Astro2020 Science White Paper

Where are the PeVatrons?

Thematic Areas:

☐ Particle acceleration in the Galaxy

☐ Star Forming Regions

☐ Cosmology and Fundamental Physics

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Abstract: The search for cosmic particle accelerators capable of reaching the PeV (10^{15} eV) range, PeVatrons, is a crucial science target of the very-high-energy (gamma-ray domain around $\sim$ TeV= 10^{12} eV) community. Such accelerators are essential in the context of the problem of the origin of Galactic cosmic rays, and more generally, in order to understand the physical mechanisms involved in the production of PeV particles. Subsequent to the acceleration of PeV particles, the production of gamma rays in the 100 TeV range is expected. Explorations in this energy domain are thus natural in the search for PeVatrons. Next generation instruments operating in the gamma-ray domain will be remarkable assets in the search for PeVatrons and the understanding of their properties. The majority of the

material is drawn from *Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere* [1]. If you'd like to cite results presented in this white paper, please cite the original paper.

1 Introduction

The search and study of sources capable of accelerating particles up to PeV = 10^{15}eV is a well identified key science project of the very-high-energy community [2]. These objects are especially important in the context of the study of cosmic rays (CRs).

Clear measurements conducted over the last decades have established that 1) CRs fill our Galaxy with an energy density comparable to the one in thermal interstellar medium (ISM), 2) they are mostly protons ($\sim 90\%$) and 3) their differential spectrum measured at the Earth follows a power-law in energy close to $E^{-2.7}$ before transitioning to E^{-3} at an energy of about $\approx 1-3$PeV [3], called the *knee*. At this moment, the sources of CRs have not unambiguously been identified, but the previously observed features set natural requirements on the sources, e.g. the sources of CRs have to be able to accelerate protons up to the knee, therefore being *PeVatrons*.

It has been understood that PeV protons, interacting with protons of the ISM, must produce gamma rays of ~ 100 TeV close to the acceleration sites. Proton-proton interaction is the only mechanism capable of producing gamma-ray photons in the ~ 100 TeV range, and therefore, detections in this energy domain are seen as a direct proof that the acceleration of PeV particle is taking place. Indeed, in this energy domain, all other mechanisms capable of producing gamma-ray photons become inefficient, as for example the inverse Compton scattering of electrons on soft photons. The 100 TeV range is therefore a natural preferred energy domain for the search of PeVatrons, and this motivates efforts to invest in instruments optimized in this domain.

While in the Northern Hemisphere, the HAWC[1] gamma-ray observatory is sensitive to a few hundred GeV to beyond 100 TeV energy range [4, 5], there is currently no gamma-ray instrument in the Southern Hemisphere optimized in the 100 TeV energy range. In this note, we discuss on the search for PeVatrons, and illustrate the possibilities offered by unbiased surveys in the 100 TeV range [1].

2 Pevatrons

Several strong arguments have supported the idea that supernova remnants (SNRs) could be the sources of Galactic CRs [see e.g. 6, 7, 8, for reviews on the topic]. These include, for example, descriptions of diffusive shock acceleration mechanisms [9, 10, 11, 12], explaining how non-thermal particles are produced, or the observations of several SNR shells in TeV gamma rays, direct evidence of efficient particle acceleration at strong SNR shocks [13].

It is however remarkable that no known SNR has yet been identified as a PeVatron [14], which would have been considered as conclusive evidence in favor of the SNR paradigm. Moreover, evidence for the acceleration of PeV protons has come to reinforce the idea that other astrophysical sources and mechanisms may be involved the acceleration of particles up to the PeV and in the contribution to the bulk of Galactic CRs. For example, the source J1745–290, whose gamma-ray spectrum in the several tens of TeV extends with a remarkably hard spectrum has not been associated to any SNR. Explanations involving the supermassive

[1] https://www.hawc-observatory.org/

black hole Sagitarrius A*, enhanced SN rate, or contribution from massive stars have been proposed, illustrating the variety of Galactic PeVatron candidates [15, 16].

2.1 Galactic Pevatron Candidates

2.1.1 SNRs

The fact that efficient particle acceleration is occurring at SNRs is no longer under debate, but many aspects of such acceleration are still unclear. Especially, the questions tackling the issue of the acceleration of PeV particles are still open: Can all SNRs be PeVatrons? How long does the PeVatron phase last? How do the PeV particles escape the SNR? [16]

Observations in the very-high-energy range have already proven to be of great interest to study SNRs. In the 100 TeV range, observations are of crucial importance for at least two reasons. First, at ∼100 TeV, observed gamma rays directly show the acceleration of PeV particles. Second, because of the Klein-Nishina effect, leptonic mechanisms are inefficient to produce photons in this range, and therefore 100 TeV gamma rays are indicative of hadronic mechanisms, offering the possibility to discriminate between the two possible origins [17].

2.1.2 Star-Forming Regions

Clusters of massive stars in star-forming regions (SFR) have emerged as objects of interest in the search for PeVatrons. Shock waves due to collective stellar winds and SN explosions of old massive stars in the stellar associations of the star forming regions can accelerate CRs up to relativistic energies [18]. The number of gamma-ray sources detected by current instruments which are associated with the stellar association is so far limited. However observations with current gamma–ray instruments of the Galactic clusters Westerlund 1, Westerlund 2, and Cyg OB2 have underlined the possibility of efficient acceleration of protons up to the PeV range [19]. Studies of energy distribution spectra for the gamma-ray emission of these sources in the TeV range could provide definitive evidence of PeVatrons in star forming regions.

2.1.3 The Galactic center

The detection of gamma rays of several tens of TeV, with hard spectrum and no evidence of cut-off in the spectrum has been presented by the H.E.S.S. collaboration [20]. This detection has been seen as evidence of the production of $\sim$ 100TeV gamma rays, thus demonstrating the acceleration of PeV protons.

Although the corresponding PeVatron has not been identified, several objects have been proposed. A natural plausible candidate is the supermassive black hole Sagittarius A* [20, 21, 22], but other mechanisms involving other sources have been proposed, and are being investigated, such as an increased SN rate in the Galactic center [23], massive stars [19], or millisecond pulsars [24], among others.

The Galactic center is accessible to instruments located in the Southern Hemisphere, therefore a Southern Hemisphere instrument optimized in the 100 TeV domain could allow deeper explorations and help identify the origin of the PeV particles. This will complement other ongoing efforts, such as radio air-shower arrays at the south pole [25].

2.2 Extra-galactic PeVatrons

Current instruments operating in the very-high-energy domain have reported on the detection of extra-galactic sources, such as Active Galactic Nuclei (AGN) [26]. Recently, the MAGIC telescope reported on the first detection of TeV gamma rays from gamma-ray bursts, potential PeVatron accelerators [27]. In addition, other sources have been proposed as potential PeVatrons, such as core-collapse supernovae (CCSNe), CCSNe in interaction with strong winds in compact stellar clusters, or clusters of galaxies [28, 29]. All these examples are mentioned to illustrate that many extra-galactic objects are expected to be PeVatrons, and that future gamma-ray instruments optimized in the 100 TeV might play a role in their identification and study, and complement observations with other messengers, such as neutrinos [30].

3 Observational challenges and prospects

Some of the questions related to PeVatron physics that we want to answer are as follows:

1. What source(s) can accelerate CRs to PeV energies?
2. Are SNRs PeVatrons? If yes, are *all* of them PeVatrons? What are the characteristics of the pevatron phase? How do SNRs contribute to Galactic CRs up to the knee?
3. What physical processes are involved at PeVatrons and in their close environment?
4. How do accelerated particles escape their accelerator?
5. How do Galactic PeVatrons distribute in the Galactic plane?
6. Can we identify subpopulations of PeVatrons?

To answer these questions, we need various abilities in our current and future generation observatories. To look for the PeVatrons' signature using very high energy gamma rays, we need gamma-ray instruments sensitive to beyond the 100 TeV range. We need these TeV observations with excellent angular and energy resolution, to obtain spatially- and spectrally-resolved maps of the CR proton population in some of the accelerators. This will help to better understand where the particle acceleration occur and how the particles propagate in the acceleration region and finally escape. An unbiased search of the Galactic plane, in a yet unexplored higher energy range can identify the yet undiscovered PeVatrons. For that we need wide field-of-view observatories. For further evidence of hadronic acceleration, we need MeV – GeV observations of characteristic pion bump signatures that we expect from neutral pion decay. We need complimentary non-thermal X-ray/radio observations to determine what percent of gamma-ray emission may be of leptonic origin. We also need thermal X-ray observations to measure densities, temperatures, composition of the plasma in the accelerator region. Even with all these abilities, the efficient study of extragalactic pevatrons will not be possible without neutrino observatories.

In Fig. 1, left panel, the differential sensitivity of several gamma–ray instruments useful in the search for PeVatrons is represented.

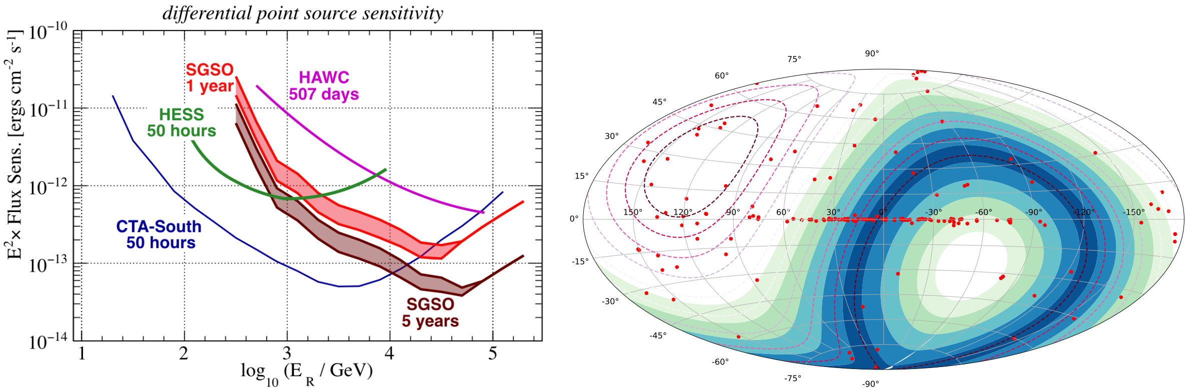

Figure 1: *Left:* Differential point-source sensitivity as a function of reconstructed gamma-ray energy for several ground-based gamma-ray observatories in the Southern Hemisphere, taken from Albert et al. [1]. *Right:* Sky map in galactic coordinates showing the complementary of the visibility ranges between HAWC and a Southern Hemisphere instrument. The color bands correspond to 10° in zenith angle (up to 45°) at latitude 25° South. The dashed contours show the same for HAWC, with the darkest line marking the edge of the field-of-view at 45° from zenith. The red markers correspond to TeV gamma-ray sources discovered by H.E.S.S., MAGIC and VERITAS (data from `http://gamma-sky.net`).

Fig. 1 shows the region of the sky explored in a systematic survey conducted by combined efforts of two wide–field instruments in the Northern and Southern Hemisphere. The observations performed with large-field instruments will complement other observatories, such as those optimized in other wavelengths, e.g. in the MeV – GeV range where signatures of hadronic mechanisms can appear, multi-wavelength efforts [31, 32], or observations with neutrino telescopes [30].

4 Conclusions

In the search for PeVatrons, two strategies are usually considered: targeted observations in the direction of identified sources of interest and systematic surveys of the sky. A wide-field Cherenkov instrument, located in the Southern Hemisphere and optimized in the 100 TeV range, would be an instrument of choice to perform a systematic survey of the Galactic plane, and identify Galactic PeVatrons. Such an instrument would thus be a remarkable asset to complement other instruments operating in the gamma-ray domain, such as CTA [2], LHAASO [33], and HAWC [34].

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