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RECENT VERY-HIGH-ENERGY RESULTS ON PULSARS AND PULSAR WIND NEBULAE*

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For many years, high-energy pulsar models were rather uncertain regarding expectations of detectable pulsed TeV spectral components from pulsars. Surprising detections of pulsations from the Crab pulsar up to 1.5 TeV opened a new window in pulsar science. H.E.S.S.-II next detected pulsed emission from the Vela pulsar (initially from 20–120 GeV and now up to a few TeV). Additionally, pulsations were detected by MAGIC from the Geminga pulsar (15–75 GeV) and by H.E.S.S.-II from PSR B1706−44 (sub-100 GeV). These new detections challenge established theoretical frameworks that explain the origin and nature of gamma-ray emission from pulsars. Moreover, these developments feed into the study of very-high-energy pulsar wind nebulae that surround some energetic pulsars. In 2018, H.E.S.S. released a pulsar wind nebula catalogue revealing new correlations and spurring on theoretical progress. HAWC detected spatially-extended TeV sources (pulsar halos) that surround several pulsars, generating new questions regarding PeV accelerators. Millisecond pulsar binaries are another class of pulsar-related systems that may manifest modulated TeV signals. In this review article, I will discuss some recent developments in the field and assess theoretical progress and challenges, also mentioning relevant questions that the Cherenkov Telescope Array may tackle.

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1. Introduction

The past decade has seen incredible progress in our understanding of energetic pulsars and pulsar-related systems. New phenomena and new details have been detected, while increasingly sophisticated modelling attempts have been initiated to explain the new findings. Thus, the dual forces of new data and renewed modelling attempts have pushed the boundaries of knowledge in this rich field.

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A census of pulsar-related sources at TeV energies reveals a dynamic field of discovery. The Kifune plot indicates the increase of source discoveries over time (figure 1). TeVCAT[1] lists 248 sources, 1.6% of which are pulsars and 12.5% are pulsar wind nebulae (PWNe). Specifically, TeVCAT lists 4 pulsars: Crab, Vela, Geminga, and PSR B1706−44 (see Section 2). These are positioned at an average distance of $\langle d \rangle \sim 1$ kpc, average absolute latitude $\langle |b| \rangle \sim 10°$ (or $4°$ if one ignores the outlier, PSR B1706−44); and they have an average characteristic age of $\sim$ 1–300 kyr. Recently, the VERITAS Collaboration searched for pulsed emission in their archival data above 100 GeV, with an exposure of more than 450 hours, and published upper limits on pulsed VHE gamma rays on 13 more northern-sky pulsars [1]. They concluded that the potential VHE flux must be much weaker in these pulsars than that of the Crab Nebula.

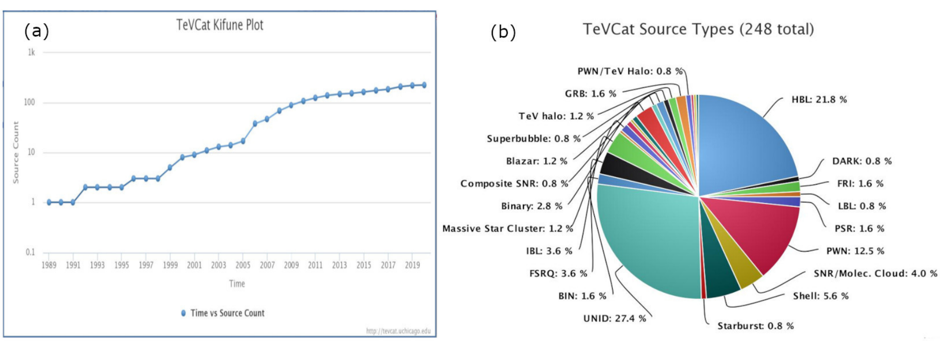

Fig. 1. The Kifune plot indicating the increase of TeV source detections with time, as well as (b) a pie chart of TeV source detections giving the relative fraction of various TeV source classes.

In addition to pulsars, 35 PWNe appear in TeVCAT with typical distances of 1–10 kpc (barring the PWN in the Large Magellanic Cloud, N 157B, located at a distance of $\sim$ 50 kpc). These sources occur close to the Galactic Plane ($\langle |b| \rangle \sim 1.5°$) and have typical ages in the range of 1–50 kyr. Lastly, 6 TeV halos are listed, including Vela X, Geminga, HESS J1825−137, and Monogem, at an average distance of ~ 1 kpc and absolute Galactic latitude $\langle |b| \rangle \sim 3°$.

Finally, the HAWC Third Catalog lists 65 sources (in the $\sim$ 0.5–300 TeV range), with the majority of HAWC sources in the Galactic Plane being potentially associated with pulsars [2]. At even higher energies, the LHAASO Collaboration detected 12 Galactic sources (including the Crab Nebula) in the 100 TeV–1 PeV range [3]. These point to the existence of a Galactic Pe-

[1] http://tevcat2.uchicago.edu

vatron population that may potentially be associated with PWNe, pulsars[2], supernova remnants (SNRs), or young massive stellar clusters. It remains an open question if the ultra-high energy photons originate via leptonic or hadronic processes.

In this review, I will discuss recent advances in our understanding of TeV pulsars (Section 2) that exhibit pulsed emission by an outflowing pulsar wind, VHE PWNe (Section 3) that manifest steady inverse Compton (IC) emission and wind outflows that may lead to PWN halos (Section 4), as well as millisecond pulsar (spider) binaries (Section 5) that may display TeV emission modulated at the orbital period due to binary wind interaction. I will lastly allude to the progress that the Cherenkov Telescope Array (CTA) can make in this arena (Section 6) before concluding (Section 7).

2. VHE pulsars

2.1. Observations

For many years, the expectations of high-energy (HE; > 0.1 GeV) pulsar models were rather uncertain regarding pulsed TeV spectral components from these sources. Although some models envisioned IC components, early non-detections led to revisions and re-evaluations of model assumptions. However, a handful of pulsars have now been detected from the ground in the > 100 GeV range.

Pulsed emission from the Crab pulsar was detected in the range of 70 GeV to 1.5 TeV by MAGIC [4]. In this energy range, both peaks (first peak P1, and second peak P2, occurring at a later observer phase; both in phase with the two radio peaks) are visible (with the photon index of the spectrum of the latter being harder by $\Delta\Gamma = 0.5 \pm 0.1$), and they are aligned in phase with the peaks measured by the *Fermi* Large Area Telescope (LAT) at GeV energies [5]. These results imply that the emission may come from near or beyond the light cylinder[3], from particles with a Lorentz factor of $\gamma > 5 \times 10^6$.

The second peak (P2) of the Vela pulsar's light curve was detected at a significance above 15σ by the CT5 telescope of H.E.S.S. in the range of 10–110 GeV [6]. The results are comparable with those found by Leung *et al.* [7] using *Fermi*-LAT data. A curved spectral shape rather than a simple power law was favoured, indicating that H.E.S.S. measured the tail of the *Fermi* spectrum. Moreover, there were some indications of the evolution of P2's morphology with energy. More recently, H.E.S.S. announced the detection of pulsed TeV emission from Vela at 3 to > 7 TeV (H.E.S.S. Collaboration,

[2] Indeed, 11 of the 12 sources are possibly associated with young, energetic pulsars: *cf.* their Extended Data Table 2.

[3] This is the radius where the corotation speed equals that of light in vacuum.

in preparation), raising the question of whether this may indicate the onset of a new spectral component, or a continuation of the GeV spectral energy distribution (SED).

The third pulsar detected from the ground in the gamma-ray range is the middle-aged Geminga. This pulsar was detected by MAGIC in the 15–75 GeV range [8]. Only P2 was visible at a significance of 6.3σ, and the SED could be fit by a power law with an index of $\Gamma = 5.62 \pm 0.54$ (the softest ever measured by MAGIC), smoothly joining the *Fermi*-LAT spectrum. A sub-exponential spectral shape was ruled out at the 3.6σ level, and this may perhaps indicate the onset of an IC component, in addition to a synchro-curvature (SC) one that dominates at GeV energies.

Finally, a fourth pulsar, PSR B1706−44, has been detected by the ground-based telescope H.E.S.S. in the 10 to > 60 GeV range [9]. The lack of statistics precluded a log-parabola fit or any conclusions regarding a spectral cutoff, but a power-law fit yielded an index of $\Gamma = 3.76 \pm 0.36$. The light curve shape was similar to that measured by *Fermi* at 15 GeV.

The SEDs of these four pulsars in the GeV–TeV range are shown in figure 2.

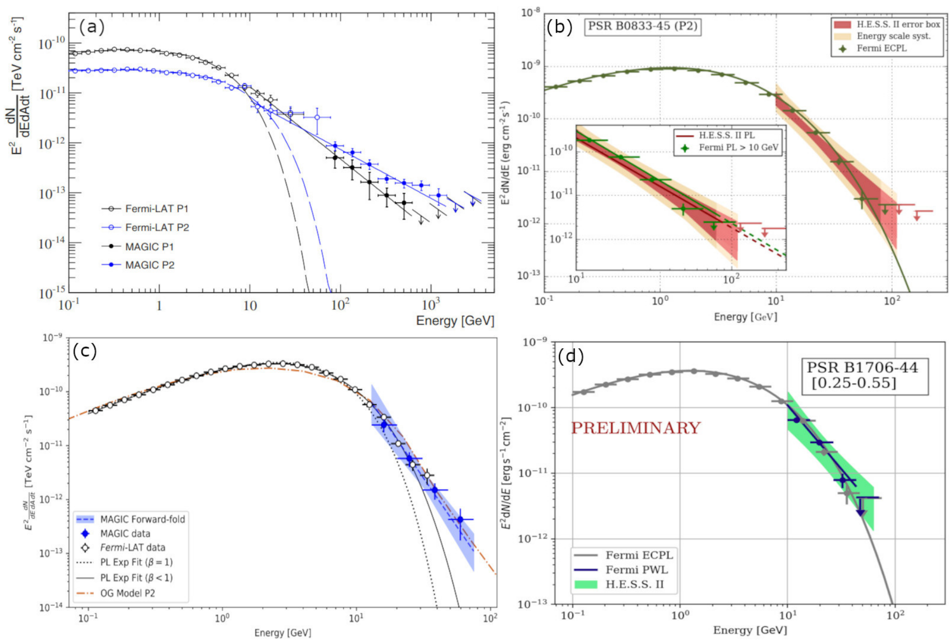

Fig. 2. SEDs for (a) the Crab pulsar [4], (b) the Vela pulsar [6], (c) the Geminga pulsar [8], and (d) PSR B1706−44 [9].

2.2. Models

The above observations generate several questions: Is the SED seen in the tens of GeV band an extension of the SC component as seen by *Fermi*, or does it represent a new spectral component? What is the spatial origin of these gamma-ray photons? What is the spectral shape of the emitting particles (*e.g.*, that of primaries or pairs)? What are the local and global electrodynamical properties, plasma characteristics, and geometry of the pulsar magnetosphere that would sustain the generation of such photons? Several models have been introduced to address these questions. What is ultimately required, is a model that can both describe the spectra and energy-dependent light curves and perhaps future polarisation properties of pulsars.

The striped-wind model of Mochol and Petri [10] invokes synchrotron radiation (SR) in the current sheet (a region near the equator where magnetic field lines of opposite polarity may form an undulating sheet for an inclined rotator; see also [11–13]) by an outflowing plasma with a bulk Lorentz factor of $\Gamma_{\rm b} \leq 50$. A GeV component in this model results from the Doppler-boosted SR from the current sheet, while a TeV component is due to synchrotron-self-Compton (SSC) emission. Their results for Vela indicate a very hard particle spectrum, low SSC due to low SR flux (undetectable by current instruments, in violation of the H.E.S.S. data described above), a small emission distance from the pulsar, a low particle number density, and a higher magnetic reconnection rate compared to the Crab pulsar.

Rudak and Dyks [14] constructed a 3D outer gap (OG) model, invoking curvature radiation (CR) by primaries in the OG layer to explain the GeV emission, SR by pairs in a layer adjacent to the OG layer to explain infrared to optical emission, and SSC of primaries on pair SR yielding a TeV component. Notably, choosing a low minimum photon energy ($E \sim 0.001$ eV) for the SR spectrum enhanced the TeV luminosity, as scattering then proceeds in the Thomson regime, boosting the TeV flux. Their model indicates that the first peak P1 of Vela's light curve will decrease in flux relative to the second peak P2 as the energy is increased (this is apart from the small third peak, P3, which has been observed at GeV energies to move to later phases as energy is increased [15]).

A separatrix/current sheet model [16, 17] was recently suggested to explain the broadband SED of several TeV pulsars, including Vela (figure 3). The model invokes global force-free magnetic fields and yields three distinct VHE components: SC from primaries (≤ 100 GeV), SSC from pairs (≤ 5 TeV), and IC from primary particles accelerated in the current sheet that scatter pair SR (≥ 10 TeV). A potential measurement of an IC spectral cutoff will constrain the maximum particle energy. The model reproduces the drop in flux of P1 *versus* P2 with energy. This is ascribed to the fact that particles responsible for P2 have trajectories characterised by relatively larger curvature radii ρ_c; in the radiation-reaction limit, the particle Lorentz factors $\gamma_{\rm CRR} \propto \rho_c^{1/2}$, thus P2 photons are associated with particles of higher γ, leading in turn to higher SC (and IC) energies and thus higher spectral cutoffs [18]. This explains the P1/P2 *versus* energy effect quantitatively.

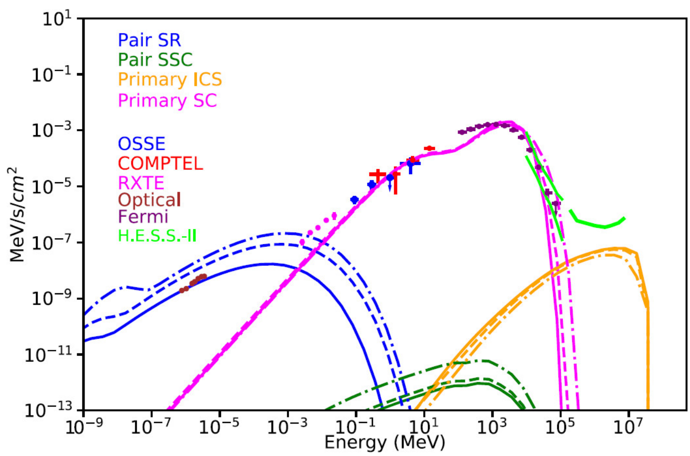

Fig. 3. A model fit to the broadband spectrum of the Vela pulsar, including pair SR, primary SC, pair SSC, and primary IC components [17].

Other models include one in which a rapid acceleration of particles (forming a cold, kinetic-energy-dominated wind) takes place close to the light cylinder of the Crab pulsar, and IC on magnetospheric infrared photons and X-rays yield pulsed gamma-ray emission [19] (although Ansoldi *et al.* [4] have argued that some assumptions of the model have been discounted by their observations), and the magneto-centrifugal acceleration model of Osmanov and Rieger [20] that invokes IC up-scattering of thermal photons from the surface of the star.

3. VHE PWNe

The H.E.S.S. Collaboration released a PWN catalogue based on the 9-year H.E.S.S. Galactic Plane Survey (HGPS), including 3 000 h of data. This catalogue contains 14 firm PWN identifications, 5 external identifications, and 18 PWN candidates as well as several upper limits [21]. A number of trends emerge, for example (figure 4):

1. There is a spatial correlation between PWNe and energetic pulsars (those with high spin-down luminosities $\dot{E}$); this is expected, as young and energetic pulsars are most likely to have an adequate energy budget to blow and sustain a nebular bubble in the form of a PWN.

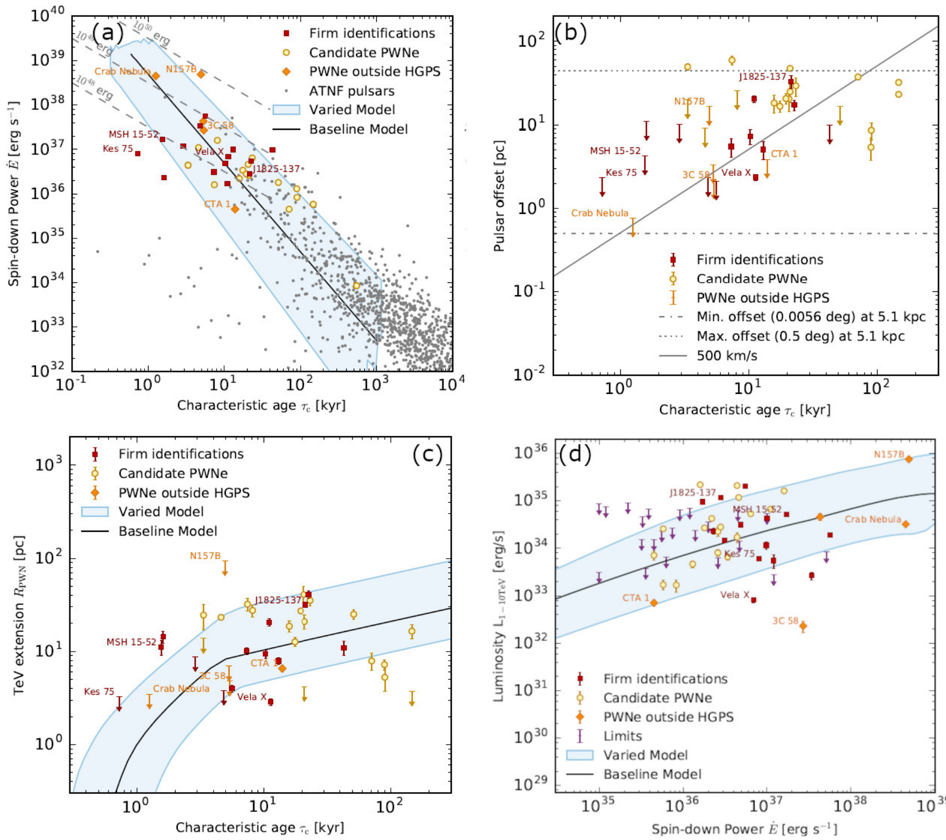

Fig. 4. Various trends found by Abdalla *et al.* [21] for a population of TeV PWNe.

2. Younger, more energetic pulsars seem to be preferentially associated with TeV PWNe, thus the spin-down luminosity over the square of the distance ($\dot{E}/d^2$) seems to be a good indicator of detectability of PWNe.

3. There is an increasing spatial offset between the associated pulsar and the PWN with the age of the pulsar; this may indicate the proper motion of the pulsar and its moving away from a central (birth) position as time goes by, but also the influence of an asymmetric environment (ambient density gradient) impacting on the asymmetric nature of the reverse shock that leads to an offset PWN with respect to its associated pulsar.

4. Older PWNe are relatively more extended than younger ones; this reflects the expansion of the PWN with time. In particular, the expected relations for the PWN radius $R_{\rm early} \propto t^{1.2}$ (for the initial, fast

free expansion) and $R_{\rm late} \propto t^{0.3}$ (in the case of evolved PWNe) during different phases of expansion seem to be roughly borne out, barring potential crushing of PWNe by the surrounding supernova remnant (SNR) in some cases.

5. The spin-down luminosity $\dot{E}$ is a good a proxy for the evolutionary stage of the PWN, with the VHE luminosity scaling as $L_{\rm VHE} \propto \dot{E}^{0.6}$. This is explained by a generic PWN model that includes a high initial particle injection rate, accumulation of particles over time, and the central pulsar spinning down with time.

On the one hand, some scatter or deviations from the general trends may have to be explained by performing multi-wavelength and spatio-spectral modelling (*e.g.*, [22]) for particular case studies. This includes, for example, the modelling of an energy-dependent morphology of the extended PWN HESS J1825−137 that may be used to constrain the velocity profile of the bulk plasma outflow [23]. On the other hand, as CTA discovers more PWNe, it is hoped that the trends found by H.E.S.S. will strengthen.

Lastly, new questions arise, given the discovery by the LHAASO Collaboration of PeV photons from the Crab Nebula [24]. Production of such high-energy photons challenges conventional models, and also raises the question as to a leptonic *versus* hadronic contribution. The statistics were insufficient to search for pulsations, leaving open the question of whether these photons are pulsed (originating in the pulsar magnetosphere) or not (originating in the PWN).

4. PWN halos

Following an earlier detection of extended TeV emission in the direction of the Geminga PWN by Millagro [25], the HAWC Collaboration detected extended TeV emission around Geminga and PSR B0656+14 (respectively at 13.1σ and 8.1σ significance [26]). This led Linden *et al.* [27] to claim the existence of a new gamma-ray source class: that of TeV halos around PWNe. These halos (figure 5) result from high-energy electrons and positrons that have escaped from their natal PWNe, but that remain trapped in a region characterised by slow diffusion [28]. A 1D diffusion model fit to the spatial and spectral morphology measured by HAWC yielded an unexpectedly low value for the (isotropic, homogeneous) diffusion coefficient, implying that these pulsars may not be strong contributors to the terrestrial positron excess as was previously thought. However, non-homogeneous (two-step) models for the diffusion coefficient (*e.g.*, [29–31]) indicate that there may be a region of slow diffusion close to the PWNe, but that the typical Galactic values for the spatial diffusion coefficient remain plausible to explain the positron excess. It is expected that CTA will discover more TeV halos, aiding in our understanding of the escape of particles from PWNe and their contribution to the local lepton spectrum.

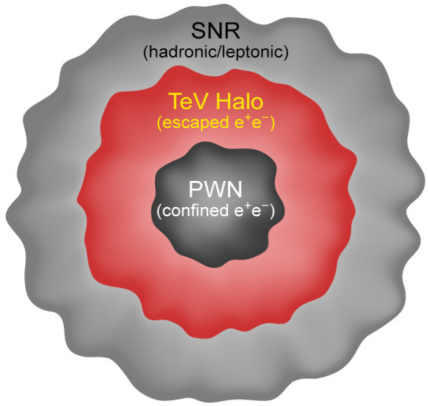

Fig. 5. Illustration of a TeV halo, situated in between the SNR and the PWN. The halo contains electron–positron plasma that has escaped from the PWN [28].

5. Millisecond pulsar ‘spider’ binaries

Black widows and redbacks are an exciting class of millisecond pulsar or ‘spider’ binaries that has substantially increased in membership over the past few years [32] due to numerous new detections of such systems, now with more than 70 members [33]. They are comprised of a millisecond pulsar and a tidally-locked companion that is being ablated by the intense pulsar wind and its pulsed emission. They typically have orbital periods $P_{\rm b} < 24$ h, and asymmetrical optical light curves originating from a heated companion surface in some cases suggest variable heating thereof [34]; long-lived optical flares may also occur. Pulsed gamma-ray emission (*e.g.*, [35]) and radio pulses (sometimes eclipsed by the companion or shock; *e.g.*, [36]) confirm the nature of the millisecond pulsar, as these are modulated at the pulsar spin period. Single or double-peaked X-ray light curves (*e.g.*, [37]) modulated at the orbital period are typically observed and are thought to originate from the Doppler-boosted SR emission by particles moving along an intrabinary shock (*cf.* [38] for recent particle-in-cell modelling of the intrabinary shock and the associated Doppler-boosted SR from the post-shock flow). Thus, the intrabinary shock where the pulsar and companion winds interact, the zone where the pulsar and companion winds mix, the bow shock due to the proper motion of the system, or the pulsar magnetosphere itself are potential locations of particle acceleration (figure 6 [39]).

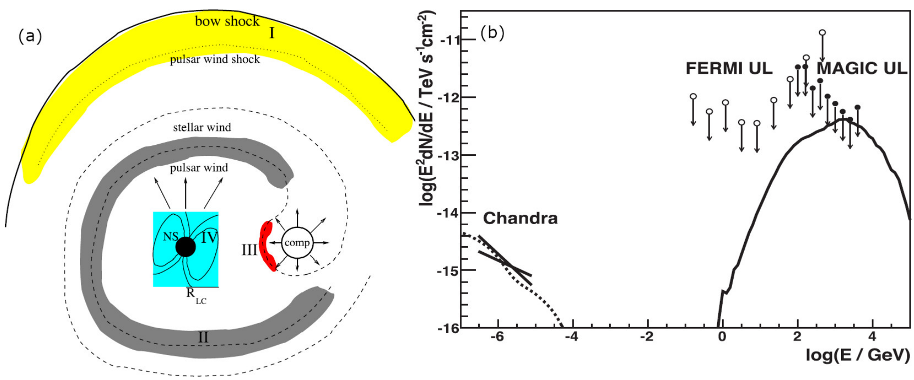

Fig. 6. (a) Illustration of potential locations for particle acceleration in spider binaries: I — bow shock due to the proper motion of the system; II — zone where the pulsar and companion winds mix; III — intrabinary shock where the pulsar and companion winds interact; IV — pulsar magnetosphere [39]. (b) *Fermi* and MAGIC upper limits and a bow-shock spectral model for PSR B1957+20 [40].

Wadiasingh *et al.* [41] note that these systems are promising TeV targets (although none has been detected in the VHE band to date): As opposed to younger pulsar gamma-ray binaries that have eccentric orbits (often with long intervals between periastrons), these systems have short, nearly circular orbits and probably a stable shock geometry; pulsar radio timing and optical data from the companion yield well-constrained member masses and orbital geometry in many cases; the rotational energy of the pulsar permits the existence of multi-TeV electrons in these systems, as is also evidenced by the observed X-ray signals; a companion situated near the pulsar implies a high density of target photons that may be upscattered by the pulsar wind via IC into the TeV domain, potentially creating an observable TeV signal modulated at the binary period; and X-ray observations anchor the particle injection spectrum, making TeV flux predictions more robust.

Several modelling attempts (*e.g.*, [42–46]) indicate that the orientation of the shock (wrapping around the pulsar *versus* around the companion) may be gleaned from the relative phasing of the X-ray peaks (*e.g.*, if the X-ray minimum occurs at pulsar superior conjunction, the shock is wrapping around the companion, and *vice versa*). Joint fitting of spectral shapes and orbital light curves constrains several system parameters. Moreover, the expected TeV flux increases for nearby binaries with hot and flaring companions, as well as cases when there are relatively high fluxes of energetic particles in the system, as hinted at by high levels of SR (although an uncertain shock B-field strength introduces some degeneracy). It may thus be worthwhile to continue to observe these systems with the Cherenkov telescopes and the future CTA, informed by optical triggers that indicate flaring activity. Lastly, these systems may potentially contribute to the rising positron fraction above a few GeV [47, 48].

6. The role of the CTA

Given the order-of-magnitude improvement in sensitivity of the CTA compared to that of current Cherenkov telescopes, one should expect a substantial increase in the number of detected VHE sources. A wider variety of pulsar subclasses as well as more examples of objects similar to currently known ones will strengthen our broader understanding of the pulsar-related source population as a whole. We will be able to better probe the evolutionary history, current state, and generic or universal properties of such systems if we have a, say, ten-fold increase in the number of sources. Thus, a deeper census of sources and their properties will bring untold advancement.

The sensitivity improvement will furthermore allow known objects to be studied in exquisite detail, given the increase in photon statistics. In particular, it is expected that pulsed spectral components of energetic pulsars will be revealed at a much deeper level of detail, faint components may come into fuller view, and new spectral components may be uncovered. Careful measurement of spectral shapes will yield vital information about particle acceleration and energetics. The better sensitivity coupled with the improved energy resolution will result in enhanced TeV light curves that will give modellers the opportunity to constrain the pulsar electrodynamics (current structure, B-field geometry), acceleration mode, and dominant emission location, since we will have unparallelled constraints on the local environment and the geometry of the regions where the emission originates.

For PWNe, population studies will be much more viable, and identified relations should be strengthened, while new trends will be uncovered. The wider energy coverage should facilitate calibration with HE measurements and help to constrain the low-energy turn-over of IC components. The wider field of view and improved angular resolution will allow the measurement of energy-dependent, extended (and faint) morphologies that will, in particular, constrain the evolutionary history of particle acceleration, outflow, and their interaction or mixing with the ambient environment.

Refined measurements of the morphology of PWN halos will constrain complex, spatially-dependent diffusion coefficients, particle mixing and escape, and will provide a window on the break-up of middle-aged PWNe as they start to merge with the interstellar medium. This will also help to evaluate the pulsar contribution to the local rise in the positron fraction beyond several GeV. Complementary observations with other multi-messenger missions (in particular neutrino observatories) could contribute to the debate of whether gamma rays originate in leptonic or hadronic (or a mix of these) processes.

In the case of pulsar binaries, the concerted efforts of multi-wavelength instruments should lead to more discoveries of these peculiar systems. Signatures of TeV variability will become evident as counterparts to the detected X-ray modulations from several systems, especially when triggered by optical flaring activity. The CTA will also be more suited to probe minute-scale variability than an instrument like the *Fermi*-LAT that needs to accumulate photons for longer times to increase the significance of detection, given its relatively smaller effective area. Spider binaries are thus laboratories that will provide valuable information on the particle acceleration and wind composition in aged pulsar systems.

7. Conclusion

There has been a flurry of activity in the field of VHE pulsar-associated systems, with much observational and theoretical progress. I broadly reviewed four subclasses in this paper: pulsars, PWNe, TeV halos, and spider binaries.

Four pulsars have been detected by the ground-based Cherenkov telescopes in the HE-VHE band so far: the Crab, Vela, Geminga, and PSR B1706−44. These detections (and the lack thereof in the case of other pulsars) are challenging standard models to consider new physics and magnetospheric geometries to explain the measured spectra and light curves. A main consideration is whether the data imply a new pulsed SED component, or whether they may be explained as an extension of the GeV component.

There is also a growing population of VHE PWNe, allowing population trends to become more clear. While a baseline model can capture many of these trends to first order, significant scatter remains in several of the uncovered trends, implying that case studies may be needed to uncover the unique environments, evolutionary histories, and physical conditions relevant to individual objects. Thus, it remains a question as to what extent a generic model may be applied to the population of PWNe, and at what point tailor-made models will be needed for particular objects.

A surprising PWN halo population has now been unveiled by HAWC. In particular, the observation of extended structures via their electromagnetic signatures constrains the particle transport and has a direct impact on the expected contribution of nearby PWNe to the electron–positron cosmic-ray flux. In essence, the inferred diffusion coefficient significantly impacts the expected flux of leptonic particles near the earth. More such objects may be detectable in the future, depending on their surface brightness level. Continued model development in this area of research will improve our understanding of the nature of sources of terrestrial cosmic rays.

There are exciting prospects for measuring orbitally-modulated TeV signals from spider binaries that have bright and flaring companions. This is because of the inferred presence of energetic particles in the intrabinary shocks and ample target photons originating from hot surfaces of tidally-locked companions. Future observations by Cherenkov telescopes, acting on triggers from lower-energy bands that indicate flaring activity, should lead to the detection of these binaries at TeV energies, potentially providing potential constraints on the particle energetics, intrabinary shock geometry, and radiation processes in these systems.

The population of pulsar-related sources continues to provide extraordinary opportunities to learn about Nature's factories of relativistic particles and the content and properties of such pulsar winds and their associated photonic signatures. Ongoing measurements by the current-generation Cherenkov telescopes as well as the future CTA, in addition to supporting multi-wavelength and multi-messenger observations as well as detailed modelling, will continue to push the boundaries of our understanding of the enigmatic, exciting, and complex pulsar-powered fields, winds, and bubbles of energy.

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