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Cosmic-Ray escape from accelerators: the case of pulsar wind nebulae and TeV γ-ray halos

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The escape of cosmic rays from their sources and their subsequent propagation in the surrounding medium remain central open issues in high-energy astrophysics, owing to their inherently multi-scale and nonlinear nature. The recent discovery of TeV γ-ray halos and X-ray filaments around middle-aged pulsars provides direct evidence of particle escape and diffusion on scales of tens of parsecs, at multi-TeV energies where direct CR measurements currently offer no constraints on transport. So far, only three TeV halos have been firmly detected, but ongoing surveys are rapidly expanding the sample of candidates. The inferred strong suppression of the diffusion coefficient in these sources raises fundamental questions about its origin and implications for Galactic cosmic ray transport, the positron fraction, and diffuse γ-ray emission. In this contribution, we review the current theoretical scenarios proposed to explain these observations—ranging from pre-existing turbulence to anisotropic or self-generated diffusion. In addition, we discuss how X-ray filaments may trace current-driven instabilities triggered by partially charge-separated escape of particles. Future observations with LHAASO, the ASTRI Mini-Array, and CTAO, combined with kinetic and MHD simulations, will be crucial to establish a consistent picture linking particle acceleration, escape, and Galactic propagation.

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1. Introduction

The mechanisms governing the escape of cosmic rays from their accelerators and their subsequent transport in the surrounding medium remain among the central open questions in high-energy astrophysics. The escape process is inherently multi-scale and often nonlinear. Close to the acceleration sites, particles move in a highly turbulent environment—an essential condition for efficient acceleration—resulting in short mean free paths, of the order of their Larmor radii (Bohm diffusion). The breaking of efficient confinement is intimately linked to the maximum energy that particles can attain at a given time.

On Galactic scales, instead, cosmic ray transport is governed by a "global", average, magnetic turbulence, with mean free paths much larger than the particle Larmor radii. This global transport regime is constrained by CR data, most notably by secondary-to-primary ratios such as boron-to-carbon ratio, which however is currently measured up to energies of a few TeV/n [1]. Bridging these two regimes; near-source and average Galactic, remains a theoretical and computational challenge. Escaping particles can significantly modify their environment by exciting plasma instabilities, while the vast spread of spatial and temporal scales makes the problem difficult to address even with advanced simulations. At intermediate distances from the source, the turbulence level may remain enhanced compared to the average interstellar medium (ISM), yet lower than within the accelerator, leading to complex, non-uniform propagation conditions.

In recent years, pulsar-powered sources have emerged as particularly valuable laboratories to investigate CR escape and near-source transport. The discovery of TeV γ-ray halos and X-ray filaments around middle-aged pulsars, that are known factories of high-energy $e^{\pm}$ pairs, has provided a direct view of CR leptons leaving their accelerator and propagating through their environment. These systems probe particle transport on scales of tens of parsecs and at multi-TeV energies, an energy range not yet directly accessible through local CR measurements.

To date, only three TeV halos have been firmly detected, around Geminga and Monogem, first detected by HAWC [2] , and around PSR J0622+3749 as reported by LHAASO [3], but ongoing wide-field surveys –particularly with LHAASO — are rapidly expanding the sample and opening a new observational window on near-source diffusion (see e.g. [4] and references therein).

As for X-ray filaments, they have been detected around the Lighthouse [5], Guitar (see [6] and references therein) nebulae.

In what follows, we summarize the current understanding of particle escape from pulsar wind nebulae (PWNe) and discuss the implications for TeV halos and X-ray filaments. We refer the interested reader to the recent detailed review [7] for a comprehensive discussion of TeV halos and to [8] and references therein for X-ray filaments.

2. Pulsars and Pulsar Wind Nebulae: Confinement and Escape

Pulsars are fast-rotating neutron stars that release a large fraction of their spin-down energy as a relativistic, magnetized wind composed primarily of $e^{\pm}$ pairs. This wind decelerates at a termination shock, due to confinement by the surrounding medium, where its bulk kinetic energy is converted into the non-thermal emission that shines as a PWN.

The nature and conditions of the medium confining the nebula strongly depend on its age. Since pulsars are born with substantial natal kicks (with typical velocities around 500 km/s), their nebulae evolve through distinct stages as they traverse their parent supernova remnant (SNR) and eventually enter the ISM. While the pulsar is located within the parent SNR, the PWN is strongly influenced by the remnant environment. Most notably, the interaction with the reverse shock leads to repeated cycles of compression and expansion. In this stage, particles cannot leave the PWN-SNR system, with the sole possible exception of very high energy particles that would not be effectively confined by the SNR shock. During a compression cycle, the pulsar can exit from the nebula. The latter becomes disconnected from the parent pulsar, which will create a new nebula, leaving the old one as a relic [9]. The relic nebula, in the absence of fresh energy input, rapidly loses high-energy particles and becomes dominated by low-energy electrons emitting radio synchrotron and TeV γ-rays via inverse Compton scattering (ICS). Relic PWN are likely the most numerous population of sources in TeV gamma-rays [10], and might be confused with pulsar halos. The latter are considered to result from $e^{\pm}$ that are probing an ambient different than the interior of the SNR.

After a time $\gtrsim$ (1–5) $\times\, 10^4$ yr (more on that in Sec. 3.4) the pulsar leaves the SNR and begins to move through some ambient medium. At this point, a new configuration arises: the *bow-shock pulsar wind nebula* (BSPWNP [11]), where the pulsar wind is not confined by the SNR but by the ram pressure due to the fast motion of the pulsar in the ISM. This transition represents the key stage for particle release, since particles are expected to naturally escape at least from the bow-shock tail.

This expectation was confirmed by dedicated numerical simulations that followed the transport of test particles with different energies in the three-dimensional MHD structure of BSPWNe (see [12] and references therein). These simulations, however, went well beyond a simple confirmation, revealing qualitatively distinct behaviors for low- and high-energy particles, relative to the pulsar's maximum potential drop $E_{\rm PD}$, which also determines the maximum achievable energy in the system.

Particles with energy $E \lesssim 0.01\, E_{\rm PD}$ also possess a Larmor radius much smaller than the size of the termination shock. The latter is comparable with the distance between the pulsar and the bow-shock, the so-called stand-off distance, d_0, defined by the balance between the wind momentum flux and the ram pressure of the incoming ISM: $d_0 = \sqrt{\dot{E}/(4\pi c \rho_{\rm ISM} v_{\rm psr}^2)}$. Such particles cannot escape from the head of the bow shock and escape by being advected in the bow-shock tail. The particle escape becomes progressively more isotropic with increasing energy. Particles with $E \in (0.01 - 0.1) E_{\rm PD}$ manage to escape only from specific regions where the PWN magnetic field reconnects with the ISM field, and typically emerge with pitch angle closely aligned with the direction of the ISM field. On the contrary, particles of higher energies $E \in (0.1 - 1) E_{\rm PD}$, escape nearly isotropically.

In addition, electrons and positrons in the range $E \in (0.01 - 0.1) E_{\rm PD}$ can escape along different paths, with the outflow being partially charge-separated. This entails the possibility that part of the escaping particles carry a net charge, which can induce current-driven instabilities, most notably the Bell instability, as discussed in Sec. 4 in the case of X-ray filaments.

Escaping leptons diffuse into the ambient medium, losing energy via synchrotron and ICS on the interstellar radiation fields, primarily on the CMB. The resulting TeV γ-ray halos or X-ray filaments thus encode valuable information on local transport properties around pulsars.

3. TeV Halos: Observation and Open Issues

Observationally, the most compelling evidence for particle escape from PWNe and subsequent diffusion in the surrounding medium came from the detection of extended TeV emission around Geminga and Monogem, first discovered by HAWC, and around PSR J0622+3749 as recently reported by LHAASO.

These halos appear roughly spherical and extend up to distances of $\approx$ 20–30 pc from the pulsar, well beyond typical PWN sizes. Their emission originates from ICS of multi-TeV $e^{\pm}$ on the CMB and other interstellar radiation fields. The halo size can be naturally related to the local diffusion coefficient, considering that high-energy particles rapidly lose energy in the ISM through ICS and synchrotron processes, traveling a characteristic distance

$$r_d(E_e) \equiv 2\sqrt{D(E_e)\tau_{\rm loss}(E_e)} \approx 26 \left(\frac{D_{100}}{5\times 10^{27}\ {\rm cm^2\ s^{-1}}}\right)^{1/2} \left(\frac{\tau_{\rm loss}}{10^4\ {\rm yr}}\right)^{1/2} \ {\rm pc}, \tag{1}$$

where D_{100} is the diffusion coefficient for particles of ∼100 TeV, which typically lose energy on a timescale of ∼ 10 kyr.

From this expression, it is immediately clear that assuming isotropic diffusion implies a diffusion coefficient suppressed by 2–3 orders of magnitude compared to the $\approx 10^{30}$ cm^2, s^{-1} expected from extrapolating the "global" Galactic diffusion coefficient inferred from CR data to $\approx$ 100 TeV.

This result immediately attracted much attention for at least three reasons: 1) its possible impact on the release of positrons by pulsars and the resulting positron flux at Earth; 2) its possible impact on the Galactic CR transport; 3) its possible impact on our understanding of diffuse γ-ray emission. Nevertheless, the physical origin of such a strong suppression remains unexplained to date.

In what follows, we summarize the main theoretical efforts made to explain this suppression (see [7] for an extensive review). These explanations can be broadly grouped into three main categories: (i) pulsars located in highly turbulent environments; (ii) pulsars embedded in typical ISM conditions, with particle transport dominated by anisotropic diffusion; and (iii) self-generated turbulence driven by the escaping particles themselves.

3.1 High environmental turbulence

In this scenario, the pulsar happens to reside in a region of strong pre-existing turbulence, possibly associated with active areas of the Galactic disk. Here, the magnetic-field coherence length $L_{\rm coh}$ is expected to be much smaller than in the typical ISM. A short $L_{\rm coh}$ naturally results in a small diffusion coefficient, and if $L_{\rm coh} \ll$ the halo size, the diffusion can be treated as effectively isotropic, naturally producing a spherical halo morphology [13].

While this scenario straightforwardly accounts for both the spherical shape and the reduced diffusion coefficient, it raises the question of the size and filling factor of such highly turbulent regions in the Galaxy. A small filling factor would imply that TeV halos around middle-aged pulsars are intrinsically rare, whereas a large one would affect global observables such as the boron-to-carbon ratio and could yield an excessive positron flux at Earth [14, 15].

3.2 Low environmental turbulence and anisotropic diffusion

A second scenario involves typical interstellar turbulence, with $L_{\rm coh}$ possibly reaching tens of parsecs. In this case, particle transport on halo scales becomes strongly anisotropic, with a diffusion coefficient parallel to the mean magnetic field ($D_{\parallel}$) comparable to the global Galactic value, and a much smaller perpendicular coefficient ($D_{\perp} \ll D_{\parallel}$). The degree of suppression of $D_{\perp}$ over $D_{\parallel}$ depends on the turbulence level, approaching isotropy only for high turbulence.

If the magnetic flux tube is approximately aligned with the line of sight, the resulting emission would appears nearly spherical and compact, due to the small $D_{\perp}$, in agreement with observed TeV halos morphology and extension. This scenario is able to reconcile the "global" CR diffusion coefficient with the one measured in TeV halos. On the other hand, the level of required alignment could be rather stringent, $\lesssim 5°$[16, 17].

However, for less favorable geometries, the emission should appear elongated and asymmetric, reflecting the structure of the local magnetic field. The fact that the first three known halos, two of which are from pulsars located within ≈ 300 pc from us, all appear roughly symmetric may indicate either that this scenario is not very likely, either an observational bias on spherical sources (see e.g. the detailed study of sources immersed in long-coherence-length fields [18]).

3.3 Self-generated turbulence

A third possibility is that the escaping particles themselves generate the turbulence that confines them. The strong CR gradient near a source can excite resonant Alfvén waves through the streaming instability—a mechanism extensively studied in the context of SNRs [19, 20]. Interestingly, this mechanism was shown to be able to work also in the case of TeV halos [21, 22], but reproducing the observed level of diffusion suppression requires that particles propagate in a flux tube with small transverse size ($\lesssim 1-2$ pc) and that a large fraction of the pulsar spin-down power is channeled into multi-TeV leptons. This scenario therefore shares with the anisotropic diffusion model the difficulty of explaining the observed spherical morphology.

3.4 The Pulsar Environment and Observational Diversity

These scenarios for interpreting TeV halos ultimately point to a broader question: in what kind of environment are middle-aged pulsars actually embedded? Do the escaping $e^{\pm}$ probe typical ISM conditions, or regions still influenced by the parent SNR or local stellar activity? A recent study [23] showed that middle-aged pulsars, even after leaving their remnants, up to a age of ≈ 300 kyr, have a high probability of residing in superbubble environments. This environment is typically characterized by region of hot gas excavated by stellar winds and repeated SN explosions, which may be naturally more turbulent than the typical ISM.

Pulsars moving through such environment may naturally produce isotropic TeV halos, based on the phenomenology described in Sec. 3.1. On the contrary, those traversing colder, more magnetically coherent regions could instead experience anisotropic diffusion, resulting in elongated and asymmetric emission, as illustrated in Sec. 3.2.

Deeper surveys with the wide field of view and high sensitivity of LHAASO, together with the superior angular resolution of upcoming Imaging Cherenkov instruments such as the ASTRI

Mini-Array and CTAO, will be essential to enlarge the sample of TeV halos and to perform detailed spectro-morphological studies.

4. X-Ray Filaments: current-driven instability from escaping particles?

X-ray observations [5, 6] revealed the presence of thin, elongated filaments emerging from a number of BSPWNe, probably synchrotron radiation produced from runaway ultra-relativistic $e^{\pm}$ propagating along the *local* Galactic magnetic field. These filaments can reach lengths of up to 15 pc, and yet remain remarkably narrow – often less than 10% of their length in thickness. The magnetic field required to explain the observation is typically a factor of a few larger than the usual $\approx 1 - 5\mu$G ISM field.

Their origin of these filaments is still debated, but a promising explanation, that invokes current-driven instabilities triggered by the escaping particles to amplify the field, has been discussed in the literature (see [8] and references therein). The idea is based on the results illustrated in Sec. 2, namely that the escape of electrons and positrons from a BSPWN can be partially charge separated, so that escaping particles may carry a net current.

In the proposed scenario, a charge-separated outflow, carrying a fraction ϵ of the pulsar spin-down luminosity, is expected to trigger the non-resonant (Bell) streaming instability, provided that the energy density exceeds that of the preexisting magnetic field B_0. In this instability, perturbations initially develop on scales $\ll r_{L0}$, namely the Larmor radius in B_0. During ≈ 5 e-folds of the instability, perturbations remain on scales $\ll r_{L0}$, and particles proceed quasi-ballistic. Near saturation, power moves to scales $\sim r_L(B_{\rm ampl})$ where scattering in the amplified $B_{\rm ampl}$ isotropizes particles and disrupts the current. In this scenario, the length of the filament would be associated to the distance traveled by particles during the typical saturation timescale. The filament width, instead, would be associated to the distance traveled by the pulsar itself during a synchrotron loss timescale of the particles in the amplified field.

The feasibility of this scenario has been tested for the cases of the Guitar and Lighthouse filaments, showing that, a modest $\epsilon \approx 10^{-3} - 10^{-2}$ can be enough to trigger the non-resonant streaming instability and to roughly reproduce the required field amplification.

Nevertheless, dedicated simulations are needed to explore the actual formation, morphology, and X-ray emissivity of such features in a self-consistent framework.

5. Conclusions and future prospects

The study of particle escape from PWNe is reshaping our understanding of CR propagation. TeV γ-ray halos and X-ray filaments offer complementary views of leptons leave their sources and interact with the surrounding medium. They demonstrate that the region around middle-aged pulsars can be very different from the "typical" ISM probed by CR transport on Galactic scales in the case of TeV halos, and that escaping particles may substantially affect their own transport in the case of X-ray filament.

At this stage it is not clear how much these phenomena are environment-dependent, with pulsars in hot, turbulent media tending to produce isotropic TeV halos, while those in magnetically coherent regions generating more complex morphologies. Also the possible connection between X-ray filaments and halo formation is far from being understood.

Current and future instruments will be crucial to advance this field. LHAASO's high sensitivity and wide field of view already allow systematic searches for new halo candidates. The ASTRI Mini-Array will provide deeper observations of nearby sources, resolving their morphology at sub-degree scales. In the future, CTAO, with its superior angular resolution and high sensitivity, could enable detailed studies of halo structures, possibly detecting features related to anisotropic diffusion. Together with numerical simulations of MHD turbulence and kinetic modeling of particle transport, these observations could ultimately allow to establish a self-consistent framework linking acceleration, escape, and Galactic propagation.

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