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LHAASO: A PeVatrons explorer

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Over the last two decades, we have seen two revolutions in γ-ray astronomy—at GeV and TeV energies. The detection of thousands of GeV and hundreds of TeV γ-ray emitters representing more than ten galactic and extragalactic source populations indicates that cosmic ray (CR) factories are distributed throughout the Universe in a wide diversity of forms and scales (see, e.g., ref. [1] and references therein).

These days, we are witnessing a new revolution, this time in the PeV band. Recently, the LHAASO Collaboration [2] reported detection of a dozen ultra-high-energy (UHE; $E\geq$ 0.1 PeV) γ-ray sources, thus opening a new window in the electromagnetic spectrum. UHE γ-rays, produced in interactions of charged particles (protons and electrons) with an order of magnitude higher energies, serve as direct messengers of CR PeV atrons.

LHAASO is a new mega-scale facility located at 4.4 km above sea level in Sichuan Province [3]. It is a dual-task detector designed for both cosmic-ray and γ-ray studies and consists of three components—the Water Cherenkov Detector Array (WCDA) [4], Kilometer Square Array (KM2A) [5], and Wide Field-of-view Cherenkov Telescope Array (WFCTA) [6] covering together more than 4 decades in energy, from 0.1 TeV to 1 PeV and beyond. KM2A is the principal component designed for the detection of UHE γ-rays. The vast (1 km^2) area of the surface detectors, coupled with the underground muon detectors providing record high (better than 10^4) γ/p separation power, results in the sensitivity, in terms of the minimum detectable energy flux, approaching $E^2 dN/dE \sim 10^{-14}$ erg cm^{-2} s^{-1} at $E\sim 0.1$ PeV. This is significantly below the sensitivities of other current and planned space-borne and ground-based γ-ray detectors. The adequate UHE photon statistics combined with the good angular and energy resolutions of about 15 arcmin and 20%, respectively, allows detailed spectroscopic and morphological studies.

This achievement of the LHAASO Collaboration is impressive especially given that the Chinese researchers are latecomers to γ-ray astronomy. Still, the great success of LHASO would not be possible without the expertise of the key collaboration members acquired during the productive work in the pioneering high altitude Tibet AS_γ [7] and ARGO-YBJ experiments [8].

The first published results of LHAASO provide a hint that the Milky Way is full of PeVatrons [2]! This is a result of extraordinary importance for the solution of the century-old mystery of the origin of galactic CRs. It promises a decisive step towards the identification of the major contributors to the locally detected CRs in the so-called *knee* region in the CR spectrum around a few PeV [1]. A prompt conclusion from the list of reported UHE sources is the absence of *young* SNRs in the vicinity of LHAASO sources raising doubts about the ability of SNRs to operate as PeVatrons.

Nevertheless, it is premature to draw the verdict. Some of the reported UHE sources could be interpreted within the scenario when the PeV CRs already have left the SNR and initiate a delayed γ-ray emission ("echo") after they reach and interact with the nearby dense molecular clouds. Future observations should provide decisive tests of this scenario

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applied to young and middle-aged SNRs. Meanwhile, in the context of the general problem of the origin of CRs, SNRs remain major sources of galactic CRs, although with a reduced role at the highest (PeV) energies.

The clusters of massive young stars represent an attractive alternative to SNRs. The colliding stellar winds and SN explosions in these clusters containing tens of massive and luminous stars can drive giant superbubbles filled by highly turbulent plasma and magnetic fields. An effective particle acceleration can be initiated by strong shocks inside the superbubbles or by interacting winds close to the stars. Conditions for the acceleration of particles to PeV energies in these objects could be more favorable than in SNRs. Remarkably, we see at least two LHAASO sources surrounding young stellar clusters. The spectrum of Cygnus Cocoon, a large diffuse structure, with the stellar cluster Cygnus OB2 inside, extends to 1.4 PeV! Because of severe radiative energy losses, such energetic photons cannot be explained by the electromagnetic interactions of electrons. This implies that we deal with a Proton PeVatron accelerating protons and nuclei to energies beyond 10 PeV/nucleon.

While the acceleration of protons and nuclei to PeV energies requires non-trivial theoretical efforts, the acceleration of PeV electrons is a challenge at the edge of reality. The only galactic sources that can accelerate electrons to PeV energies are the so-called Pulsar Wind Nebulae (PWNe). In these objects, we deal with perfectly designed accelerators operating at almost 100% efficiency concerning (1) the conversion of the available kinetic energy of the rotating neutron star to relativistic particles, and (2) the acceleration rate at the margin allowed by classical electrodynamics and ideal magnetohydrodynamics. Among the UHE sources, we have one unambiguously identified Extreme Electron accelerator - the famous Crab Nebula. The extension of radiation to 1.1 PeV [9] gives us unambiguous information about the energy of the parent electron, $E \geq 0.1$ PeV. For the magnetic field of about $B \approx 110$ μG, extracted from the multi-wavelength data, it is the half of the maximum achievable energy. Because of the synchrotron cooling of electrons, the efficiency of conversion of the energy of accelerated electrons to γ-rays is very small. Therefore, despite the modest UHE γ-ray luminosity, the injection power of PeV electrons in then Crab is huge. It constitutes almost 1 per cent of the pulsar's rotational energy, $\dot{W}_e\,(\mathrm{PeV}) \approx 2.5\times10^{36}$ erg s^{-1} that exceeds by three orders of magnitude the luminosity of the Sun!

The Crab Nebula and its pulsar are exceptional in many respects. The pulsar's spin-down luminocity exceeds, by at least one order of magnitude, the rotational powers of other pulsars in the Milky Way. On the other hand, because of the significantly smaller nebular magnetic fields, the TeV and PeV γ-ray production efficiencies are dramatically enhanced compared to the Crab Nebula. This compensates, to a large extent, the relatively modest rotational powers of other pulsars making detectable their nebulae in TeV and PeV γ-rays. At least several extended objects from the LHAASO source list seem to have links to nearby pulsars [2]. These large diffuse structures are composed of two components—the pulsar wind nebulae, a relativistic MHD structures created at the termination of the pulsar winds, and the halo of electrons and positrons that escaped the nebulae and presently propagate freely in the interstellar medium.

The first LHAASO results reveal only the tip of the Iceberg. In the coming years, one can anticipate discoveries in a few research areas that would dramatically change our current concepts about the most energetic and extreme phenomena in the non-thermal high energy Universe. For the next decade, LHAASO will be the major contributor to these discoveries.

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