Reconciling ultra-high-energy diffuse $\gamma$-rays and the knee of cosmic ray light nuclei

Pei-pei Zhang,$^{a,b,c}$ Yi-qing Guo$^{c,d,1}$ Bing-qiang Qiao$^{c,1}$ and Wei Liu$^{c,1}$

$^a$Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China

$^b$School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, Anhui, China

$^c$Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

$^d$University of Chinese Academy of Sciences, Beijing 100049, China

E-mail: zhangpeipei@ihep.ac.cn, guoyq@ihep.ac.cn, qiaobq@ihep.ac.cn, liuwei@ihep.ac.cn

ABSTRACT: The diffuse $\gamma$-ray was measured up to 957 TeV by the Tibet-AS$\gamma$ experiment. Presuming it is produced by the hadronic interaction between cosmic ray nuclei and the interstellar medium, it requires that the cosmic ray nuclei should be accelerated well beyond PeV energies. However, measurements of the spectrum of proton and Helium by a few experiments show break below PeV. To solve this apparent discrepancy, we propose in this work that a new structure of cosmic rays may exist beyond PeV, which can contribute to the highest energy diffuse $\gamma$ rays. This additional component may serve as another population of Galactic cosmic ray accelerators, and can contribute to the cosmic ray fluxes beyond the second knee. Future measurements of the energy spectra of different nuclei species may test the existence of this new component.

$^1$Corresponding author.
1 Introduction

It is generally believed that the spectral knee signify the up-limit of acceleration ability for galactic cosmic rays (GCRs)[1, 2]. The individual nuclear spectrum at knee region plays very important role to unveil its origin. Due to the limited precision of species separation, the measurement of individual nuclear spectrum step into dilemma since the discovery of knee structure in 1958[3]. The ground-based experiments have made great efforts to fulfill this task. There are three experiments, in Tibet of China, as ASγ-YBJ, ARGO-YBJ and the hybrid one of ARGO-YBJ/WFCTA. They all reported similar results of knee structure below 1 PeV for Proton and Helium (PHe)[4–7]. Particularly for the hybrid ARGO-YBJ/WFCTA experiments, the multi-parametric analysis was applied through the combined detection shower with ARGO-YBJ and Cherenkov technology. So they improved the resolution of reconstructed energy and the separation ability of PHe from heavier nuclei[7]. In their observation, the knee position located at 700 TeV in PHe spectrum[7]. Is it a truth that the astrophysical objects in galaxy can only accelerate the nuclei below 700 TeV? Further multi-messenger, such as ultra-high-energy diffuse γ-rays, is required to test this point of view.

The Galactic diffuse γ-ray emission (DGE) is expected to be produced by interactions between CRs and the interstellar medium (ISM) as well as the interstellar radiation field (ISRF), during the propagation of CRs in the Milky Way. Justly recently, the DGE in the Galactic plane at 957 TeV energies was for the first time measured by the Tibet-ASγ experiment [8], which has attracted wide attention for possible physical discussion [9–21]. This measurement shed new light to study the individual nuclear spectrum. In the measurement, the γ-rays from point sources within 0.5 degree region has been eliminated.
So, due to the fast cooling time of lepton [22], the dominant contribution to ultra-high-energy DGE should be from pp-collisions [23–25]. The proton should be accelerated to a few PeV energy to supply the production of $\gamma$-rays [26]. It seems that there exists a group of accelerators at PeV energy, named PeVatrons.

The Sagittarius A*, stellar cluster, Cyg OB2 and Cyg cocoon are the possible candidates of PeVatrons [27–31]. HESS experiment claimed the first PeVatron, Sagittarius A*, by the spectrum of diffuse $\gamma$-rays without a cut-off to tens of TeV [27, 28]. Just recently, Cyg cocoon becomes the potential PeVatron with the observations of hundreds TeV of $\gamma$-rays and neutrino [30–33]. Simultaneously, several works reported other candidates of PeVatrons [26, 34]. It is to say that a group of PeVatrons exists in galaxy. The accelerated nuclei beyond PeV energy should also contribute the spectrum of the locally observed CRs’ fluxes. Considering the PeVatrons’ contribution, the observed spectrum should include three components at tens of, hundreds of TeV and several PeV, which is also proposed by Gaisser [35].

Based on above discussions, there possibly exists a new component beyond PeV energy in the individual nuclear spectrum. In this work, we discuss the extra-component in PeV energy and calculate its contribution to the diffuse $\gamma$-ray. The paper is organized as follows. Section 2 gives model description, Section 3 presents the calculated results and Section 4 describes the conclusion.

2 Model Description

2.1 Propagation of CRs

It has been recognized in recent years that the propagation of CRs in the Milky Way should depend on the spatial locations, as inferred by the HAWC observations of extended $\gamma$-ray halos around pulsars [36] and the spatial variations of the CR intensities and spectral indices from Fermi-LAT observations [37, 38]. The spatially-dependent propagation (SDP) model was also proposed to explain the observed hardenings of CRs [39–45], and also the large-scale anisotropies with the help of a nearby source [46–48].

In the SDP model, the diffusive halo is divided into two parts, the inner halo (disk) and the outer halo. In the inner halo, the diffusion coefficient is much smaller than that in the outer halo, as indicated by the HAWC observations. The spatial diffusion coefficient $D_{xx}$ can be parameterized as

$$D_{xx}(r, z, R) = D_0 F(r, z) \beta^n \left( \frac{R}{R_0} \right) \delta(r, z), \quad (2.1)$$

where $r$ and $z$ are cylindrical coordinate, $R$ is the particle’s rigidity, $\beta$ is the particle’s velocity in unit of light speed, $D_0$ and $\eta$ are constants. For the parameterization of $F(r, z)$ and $\delta(r, z)$, one can refer to [45]. The total half-thickness of the propagation halo is $z_h$, and the half-thickness of the inner halo is $\xi z_h$.

In this work, we adopt the diffusion reacceleration model, with the diffusive-reacceleration coefficient $D_{pp}$, which correlated with $D_{xx}$ via $D_{pp}D_{xx} = \frac{4p^2v_A^2}{3\delta(4 - \delta^2)(4 - \delta)}$, where $v_A$ is the
Alfvén velocity, $p$ is the momentum, and $\delta$ is the rigidity dependence slope of the diffusion coefficient \[49\]. The numerical package DRAGON is used to solve the propagation equation of CRs \[50\]. For energies smaller than tens of GeV, the fluxes of CRs are suppressed by the solar modulation effect. We use the force-field approximation \[51\] to account for the solar modulation.

2.2 Background source distribution

As discussion in Section 1, the background source should include two categories as SNRs and PeVatrons. For simplicity, the spatial distribution of them are approximated as an axisymmetric form, which can be parameterized as

$$f(r, z) = \left(\frac{r}{r_\odot}\right)^\alpha \exp\left[-\frac{\beta(r - r_\odot)}{r_\odot}\right] \exp\left(-\frac{|z|}{z_s}\right),$$

(2.2)

where $r_\odot \equiv 8.5$ kpc represents the distance from the Galactic center to the solar system. Parameters $\alpha$ and $\beta$ are taken as 1.69 and 3.33 in this work \[52\]. The density of the SNR distribution decreases exponentially along the vertical height from the Galactic plane, with $z_s = 200$ pc.

The injection spectrum of nuclei are assumed to be exponentially cutoff broken power-law function of particle rigidity, $q(R) \propto R^{-\nu} \exp\left[-\frac{R}{R_c}\right]$.

2.3 Local SNR

The fine structure of spectral hardening and break-off at 200GV and 14 TeV respectively seems to be from local source. The local source is necessary to explain the evolution of anisotropy with energy. Here the progenitor of Geminga, a SNRs, was introduced in this work. The injection process of the SNR is approximated as burst-like. The source injection rate as a function of time and rigidity is assumed to be

$$Q(R, t) = Q_0(t) \left(\frac{R}{R_0}\right)^{-\gamma} \exp\left[-\frac{R}{R_c}\right],$$

(2.3)

$$Q_0(t) = q_0 \delta(t - t_0),$$

(2.4)

where $R_c$ is the cutoff rigidity and $t_0$ is the time of the supernova explosion. The propagated spectrum from Geminga SNR is thus a convolution of the Green’s function and the time-dependent injection rate $Q_0(t)$ \[22\]

$$\varphi(\vec{r}, R, t) = \int_{t_i}^t G(\vec{r} - \vec{r}', t - t', R)Q_0(t')dt'.$$

(2.5)

The normalization is determined through fitting Galactic cosmic rays energy spectra, which results in a total energy of $\sim 2.2 \times 10^{50}$ erg for protons and $\sim 7.5 \times 10^{49}$ erg for helium. If 10% of kinetic energy is used to accelerate CRs, the total energy of supernova explosion is estimated to $\sim 3 \times 10^{51}$ erg.
3 Results

3.1 Spectra of individual species

Based on the above discussion, we predict a hard additional component will contribute to CR energy spectra. Fig. 1 shows the proton and helium energy spectra expected from the model, compared with the measurements by AMS-02 [53, 54] and DAMPE [55, 56]. The phenomenon that the hardening of the proton and helium nuclei spectra around several hundred GeV and then the softening around $\sim$ ten TeV are mainly due to the local SNR contribution. In Fig. 1, the blue dotted line represents the contributions from the background sources, which the proton cutoff is at 980TV. The green and red lines demonstrate the local source and an extra hard component. The black solid line is the sum of them. Here, the injected and propagation parameters are listed in Table 1.

![Figure 1](image-url)

**Figure 1.** The spectra of protons (left) and helium nuclei(right). The proton and helium data are taken from AMS-02 [53, 54] and DAMPE [55, 56].

3.2 Spectra of H+He and all-particle

The left panel of Fig. 2 shows the energy spectra of protons plus helium nuclei compared with measurements from direct (CREAM[57] and NUCLEON[58]) and indirect (WFCTA[7, 59], HAWC[60], ARGO-YBJ[5, 6] and Tibet-AS$\gamma$[4]) experiments. In the right panel of Fig. 2 we show the all-particle spectra, compared with observations([61–68]). As can be seen, When the proton cutoff rigidity $R_c$ is 980TV, the expected H+He spectra from the background sources is consistent with the Tibet observation, but in such a case, that model calculation can not describe the all-particle spectra. The Tibet experimental data gives the knee energy of light componentsand is not consistent with the all-particle spectra above tens of PeV. After adding the contribution from the hard component, the agreement between model calculations and observations. The best-fit parameters are given in Table 1.

3.3 Diffuse $\gamma$ rays

We calculated the diffuse $\gamma$ rays distribution from the $\pi^0$ decay component. In Fig. 3, we show the theoretical predictions for diffuse $\gamma$ rays from the Galactic plane in two different...
Figure 2. The spectra of H+He and all-particle spectra. The measurements are from WFCTA[7, 59], HAWC[60], ARGO-YBJ[5], NUCLEON[58], CREAM[57] and Tibet-ASγ[4]. The all-particle data are taken from Horandel [61], TALE[62], IceTop[63, 64], Tibet[65], HAWC[66], NUCLEON[67] and ARGO-YBJ[68].

angular regions: (a)Inner Galactic Plane: $25^\circ < l < 100^\circ$, $|b| < 5^\circ$ and (b)Outer Galactic Plane: $50^\circ < l < 200^\circ$, $|b| < 5^\circ$. When the proton cutoff rigidity $R_c$ is 980TeV, the expected gamma-ray spectrum from the background sources is not consistent with the Tibet ASγ observation, which requires an extra hard component of CRs, so that it can reproduce the data well. The hard diffuse $\gamma$ rays spectra is produced by hard CRs interactions with the interstellar gas, is shown by red line in Fig. 3. Note that at very high energies ($E \gtrsim 100$ TeV), the absorption of $\gamma$ rays due to pair production with ISRF becomes important [69], which leads to a reduction of the DGE spectrum. The dashed and solid lines are the model predictions without and with the absorption in the Milky Way ISRF.

Figure 3. Diffuse $\gamma$-ray spectra from the model calculation, compared with the measurements by ARGO-YBJ [70] and Tibet ASγ [8].

4 Conclusion

The knee for PHe spectrum has been measured at 700 TeV by the hybrid experiment of ARGO-YBJ/WFCTA. This means that the accelerated energy will be below 700 TeV for
Table 1. Injection parameters of different source components.

proton. Just recently, the ultra-high-energy diffuse $\gamma$-rays, produced through hadronic interactions, has published in the first time by AS$\gamma$ experiment. The proton energy was required as higher as to a few PeV. In this work we propose that a new structure around PeV was existed to resolve the tension between them. The new structure was reasonable because the existence of PeVatrons was more and more definite, such as galactic center, Cygnus cocoon, OB stars. After considering the new structure, the model calculation of ultra-high-energy diffuse $\gamma$-rays, PHe spectrum and all-particle spectrum can reproduce the observations quit well. In future, we hope that the bending at several hundreds of TeV and hardening at around PeV can be observed by space-borne HERD and ground-based LHAASO experiments.

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