Review
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Received: December 20, 2021; Accepted: June 15, 2022

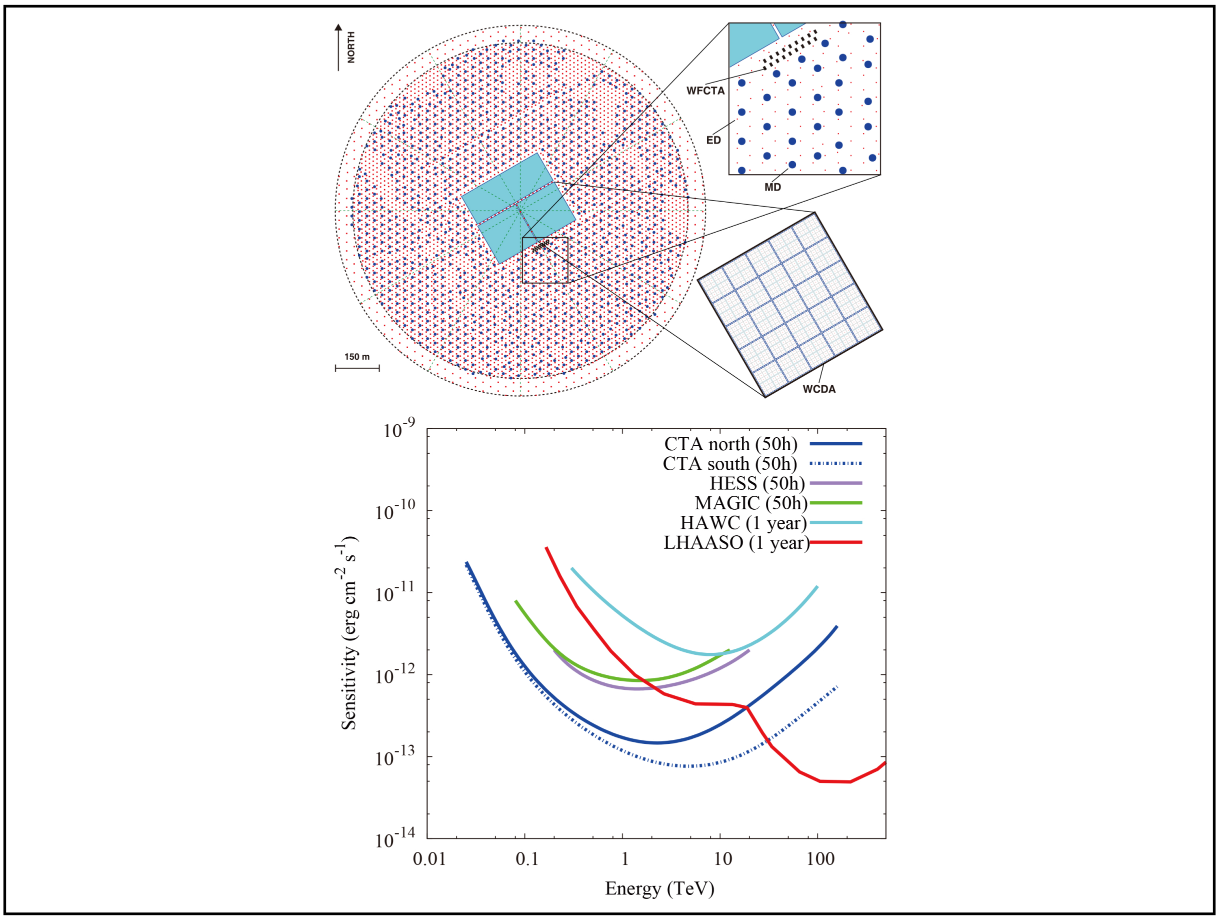
Investigating Galactic cosmic rays with γ-ray astronomy

Ruizhi Yang[1,2,3] ✉

[1]*Department of Astronomy, School of Physical Sciences, University of Science and Technology of China, Hefei 230026, China;*
[2]*CAS Key Laboratory for Research in Galaxies and Cosmology, University of Science and Technology of China, Hefei 230026, China;*
[3]*School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, China*

✉Correspondence: Ruizhi Yang, E-mail: yangrz@ustc.edu.cn

Graphical abstract



Due to the unprecedented sensitivity in the ultrahigh energy γ-ray band (red curve in lower panel), LHAASO (layout shown as the upper panel) will play a leading role in the cosmic ray study.

Public summary

- γ-rays are an important tool to study cosmic rays (CRs).
- γ-rays can be used to probe the CR accelerator and the CR distributions.
- LHAASO and other future experiments will shed light on the origin of CRs.

Citation: Yang R Z. Investigating Galactic cosmic rays with γ-ray astronomy. *JUSTC*, **2023**, 53(1): 2. DOI: 10.52396/JUSTC-2021-0269

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[3]School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, China

✉Correspondence: Ruizhi Yang, E-mail: yangrz@ustc.edu.cn

Cite This: *JUSTC*, **2023**, 53(1): 2 (12pp)   Read Online

Abstract: Cosmic rays (CRs) are one of the most important components in the interstellar medium (ISM), and the origin of CRs remains a mystery. The diffusion of CRs in turbulent magnetic fields erases the information on the distribution of CR accelerators to a large extent. The energy dependent diffusion of CRs also significantly modifies the initial (acceleration) spectra of CRs. In this regard, γ-rays, the secondary products of interactions of CRs with gas and photons in the ISM, provide us with more information about the origin of CRs. More specifically, the γ-ray emissions associated with gas, can be used to study the distribution of CRs throughout the Galaxy; discrete γ-ray sources can elucidate the locations of individual CR accelerators. Here, the current status and prospects in these fields are reviewed.

Keywords: cosmic ray; γ-rays

CLC number: P172.3   **Document code:** A

1 Introduction

Cosmic rays (CRs) are relativistic charged particles in the interstellar medium (ISM). They are mainly protons (hydrogen nuclei) with an approximately 10% fraction of helium nuclei and smaller abundances of heavier elements. The energy density of CRs is approximately 1 eV/cm^3 [1] in the vicinity of the solar system, which is similar to that of the magnetic fields and interstellar radiation fields (ISRF) in the Galactic plane. CRs also determine the ionization rate and heating of gas in the dense core of molecular clouds, where both UV photons and X-rays are effectively shielded[2, 3]. Thus, CRs play a leading role in the astro-chemistry processes therein and control the star-forming processes[4, 5]. CRs are also the most important background in the indirect search of dark matter[6]. More than a century has passed since Hess discovered the extra-terrestrial origin of CRs in 1912, yet the origin of CRs remains a mystery.

The direct measurement of CRs can be performed by both ground-based detectors and space-borne detectors, such as Pierre Auger[7], Telescope Array[8], ARGO-YBJ[9], AMS-02[10] and DAMPE[11]. One of the most striking features of these direct measurements is that the energy spectrum above 1 GeV can be described by a single power-law, and the first structure is the so-called "knee" at approximately 1 PeV, where the spectral index increases from approximately 2.7 to 3.3[12]. The current paradigm of CRs postulates that the bulk of the CR flux up to the "knee" is linked to galactic sources. However, these direct studies of CRs, which include measurements of the energy spectrum, mass composition and arrival directions of particles, provide important but not decisive information about the production sites of CRs and their propagation in the Galaxy. CR are charged particles and will deflect when propagating in the interstellar magnetic fields. Thus, the locally measured CRs already lose nearly all the spatial information of their sources. The CRs are believed to diffuse in the ISM with an energy-dependent diffusion coefficient[13], which will distort the measured CR energy spectrum. Furthermore, it is not straightforward that CRs are distributed uniformly in the Galaxy and the direct measurement near the Earth can be a good representative of the CRs in the Galaxy.

On the other hand, CRs will inevitably interact with other components in ISM which will produce γ-rays and neutrinos. These secondary particles propagate rectilinearly and can provide direct information on the distributions and sources of CRs. Neutrino detectors have made impressive progress in recent years[14, 15], but neutrino astronomy still suffers from limited statistics and angular resolutions. To date, no high-energy neutrino sources have been firmly identified. In this regard, γ-ray astronomy, with a development of more than 30 years and identifications of more than 5000 sources[16], is the ideal tool for such a kind of study. More specifically, γ-ray emissions can be utilized to investigate CR physics in two ways: the discrete γ-ray sources can be used to elucidate the locations of individual CR accelerators, identify which objects are responsible for the CR acceleration and investigate the acceleration mechanisms; the γ-ray emissions associated with gas, such as the γ-rays from the molecular clouds and the diffuse emissions in the Galactic plane, can be used to study the distribution of CRs throughout the Galaxy.

In this review, I will present the current state of art in this field. The rest of the paper is organized as follows. In Section 2, I will describe the current status of γ-ray astronomy, especially the recent progress of γ-ray detectors. Then I will discuss the study on the potential CR sources by γ-rays in Section 3, in which I will focus on the supernova remnants

DOI: 10.52396/JUSTC-2021-0269
JUSTC, **2023**, 53(1): 2

(SNRs) and young massive star clusters (YMCs), as well as the ultra-high-energy γ-ray sources recently detected by LHAASO. In Section 4, I will describe the γ-ray observations on giant molecular clouds and diffuse γ-ray emissions in the Galactic plane, which can provide unique information on CR distribution and propagation in our Galaxy. In Section 5, I will summarize and discuss the possible prospects.

2 Recent progress in γ-ray astronomy

The atmosphere is opaque for γ-rays. Thus, there are two ways to detect γ-rays: one is to place the detector into space, and the other is to detect the secondary produced in the interaction between γ-rays and the atmosphere. In space, pair conversion telescopes such as the Fermi Large Area Telescope (LAT)[17], AGILE[18] and DArk Matter Particle Explorer (DAMPE)[11] have made prominent progress in recent years. In such detectors, the primary γ-ray is converted into electron-positron pairs, and the pairs are traced to reconstruct the direction and energy of the primary γ-ray. As a result, such detectors can only operate above dozens of MeVs, below which the Compton scattering of incident γ-rays will dominate the pair production process. Thanks to the development of the technology of both detectors and electronics, such detectors can reach an angular resolution of several arcminutes above 10 GeV and an energy resolution of approximately 10%. The geometry of such detectors also allows a large field of view (FOV) of several steradians. Another advantage of such space-borne detectors is the long duty-cycle; in principle, they can operate continuously. However, since these detectors are deployed in space, the effective area can hardly be larger than 1 m^2; thus, the detection of γ-rays above 1 TeV is limited by statistics. Consequently, such detectors mainly focus on GeV γ-rays and have obtained fruitful results. Remarkably, more than 5000 sources have been detected by the Fermi-LAT[16] after an exposure of more than 10 years.

The interaction of γ-rays with the atmosphere is described by the cascade processes of electromagnetic interaction and produces the air showers (for a review, see Ref. [19]). Thus, the ground-based γ-ray telescopes indeed observe the air showers. Ground-based telescopes can be further divided into two types. One is called the extensive air shower array (EAS), which detects the electrons/muons in air showers directly using a particle detector array. The other is imaging air Cherenkov telescope arrays (IACT), which detect the Cherenkov radiation of the secondaries (mainly electron/positrons) in the air showers. EAS can be deployed in large areas and can easily reach an effective area of more than 10^5 m^2. It can also operate in a nearly full duty cycle. The detection efficiency of the air shower drops with an increasing zenith angle, but the FOV with a reasonable effective area can still be larger than several steradians. However, due to the large fluctuation of the lateral distribution of the particles in the air shower, the angular resolution is limited for EAS, which can hardly be better than 0.2°. Typical EAS arrays include ASγ[20], HAWC[21], ARGO-YBJ[9] and LHAASO[22]. Such detectors are most effective for γ-rays above 1 TeV. Since not only γ-rays but also CR can also produce air showers, EAS are also powerful direct CR detectors. CRs are the dominant background in ground-based γ-ray astronomy, and the particle identification directly determines the sensitivities of both EAS and IACTs.

Cherenkov radiation is dominated by near-UV and optical bands, and IACTs are indeed optical telescopes. With stereo reconstructions, the angular resolution of such systems can reach 2 arcminutes, which is the best in γ-ray astronomy. However, as optical telescopes, the FOVs of such systems are limited. For current instruments, the diameters of FOVs are all smaller than 5°. Furthermore, the Cherenkov light can only be detected on clear nights. If the camera uses traditional photo-multipliers (PMTs), the observations are further limited to clear nights without a moon. Thus, the duty cycles for such systems are much smaller than the EAS arrays. Due to the different advantages, EASs are especially suitable for sky surveys and studies of extended or diffuse emissions, while IACTs are good at obtaining deep observations on the compact sources. In principle, the energy range of IACTs can be as low as 1 GeV, but the low energy threshold requires an extremely large collection area of mirrors. The current IACT is equipped with a mirror with a diameter of approximately 10 m, which provides an energy threshold of approximately 100 GeV. H.E.S.S.[23], MAGIC[24] and VERITAS[25] are the operating IACTs, which have contributed significantly to TeV astronomy and have detected more than 200 TeV sources. Cherenkov Telescope Array (CTA)[26], the next generation of IACTs, is also under construction. CTA will be equipped with more than 100 telescopes located in both the Northern and Southern Hemispheres. The total collection area will be larger than 1 km^2. The telescopes with three different sizes will also provide an energy coverage between 20 GeV and 300 TeV. With an angular resolution of several arcminutes and a large collection area, the sensitivity of CTA would be improved by one order of magnitude compared with the current IACTs.

The most exciting progress in recent years is the operating of LHAASO (Large High Altitude Air Shower Observatory), which opened the new window of ultra-high energy (UHE, > 100 TeV) γ-ray astronomy. LHAASO is a dual-task (CRs and γ-rays) EAS. It is one of the Chinese major national scientific and technological infrastructure facility focusing on cosmic ray observation and research[27]. It is located on Haizi Mountain in Sichuan Province at an altitude of 4410 m. The construction began in 2017 and was completed in August 2021. It started operation in 2019, when half of all arrays were complete. It contains three sub-arrays, which will be described below.

(Ⅰ) km^2 array (KM2A), which contains 5216 electromagnetic particle detectors (ED) and 1188 muon detectors (MD). Each ED is made of plastic scintillators with a surface area of 1 m^2. A total of 4922 EDs are distributed in the central part of the array with a distance of 15 m, and the other 294 EDs are placed in an outskirt ring with a distance of 30 m between neighboring EDs. MDs are underground water Cherenkov detectors, each with an area of 36 m^2. The distance between the neighboring MDs is set to 30 m. The EDs and MDs occupy a total area of more than 1 km^2. KM2A are designed to measure the energy of γ-rays and CRs above 100 TeV. KM2A are designed to measure the γ-rays above 10 TeV and CRs

DOI: 10.52396/JUSTC-2021-0269
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between 10^{13} and 10^{17} eV.

(Ⅱ) The Water Cherenkov Detector Array (WCDA) consists of 3 water ponds with a total area of 78000 m^2, and the effective water depth is 4 m. The WCDA focuses on surveying the northern γ-ray sky in the energy range between 100 GeV and 20 TeV.

(Ⅲ) Wide Field Cherenkov Telescope Arrays (WFCTA) are composed of 18 Cherenkov telescopes. The Cherenkov telescope is equipped with a mirror with an area of approximately 5 m^2 and a camera with a filed of view of more than 10 degrees. WFCTA will be used to measure the longitudinal development of air showers, which will provide unique information on the composition of UHE CRs. The layout of the whole LHAASO array is shown in Fig. 1. In the field of γ-ray astronomy, LHAASO KM2A provides unprecedented sensitivities above 20 TeV. As mentioned above, the cosmic ray background dominates the γ-ray signals in ground-based γ-ray astronomy. Fortunately, the contents of air showers generated from γ-rays and CR hadrons are different and can be used to distinguish the primary particles. Generally , the electromagnetic showers generated by γ-rays are dominated by the cascade process, which mainly consists of pair production and bremsstrahlung processes. The detected particles are then dominated by electrons/positrons. On the other hand, for hadronic showers, pion production and decay processes dominate and a significant portion of energy goes to muons. Thus the number of muons detected in the shower can be used as a straightforward parameter to distinguish γ-ray showers from CR showers. LHAASO KM2A, with more than 1000 MDs, possesses the most powerful muon measurement ability thus far. Together with the large effective area of more than 1 km^2, the sensitivity of LHAASO KM2A above 20 TeV is much better than that of any other operating and even planned detectors. The sensitivity curves of LHAASO and other major γ-ray detectors are shown in Fig. 2.

3 γ-ray emission from CR sources

In the current consensus, SNRs are the most likely accelerators for CRs. Several hints support this hypothesis. First, the diffusive shock acceleration (DSA)[30] is regarded as one of the most efficient particle acceleration, and the shock front of the SNRs are the ideal place for such processes. Second, the energy input of one supernova explosion event is on the order of 10^{51} erg, and it is believed that the rate of supernova in our Galaxy is approximately 3 per century. If 10% of the kinetic energy is used to accelerate CRs, the CR injection rate can be estimated as $W_{\rm CR} \approx \dfrac{3\times10^{50}}{3\times10^{7}\times100}$ erg/s $\approx 10^{41}$ erg/s, which is similar to the required CR injection rate estimated from the direct observations of CRs and γ-rays[31]. Third, γ-ray observations also provide clues.

One of the most important achievements in GeV astronomy is the discovery of the so-called pion-bump feature in GeV γ-ray emissions from the mid-age (on the order of 10^4 years) SNRs[32, 33]. A distinct break in the low energy (below 1 GeV) γ-ray spectra of W44 and IC 433 is observed, which is predicted by the pion-decay process of γ-ray production. This is regarded as direct evidence that the SNRs accelerate CR protons. However, as mentioned above, it is believed that at least up to the knee (PeV), CRs should be accelerated by Galactic sources. The search for PeV CR accelerators (dubbed as PeVatrons) is the most important question in current CR-related studies. In this regard, mid-age SNRs can hardly be responsible for CRs with energies higher than TeV. This is because the γ-ray spectra of these CRs reveal a cutoff at approximately 10 GeV, which corresponds to the parent CR proton energy of about 100 GeV. Indeed in the mid-age SNRs, the shocks have already been effectively decelerated, and the current shock speed is already less than 1 000 km/s. In diffusive shock accelerations, the maximum acceleration energy is directly related to the shock speed[34]; thus, it is expected that these mid-age SNRs cannot accelerate the highest energy CRs. The natural acceleration sites for higher energy CRs are the younger SNRs with higher shock speeds. Young SNRs (with age approximately 1000 yrs) are bright TeV γ-ray sources[35–37]. In general, the available data can be modeled by both the hadronic ("π^0-decay") and leptonic ("inverse Compton") scenarios of TeV γ-rays production. By ignoring this ambiguity, and assuming that γ-rays are produced by ac-

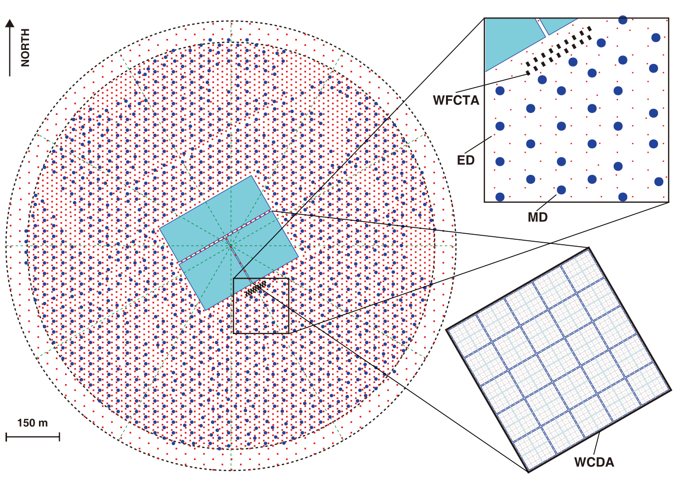

Fig. 1. The layout of three arrays in LHAASO. The figure is from Ref. [27].

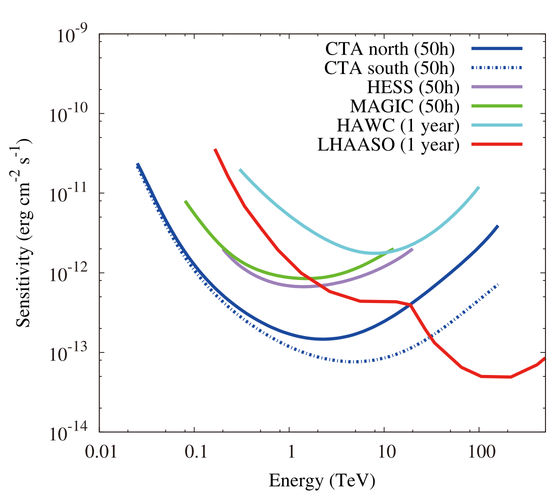

Fig. 2. The one year LHASSO sensitivity for γ-rays, compared with the sensitivities of other instruments. The sensitivities of other instruments are from Refs. [21, 26, 28, 29].

DOI: 10.52396/JUSTC-2021-0269
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celerated protons, there is still a problem with the TeV γ-ray spectra. The measured TeV γ-ray spectra are quite steep with a differential slope $\Gamma \sim 2.4-2.7$[38] (also shown in Fig. 3), which does not agree with the predictions of the standard DSA theory for strong shocks of young SNRs. This result can be interpreted in three different ways. First, the steep power-law proton spectrum can be explained as the combination of a hard (E^{-2} type) power-law spectrum and an "early" exponential cutoff, $E_0 \ll 100$ TeV. This simple explanation is predicted by the standard DSA and the conclusion of Lagage and Cesarsky[45]. If this explanation is correct, observations with higher sensitivities will find clear cutoffs. In this case, then young SNRs can hardly account for all the CR up to PeV. Second, the prediction of the hard accelerated CR spectrum and early exponential cutoff in strong shock acceleration may be incorrect. Indeed, steep power-law proton spectra can be formed over a wide energy interval in certain realistic environments and scenarios (see, e.g., Refs. [46–49]). The steep power-law spectra can extend over a wide energy interval and even up to 1 PeV. In this case the resulting steep power-law γ-ray spectra could continue up to 100 TeV and the young SNRs with steep observed TeV γ-ray spectra can still be PeVatrons, but the CR injection spectrum at the acceleration site may be steeper than expected before. Finally, the PeVatron phase can only be achieved at the very early stage of SNR evolution, such as the first 10 to 100 years[50], in particular, because the shock speed exceeds 10000 km/s. The multi-TeV CRs have already escaped from the SNRs so the current γ-ray spectra are soft, even for very young ones, such as Cas A[37, 51, 52] and Tycho[53]. In this case, the γ-ray radiation outside the remnant will be different from the first case in which the

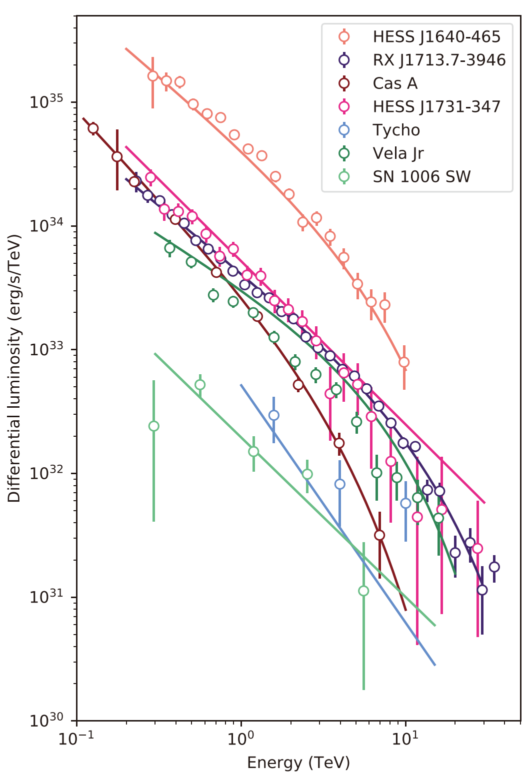

Fig. 3. The differential spectrum of several TeV-bright SNRs; the data points are from Refs. [37, 39–44]. The figure is from Ref. [38].

SNR cannot accelerate PeV particles at all. Any detection or upper limit of γ-rays at tens to hundreds of TeV in the vicinity of young SNRs would provide important clues to whether specific SNRs could accelerate protons 1 PeV at any epoch of their evolution. Pioneering works in this direction have been performed by H.E.S.S. collaborations[54]. The youngest known SNR in our Galaxy is SNR G1.9+0.3. X-ray observations have estimated the age of this SNR to be approximately 150 years[55], and the current shock speed is as high as 18000 km/s, which makes it the most plausible candidate for PeVatrons. Due to the limited age of this source, the multi-TeV particles cannot run too far away from their remnants. In the case of G1.9+0.3 located in the Galactic Center, the propagation depth of $E \geqslant 10$ TeV protons for 100 years could hardly exceed 30 pc. For a distance to the source of 8.5 kpc, the angular size of this region is expected to be less than 10 arcminute; therefore, the upper limit on the point source γ-ray luminosity $L_\gamma(\geqslant 1\ \mathrm{TeV}) \leqslant 2\times10^{32}$ erg/s reported by the H.E.S.S. collaboration[54] can be used to constrain the total energy of CRs within the $R \leqslant 30$ pc environment around the source:

$$W_\mathrm{p}(\geqslant 10E) = L_\gamma(\geqslant E)\ t_{\pi^0}\ \eta^{-1}, \tag{1}$$

where $t_{\pi^0} \approx 1.5\times10^{15} n^{-1}$ s is the cooling time of protons through the π^0 production and decay channel; the parameter $\eta \approx 1.5-2$ takes into account the production of γ-rays in interactions with the involvement of nuclei of both CRs and ISM[56]. Due to the proximity to the Galactic Center, the gas density in the region surrounding G1.9+0.3 can be very high, $n \approx 100\ \mathrm{cm}^{-3}$; thus, the upper limit of the energy content of 0.01–1 PeV protons is estimated to be $\approx 10^{45}$ erg, i.e., several orders of magnitude below the CR release in an SNR required by former estimations.

To conclude, although SNRs have been established as a main source population in TeV astronomy, further observations of these objects can still provide important information, especially on the identification of PeVatrons. Such observations can be performed in two ways. One is to measure the energy spectrum of young SNRs up to the energy range of more than 100 TeV. Such measurements can distinguish whether the soft γ-ray spectra of the young SNRs are caused by the energy cutoff in the acceleration CR spectra or just because the accelerated CR spectra are steep. In the latter case, young SNRs can still be PeVatrons but with a steeper injection spectrum; thus, the current understanding of CR propagation in the Galactic halo may also reveal modifications. The other way is to measure the diffuse γ-ray emission near the young and very young SNRs; for those objects, the CR propagation is limited by age. If such objects have accelerated PeV CRs at the very beginning of their evolution, these particles cannot propagate too far, and γ-ray observations above 100 TeV can provide clues or upper limits of these PeV CRs. The first method indeed measures the energy spectrum in the cutoff/break region, and the second method observes the faint diffuse emissions; both require extremely high sensitivities. In this regard, LHAASO and CTA will be ideal tools for such studies in the future.

In addition to SNRs, YMCs have recently also been considered as major CR accelerators. There are also several hints

DOI: 10.52396/JUSTC-2021-0269
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supporting such a scenario. First, the recent measurements of ^{60}Fe abundance in CRs[57] indicate that a substantial fraction of CRs could be accelerated in super bubble structures, where both SNRs and massive stars exist. Second, the measurements of the Galactic diffuse γ-ray emission show that the CRs have a similar radial distribution to OB stars rather than SNRs[58, 59] (see also the discussion in the next section). Finally, massive stars have sufficient kinetic energies, supplied by collective stellar winds, to provide the flux of locally measured CRs[60, 61]. Indeed, the idea that the stellar wind can accelerate protons to PeV energies, has already been discussed by Cesarsky and Montmerle[62] as early as 1983. The speed of stellar wind can be as high as 3000 km/s, which is still significantly lower than the shock speed in very young SNRs, but the stellar wind can last 10^6 years; thus, the stellar wind may be able to accelerate CRs even to higher energy than SNR shocks [62]. In addition, thanks to the advance of the γ-ray astronomy, several YMCs have recently been identified as γ-ray sources. This is also predicted if these objects are CR accelerators due to the fresh accelerated CRs interacting with ambient gas. Several YMCs have been detected in γ-rays, such as Cygnus Cocoon[63], NGC 3603[64, 65], Westerlund 1[66], Westerlund 2[67], RSGC 1[68, 69], W40[70], and W43[71]. They all reveal a extended γ-ray morphology with a hard (index ~ 2.3 type) γ-ray spectra. The spectra of some bright YMCs are shown in Fig. 4. We found that the spectra of several systems, such as the Cygnus cocoon, Westerlund 1 and Galactic Center regions, can extend to approximately 10 TeV without any hint of cutoff, which makes them promising PeVatron candidates.

The observations of such systems at even higher energy would be crucial in determining whether these systems are PeVatrons or not. Indeed, a hard γ-ray spectrum with no break/cutoff above dozens of TeV can be regarded as the direct evidence of PeVatrons. This is because in this energy range, the γ-ray production mechanism should be either pion-decay process in the inelastic collision between CR protons with ambient gas, or the inverse Compton scattering (IC) process of the relativistic electrons. In the energy range above 10 TeV, the main low energy photon field for IC is CMB, and the Klein-Nishina effects are significant[72]. Thus, even the parent electron spectrum has no break or cutoff, the decline of cross section would introduce a softening in the produced γ-ray spectrum. Such a method has already been invoked by H.E.S.S. collaborations in the study of HESS J1641-463[73] and the Galactic Center[74], and they also concluded that GC harbors a PeVatron by studying the spectrum of the diffuse γ-ray emissions. Such a method requires accurate measurement above 10 TeV; again, thanks to the unparalleled sensitivities in this energy range, LHAASO would be the ideal tool to implement this kind of study.

In addition to the spectral features, the spatial distribution also provides unique information on CR related studies. Aharonian et al.[38] studied the CR distribution around several YMCs by taking into account the γ-ray observations as well as the gas distributions. The results are summarized in Fig. 5. A universal $1/r$ relation was derived for all three systems. Such a CR distribution is predicted for continuous injection in the standard paradigm of diffusion dominated propagation of

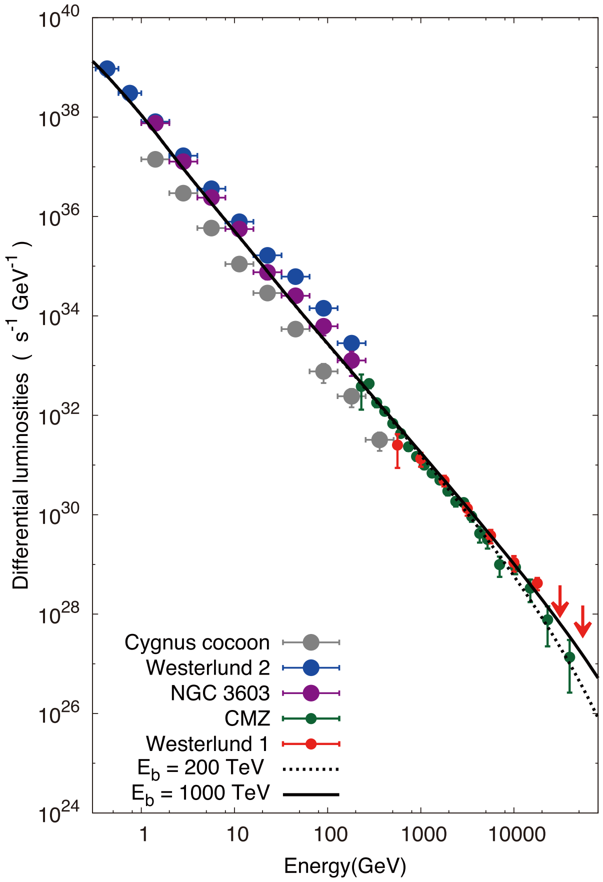

Fig. 4. The differential luminosities of in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon), Westerlund 1, Westerlund 2, NGC 3603, as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in Arches, Quintuplet and Nuclear clusters. The error bars contain both the statistical and systematic errors. The differential γ-ray luminosities, $\frac{dL}{dE} = 4\pi d^2 E f(E)$. The luminosities of all sources have similar energy dependence close to $E^{1.2}$ as shown in the curve. We also show the γ-ray spectra expected from interactions of parent proton population with a spectrum of $E^{-2.3} e^{-\frac{E}{E_b}}$ with E_b = 0.2 PeV and 1 PeV, respectively. The data points are from Ref. [38].

CRs. Considering the size and energy budget of these sources, the CRs should be continuously injected for approximately 10^6 years, which is much longer than the lifetime of SNRs, but consistent with the lifetime of massive stars, which is additional proof that these CRs are accelerated by stellar winds.

The spatial morphology can also be used to study the radiation mechanisms. Recently, a new γ-ray source population was detected by the HAWC collaboration[76], who found halo structures near old pulsars and derived the diffusion coefficient of the relativistic electrons therein from the brightness profiles. The derived diffusion coefficient is orders of magnitude smaller than the average value in the Galactic plane and such structures are named “TeV halos”. Thus, it would be important to distinguish TeV halos with the extended γ-ray structures near the YMCs. Indeed, due to the fast cooling of electrons, the spatial distribution of TeV halos should be sharper. Considering both the energy loss and projection effects, the difference between the two cases is studied in detail

DOI: 10.52396/JUSTC-2021-0269
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in Ref. [77], and the main results are shown in Fig. 6. The difference can be used in the future to distinguish the two different scenarios of extended γ-ray emissions. It should be noted that for TeV halos, the target photon fields (CMB) are extremely uniform and the γ-ray emissions directly reflect the distribution of CR protons. For the emissions around YMC, the γ-ray distribution is determined by both CR and gas distribution, which may make such a study difficult.

Recently, LHAASO detected 12 UHE sources in the Galactic plane[78], opening the new window of γ-ray astronomy. As mentioned above, LHAASO is extremely powerful in CR-related studies. Both SNRs and YMCs require VHE observations to identify whether they can be PeVatrons. The discovery of 12 UHE sources is a landmark in this area, however, due to the complexity in the Galactic plane and the limited angular resolution of LHAASO, the nature of these 12 sources cannot yet be determined. One interesting point is that nearly all the sources except Crab nebular reveal an extended morphology, which makes them possible candidates for TeV halo or CR cocoons near YMCs. The accumulation of exposure and multiwavelength studies, as well as higher angular resolution observations with IACTs, will shed light on this issue.

4 γ-ray emissions as a tool to study CR distribution in the Galaxy

The study of γ-ray sources provided direct information on the possible acceleration site of CRs. The diffuse γ-ray emissions can provide information on CR distributions in our Galaxy and then can be used to study the propagation process of CRs. The diffuse γ-ray emission in our Galaxy are mainly consists of the pion-decay process of CR protons interacting with ambient gas, IC and bremsstrahlung radiation of relativistic electrons. In dense environments such as giant molecular clouds (GMCs) and Galactic plane, the pion-decay process dominates above several hundred MeV[79]. In this case the γ-ray spectrum shape is determined solely by the CR spectrum. The normalization of γ-ray emission is determined by the normalization of CR flux and gas density. Thus, combining the gas information determined from the infrared/radio observations and the γ-ray measurement, one can in principle derive the CR spectrum and density.

In this direction, GMCs are regarded as the best sites for this kind of study. These objects are believed to be free of other γ-ray sources, and the high density therein makes them ideal CR "calorimeters"[80]. After the launching of Fermi-LAT, the γ-rays in GMCs have already been extensively studied,and similar CR density and spectra inside the GMCs in the Gould Belt have been derived[81, 82]. As an example we show the Fermi-LAT γ-ray observations above 1 GeV towards the GMC Orion A as well as the Planck dust opacity map in the same region in Fig. 7. The Planck dust opacity (τ_{353}) map can be used to represent the distribution of gases[83]. By eye we can find that the gas and γ-rays are in good correlation with each other, which is expected if the γ-rays are uniformly distributed inside GMCs. It should also be mentioned that the γ-ray counts maps shown here are nearly raw data before subtracting any contributions from background/foreground sources, which means that the results derived with this method are robust and free of any assumption of radiation models. With this information, one can further derive the CR spectrum and density in these clouds. For Orion A the results are shown in Fig. 8. The derived CR spectrum in Orion A is consistent with the direct measurement of CR spectrum by PAMELA[84] above dozens of GeV. At low energy, the difference may come from the solar modulation effects of the local measured CR spectrum. Thus, the results imply that the CR density and spectrum in our solar system are similar to those

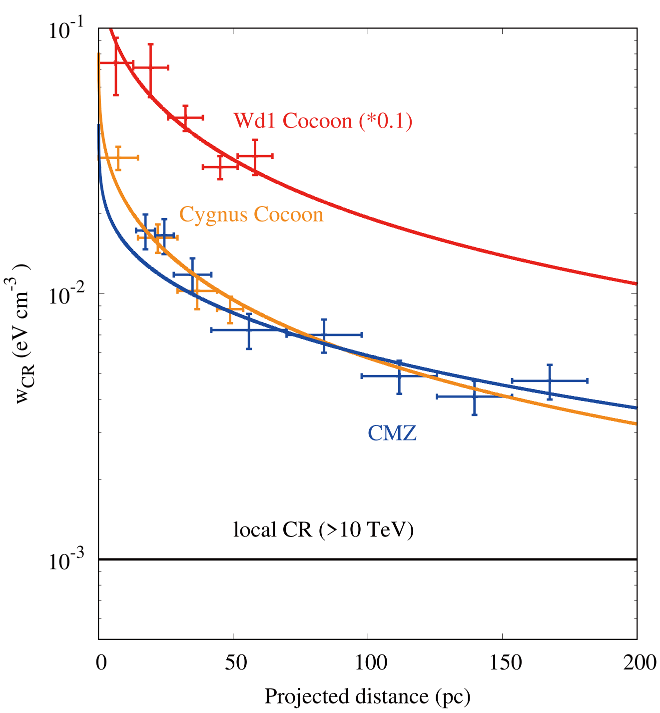

Fig. 5. The CR proton radial distributions in the Cygnus Cocoon, Wd 1 Cocoon and CMZ above 10 TeV. For the Cygnus Cocoon, the energy density of protons above 10 TeV is derived from the extrapolation of the Fermi-LAT γ-ray data to higher energies. The flux reported by the ARGO collaboration at 1 TeV supports the validity of this extrapolation. For comparison, the energy densities of CR protons above 10 TeV based on the measurements by AMS-02 are also shown in Ref. [75]. The figure is from Ref. [38].

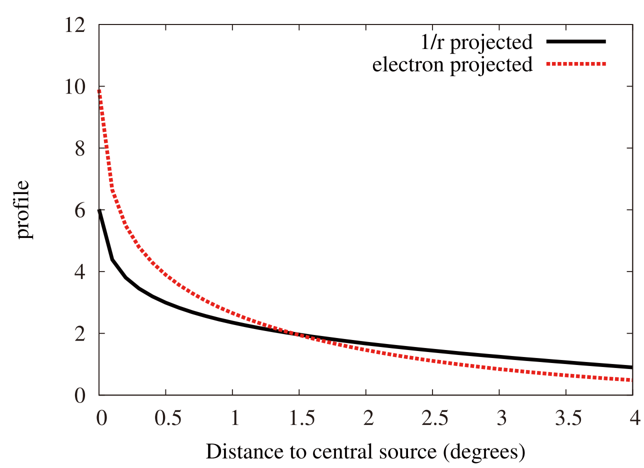

Fig. 6. The surface brightness profile of both the TeV halo (electron) and CR continuous injection case ($1/r$). The figure is from Ref. [77].

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in Orion A, which is approximately 500 pc away. This is also compatible with the current understanding of CR propagation that CR are well mixed in Galactic magnetic fields.

Such a study can also be promoted to a large scale, such as the whole Galactic plane. In Refs. [58, 59], the diffuse γ-ray emission from the whole Galactic plane has been used to study the large-scale distributions of CRs in the whole Galaxy. The Galactic diffuse γ-ray emissions in the Galactic plane are also dominated by CR interaction with the ambient gas; however, due to the complex nature of the Galactic plane, the contributions from discrete γ-ray sources as well as the IC emissions cannot be ignored. Thus the analysis is more complex and model-dependent compared with the results from nearby GMCs. The current method assumed a cylindrically symmetric distribution of CRs in our Galaxy, and then divided the gas distribution into several rings with different Galactocentric radiuses. The normalization and spectrum of γ-rays associated with these gas rings are derived from global likelihood fitting and then the CR density and spectrum are derived. The results in Refs. [58, 59] are compatible with each other, although they used different regions of interest. The CR distributions in different Galactocentric rings from Ref. [59] are shown in Fig. 9. It is quite unexpected that there is a peak in the distributions at the ring 4 – 6 kpc away from the Galactic Center, which cannot be addressed in the standard CR propagation models (e.g., Ref. [87]), in which the CR should be well mixed and the distribution should be much flatter. Additionally, plotted in Fig. 9 are the distributions of SNRs[85] and OB stars[86]. We found that the peak positions of the derived CR distributions are in good agreement with the OB stars rather than SNRs, which was also cited as a hint that the OB stars can contribute significantly to CRs. The derived CR radial distribution in our Galaxy also motivates related theoretical studies, in which such a distribution is explained as the consequence of the fact that CR propagation is dominated by scattering with CR self-generated turbulence[88] or by the spatial-dependent diffusion[89].

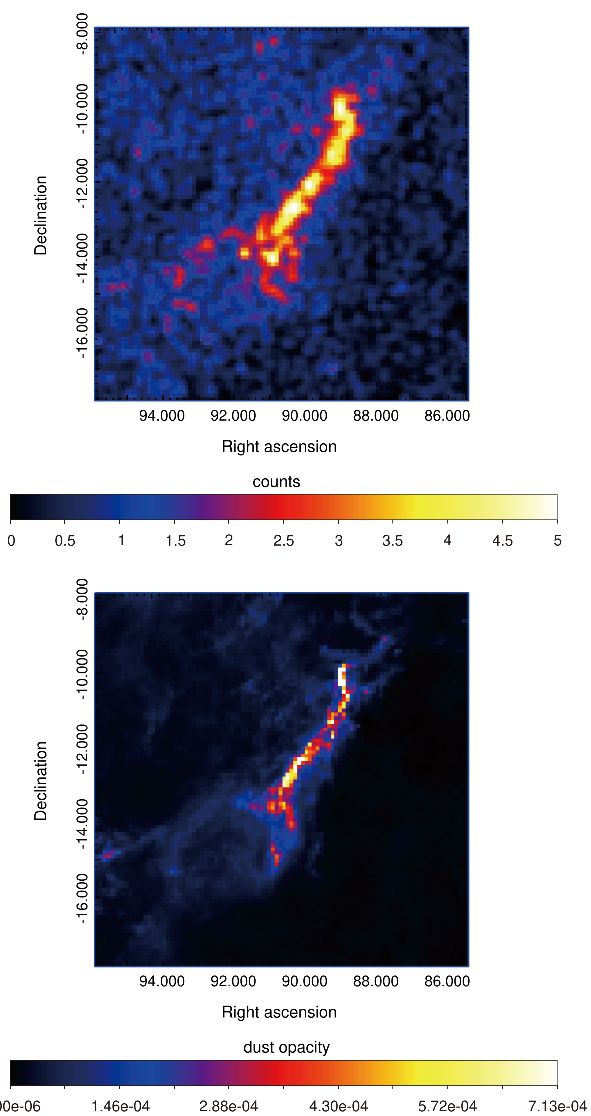

Fig. 7. Top panel: The Fermi-LAT γ-ray counts map above 1 GeV towards Orion A. Bottom panel: The Planck dust opacity (τ_{353}) map, which is proportional to the gas column density.

In the higher energy range, diffuse γ-ray emission in the Galactic plane has also been detected by Milagro[90] and ASγ[91]. Remarkably, ASγ detected diffuse emission up to nearly PeV in the Galactic plane, which implies that cosmic rays are accelerated beyond PeV energies in our Galaxy and spread over the Galactic disk. Indeed, the γ-ray flux in this energy range depends not only on the parent CR spectrum but also on the CR mass composition near the knee, which is not well measured by direct CR observations. Thus, γ-ray emission can provide an independent measurement of the knee of CRs. In addition, as in the GeV energy range, combining the γ-ray observations above 100 TeV and the gas information, one can derive the PeV CR distribution in our Galaxy, which would provide us with direct insight into their origin. The current statistics of data are not yet sufficient to carry out these studies, but as the exposure accumulates, LHAASO will definitely make significant progress in this area in the next few years.

This kind of analysis used an assumption that CRs are distributed cylindrically symmetric in our Galaxy, which may be oversimplified. A possible improvement is to use the GMCs in different positions of the Galaxy rather than the solar

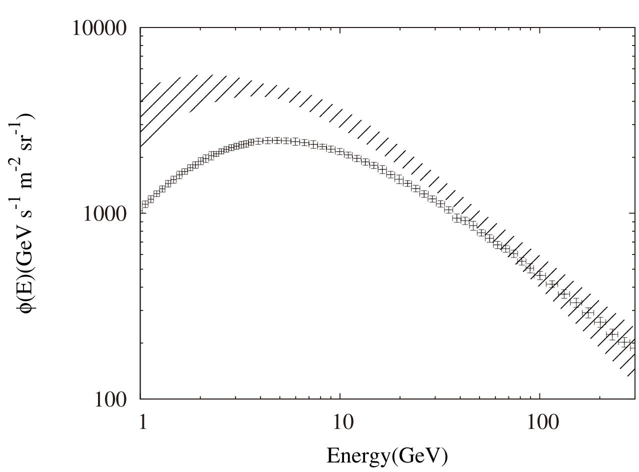

Fig. 8. The derived CR spectrum in Orion A (shaded area) compared with the direct measurement of the CR spectrum from PAMELA (data points)[84]. The figure is from Ref. [82].

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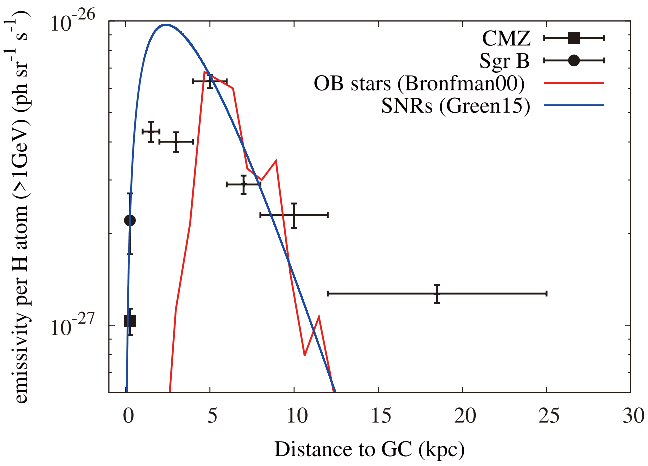

Fig. 9. The derived γ-ray emissivities per H atom (proportional to CR density) Galactocentric distributions compared with the distribution of SNRS[85] and OB stars[86]. The CR radial distributions are derived in Ref. [59].

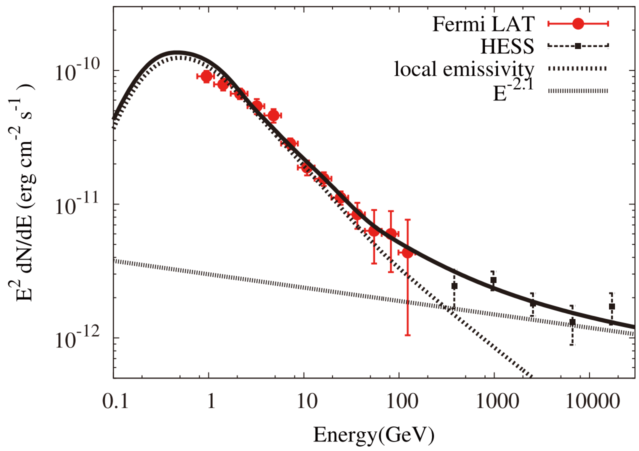

Fig. 10. The energy distribution of γ-rays in the Sgr B complex. The data points are from Refs. [93, 94].

neighborhood. This is not a simple task since the γ-ray flux from a GMC scale is M/d^2, where M and d are the mass and distance of the GMC, respectively. Thus, to detect these objects, we must use very massive clouds. One natural choice is the Sgr B complex near GC, which is one of the densest regions in our Galaxy. Yang et al.[92] and Aharonian et al.[93] measured the γ-ray emission in this region and the results are shown in Fig. 10, where the derived CR flux and spectrum are quite similar to those in the solar neighborhood, and above several hundred GeVs, there is a hint of hardening, which may be connected to the diffuse TeV γ-ray emissions observed by H.E.S.S.[74] and related to the fresh accelerated CR in the GC region. Later, thanks to the progress in the distance determination in our Galaxy, Rice et al.[95] identified several thousand molecular clouds in our Galaxy. With this new information, Aharonian et al.[93] and Peron et al.[96] analyzed the Fermi-LAT γ-ray observation towards several massive GMCs in different positions of the Galaxy and measured the CR density and spectra therein. The results of Aharonian et al.[93] are summarized in Fig. 11. They found that the galactocentric radial distribution of the CR density derived from γ-ray and gas observations unveils a homogeneous "sea" of CRs with a constant density and spectral shape close to the flux of directly (locally) measured CRs. This applies to the galactocentric distances exceeding 8 kpc, as well as the Sagittarius B complex, in the region of the Galactic Center. And in the region 4 – 8 kpc from the GC, there are significant variations in the CR density and spectrum from cloud to cloud. In Ref. [96], the Galactocentric ring with a radius of 1.5 – 4.5 kpc away from the GC, in which a peak in CR density is discovered by using diffuse γ-ray emissions discussed above[58, 59], are further studied by using GMCs. The CR density measured at the locations of these clouds is compatible with the locally measured one. Thus, the CR density gradient derived from the diffuse γ-ray emission (see also Fig. 9) may be the result of the presence of CR accelerators rather than a global change in the sea of Galactic cosmic rays due to their propagation. The results from Refs. [93, 94] reveal a different picture of CR distributions in our Galaxy, as well a different explanation of the CR density profile derived from diffuse γ-ray emissions in the Galactic plane. In such a picture, CR is distributed nearly homogeneously in the whole Galaxy, and the spectral and density variations found in Refs. [58, 59] are a result of the influence of local CR sources in the inner ring of our Galaxy. We note that a uniform CR density in the Galaxy is also far from the prediction of the "standard" CR propagation models[13], in which the diffusion can smooth but cannot totally erase the spatial distribution of the CR sources. The origin of such a uniform CR distribution requires further phenomenological and theoretical investigations.

5 Discussion and prospects

The γ-ray astronomy has provided plentiful information for CR studies. Potential CR accelerators such as SNRs and YMCs are detected in γ-rays from the GeV to PeV energy ranges. The spectral and spatial distributions of these sources are well studied, which significantly extend our understanding of these objects, although the site of PeV CR acceleration has not yet been finalized. We expect LHAASO to shed light on this question very soon.

However, although LHAASO is expected to make great progress in this field, the PSF of LHAASO may still be a lim-

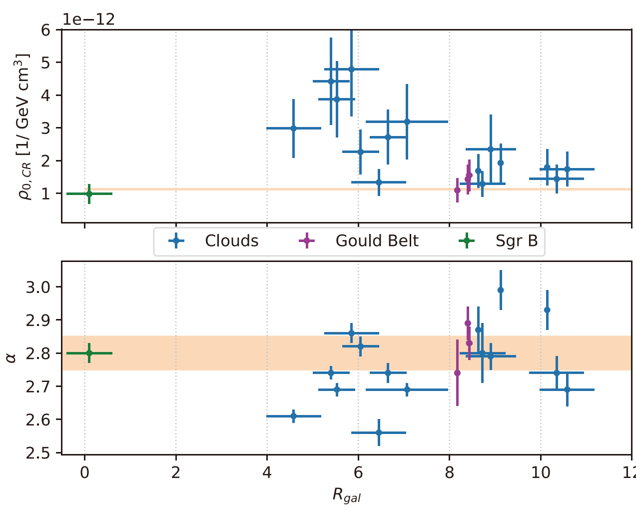

Fig. 11. The derived CR density and index in different position of the Galaxy using GMCs in Ref. [93].

DOI: 10.52396/JUSTC-2021-0269
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itation in specific questions. For example, in the first 12 sources detected by LHAASO, except for Crab nebular, no confirmed association between the sources and the astrophysical objects has yet been established. Even for the brightest sources, such as LHAASO J1825-1326, LHAASO J1908+0621 and LHAASO J2226+6957[78], whose fluxes above 100 TeV are higher than Crab, we cannot confirm which astrophysical objects correspond to the γ-ray emissions. This is because all these sources are located inside very crowded regions and inside the LHAASO PSF several possible CR accelerators are present, such as the PWN and SNRs. As one example we show the LHAASO KM2A significance map of LHAASO J1825-1326 overlaid with the astrophysical sources in Fig. 12. We found that in the γ-ray bright region observed by LHAASO KM2A, there are two bright pulsars, two H.E.S.S. sources as well as several gas clumps. To understand the origin of these γ-rays and finally identify PeVatrons the observations with better angular resolution are required. One natural choice is IACTs, whose angular resolution can reach 0.05°. Indeed, these sources are already well studied by H.E.S.S.[99] However, as shown in Fig. 2, the sensitivity of H.E.S.S. are nearly two orders of magnitude worse than LHAASO. Therefore, the observations from H.E.S.S. and other current IACTs are in fact for much lower energy range and cannot help us to pin down the origin of the UHE γ-rays. In this regard, CTA as the next generation IACTs will have great potential in this direction. In particular, CTA-south, which will be equipped with small size telescope (SST) arrays whose effective areas are also larger than 1 km^2 will have good sensitivity above 100 TeVs. However, we note that CTA south will not cover most of the LHAASO field of views due to the different latitudes of their sites. Thus, a Cherenkov telescope array for high energy (above 10 TeV) with the same FOV as LHAASO can provide the best synergy with LHAASO in PeVatron searching. One recent progress is the ASTRI mini-array[100] which will be installed in Tenerife in the Canary Islands. It consists of 9 small size telescopes and will significantly improve sensitivities compared with the current IACTs. A more ambitious idea is to build an IACT array inside the LHAASO site; the small telescopes occupy the same 1 km^2 as KM2A and will provide sufficiently good sensitivities to collaborate with KM2A above 100 TeV. The MDs in KM2A can be used to help the particle identifications of IACT array, which can also potentially improve its sensitivities[101].

The progress and prospects above mainly focus on the energy range above GeV. MeV γ-rays can also be used to study CR physics. In fact, due to the power law shape of the CR spectrum, a significant portion of the energy density of CRs is contributed by particles below 1 GeV. More importantly, the ionization and heating of ambient gas are also dominated by low energy CRs (LECRs). It is these CRs that control the ionization rate in the dense core of molecular clouds and thus the astro-chemistry chain as well as the star-forming processes. However, the pion production process has an energy threshold of approximately 280 MeV, which means that most MeV CRs do not produce pion-decay γ-rays. At energies below this kinematic threshold, the nuclear de-excitation lines provide the most straightforward information about the LECR

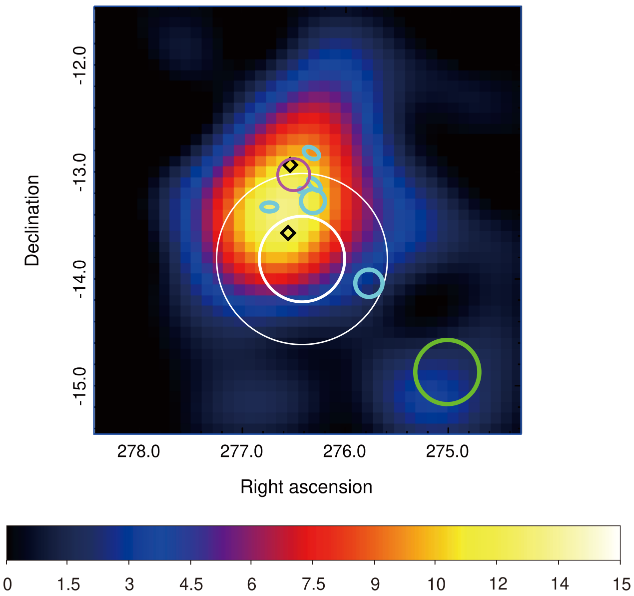

Fig. 12. The significance map above 25 TeV from the LHAASO-KM2A observations on LHAASO J1825-1326. The green circle in the right bottom is the point spread function of LHAASO-KM2A. The white circles are the extensions of HESS J1825-137 at lower (large) and higher (smaller) energies. The purple circle is the extension of HESS J1826-130. The two black diamonds label the position of two pulsars while the cyan ellipse is the dense molecular gas clump identified in Ref. [97]. The figure is from Ref. [98].

protons and nuclei (e.g., Refs. [102, 103]. Because of the slow propagation and severe energy losses, the local LECRs make negligible contributions to the fluxes beyond 100 pc. For the same reason, LECRs are expected to be inhomogeneously distributed in the Galactic disk; subrelativistic protons and nuclei are expected to be concentrated around their acceleration sites. Because all potential CR source populations (SNRs, stellar clusters, individual stars, etc.) are linked in one way or another to the star-forming region, the effective confinement of LECRs in these regions is expected to produce feedback that stimulates the star formation through the ionization of the nearby molecular clouds. Thus an unbiased, observation based information about LECRs at the sites of their concentrations in the Milky Way is crucial for understanding the fundamental processes linked to the dynamics and chemistry of the interstellar medium, star formation, etc. The most direct channel of information is provided by nuclear de-excitation γ-ray lines resulting from the interactions of protons and nuclei of LECRs with the ambient gas[104]. However, the expected γ-ray fluxes are unfortunately well below the sensitivity of current γ-ray detectors. With the arrival of the proposed γ-ray detectors that are dedicated to low energies, such as e-ASTROGAM[105] and AEMGO[106], the detection of nuclear γ-rays, in particular, the lines at 0.847, 1.63, 4.44, and 6.13 MeV of nearby (within a few kpc) accelerators of LECRs would become feasible provided that the LECR accelerators are surrounded by dense ($\geqslant 100\,\mathrm{cm^{-3}}$) gaseous regions in which LECRs propagate significantly more slowly than in the interstellar medium.

In conclusion, γ-rays provide a unique tool for studying CRs. Great progress has already been achieved. The diffuse γ-ray emissions are well studied from GeV to PeV. A handful

DOI: 10.52396/JUSTC-2021-0269
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of GMCs have been detected in the GeV energy range, and progress is still ongoing. The diffuse emissions in the Galactic plane are also well studied, and together with gas distributions, the spatial distributions of GeV CRs in our Galaxy are studied. Diffuse VHE/UHE γ-ray emissions are also detected in the Galactic plane, but current statistics prevent any strong conclusion. After several years of data accumulation of LHAASO, we expect the GMC and the longitudinal profile of the diffuse γ-ray emissions in the Galactic plane to be detected above 100 TeV. The potential CR accelerators are also well measured, and LHAASO will continue unveiling the PeV γ-ray sky. The synergy with current and forthcoming IACTs will bring us direct insight into the extreme particle acceleration processes. The future MeV instruments will also provide information on low-energy CRs and their interplay with other astrophysical processes. We expect that the mystery of CRs will eventually be solved with the continuous progress of γ-ray astronomy.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (12041305) and the National Youth Thousand Talents Program in China.

Conflict of interest

The author declares that he has no conflict of interest.

Biographies

Ruizhi Yang is currently a Professor at the University of Science and Technology of China (USTC). He received his bachelor's degree from USTC in 2007 and his Ph.D. degree in Astrophysics from the Purple Mountain Observatory, CAS in 2013. His research mainly focuses on high-energy astrophysics and γ-ray astronomy.

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