analysis of this off-pulse source reveals a hard spectrum which, once renormalized to the total phase, connects with the TeV spectrum of HESS J1023-575, then supporting a common origin of the γ-ray emission. The estimated luminosity above 380 GeV (for an assumed distance of 8 kpc) is 1.5×10^{35} erg s^{-1}, i.e. less than 1.5% of the pulsar rotational energy. The extension of the TeV source and the detection of this very young and energetic pulsar presenting a significant signal in its off-pulse point towards a nebular origin. The very large number of PWNe detected in the TeV energy range and the significant number of PWNe associated with *Fermi*-LAT pulsars make this scenario highly probable. More details can be found in [6].

7. Conclusions

After 2 year of observations, 3 PWNe and their associated pulsars have been detected and identified by *Fermi*-LAT: the Crab Nebula, Vela-X and the PWN in MSH 15-52. In addition, the PWN HESS J1640-465 was also detected in the HE domain, but no pulsed emission could be observed [25]. A new candidate related to the pulsar J1023-5746 is also proposed. Each of these

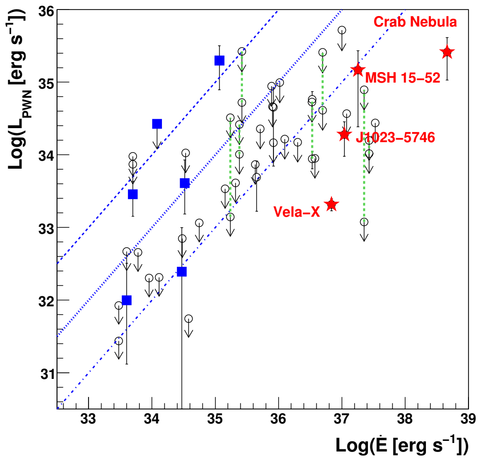

Figure 5: Dependence of the PWN luminosity and the pulsar spin-down power for 54 LAT detected pulsars. Detected PWNe and the PWN candidate coincident with PSR J1023-5746 are marked with red stars. Pulsars showing a significant off-pulse emission with a plausible magnetospheric origin are marked with blue squares. Error bars take into account both the statistical uncertainties on the luminosity and the uncertainty on the distance of the pulsar. Blue lines correspond to constant γ-ray efficiency: 100% (dashed), 10% (dotted), 1% (dotted-dashed) [6].

PWNe or PWN candidate is associated to a TeV source. As summarized in [6], except for HESS J1640-465 for which no central pulsar is known, each of these sources is powered by a young (age of $\sim 1-11$ kyr) and very energetic (spin-down power $\dot{E} > 7 \times 10^{36}$ erg s^{-1}) pulsar. Moreover, a systematic analysis to detect PWNe using the off-pulse window of each pulsar detected by *Fermi* was performed, thus providing a first population study of PWNe in the HE γ-ray domain. This study together with the first detections of TeV PWNe in the *Fermi*-LAT energy range have shown that less that 1% of the rotation energy of the pulsar is required for conversion into γ-ray luminosity of their PWNe, as seen in Figure 5. Several TeV PWN candidates are still under investigation using *Fermi*-LAT data, but their studies require a larger photon statistics.

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