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Pulsar Wind Nebulae and Unidentified Galactic Very High Energy Sources

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Abstract: The riddle of the origin of Cosmic Rays (CR) has been an open question for over a century. Gamma ray observations above 100 MeV reveal the sites of cosmic ray acceleration to energies where they are unaffected by solar modulation; recent evidence supports the existence of hadronic acceleration in Supernova Remnants (SNR), as expected in the standard model of cosmic ray acceleration. Nevertheless, the results raise new questions, and no final answer has been provided thus far. Among the suggested possible alternative accelerators in the Very High Energy (VHE) gamma ray sky, pulsar wind nebulae (PWNe, which together with dark matter are the main candidates to explain the local positron excess as well) are the dominant population among known Galactic sources. However, the most numerous population in absolute terms is represented by unidentified sources (~50% of VHE gamma ray sources). The relationship between PWNe and unidentified sources seems very close; in fact, in a PWN, the lifetime of inverse Compton (IC) emitting electrons not only exceeds the lifetime of its progenitor pulsar, but also exceeds the age of the electrons that emit via synchrotron radiation. Therefore, during its evolution, a PWN can remain bright in IC such that its GeV-TeV gamma ray flux remains high for timescales much larger than the lifetimes of the pulsar and the X-ray PWN. In addition, the shell-type remnant of the supernova explosion in which the pulsar was formed has a much shorter lifetime than the electrons responsible for IC emission. Hence, understanding PWNe and VHE unidentified sources is a crucial piece of the solution to the riddle of the origin of cosmic rays. Both theoretical aspects (with particular emphasis on the ancient pulsar wind nebulae scenario) and their observational proofs are discussed in this paper. Specifically, the scientific cases of HESS J1616-508 and HESS J1813-126 are examined in detail.

Keywords: cosmic rays; supernova remnants; pulsar wind nebulae; high energy astrophysics; unidentified high energy sources; HESS J1616-508; HESS J1813-126

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1. Introduction to the Standard Model of Cosmic Ray Origin: Successes, Limits, and Possible Solutions

The origin of Cosmic Rays is one of the longest-standing questions in astrophysics; entire conferences have been devoted to trying to answer this question over the last century, starting with the NATO Advanced Study Institute conference [1] held in Durham, England in 1974, followed shortly afterwards by [2], and culminating in the most recent "Cosmic Ray Origin—Beyond the Standard Models" international conference series (CRBTSM, http://crbtsm.eu, accessed in April 2022). Over this time, the answer has become ever longer and more complex (e.g., [3,4]).

Early ideas about the existence of cosmic rays (CRs) and their possible extraterrestrial origin started at the beginning of the twentieth century (e.g., [5]); they were detected shortly thereafter using a variety of experimental techniques. Their discovery in water (in Lake Bracciano and later in the Tirreno Sea) in the years between 1907 and 1912 is attributed to the Italian physicist Domenico Pacini [6]. Early measurements using an electroscope on the Eiffel Tower were made by the German Jesuit physicist Theodor Wulf [7], who was the first to explicitly speak about "Hoehenstrahlung" (literally, "radiation from above"). Wulf's invention of the electroscope then led his colleagues to much more precise experiments, i.e., the balloon flights at 5 km altitude conducted by the Austrian physicist Victor Hess [8] and at 9 km altitude by the German physicist Werner Heinrich Gustav Kolhörster [9]. Most notably, the first flight by Hess convinced almost the whole scientific community that CRs are an astrophysical phenomenon, and in 1936 Hess was awarded by the Nobel prize for the discovery of cosmic rays. The U.S. physicist Robert Andrews Millikan remained sceptical about the conclusions of his European colleagues, disputing the results for several years before confirming the discovery; ironically the term "cosmic rays" originated with Millikan himself.

A connection between supernovae and CRs was suggested at an early stage [10], and several mechanisms to explain CR origin were postulated (e.g., [11]). The terms "standard picture" or "standard model" generally refer to the majestic monograph book of Ginzburg and Syrovatskii [2]. Summarizing their conclusions, they claimed that primary Galactic CRs up to energies of what they termed the "knee" (at about 10^{15} eV) are accelerated in Supernova Remnant (SNR) shells. About one supernova event every 30–50 years is expected, and in order to account for the energy density of CRs (about 1 eV cm^{-3}) and the CR confinement time deduced from spallation, the typical non-thermal energy release per supernova has to be about 10^{50} ergs, which is about 10% of the total energy released in a typical SN explosion. In other words, according to the standard model, at least 10% of the kinetic energy of an SN explosion has to be dissipated into CR acceleration.

This idea was significantly strengthened during the late 1980s by the fact that this prediction of the standard model seemed to be in perfect agreement with the typical amount of energy predicted to be produced during the acceleration of relativistic particles in SNR shocks (e.g., [12–14]).

Finally, the detection of TeV gamma rays from SNRs by the Imaging Atmospheric Cherenkov Telescopes (IACTs) which spatially coincide with the sites of non-thermal X-ray emission, e.g., the SNRs RX J1713.7-3946 [15] and RX J0852.0-4622 [16], has strengthened the hypothesis of the "standard" picture of CR origin up to the "knee" energies; however, the TeV gamma ray signal can be explained in either of two different ways, by leptonic or hadronic acceleration, as follows:

- Inverse Compton scattering of relativistic electrons/positrons on background photons (CMB, infrared, X-rays, etc.) leads to leptonic models of acceleration;
- Neutral pion decay due to proton–proton inelastic interactions leads to hadronic models.

It is important to underline that the hadronic and leptonic models are essentially indistinguishable in TeV gamma rays; e.g., [17]). Moreover, SNRs were proven to be sources of CR electrons decades ago through study of their radio and X-ray emissions (e.g., [18]), while compelling evidence for the acceleration of hadrons in SNRs has yet to be found. This question, together with the fact that protons make up more than 90% of the total amount of CRs, makes it clear that hadronic models are necessarily the final target of research into the origin of CRs.

2. The Picture from *Fermi*-LAT

By considering the broader GeV and TeV gamma ray spectrum, i.e., utilizing a GeV gamma ray observatory together with IACTs, it should be possible to disentangle leptonic and hadronic models and hence finally prove or disprove the "standard picture" of CR origin. Investigating the origin of CRs was indeed among the main scientific purposes of *Fermi*-LAT (*GLAST* Science Brochure 1996; http://glast.gsfc.nasa.gov, accessed in April 2021) , which among other things was designed to be an excellent observatory for SNRs (e.g., [19]). In fact, *Fermi*-LAT detected several SNRs, together with SNRs interacting with Molecular Clouds (MCs), such as the Cygnus Loop [20], RX J0852.04622 [21], Tycho SNR [22], W51C [23], W44 [24], Cassiopeia A [25], RX J1713.73946 [26], G8.70.1 [27], W28 [28], and W49B [29]. However *Fermi*-LAT has provided only partial and often contradictory answers thus far, and these are characterized by both notable successes for, and limits to, the standard model.

The greatest success of the standard model can be found among the *Fermi*-LAT SNR samples, namely, a crucial discovery in relation to the Tycho SNR. In this case, leptonic models are essentially disproven; Tycho represents a “smoking gun” or “hadronic fingerprint”, i.e., the answer to the 60–100-year-old question concerning the origin of CRs [22]. Moreover, the efficiency of CR acceleration in the Tycho SNR, i.e., the percentage of kinetic energy of the SN explosion which must be transferred into CR acceleration, is more than the 10% needed to confirm the “standard” model; for example, [30] calculated it to be $\sim$16%.

In addition, with *Fermi*-LAT it is possible to detect the characteristic neutral pion “shoulder” around 100 MeV for IC 443 and W44 [31]. However, these two exceptional measurements, which are indeed very important (especially from a particle physics perspective), are astrophysically less relevant than the Tycho SNR result, as these are SNR/MC interacting systems in which hadronic acceleration is quite obvious and unavoidable; this is not the case with “naked SNRs”, the results from which point straight to the center of the CR origin riddle.

Despite the important findings, several major obstacles have been raised for the standard model as well:

- *Fermi*-LAT observations of one of the most promising targets to confirm the standard model of CR origin seem to contradict the results described above. Before the launch of *Fermi*-LAT in 2008, results from IACTs [15] indicated that the shell SNR RX J1713.7-3946 was probably one of the most promising targets [32], and it is surely one of the best-described by theoretical models (e.g., [32]). However, *Fermi*-LAT observations showed that leptonic models fit the energy spectrum of RX J1713.7-3946 very well, while hadronic models are essentially disproved [26].
- While hadronic models are favoured for most of the LAT-detected SNRs (although for most of these leptonic models cannot be fully discarded either), in general these models do not seem efficient enough at accelerating CRs to reach the 10% predicted in the standard model, which is known as the “efficiency problem". In this regard, let us take Cassiopeia A (which, together with the Crab, is one of the two most powerful explosions our side of the Galaxy) as an example: even assuming that the whole GeV and TeV gamma ray spectrum originates in hadronic processes, the total energy of the CRs accelerated in Cas A would correspond to only $\sim$2% of the kinetic energy of the initial SN explosion (e.g., [25,33]).

Hence, the results from *Fermi*-LAT seem to be contradictory, underlining that the CR origin issue may be more complex than previously thought.

3. Possible (Obvious) Solutions

The most immediate solution would imply slight modifications to the “standard model” (e.g., [34]). More substantial modifications could be made by considering SNRs as the main CR accelerators in a not in the conventional sense, e.g., by considering diffusive re-acceleration of primary CRs in the interstellar medium [35].

However, another immediate way of proceeding is represented by searching for different CR accelerators in order to supply the amount of CRs required to explain local CR density. Indeed, several other CR accelerators have been proposed, such as binary systems in open star clusters (e.g., [36]), protostellar jets (e.g., [37]), and novae (e.g., [38]), as well as extragalactic sources such as gamma ray bursts (e.g., [39]) and active galactic nuclei (e.g., [40]). The Galactic Center itself has been proposed (e.g., [41]), and has been proven to be an efficient CR accelerator [42]. Other well-established leptonic accelerators might contribute as well, such as pulsars (e.g., [43]) and pulsar wind nebulae (e.g., [3,44]); these are extensively discussed in this section.

3.1. Pulsar Wind Nebulae: A Natural Explanation

A very natural solution seems to be offered by pulsar wind nebulae (PWNe). Looking at the very-high-energy "non-thermal" sky, the dominant population is not represented by shell-type SNRs; rather, among the identified Galactic gamma ray sources, PWNe are the most numerous category by far. Understanding pulsars, and hence PWN, as particle accelerators is another longstanding problem in astrophysics; the production and coupling of the high sigma (i.e., highly magnetized) wind with the surrounding medium continues to be a well-posed problem that has proven difficult to solve. The wind magnetization parameter sigma is defined as the ratio of the wind Poynting flux to its kinetic energy flux, (e.g., [45–48]). Early ideas about particle acceleration by electromagnetic waves emitted by pulsars [49] led to the discovery that a significant fraction of the spin-down power of the Crab pulsar is dissipated through a relativistic wind with local acceleration of particles at its termination shock, due to the cooling timescales of the synchrotron-emitting electrons being very short in X-rays [45]. This and further developments led to the Crab model of [46] involving a low level of magnetization at the shock, raising the question of the transition from high to low sigma. Our current understanding of PWNe is that they are equatorial and highly relativistic, showing features such as backflows and jets; these might provide clues to their observational identification, as flares due to relativistic transport effects and beaming (such as those observed in the Crab Nebula) are characteristic. Magnetohydrodynamic (MHD) models and simulations [50] of pulsar winds provide clues for predicting the temporal evolution of PWNe, and are able to reconcile this with the observations of a large sample of putative PWNe of different ages. Hence, PWNe are well-established leptonic accelerators not only from a observational perspective, but also from a theoretical one; nonetheless, the crucial question remains whether they can be efficient hadronic accelerators as well. It has been proposed that both hadrons and leptons could be accelerated at the termination shock of the pulsar wind (e.g., [51–54]). It is important to underline here that, in general, the total energy of PWNe is lower than that of SNRs, although comparable; hence, if hadrons can really be accelerated at the termination shock of a pulsar wind, this could represent a strong clue in solving the global picture of CR origin.

3.2. Unidentifed Gamma Ray Sources: the Dominant Population

Even after the famous H.E.S.S. Galactic Plane Survey of 2004/2005 [55], almost 50% of the Galactic TeV sources remain unidentified. Observations with the current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), H.E.S.S., MAGIC, and VERITAS as well as with water Cherenkov instruments such as HAWC and LHAASO have increased the number of known TeV gamma ray sources considerably, to around 250 objects (http://tevcat.uchicago.edu/, accessed on 13 May 2022). While a large fraction of this is represented by Galactic sources, the $\sim$50% of Galactic sources that seem to resist firm identification persists. At GeV energies, the percentage of unidentified sources is similarly constant; 67% of EGRET sources were unidentified [56], and the newer generation of gamma ray satellites have reached a similar result: at low Galactic latitudes ($b < 10$ deg), 62% of sources detected by the Fermi-LAT have no formal counterpart [57]. Hence, it is clear that understanding these unidentified high-energy sources could be very important for our understanding of the origin(s) of Galactic cosmic rays. It has been suggested on several occasions that the correlation between unidentified Galactic sources and PWNe could be very close; most notably, a relic PWN scenario is the only plausible explanation thus far for these unidentified or "dark" sources.

It is possible to divide Galactic unidentified TeV gamma ray sources into three broad classes:

- "Dark" sources, for which there are no known counterparts at lower energies (e.g., HESS J1427-608 and HESS J1708-410);
- Sources which show plausible lower-energy counterparts which are unidentified at these lower energies (e.g., HESS J1626-490);

- Gamma ray sources which show several possible lower-energy counterparts (e.g., HESS J1841-055 or HESS J1843-033); these sources are typically very extended in angular size. Deeper gamma ray observations have shown that several of these sources are in fact the convolution of several nearby sources, e.g., HESS J1745-303, which was previously considered a unique source and is now considered to consist of three distinct sources [58].

These classes, however, are not definite or even definitive, and there are other possibilities which must be considered:

- Sources where the initial identification was disproven by deeper observation, typically multi-wavelength campaigns (e.g., HESS J1702-420, which was considered a clear example of a middle-age PWN powered by the high spin-down luminosity pulsar PSR J1702-4128, a scenario which was disproven by deeper X-ray campaigns);
- Unidentified sources which can be identified by means of deeper multi-wavelength campaigns (e.g., HESS J1731-347, the first SNR discovery triggered by TeV gamma ray observations).

It is possible to add an additional class of sources represented by unidentified sources which have a very exotic tentative identification, i.e., they have possible lower-energy counterparts that are unusual sources to explain a TeV gamma ray source. For example, HESS J1503-582 has been tentatively associated with a Forbidden Velocity Wing (FVW), that is, HI 21cm line structures visible at velocities that deviate from the Galactic rotation curve [59].

A milestone in terms of associating PWNe with unidentified TeV sources was the discovery of HESS J1507-622 [60], a slightly extended Galactic TeV gamma ray source $\sim 3^{\circ}$ offset from the Galactic plane. This intriguing object escaped identification until much deeper multiwavelength campaigns revealed a faint X-ray source which might be a plausible counterpart [61] and until models of PWNe evolution over time were developed [62–64] which demonstrated that HESS J1507-622 can be interpreted as a relic PWN which shows a bright TeV gamma ray nebula with a faint and much smaller X-ray nebula.

While PWNe models are often built to describe a single source, the purely leptonic model of [64] described above is a very powerful tool which enables the description of any type of PWN and many unidentified gamma ray sources (treated then as "ancient" PWNe). These include both young PWNe systems, such as G21.5-0.9 ([64] (successfully described by a model developed by O. de Jager [62] which was the starting point of our own models) and HESS J1420-607 [65], and aged/relic PWNe systems, such as HESS J1507-622 and HESS J1427-608 [64], HESS J1837-069, HESS J1702-420, and HESS J1708-410 [66], and IGR J1849-0000 [65].

In the following section, we present a detailed description of two other intriguing objects, HESS J1616-508 and HESS J1813-126.

4. HESS J1616-508

The discovery of the VHE gamma ray source HESS J1616-508 was reported in [67]. Here, even though the absence of a solid lower-energy counterpart was underlined, a possible association with a nebula powered by PSR J1617-5055, a young nearby pulsar, was suggested. HESS J1616-508 is one of the brighter sources in the first H.E.S.S. Galactic plane survey, with a flux of $\sim$19% of the Crab Nebula above 200 GeV) [55] and an extension of $\sim$20 arcmin. From [55], it is clear that a relation between HESS J1616-508 and the nearby SNRs RCW 103 and Kes 32 is rather unlikely, as the TeV gamma ray source is not spatially coincident with either of the two SNRs; furthermore, it was remarked that the only plausible option was that it could be a PWN powered by the energetic pulsar PSR J1617-5055. Moreover, it was noted that the position of HESS J1616-508 lines up with the Norma spiral arm, one of the most important massive star-forming regions of the Galaxy.

Hence, considering the lack of a reasonable lower-energy counterpart, this source has often been mentioned among the "dark sources" together with HESS J1427-608 and HESS J1507-622 (e.g., [60,62]), and has been tentatively modelled as such [66]; this preliminary study of its spectral energy distribution, along with the TeV gamma ray spectrum and an upper limit in X-rays, concluded that HESS J1616-508 could be interpreted as an ancient PWN system.

Two pulsars, PSR J1617-5055 and PSR J1616-5109, are located within the 5σ significance contours of the TeV gamma ray source (see Figure 1), and another pulsar, PSR J1614-5048, is nearby, making HESS J1616-508 an ideal case for investigation with the PWN evolution tool described above [64]. PSR J1617-5055 is a 69 ms pulsar with a high spin-down luminosity of 1.6×10^{37} erg/s and a characteristic age of 8.13 kyrs, located at a distance of 4743 pc. PSR J1616-5109 is faint pulsar with a spin-down luminosity of 4.2×10^{32} erg/s and a characteristic age of 1010 kyrs, located at a distance of 6842 pc. PSR J1614-5048 has a spin-down luminosity of 1.6×10^{36} erg/s and a characteristic age of 7.42 kyrs, and is located at a distance of 5148 pc. The characteristics of these three pulsars are taken from the ATNF pulsar catalogue [68].

In 2005, observations of the central region of HESS J1616-508 by *Suzaku* failed to find an X-ray counterpart, resulting in an upper limit of 3.1×10^{-13} erg cm^{-2} s^{-1} in the 2–10 keV band [69].

Kargalsev et al. [70] studied the *Chandra* X-ray observations of the pulsar PSR J1617-5055 and the central part of the TeV emission in detail. Their data analysis reveals a faint PWN with an extension of $\sim$1 arcmin and a ratio of PWN to pulsar luminosity of $L_{PWN}/L_{PSR} \approx 0.18$ [70]. Their study of the X-ray spectrum of the "inner" PWN (the annulus region from 0.75 to 1.25 arcsec, which is influenced by the pulsar emission; the pulsar spectrum was used as background spectrum) and the "outer" PWN (the polygon region) with negligible influence of the pulsar emission resulted in an absorbed flux of $F_{\text{inner}} = (1.6 \pm 0.3) \times 10^{-13}$ erg cm^{-2} s^{-1} and $F_{\text{outer}} = (1.7 \pm 0.1) \times 10^{-13}$ erg cm^{-2} s^{-1}, respectively, in the $0.5 - 8$keV band. Using the spectral parameters, the unabsorbed flux in the 2–10 keV energy band was calculated to be $F_{\text{outer,unabs}} = (2.4 \pm 0.1) \times 10^{-13}$ erg cm^{-2} s^{-1}. They interpreted these results as showing no clear connection with the TeV source, as there is no significant extension of the X-ray PWN towards the center of the TeV emission. Due to the faintness of the X-ray PWN, and considering its location within the extension of the TeV emission, this should instead be considered as a possible low-energy counterpart of the TeV emission.

The analysis of the *Chandra* observation covering the central part of the TeV gamma ray emission reveals another possibly extended source, CXOUJ161610.0-505430, called "source X" in [70], with a low X-ray flux of $\sim 2 \times 10^{-14}$ erg cm^{-2} s^{-1}, and hence a low ratio of X-ray to TeV luminosity $L_x/L_{TeV} = (1-2) \times 10^{-3}$ [70].

In 2015, several further *Chandra* observations covering the HESS J1616-508 region took place. Hare et al. [71] studied these observations in detail and revealed that the "source X" (CXOUJ161610.0-505430) of [70] could be resolved into several point-like sources coincident with a star-forming region, making it unlikely as the counterpart of the TeV source. Moreover, an X-ray source without low-energy counterparts was found in the central part of the TeV gamma ray emission region, CXOU J161643.5–504604. This has a spectrum represented by a power law with $\Gamma = 1.8$ and a flux of $F_{0.5-7\text{keV}} \approx 5 \times 10^{-14}$ erg cm^{-2} s^{-1}, resulting in a TeV to X-ray luminosity ratio of $L_{1-10\text{TeV}}/L_{0.5-8\text{keV}} = 340$ [71]. No extended X-ray emission has been found for this source, possibly due its faintness. Hare et al. [71] interpreted CXOU J161643.5–504604 as a possible isolated pulsar hosting a relic PWN. Interestingly, [71] set a very stringent upper limit on the X-ray flux of PSR J1614–5048, in the 0.5–8 keV band, which makes this pulsar one of the least X-ray-efficient pulsars known, considering that there is no evidence supporting the association between this pulsar and the TeV source.

Using 45 months of *Fermi*-LAT data, Acero et al. [72] found that the GeV gamma ray source which is coincident with HESS J1616-508 has a 0.25 deg extension in GeV gamma rays, possibly connected to the pulsar PSR J1617-5055, although this is not a gamma ray-emitting pulsar.

The gamma ray source 3FGL J1616.2-5054e [73], detected by *Fermi*-LAT after four years of operation, is spatially coincident with HESS J1616-508 and has an extension of 0.32 degrees. Moreover, the source 2FHL J1616.2-5054e of the high-energy *Fermi* catalog FHL [74] is spatially coincident with HESS J1616-508, and the spectral data points combine very well with the TeV gamma ray spectrum.

Detailed studies at radio wavelengths were conducted by Lau et al. [75] using results from the Mopra Southern Galactic Plane CO Survey, the Millimetre Astronomer's Legacy Team-45 GHz survey, the HEAT telescope, and HI archival data from the Southern Galactic Plane Survey. They did not find any conclusive evidence to link HESS J1616–508 to any known counterparts, and considered an association with the two SNRs or a PWN powered by the young energetic pulsar PSR J1617-5055 to be unlikely. Instead, they speculated that an undetected accelerator, such as a young SNR at the centre of HESS J1616-508 and interacting with the ISM gas, might be able to readily explain the TeV gamma ray flux.

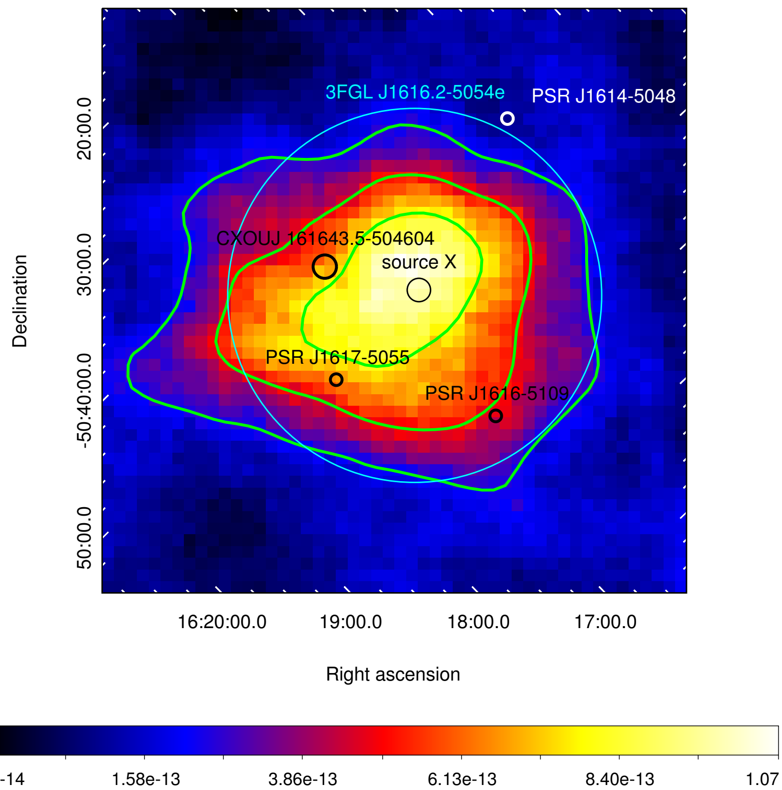

Figure 1. The significance contours of HESS J1616-508 overlapped on the flux map, as measured by H.E.S.S. [76]. The positions of the pulsars, the *Fermi* 3FGL source, and the interesting *Chandra* sources are marked.

Combining the multi-wavelength spectral information from the TeV gamma ray source HESS J1616-508 [76] with the GeV gamma ray sources 3FGL J1616.2-5054e [73] and 2FHL J1616.2-5054e [74] and the X-ray PWN detected by Kargaltsev et al. [70] results in the spectral energy distribution shown in Figure 2. The time-dependent PWN model [64] was applied, and the results are further illustrated in Figure 2. In this first scenario, we model the SED under the hypothesis that the VHE gamma ray emission is connected to a PWN powered by PSR J1617-5055. The different physical sizes of the X-ray to TeV gamma ray PWN would be typical for an aged PWN (e.g., [60]), and can be explained easily by the very long lifetime of inverse Compton emitting electrons in gamma rays, while the synchrotron emission has faded away due to the decay of the magnetic field.

The characteristics of PSR J1617-5055 as measured by [68] were used as the fixed parameters in the model. The model shown with the gray dotted line in Figure 2 represents the emission expected from a PWN with a present-day age of 12 kyrs. The electron distribution was chosen to have a minimum energy of $E_{\mathrm{min}} = 0.01$ TeV, a break energy of $E_{\mathrm{b}} = 0.2$ TeV, and a maximum energy of $E_{\mathrm{max}} = 10$ TeV. As the source for the IC, both the CMBR and IR background photons have been considered. The diffusion coefficient was chosen to be $\kappa_0 \approx 2 \times 10^{23}$ $\mathrm{E_{TeV}}$ $\mathrm{cm^2\ s^{-1}}$, resulting in a present-day diffusion coefficient of $\kappa \approx 7.5 \times 10^{26} \mathrm{E_{TeV}}$ $\mathrm{cm^2\ s^{-1}}$.

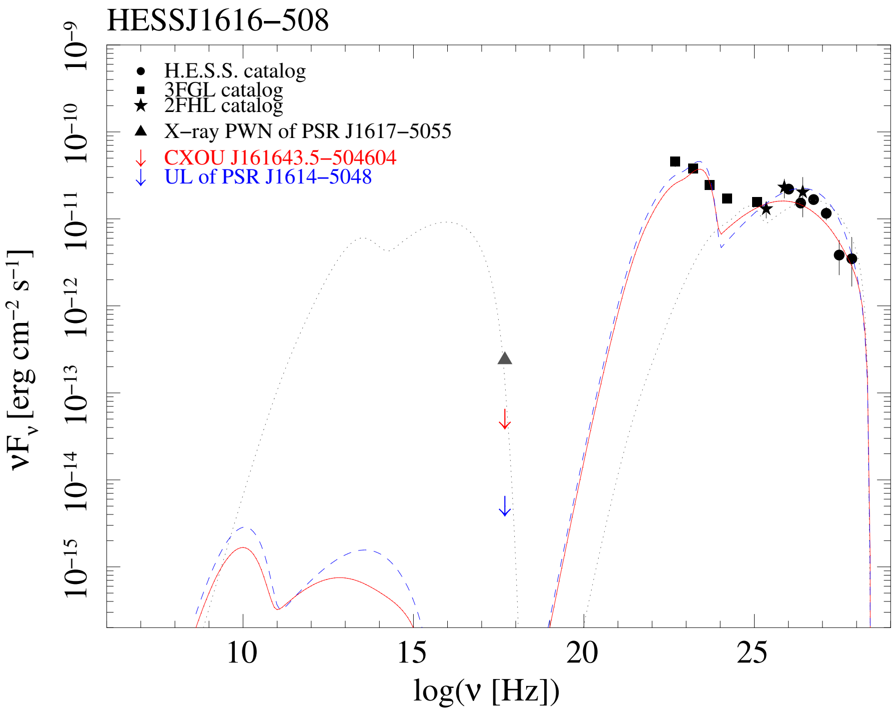

Figure 2. Spectral energy distribution of HESS J1616-508 with the TeV gamma ray spectrum from the H.E.S.S. catalog [76] (circles), GeV spectrum of 3FGL J1616.2-5054e (squares) from the 3FGL catalog [73], the 2FHL catalog spectral points of 2FHL J1616.2-5054e (stars) [74] . The single X-ray measurement of the X-ray PWN around PSR J1617-5055 by [70] is shown as triangle, the upper limit based on the detection of the X-ray source CXOUJ 161643.5–504604 [71] is shown as a red arrow, and the upper limit of PSR J1614-5048 [71] is shown as a blue arrow. The time-dependent PWN models are shown as described in the text. The dotted line represents the first scenario (i.e., connecting HESS J1616-508 to the X-ray PWN powered by PSR J1617-5055), the dashed line HESS J1616-508 represents the predicted emission when the object is considered as a PWN powered by PSR J1614-5048, and the solid line represents the gamma ray source as a PWN powered by the candidate pulsar CXOUJ 161643.5–504604, as described in the text.

The radio conversion efficiency is 0.65 and the X-ray conversion efficiency is 0.30. The ratio of the electromagnetic to particle energy in the nebula is $\sigma = 0.04$, comparable to that found in [64] for HESS J1507-622, which was $\sigma = 0.03$. The model predicts a present-day magnetic field of $B \approx 4.24$ μG.

While the model predicts the multi-GeV and TeV gamma ray spectrum well, it is difficult to reproduce the low-energy gamma ray spectrum together with that of the X-ray PWN. These difficulties do not represent a strong counter-argument to this scenario, however, as the discrepancy can be explained by the possible influence of the SNRs Kes 32 and RCW 103 on the overall GeV emission, both of these lying inside the extension of 3FGL J1616.2-5054e. However, the killer blow to this scenario is provided by the flux of the X-ray PWN powered by PSR J1617-5055, which represents a crucial constraint. If PSR

J1617-5055 powers the TeV PWN, i.e., HESS J1616-508, as well, there should be high flux at radio energies, and no such flux has been detected [75,77].

Hence our model strongly disfavors a connection between HESS J1616-508 as the X-ray PWN powered by PSR J1617-5055 and hence a connection between the TeV gamma-ray source and this energetic pulsar. This is in line with the conclusions of [75] and of [70] based on their consideration of the morphology of the X-ray PWN. However, even though PSR J1617-5055 does not appear to be a member of a close binary system, we cannot fully exclude PSR J1617-5055 as an old millisecond pulsar that has been spun up through accretion of matter (e.g., [78]); in this exotic scenario, HESS J1616-508 would be an extremely old relic PWN, while the X-ray PWN would be very young, and hence represent a totally new stage of the system, i.e., after the spinning-up of PSR J1617-5055.

However, there is a second, more natural, scenario. HESS J1616-508 could simply be a PWN powered by PSR J1616-5109, PSR J1614-5048, or by the above-mentioned unidentified *Chandra* source CXOUJ 161643.5–504604, which has been interpreted by [71] as a possible isolated pulsar. We investigate these three additional scenarios below.

Our model fails to describe HESS J1616-508 as PWN powered by PSR J1616-5109; in fact, even when increasing the age of this eventual PSR–PWN system unphysically (i.e., such that it exceeds the inverse-Compton lifetime of the electrons, that is, $t_{IC} \approx 1.2 \times 10^6 (\mathrm{E_e}/1\mathrm{TeV})^{-1}$years) to an age of tens of millions of years in order to maximize the accumulation of VHE electrons (to increase gamma ray production due to up-scattering of CMB photons), the resulting TeV PWN is orders of magnitude fainter than HESS J1616-508. Thus, our model strongly excludes any connection between HESS J1616-508 and PSR J1616-5109.

Instead, despite the very stringent X-ray upper limits, HESS J1616-508 is described very well by our model as a very old PWN powered by either PSR J1614-5048 (the blue dashed line in Figure 2) or the candidate pulsar CXOUJ 161643.5–504604 (the red solid line in Figure 2).

The characteristics of PSR J1614-5048 as measured by [68] were used as fixed parameters in our model. Hare et al. [71] set an upper limit of $F_{0.5-8\mathrm{keV}} = 5 \times 10^{-15}$ erg cm^{-2} s^{-1} for the pulsar PSR J1614-5048 on the basis of the non-detection of X-ray emissions in a long exposure observation, making it one of the least X-ray-efficient pulsars known [71]. The blue dashed line in Figure 2 represents the emission expected from a PWN with a present-day age of 170 kyrs. The electron distribution was chosen to have a minimum energy of $E_{\mathrm{min}} = 0.01$ TeV, a break energy of $E_{\mathrm{b}} = 0.04$ TeV, and a maximum energy of $E_{\mathrm{max}} = 10$ TeV. As the source for the IC, both the CMBR and IR background photons were considered. The diffusion coefficient was chosen to be $\kappa_0 \approx 2 \times 10^{22}\ \mathrm{E_{TeV}}$ cm^2 s^{-1}, resulting in a present-day diffusion coefficient of $\kappa \approx 7.1 \times 10^{25} \mathrm{E_{TeV}}$ cm^2 s^{-1}. The radio conversion efficiency is 0.9 and the X-ray conversion efficiency is 0.07. The ratio of electromagnetic to particle energy in the nebula is $\sigma = 5 \times 10^{-7}$. The model predicts a present-day magnetic field of $B \approx 0.048$ μG.

For the candidate pulsar CXOUJ 161643.5–504604, the X-ray flux measured by [71] was used as an upper limit for the corresponding X-ray PWN. The characteristics of this candidate pulsar were chosen as a distance of 6kpc, a characteristic age of 10 kyrs, and a spin-down luminosity of 2.3×10^{37} erg/s. The red solid line in Figure 2 represents the emission expected from a PWN with a present-day age of 53 kyrs. The electron distribution was chosen to have a minimum energy of $E_{\mathrm{min}} = 0.01$ TeV, a break energy of $E_{\mathrm{b}} = 0.04$ TeV, and a maximum energy of $E_{\mathrm{max}} = 10$ TeV. Both the CMBR and IR background photons were considered as source for the IC. The diffusion coefficient was chosen to be $\kappa_0 \approx 2 \times 10^{23}\ \mathrm{E_{TeV}}$ cm^2 s^{-1}, resulting in a present-day diffusion coefficient of $\kappa \approx 8.2 \times 10^{26} \mathrm{E_{TeV}}$ cm^2 s^{-1}. The radio conversion efficiency is 0.85 and the X-ray conversion efficiency is 0.14. The ratio of the electromagnetic to particle energy in the nebula is $\sigma = 5 \times 10^{-7}$. The model predicts a present-day magnetic field of $B \approx 0.04$ μG.

Hence, under the circumstances described above, both PSR J1614-5048 and CXOUJ 161643.5–504604 represent viable options for explaining HESS J1616-508, and a relic PWN scenario seems once more to be the best option to explain TeV gamma rays from a "dark source".

5. HESS J1813-126

The TeV gamma ray source HESS J1813-126 was detected with H.E.S.S. in 2015 [79], and has an extension of 0.21 degrees. It is one of few Galactic VHE gamma ray sources located off-plane (b = 2.5 deg), and with its small extension, TeV brightness, and as we will discuss, the absence of any plausible lower-energy counterpart, HESS J1813-126 immediately seems extremely similar to the unique (at least until the discovery of HESS J1813-126) astrophysical case of HESS J1507-622 [60].

Moreover, the water Cherenkov observatory HAWC detected a source at a distance of 0.17 deg from the HESS source, 3HWC J1813-125, which could be associated with HESS J1813-125, as mentioned in the 3HWC catalog [80].

One plausible low-energy counterpart of this TeV gamma ray source could be the pulsar PSR J1813-1246, considering the spatial coincidence of PSR J1813-1246 with HESS J1813-126. It is important to underline here that PSR J1813-1246 is one of the brightest gamma ray pulsars; it is catalogued in the third *Fermi*-LAT catalog as 3FGL J1813.4-1246 [73], and is the second-most energetic radio-quiet pulsar. No off-pulse emission in high energy gamma rays has been found by *Fermi*-LAT.

Deep *XMM-Newton* (130ks) and *Chandra* (50ks) observations took place and while X-ray pulsations were detected from the pulsar PSR J1813-1246, no X-ray PWN could be detected [81], which is unusual for such an energetic pulsar. The non-detection of an X-ray PWN is even more surprising when considering the off-plane position of this source. An upper limit of $F_{0.3-10\mathrm{keV}} = 1.5 \times 10^{-13}$ erg cm^{-2} s^{-1} for a possible PWN connected to this pulsar was determined by [81].

The distance of PSR J1813-1246 was constrained as $>$2.5kpc [81]; hence, if HESS J1813-126 is indeed physically connected to PSR J1813-1246, this large distance constitutes another strong similarity with HESS J1507-622 (e.g., [60,82]). In fact, it could be challenging for current stellar astrophysical lore to explain how a pulsar (and its PWN) formed outside the Galactic plane, and even more challenging to explain how such a pulsar could have escaped from it. The riddles we face now in relation to HESS J1813-126 have been extensively discussed for HESS J1507-622 as well (e.g., [60,82,83]).

Hence, in light of all its similarities with HESS J1507-622, HESS J1813-126 seems to be another "dark source" which could be well described as a relic PWN by our model.

Due to its positional coincidence with an old and very energetic gamma ray pulsar, the characteristics of PSR J1813-1246, such as its spin-down luminosity of 6.24×10^{36} erg/s and characteristic age of 43 kyrs [68], were used as fixed parameters in the model. The model shown in Figure 3 represents the emission expected from a PWN with a present-day age of 23 kyrs, in line with the suggestion of [81] that PSR J1813-1246 could be younger than its characteristic age ($\tau_c = 43$ kyr). The electron distribution was chosen to have a minimum energy of $E_{\mathrm{min}} = 0.01$ TeV, a break energy of $E_{\mathrm{b}} = 0.02$ TeV, and a maximum energy of $E_{\mathrm{max}} = 30$ TeV. As a source for the IC scattering, both the CMBR and IR background photons were considered. The diffusion coefficient was chosen to be $\kappa_0 \approx 9 \times 10^{23}$ $\mathrm{E_{TeV}}$ cm^2 s^{-1}, resulting in a present-day diffusion coefficient of $\kappa \approx 3.4 \times 10^{26} \mathrm{E_{TeV}}$ cm^2 s^{-1}.

The radio conversion efficiency is 0.55 and the X-ray conversion efficiency is 0.38. The ratio of electromagnetic to particle energy in the nebula is $\sigma = 5.4 \times 10^{-6}$. The model predicts a present-day magnetic field of $B \approx 0.18$ µG.

As is the case for most "dark sources", HESS J1813-126 is well-described as a relic PWN.

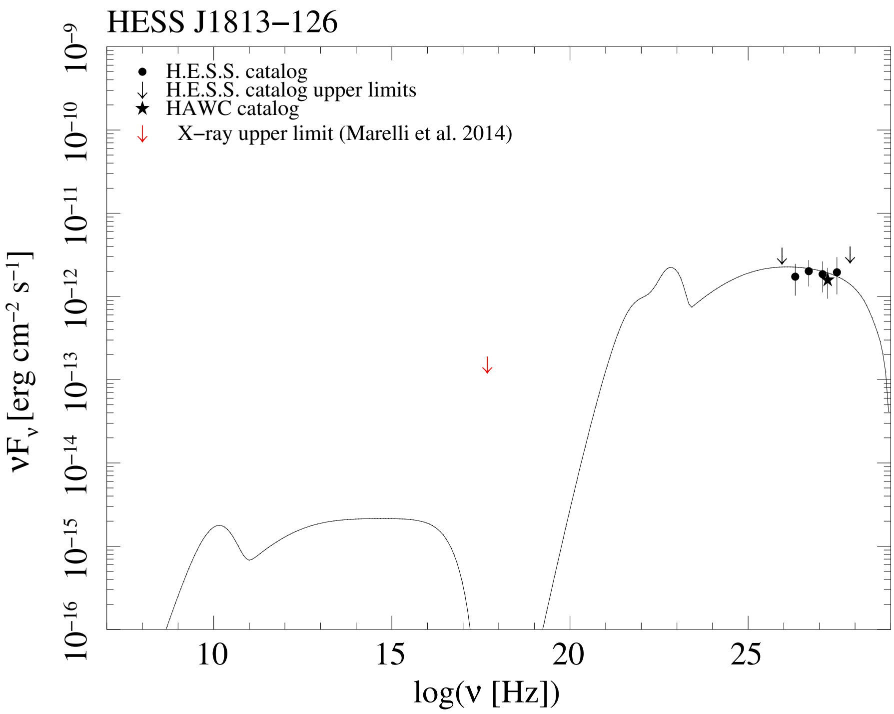

Figure 3. Spectral energy distribution of HESS J1813-126, with the TeV gamma ray spectrum from the H.E.S.S. catalog [76] shown as circles and upper limits and that from the HAWC catalog [80] shown as star. The X-ray upper limit (arrow) is taken from [81], and the results of emission modelling using the time-dependent PWN model described in the text is shown.

6. Corollaries

It is important to underline here certain other consequences of PWNe studies.

One of the most relevant consequences of the scenarios described previously (i.e., both hadronic "standard model" acceleration and leptonic PWNe time-dependent modelling) involves the interpretation of more complex objects such as starburst galaxies. The TeV discoveries of NGC 253 [84] and M82 [85] were interpreted as strong confirmation of standard models of hadronic CR acceleration. However, in [86], it was demonstrated how this TeV luminosity can be the natural consequence of purely leptonic acceleration, i.e., by using an average PWN population. This work is deeply connected with the standard CR acceleration models, and shows how the PWN scenarios cannot be neglected. PWNe associated with core-collapse supernovae can readily explain the observed high TeV luminosities; the final proof of this could simply arrive from deeper gamma ray observations of other galaxies. In conclusion, this study strongly supports PWN-like objects as candidates for supplying the missing fraction of hadrons that do not seem to be as efficiently accelerated in SNR shells, especially if hadron acceleration at PWN termination shocks can finally be proven.

Finally, pulsars (and hence PWNe) have been the main competitor of Dark Matter (DM) models to explain several astrophysical discoveries, such as the GeV Excess signal from the Galactic Center (GC) and the *PAMELA* positron excess. In the framework of cold dark matter (CDM) scenarios, most of the matter is composed of non-baryonic Weakly Interacting Massive Particles (WIMPs). The Standard Model of particle physics does not provide a natural and suitable candidate for the DM particle, and many theories beyond the standard model have been proposed to explain its origin and properties. In various models, the self-annihilation of WIMPs results in a gamma ray continuum emission resulting from the hadronization of primary annihilation products.

The GeV Excess is an anomalous flux of GeV gamma rays peaking at ∼2–3 GeV; following its discovery in 2009 [87], it was immediately considered to fit several DM models (e.g., [87–89]). However, pulsars (and PWNe) seemed more natural candidates, in particular, millisecond pulsars; in fact, millisecond pulsar populations in other environments, such as globular clusters, produce gamma ray spectra which are very similar to that observed in the GC. There have been strong indications of clumpy, rather than smooth, GC signals (e.g., [90,91]), which strongly supports an origin of the signal in point sources (i.e., pulsars) rather than a DM interpretation.

Another discovery which was tentatively explained as a result of either DM annihilation or a pulsar population is the *PAMELA* positron excess. This is an excess of ∼10–1000 GeV positrons [92], later confirmed by *AMS-02* observations [93,94]. While this signal has been interpreted as a result of DM annihilation (e.g., [95–97]), once again pulsars seem to be a more solid and more natural explanation (e.g., [98]), as they are expected to produce a comparable positron energy spectrum to that observed in the positron excess. Despite the questions raised by the diffusion coefficient of the positrons [99], pulsars (and their relatives, PWNe) remain the most likely source of the positron excess [100,101].

7. Conclusions

PWNe are a very natural way to explain unidentified very-high-energy sources. Moreover, ancient PWN models seem to be able to explain most of these sources (e.g., [64–66]), as confirmed by the present interpretations of HESS J1616-508 and HESS J1813-126.

In addition to being a well-established and efficient leptonic accelerator, if hadrons could indeed be accelerated at the termination shock of a pulsar wind in addition to leptons, PWNe (and unidentified sources, i.e., the dominant population both at high energies and in VHE gamma rays) would be an helpful ingredient in solving the riddle of the origin of CRs.

Finally, we note that PWNe represent a viable and more realistic alternative to DM models in explaining both the *PAMELA* positron excess and the GeV Excess signal from the GC.

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H.E.S.S. catalog [76], https://www.mpi-hd.mpg.de/hfm/HESS/hgps/ (accessed in April 2022); *Fermi* 3FGL catalog [73], https://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/ (accessed in April 2022); *Fermi* 2FHL catalog [74], https://fermi.gsfc.nasa.gov/ssc/data/access/lat/2FHL/ (accessed in April 2022); HAWC 3HWC catalog [80], X-ray PWN around PSR J1617-5055 taken from [70], X-ray source CXOUJ 161643.5–504604 taken from [71], X-ray upper limit of PSR J1614-5048 taken from [71], X-ray upper limit of HESS J1813-126 taken from [81].

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Abbreviations

The following abbreviations are used in this manuscript:

CDM	Cold Dark Matter
CMB	Cosmic Microwave Background
CR	Cosmic Rays
DM	Dark Matter
GC	Galactic Center
HAWC	High-Altitude Water Cherenkov Observatory
H.E.S.S.	High-Energy Stereoscopic System
IACT	Imaging Atmospheric Cherenkov Telescopes
IC	Inverse Compton
IR	Infrared
LAT	Large Area Telescope
LHAASO	Large High-Altitude Air Shower Observatory
MAGIC	Major Atmospheric Gamma Imaging Cherenkov Telescope
MC	Molecular Cloud
PWN	Pulsar Wind Nebula
SNR	Supernova Remnant
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VHE	Very High Energy
WIMP	Weakly Interacting Massive Particles

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