LHAASO and Galactic cosmic rays

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Cosmic rays (CRs) are relativistic charged particles in the interstellar medium (ISM). They are mainly protons (hydrogen nuclei) with about 10% fraction of helium nuclei and smaller abundances of heavier elements. CRs are an important component in ISM. In our galaxy, the energy density of CRs is similar to that of the magnetic fields and interstellar radiation fields (ISRFs). CRs also determine the ionization rate and heating of gas in the dense core of molecular clouds, thus playing a leading role in the astro-chemistry processes therein and controling the star-forming processes. More than a century has passed since Hess discovered the extra-terrestrial origin of CRs (in 1912), yet the origin of CRs still remains as a mystery.

The spectrum, direction, and composition of CRs can be measured directly by both ground-based and space-borne detectors. One of the most striking features of these direct measurements is that the energy spectrum above 1 GeV can be roughly described by a single power law, and the first structure is the so-called "knee" at about 1 PeV, where the spectral index increases from about 2.7 to 3.3. The current paradigm assumes that the bulk of the CR flux up to the knee is linked to galactic sources. Searching for the astrophysical accelerators that can accelerate particles up to 1 PeV in our galaxy, dubbed "PeVatrons," is one of the key issues in CR studies. However, CRs are charged particles and will deflect when propagating in interstellar magnetic fields. Thus, the locally measured CRs already lose nearly all spatial information of their sources.

On the other hand, CRs interact inevitably with other components in ISM and will produce gamma rays and neutrinos. These secondary particles propagate rectilinearly and can provide useful information on the distributions and sources of CRs. While neutrino astronomy still suffers from limited statistics and angular resolutions, gamma-ray astronomy, with a development of more than 30 years and identifications of more than 5,000 sources, is the ideal tool for CR studies.

So far, the most promising galactic CR sources are supernova remnants (SNRs). The shock in SNRs is regarded as the ideal environment for first-order Fermi accelerations of relativistic particles, and the gamma-ray observations in the GeV band have already found the spectral feature produced by the decay of neutral pions, which comes from the interaction of CR protons with ambient gas toward mid-aged SNRs. Such spectral features are regarded as direct evidence that SNRs do accelerate CR protons. But whether SNRs can accelerate CRs up to the energy of the knee, about 1 PeV, is still unknown. Generally speaking, gamma rays produced in the interaction of CRs and ambient gas bring about 1/10 of the energy from parent CRs. Thus, the break of the gamma-ray spectra of about dozens of GeV in mid-aged SNRs reveals a break of about several hundred GeV in the parent proton spectrum. Indeed, the shock speed in such mid-aged SNRs has already been effectively decelerated below 1,000 km/s, and the maximum energy of accelerated particles is expected to be lower than 10 TeV. On the other hand, the shock speeds in young SNRs are

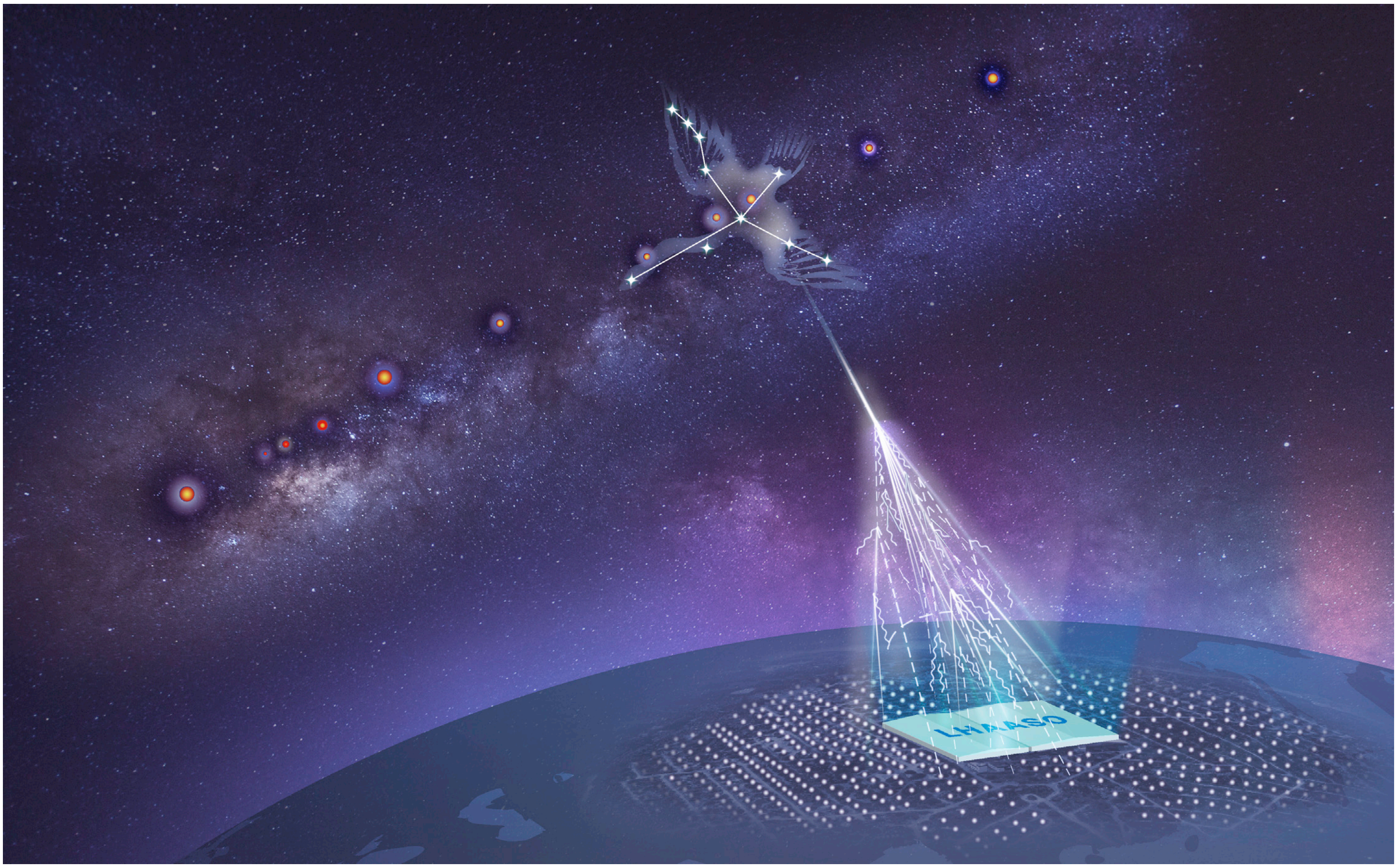

Figure 1. A schematic view of the air shower observed by LHAASO array, and the 12 sources detected by LHAASO using 11 months data of half array Right top panel shows the significance map of the Crab nebula observed by LHAASO-KM2A.

much higher, and they are regarded to be responsible for the acceleration of CRs up to higher energeis. Several young SNRs are already detected at the TeV band. However, the spectral shapes of the observed TeV emission from these young SNRs all show breakage or softening before 10 TeV. Even if these TeV emissions are of hadronic origin, it seems that the energy of parent CR protons can only extend to 100 TeV, which is still one order of magnitude smaller than 1 PeV. To identify whether these young SNRs are PeVatrons or not, observations above 100 TeV would be crucial.

In addition, young massive clusters (YMCs) have recently been considered as another population of CR accelerators.[1] Massive stars have sufficient kinetic energies, supplied by collective stellar winds, to provide the flux of locally measured CRs. The speed of stellar wind can be as high as 3,000 km/s. It is still significantly lower than the shock speed in very young SNRs, but stellar winds can last 10^6 years, thus they may be able to accelerate CRs even to higher energies than that in SNR shocks. And thanks to the advancement of gamma-ray astronomy, recently, several YMCs have been identified as gamma-ray sources. They all reveal an extended gamma-ray morphology with a hard (index $\sim$2.3 type) gamma-ray structure. The spectra of several systems, such as the Cygnus Cocoon, Westerlund 1, and Galactic Center regions, can extend to about 10 TeV without cutoff, which make them also promising PeVatron candidates. More interestingly, the observed morphology of the gamma-ray emissions in these regions also reveals a 1/r spatial distribution of CRs with respect to the central source,[1] which indicates a continuous CR injection process therein.

The observations of both SNRs and YMCs above 10 TeV are crucial to identify whether these systems are PeVatrons or not. Indeed, a hard gamma-ray spectrum with no break/cutoff above dozens of TeV can be regarded as direct evidence of PeVatrons. This is because in this energy range, the gamma-ray production mechanism should either be the pion-decay process in the inelastic collision between CR protons with ambient gas or the inverse Compton (IC) scattering process of the relativistic electrons. In the energy range above 10 TeV, the main low-energy photon fields for IC are cosmic microwave backgrounds (CMBs), and the Klein-Nishina effect is significant. In this case, where even the parent electron spectrum has no break or cutoff, the decline of a cross section would introduce a softening in the produced gamma-ray spectrum. Thus, the Klein-Nishina effect inevitably makes a cutoff structure at $\sim$ 10 TeV in IC spectra. Such a method has already been invoked by H.E.S.S. collaborations in the study of the galactic center (GC),[2] and they also conclude that the GC does harbor a PeVatron by studying the spectrum of diffuse gamma-ray emissions. Such a method requires accurate measurement above 10 TeV. Further interesting information may come from morphology information of the gamma-ray emissions. Such information can provide direct clues on the injection of CRs. However, the current observations above 10 TeV mainly come from imaging Cherenkov telescope (IACT) arrays. The fields of view (FOVs) of such instruments are typically a circle with a diameter of less than 5°. Such an FOV is even smaller than the size of the detected gamma-ray emissions toward the YMC Cygnus OB2. Thus, an instrument with a larger FOV is required to study the morphology of such extended sources.

In this regard, the Large High Altitude Air Shower Observatory (LHAASO), with much higher sensitivities above 10 TeV compared with other operating gamma-ray instruments and an FOV as large as several steradians, is the most powerful tool to perform PeVatron searching and corresponding studies. LHAASO is one China's major national scientific and technological infrastructure facilities focusing on CR observation and research. It is located at Haizi Mountain in Sichuan Province with an altitude of 4,410 m. The construction began in 2017 and was completed in July 2021. It started operation in 2019, when half of the whole arrays were complete. In ground-based gamma-ray astronomy, the detectors indeed detect air showers produced by the interaction of astrophysical gamma-rays with the atmosphere of the earth. Thus, the main background comes from the air showers produced by CRs. Due to the much higher fluxes of CRs compared with the gamma rays, the background dominates the signal. As a result, the background rejection power determines the sensitivity of ground-based gamma-ray detectors. LHAASO, equipped with the largest muon-detector arrays, can provide the best discrimination power between air showers produced by gamma rays and CRs.[3] Thanks to the large area and high background rejection power, the sensitivity of LHAASO is at least one order of magnitude higher, at 100 TeV, than any other running or even planned instrument.[3]

Due to the unparalleled sensitivity in the energy range, only after 11 months of running the half array of LHAASO-KM2A, 12 sources above 100 TeV have been detected (see Figure 1).[4] Considering the sources detected above 100 TeV before LHAASO were less than a handful, it would be fair to claim that LHAASO has opened a new era of ultra-high energy (UHE) astronomy. Except for the Crab nebula, all the sources are extended, but the potential astrophysical counterparts cannot be confirmed yet. The most probable candidates include SNRs, and YMCs, as mentioned above, and also pulsar wind nebulae (PWN). The only established source is Crab nebula,[5] toward which the highest energies of the detected photons are higher than 1 PeV. The compact size of the source and the energy of the radiated photons have demonstrated that the acceleration efficiency of this object is very near the limit allowed by standard magnetohydrodynamics (MHD). Furthermore, current measured spectra already reveal possible deviation from the traditional one-zone leptonic modeling of PWNs.

Eight out of 12 sources are potentially linked with SNRs, which make SNRs as PeVatron still an attractive scenario. Detailed spectral and morphological studies, which require more exposure on these sources, are required for further identification. Another interesting case is that the highest energy photons detected so far, with an energy of 1.4 PeV, are from the aforementioned Cygnus region. Considering the former observations in a lower energy band, the Cygnus region probably does harbor a galactic PeVatron, which may be the YMC Cyg OB2. After 2 to 3 years of exposure to the full LHAASO array, in the future, it is quite promising that we will be able to draw clear conclusions on this region. In addition to these 12 sources, two new UHE gamma-ray sources, LHAASO J0341+5258 and LHAASO J0621+3755, have also been detected; the latter was further identified as the third Pulsar halo.

In associating the astrophysical sources with the gamma-ray sources as well as identifying the PeVatrons, multiwavelength studies will also provide decisive information. If the gamma rays are of hadronic origin, then the gas distributions, together with gamma-ray morphology, can provide decisive clues on the distribution, injection, and propagation of CRs. In this aspect, the Milky Way Imaging Scroll Painting (MWISP) will provide highly accurate molecular gas distributions toward the LHAASO sources and help determine the radiation mechanism, and the Five-hundred-meter Aperture Spherical radio Telescope (FAST) will provide atomic gas distributions as well as a state-of-the-art pulsar catalog, which is also crucial in identifying the pulsar-related UHE sources such as PWN and pulsar halos. In the coming years, LHAASO will continue monitoring the UHE gamma-ray sky. In addition, LHAASO will also measure directly CR spectra and compositions with an unprecedented accuracy in the energy range of the knee, especially with the LHAASO-WFCTA subarray.[3] Combining CR direct measurements and UHE gamma-ray astronomy, as well as multiwavelength information from MWISP and FAST, LHAASO will definitely make important progress in solving the century-long puzzle of CR origin.

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DECLARATION OF INTERESTS

The authors declare no competing interests.