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High-energy Pulsar Wind Nebulae and SuperNova Remnants

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Summary. — After the second year of Fermi orbiting, the number of galactic sources associated with Pulsar Wind Nebulae (PWNe) and SuperNova Remnants (SNRs) has largely increased. For all these sources multi-wavelenghts spectral energy distributions have been investigated and information about acceleration mechanisms and interaction sites have been collected and studied. The GeV-TeV connection of some recently detected sources will be presented and different interpretation of the observed spectra will be discussed.

PACS `95.85.Pw` – γ-ray.
PACS `98.35.Ac` – Origin, formation, evolution, age, and star formation.
PACS `98.38.Mz` – Supernova remnants.
PACS `98.70.Sa` – Cosmic rays (including sources, origin, acceleration, and interactions).

1. – SNRs and PWNe as galactic cosmic-ray sources

PAMELA observations of the positron fraction $e^+/(e^- + e^+)$ [1] showing an excess relative to the prediction of a cosmic-ray (CR) propagation model [2] in the energy range between 10 and 100 GeV has opened new windows of possible interpretations in exotic scenario and astrophysical field. According to the model, the e^+ are produced as secondaries by the Galactic CRs interactions with the interstellar medium along the propagation path, assuming a power-law spectrum with an index of 2.75. Other indications that more effort needs to be done to completely understand the cosmic-ray theory comes from the electron and positron spectrum observed by the Fermi-LAT [3]. In order to try to solve the mystery, different sources of e^+ have been proposed, including pulsars (PSRs), Pulsar Wind Nebulae (PWNe) [4-8], or SuperNova Remnants (SNRs) [9-11], together with propagation effects [12,13] and dark matter annihilation or decay interpretations [7,14]. For this reason, it has become more crucial than before to be able to detect these sources as high-energy γ-ray sources and try to investigate in details the origin of the observed spectra, disentangling all contributions coming from leptonic population and/or hadronic accelerated particles.

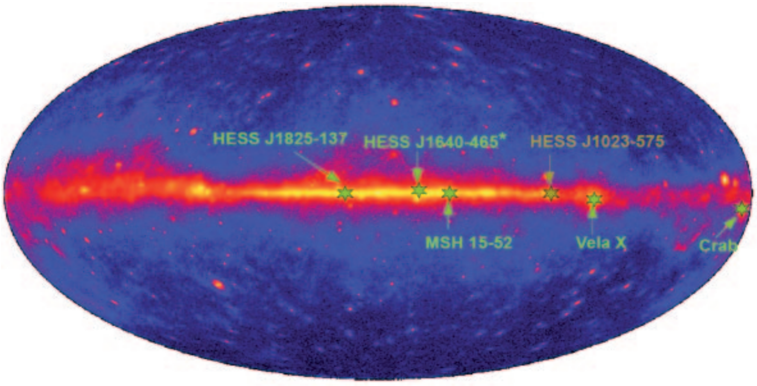

Fig. 1. – High-energy PWNe detected in two years by Fermi-LAT.

2. – High-energy Pulsar Wind Nebulae

Since the launch of the Fermi Gamma-Ray Space Telescope the number of detected pulsars in the γ-ray domain has dramatically increased [15]. The list of Fermi-LAT pulsars now contains 56 bright sources and certainly many more will be detected in the upcoming months. Yet most of the pulsar spin-down luminosity is not observed as pulsed photon emission and is instead carried away as a magnetized particle wind [16]. 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 scattered and accelerated to ultra-relativistic energies. The PWN emission, including synchrotron and inverse Compton components, extends across the electromagnetic spectrum from radio to TeV energies. PWNe studies can supply information on particle acceleration mechanisms at relativistic shocks, on the evolution of the pulsar spin-down and, at later phases, on the ambient interstellar gas. Figure 1 shows the PWNe Fermi-LAT detections after 2 years of sky survey [17].

2˙1. *The Fermi PSRs off-pulse detections.* – During the first year of Fermi data taking, 56 bright PSRs have been detected and studied in details to try to highlight possible emission in the off-pulse windows.

The Crab Nebula. The Crab Nebula was the first detection as off-pulse emission from PSRJ0534+2200 Fermi-LAT. The Crab Nebula belongs to the class of filled-center supernova remnants [18] and is well studied in almost all wavelength bands of the electromagnetic spectrum from the radio (10^{-5} eV) to very high-energy γ-rays (nearly 10^{14} eV). Several models [19-21] describe the photon production processes taking place in this nebula as a double component spectrum: a synchrotron radiation from high-energy electrons in the nebular magnetic field, responsible for the observed spectrum from radio to MeV, and an Inverse Compton (IC) scattering of the primary accelerated electrons off the synchrotron photons, far infrared and Cosmic Microwave Background (CMB), which produces high-energy γ-rays [22]. Other possible deviations from this simplified picture [23] propose that significant production of high-energy γ-rays may come from bremsstrahlung radiation of relativistic electrons taking place in the Crab filaments.

The VelaX PWN. The Vela pulsar (PSR B0833-45) at a distance of 290 pc is one of the closest pulsars to Earth and among the brightest and has always generated a lot of

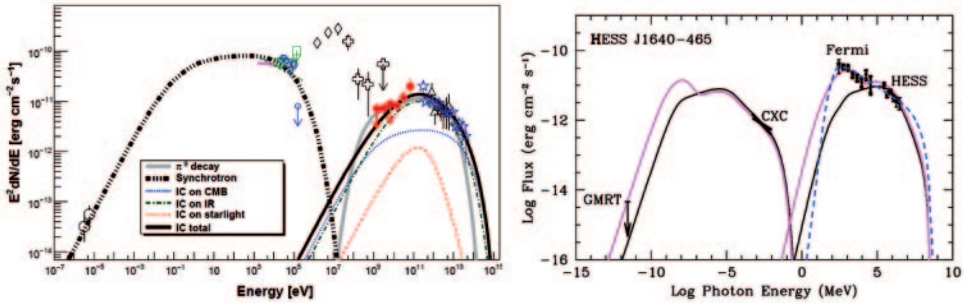

Fig. 2. – The SEDs of the MSH 15-52 (left) and of the HESS J1640-465 (right). For the MSH 15-52, one single electron population is enough to interpret correctly the observed data [29]. For the HESS J1640-665, like the VelaX PWN, a scenario with a low-energy Maxwellian electron component replacing the low-energy portion of the electron power-law spectrum is needed to explain the observed GeV excess [34].

interest in studying the mechanisms at the base of such huge energy emission. About the 99% of the pulsar spin-down luminosity is not observed as pulsed photon emission and is apparently carried away as a magnetized particle wind. Radio and X-ray observations established the presence of large-scale diffuse emission surrounding PSR B0833-45 possibly related to the Vela supernova remnant [24-26]. These radio observations show that in roughly 8′ diameter there are three distinct central regions (Vela-X, Vela-Y and Vela-Z). The most intense of these, Vela-X, is an extremely bright (∼ 1000 Jy) diffuse radio structure of size 2′–3′ located close to PSR B0833-45. The observations of a flat radio spectral index and the large degree of radio polarization in Vela-X were interpreted as indications of a diffuse radio emission from a PWN powered by the spin-down of PSR B0833-45. The PWN emission extends across the electromagnetic spectrum in synchrotron and inverse Compton components from radio to TeV energies [16, 27]. From a detailed study of the overall Spectral Energy Distribution (SED) [28], there are indications of a cocoon emission by significantly cooled electrons, dominated by relatively recent injection of high-energy electrons from the pulsar and its termination shock, and a halo component consisting of older electrons.

Ths MSH 15-52. Two possible interpretations for the origins of γ-ray photons from PWNe, *i.e.* hadronic (from proton-proton interactions) or leptonic (via the inverse Compton process) have been proposed recently [29] for the MSH 15-52. The multi-wavelength picture of MSH 15-52 is shown in fig. 2 (left). With the Fermi-LAT data added in the multi-wavelength spectrum [30], new constraints on the model parameters have been defined. A simple one-zone model has been assumed, which utilizes the interstellar radiation field described in [31] as target photons for inverse Compton scattering, neglecting γ-rays production via bremsstrahlung due to the low density of the region ($\leq 0.4\,\mathrm{cm}^{-3}$). What arises from the fit of the SED is that a single power-law electron spectrum does not reproduce correctly the data; a more accurate description that takes into account an electron population following a broken power law with an exponential cut-off surely interprets more appropriately the spectrum. The fitted average magnetic field strength is $17\,\mu$G, which is in an excellent agreement with the value suggested by TeV observations [32] and consistent with the lower limit of $< 8\,\mu$G obtained from X-ray observations [33].

2˙2. *The GeV counterpart of the H.E.S.S. PWNe.* – The last two detections as PWNe sources by the Fermi-LAT have been the HESS J1640-465 [34] and the HESS J1825-137 [35]. As in the case of evolved VelaX PWN, to describe the SED of the HESS J1640-465, simple power-law models for the radiating particles fail to reproduce the observed broadband spectrum. The presence of an excess population of low-energy electrons is inferred, and models for the IC scattering of photons from this population predict an excess of γ-rays in the GeV range (fig. 2 (right)).

3. – High-energy SuperNova Remnants

It is almost uniformly accepted that SNRs are possible candidates sites for particle acceleration. There are some aspects still not perfectly understood, like the exact mechanisms which bring particles up to the knee of the galactic cosmic-ray spectrum, as well as the evolution and the subsequent release of particles in the outer space of the remnants. To maintain the energy density of the Galactic CRs, the kinetic energy released in supernova explosions has to be efficiently transferred to CRs with a conversion efficiency of 10%. For these reasons the discovery of the emission from many SNRs at GeV and TeV γ-ray energies has added new ingredients to the galactic cosmic-ray puzzle. Moreover, after two years of data taking, the number of SNRs has increased up to about 10, a sample that is expected to double in the next future, collecting data from young and middle-aged SNRs, interacting with dense environment like molecular clouds or expanding in pretty clear ambient, which is guiding the comprehension of the properties of the radiating particle population and disentangling the main mechanisms which produce the observed γ-ray spectra.

3˙1. *Young SNRs: CasA and Tycho.* – Regardless of the origin of the observed gamma rays, the total content of CRs accelerated in Cas A can be obtained as the sum of leptonic and hadronic contributions $W_e + W_p$ and can be estimated to be about (1–4) $\times 10^{49}$ erg. Moreover, as a complementary effect of the conversion of the shock energy, there is evidence of turbulent magnetic fields with amplification factors much beyond the value predicted by the compression of the interstellar field without CR perturbations, estimating for B a value of $\sim 0.12\,\mathrm{mG}$. Even though Cas A is considered to have entered the Sedov phase, the total amount of CRs accelerated in the remnant constitutes only a minor fraction ($< 2\%$) of the total kinetic energy of the supernova. The bremsstrahlung spectrum and π^0-decay spectrum have rather different predictions below 1 GeV. The hard spectrum below 1 GeV (fig. 3) would favor the π^0-decay origin, though the current Fermi-LAT data [36] does not rule out the bremsstrahlung model. In fig. 3 (left) the bremsstrahlung components (dashed lines) as well as the IC component (dotted lines) are shown for the leptonic model, for two different values of the magnetic field (0.12 mG and 0.3 mG). The π^0-decay spectra are shown in the right panel for two possible proton spectra, one harder with an index of 2.1 which stops the acceleration at 10 TeV (blue line) and the other with a softer population with an index of 2.3 without any cutoff (red line). The data do not strongly discriminate among any of the proposed interpretations.

Recently the detection of the Tycho SNR has been announced by the VERITAS collaboration [37]. It is the remnants of the star explosion noted by the astronomer Tycho Brahe in AD 1572. The GeV analysis with Fermi is in progress; very preliminary results seem to suggest also a GeV emission compatible with the position of the SNR from X-ray data [38].

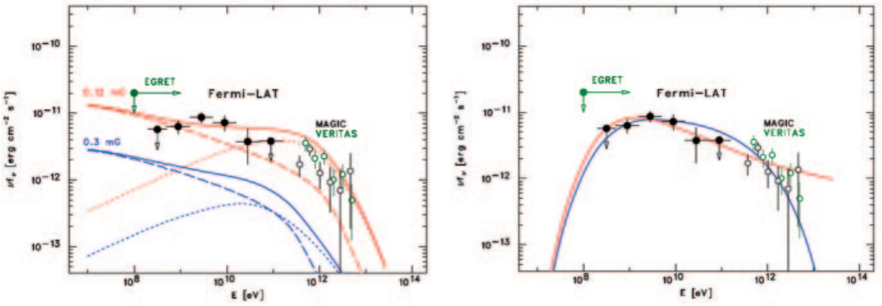

Fig. 3. – Energy spectrum of Cas A in a leptonic emission model (left) and in a hadronic emission model (right). See the text for the different models shown.

3˙2. *Middle-aged SNRs interacting with molecular clouds.* – Bright and extended GeV γ-ray emission associated with middle-aged supernova remnants has recently been detected by the Fermi-LAT, and some also by AGILE. Specifically, SNRs W51C [39], W44 [40], IC443 [41, 42], and W28 [43, 44] are spatially resolved, all interacting with molecular clouds. Some other SNRs [45] have still been detected by the Fermi-LAT in the class of objects with an age of about few tens of thousands years, expanding in dense molecular environments. The list of detected SNRs is in table I. Some authors [46] started collecting similarities and differences in this class of SNRs studying the emission in radio and in the γ-ray band. The synchrotron radio emission has a large flux of few hundreds of Jy at 1 GHz with flat spectral index ($\sim \alpha = 0.26$–0.40). The GeV γ-ray spectrum commonly exhibits a spectral break at few GeV, and an integrated luminosity in the range 1–100 GeV in the interval $L_\gamma = (0.8\text{–}0.9) \times 10^{35}\,\mathrm{erg\,s^{-1}}$.

The number of detected SNRs illuminating molecular clouds is enough to test different theories which may take into account the gamma luminosity at both GeV and TeV bands and the radio luminosity. In [46] for instance is shown that the radio and γ-ray emission observed can be explained by a model in which a shocked cloud and shock-accelerated cosmic rays (CRs) are simultaneously compressed by the supernova blast wave as a result of formation of a radiative cloud shock. A re-acceleration process of pre-existing CRs can explain the observed γ-ray emission through the decays of π^0-mesons produced in

Table I. – *List of Fermi detected SNRs in two years.*

Object	Diameter (pc)	Age (y)	Cloud interaction	L_γ (erg s^{-1}) 1–100 GeV
Cas A	5	330	No	4×10^{34}
W49B	10	$\sim$ 3000	Yes	9×10^{35}
3C 391	15	$\sim$ 6000	Yes	6×10^{34}
G349.7+0.2	17	$\sim$ 6000	Yes	9×10^{34}
IC 443	20	$\sim$ 10000	Yes	8×10^{34}
W44	25	$\sim$ 10000	Yes	3×10^{35}
W28	28	$\sim$ 10000	Yes	9×10^{34}
CTB 37A	50	$\sim$ 20000	Yes	9×10^{34}
G8.7-0.1	63	$\sim$ 30000	Yes	8×10^{34}
W51C	76	$\sim$ 30000	Yes	8×10^{35}

hadronic interactions between high-energy protons and the gas in the compressed-cloud layer. In [47] the GeV-TeV spectrum has been interpreted as a delayed emission of cosmic rays diffusing from IC 443 and interacting with a cloud in the foreground of the remnant, and in [48] the non thermal emission from a molecular cloud located in proximity of a SNR is the result of the interactions of CRs that penetrate the cloud.

4. – Conclusions

Accumulating more data and fitting with more details and precision the galactic γ-ray diffuse emission, more information about PWNe and SNRs as high-energy γ-ray emitters are being collected. Hints about the possibility to have hadronic interpretation of the gamma emission from SNRs seem to confirm the idea to identify the SNRs as possible CRs sources and accelerators. On the other sides, recent detections of PWNe and of course a numerous class of high-energy pulsars are giving new ingredients to a possible interpretation of astrophysics explanation of the cosmic-rays spectra and composition detected so far [3]. It is well accepted that pulsars also dissipate their energy via magnetized particle winds, which consist of electron and positron pairs confined in the wind outflow. A PWN is created at the collision of the particle wind and the surroundings medium. With the data in hand many new constraints have been obtained about the bulk injection from the pulsar and its termination shock, and it may be hoped that starting from what has been just discovered, together with new data and results on other PWNe, will help in understanding the physics of these relativistic outflows. Concerning the detections of SNRs as γ-ray sources, new indications about possible hadronic interpretation of the observed spectra are being acquired. Though, there are no clear and stringent signatures about *p-p* collisions as well as diffusion or emission from the crushed dense material surrounding the remnants. In the next future more data will be collected and the sample of SNRs will account for different progenitors, environments and age, making possible differences and similarities crucial for the understanding of the process behind the observed γ-ray emission.

* * *

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