Ultrahigh-energy diffuse gamma-ray emission from cosmic-ray interactions with medium surrounding acceleration sources

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The diffuse γ-ray spectrum at sub-PeV energy region has been measured for the first time by the Tibet-ASγ experiment. It will shed new light on the understanding of the origin and propagation of Galactic cosmic rays at very high energies. It has been pointed out that the traditional cosmic ray propagation model based on low energy measurements undershoot the new data, and modifications of the model with new ingredients or alternative propagation framework is required. In this work, we propose that the hadronic interactions between freshly accelerated cosmic rays and the medium surrounding the sources, which was neglected in the traditional model, can naturally account for the Tibet-ASγ diffuse emission. We show that this scenario gives a consistent description of other secondary species such as the positron spectrum, the boron-to-carbon ratio, and the antiproton-to-proton ratio. As a result, the electron spectrum above 10 TeV will have a hardening due to this secondary component, which may be tested by future measurements.

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I. INTRODUCTION

The Galactic diffuse γ-ray emission (DGE) is expected to be produced by interactions between cosmic rays (CRs) and the interstellar medium (ISM) as well as the interstellar radiation field (ISRF), during the propagation of CRs in the Milky Way. The DGE includes mainly three components: the decay of π0 from inelastic hadronic interactions between CR nuclei and the ISM, the bremsstrahlung of CR electrons and positrons (CREs) in the ISM, and the inverse Compton scattering (ICS) component of CREs scattering off the ISRF [1]. This model can consistently describe most of the DGE data below 100 GeV and the locally observed results of CRs [2–4], with only slight excesses in the inner Galactic plane which was suggested to be due to unresolved sources or spectral variations of CRs throughout the Milky Way [3]. Measurements of DGE at higher energies are thus very important to further test the model.

The ground based experiments Milagro and ARGO-YBJ measured the DGE above TeV energies, for a few selected sky regions along the Galactic plane [3, 4]. Particularly, in the Cygnus region, the Milagro observation identified an excess [3] compared with the CR propagation model tuned to account for the low-energy DGE [2]. Some fresh sources in such a region may explain the excess [8, 9]. Very recently, the DGE in the Galactic plane above 100 TeV energies was for the first time measured by the Tibet-ASγ experiment [10], which has attracted wide attention for possible physical discussion [11–23]. The Tibet-ASγ fluxes are higher than the prediction of the conventional CR propagation model, and additional components or modification of the conventional propagation framework may be needed [10, 14, 15].

However, in the traditional DGE modeling the secondary particle production (including γ rays) due to interactions between newly accelerated CRs and the gas surrounding the sources is usually omitted. This component may not be small [24], and is expected to be more and more important at high energies since the CR spectra around the sources are harder than those diffusing out in the Milky Way. The possible confinement of CRs around the sources may further enhance this component of secondary particles. In this work, we investigate this scenario in light of the ultrahigh-energy (UHE) diffuse emission measured by Tibet-ASγ. The consequence of such interactions for other types of secondary particles, such as the B/C ratio, the positron and antiproton fluxes will also be investigated. We confront this model with the up-to-date measurements of γ rays and CRs, and find a consistent description of these new data.

II. MODEL DESCRIPTION

A. 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 and
LHAASO observations of extended γ-ray halos around pulsars [25, 26] and the spatial variations of the CR intensities and spectral indices from Fermi-LAT observations [27, 28]. The spatially-dependent propagation (SDP) model was also proposed to explain the observed hardenings of CRs [29, 33], and also the large-scale anisotropies with the help of a nearby source [34, 38].

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 pulsar halo observations. To enable a smooth variation of the diffusion coefficient $D_{xx}$, we parametrize it as

$$D_{xx}(r, z, R) = D_0 F(r, z) \beta^n \left( \frac{R}{R_0} \right)^{\delta_0 F(r, z)} \, ,$$

(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 $\delta_0$ are constants representing the diffusion coefficient and its high-energy rigidity dependence in the outer halo, $n$ is a phenomenological constant in order to fit the low-energy data. The spatial dependence function $F(r, z)$ is given as [37],

$$F(r, z) = \begin{cases} \frac{g(r, z) + [1 - g(r, z)]}{\xi z h^n}, & |z| \leq \xi z h \\ 1, & |z| > \xi z h \end{cases},$$

(2)

in which $g(r, z) = N_m/[1 + f(r, z)]$, and $f(r, z)$ is the source density distribution (see below Sec. II. B), $z_h$ is the half-thickness of the propagation cylinder, and $\xi z_h$ is the half-thickness of the inner halo. The factor $(\frac{z}{\xi z_h})^n$ describes the smoothness of the parameters at the transition between the two halos. Note that the spatial dependence of the diffusion coefficient is phenomenologically assumed. Physically it may be related with the magnetic field distribution, or possibly the turbulence driven by CRs [39]. The model parameters used in this work are listed in Table I. We adopt the diffusion reacceleration model in this work, with the reacceleration being described by a diffusion in the momentum space. The momentum diffusion coefficient, $D_{pp}$, correlates with $D_{xx}$ via

$$D_{pp} D_{xx} = \frac{4p^2 v_A^2}{3(4 - \delta^2)(4 - \delta)},$$

where $v_A$ is the Alfvén velocity, $p$ is the momentum, and $\delta$ is the rigidity dependence slope of the spatial diffusion coefficient [40]. The numerical package DRAGON is used to solve the propagation equation of CRs [41]. For energies smaller than tens of GeV, the fluxes of CRs are suppressed by the solar modulation effect. We use the force-field approximation [42] to account for the solar modulation.

| $D_0$ | $\delta$ | $N_m$ | $\xi$ | $n$ | $R_0$ | $v_A$ | $z_h$ |
|-------|----------|--------|--------|-----|------|------|-----|
| 4.9   | 0.55     | 0.57   | 0.1    | 4   | 0.05 | 2    | 6   | 5   |

Table I. Propagation parameters of the SDP model.

B. Background source distribution

Supernova remnants (SNRs) are considered to be the most plausible candidates for the acceleration of CRs. The spatial distribution of SNRs are approximated as an axisymmetric form parametrized as

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

(3)

where $r_\odot \equiv 8.5$ kpc represents the distance from the Galactic center to the solar system. Parameters $\alpha$ and $\beta$ are taken to be 1.69 and 3.33 [43]. The density of the SNR distribution decreases exponentially along the vertical height from the Galactic plane, with $z_h = 200$ pc.

The injection spectrum of nuclei and primary electrons are assumed to be an exponentially cutoff broken power-law function of particle rigidity $R$

$$f(R) = q_0 \begin{cases} \left( \frac{R}{R_{br}} \right)^{\nu_1}, & R \leq R_{br} \\ \left( \frac{R}{R_{br}} \right)^{\nu_2} \exp \left[ -\frac{R}{R_c} \right], & R > R_{br} \end{cases},$$

(4)

where $q_0$ is the normalization factor, $\nu_{1,2}$ are the spectral indices, $R_{br}$ is break rigidity, $R_c$ is the cutoff rigidity. The spectral break is employed to fit the low-energy spectra of CRs, which is not the focus of the current work.

C. Local pulsar and local SNR

At TeV energies, CREs originate from sources within $\sim 1$ kpc around the solar system [44]. In this small region, the hypothesis of continuous distribution may not be valid any more. Studies show that the discrete effect of nearby CR sources could induce large fluctuations, especially at high energies [45-47]. The contribution of nearby sources to CREs has been studied in the past works (see e.g., [48, 51]). In this work, we assume a nearby pulsar to account for the positron excess above $\sim 20$ GeV. The propagation of CREs injected instantaneously from a point source is described by a time-dependent propagation equation [52]. The injection rate as a function of time and rigidity is assumed to be

$$Q_{\text{pax}}(R, t) = Q_{0, \text{pax}}(t) \left( \frac{R}{R_0} \right)^{-\gamma} \exp \left[ -\frac{R}{R_{c, \text{ax}}} \right],$$

(5)
where $R_c^{\text{cutoff}}$ is the cutoff rigidity of its accelerated CRs. A continuous injection process of electron and positron pairs with injection rate proportional to the spindown power of the pulsar is assumed, i.e.,

$$ Q_{\text{spr}}^0(t) \propto \frac{q_0^\text{spr}}{\tau_0(1 + t/\tau_0)^2}, $$

where $\tau_0$ is a characteristic time scale of the decay of the spindown $\overline{\text{pulsar}}$.

The progenitor of this pulsar produces an SNR, which may accelerate primary nuclei and electrons during its early evolution stage. This local source contribution of primary electrons may be necessary, given the different spectral behaviors of positrons and electrons. The injection process of the SNR is approximated as burstlike.

The normalization is determined through fitting Galactic cosmic rays energy spectra, which results in a total energy of $\sim 2.3 \times 10^{50}$ erg for protons and $\sim 1.4 \times 10^{50}$ erg for helium. If 10% of kinetic energy is used to accelerate primary helium nuclei from the background SNRs, the total energy of supernova explosion is estimated to $\sim 3.7 \times 10^{51}$ erg. Note that the local source introduced here is to account for the energy spectra of CRs, and is independent of the excess of the UHE diffuse $\gamma$ rays.

D. Secondary particles from interactions of freshly accelerated CRs

The freshly accelerated CRs at sources could also interact with the surrounding gas before they escape from the source regions and enter the diffusive halo. Secondary electrons, positrons, antiprotons, and $\gamma$ rays could be produced, whose yields can be calculated as

$$ Q_{\text{sec},i} = \sum_{i=p,He}^{+\infty} \int_0^{E_{\text{th}}} dE_i v \left\{ n_{\text{He}} \frac{d\sigma_{i+He \rightarrow j}}{dE_j} + n_{\text{He}} \frac{d\sigma_{i+He \rightarrow j}}{dE_j} \right\} Q_i(E_i), $$

where $n_{\text{He}}$ is the number density of hydrogen and helium, $d\sigma_{i+He \rightarrow j}/dE_j$ is the differential cross section of the production of secondary particle $j$ from primary particle $i$. The yields of secondary nuclei (such as boron) are simply

$$ Q_{B,j} = \sum_{i=C,N,O} \left( n_{\text{He}} \sigma_{i+He \rightarrow j} + n_{\text{He}} \sigma_{i+He \rightarrow j} \right) vQ_i(E). $$

Secondary charge particles also propagate in the Galaxy, which are also calculated with the DRAGON package.

III. RESULTS

A. Spectra of CR nuclei

The left panel of Fig. 1 shows the proton spectrum expected from the model, compared with the measurements. The model parameters for different source components are given in Table I. The hardening of the proton spectrum around several hundred GeV can be attributed to the summation of the background contribution and the local SNR contribution, and the softening around 14 TeV is mainly due to the spectral cutoff of the local SNR. Similar spectral features are expected to be present for all species, as revealed recently by the DAMPE helium spectral measurement.

B. Diffuse $\gamma$ rays

The DGE is produced through three major processes: decay of $\pi^0$ produced in $pp$-collisions, ICS and bremsstrahlung of CRs. At high energies, the $\pi^0$ decay component dominates the DGE. Therefore we only consider the $\pi^0$ decay component in the following calculation. Comparisons between the model calculation and the measurements by ARGO-YBJ and Tibet-AS$\gamma$ are given in Fig. 2 for two sky regions, $25^\circ < l < 100^\circ$, $|b| < 5^\circ$ and $50^\circ < l < 200^\circ$, $|b| < 5^\circ$, respectively. The DGE fluxes from the background sources are lower by a factor of several than the data, as also shown in [15]. The inclusion of the secondary production from freshly accelerated CRs interacting with the surrounding gas, which has a harder spectrum than the CRs diffusing out, can reproduce the data well. We can also estimate the interaction time of the source component, which is about $5 \times 10^5$ years for the Galactic gas density distribution as adopted in DRAGON. It may be even shorter if some of the sources were located in denser molecular medium. This time reflects the confinement time of CRs in the vicinity of the sources. Note that at very high energies ($E \gtrsim 100$ TeV), the absorption of $\gamma$ rays due to pair production with ISRF becomes important, which leads to a reduction of the DGE spectrum, as shown by the solid line.
C. Ratios of B/C and $\bar{p}/p$

The same process to produce secondary $\gamma$ rays will generate simultaneously secondary boron nuclei and antiprotons. The results of the B/C and the $\bar{p}/p$ ratios are shown in Fig. 3. Good consistency between the model and the data can be seen. We note that the contribution of the “fresh” component exceeds the background component when $E \gtrsim 100$ GeV for $\gamma$ rays and antiprotons, but it happens at much higher energies for B/C. This is due to the fact that energies of secondary particles from inelastic $pp$ interactions are much lower than those of parent protons. However, for the nuclear fragmentation the kinetic energy per nucleon keeps almost unchanged. Note that for kinetic energies higher than $\sim 100$ GeV, the measured $\bar{p}/p$ is slightly higher than the model prediction. Further refinement of the model parameters or additional source of antiprotons such as the dark matter annihilation may improve fitting to the data. This may also not be an issue due to the relatively large uncertainties of the measurements.

D. Spectra of electrons and positrons

Finally we discuss the results of positrons and electrons. There are three components of CR positrons, the secondary contributions from CRs interacting when propagating in the Milky Way and around the acceleration sources, and the primary contribution from the local pulsar. For CR electrons, besides the same components as positrons, there are additional primary components from both the background sources and the local SNR.
Fig. 3. The secondary-to-primary ratios of B/C (left) and $\bar{p}/p$ (right). The data are from AMS-02 [64, 65].

The results are given in Fig. 3. Model parameters of electrons are also given in Table II. For the total CRE spectra, we give two groups of parameters according to the fittings to the H.E.S.S. [66] and DAMPE [67] data, which differ slightly. A clear feature of the model prediction is that for energies above TeV, the fresh CR interactions dominate the positron and electron spectra, resulting in hardenings of their spectra. Such a property may be tested by further precise measurements of the positron and electron spectra.

IV. CONCLUSION

The DGE at ultra-high energies is believed to be produced through the interaction of CRs with the ISM, and is thus a good tracer to study the propagation of galactic CRs. The ever first measurements of DGE above 100 TeV energies by Tibet-AS$\gamma$ recently shows a significant excess compared with the conventional CR propagation and interaction model prediction. We find that possible hadronic interactions of CRs with ambient gas surrounding the acceleration sources can account for the ultra-high energy DGE by Tibet-AS$\gamma$. The harder spectrum of CRs in the vicinity of the sources can naturally explain the high-energy part of the DGE, while keeps the low-energy part unaffected. The secondary interactions around the sources generate simultaneously positrons and electrons, antiprotons, and boron nuclei. With proper model parameters, we find that all these CR measurements can be well reproduced. This model predicts hardenings of the spectra of both positrons and electrons above TeV energies, and can be tested with future measurements.

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Fig. 4. The spectra of positrons and electrons (top) and total spectra of positrons plus electrons (bottom). The measurements are from AMS-02 [68, 69], H.E.S.S. [66], and DAMPE [67].

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| background    | $Q_0$ [$m^{-2}\text{sr}^{-1}\text{s}^{-1}\text{GeV}^{-1}$] | $\nu_1$ | $R_{\text{sw}}$ [GV] | $\nu_2$ | $R_c$ [GV] |
|--------------|-----------------------------------|--------|----------------|--------|------------|
| $e^-$ for HESS fitting | $2.70 \times 10^{-1}$ | 1.14 | 4.5 | 2.77 | $1 \times 10^4$ |
| $e^-$ for DAMPE fitting | $2.60 \times 10^{-1}$ | 1.14 | 4.5 | 2.70 | $110^4$ |
| P             | $4.49 \times 10^{-2}$ | 2.20 | 7.2 | 2.38 | $7 \times 10^6$ |
| He            | $3.74 \times 10^{-3}$ | 2.20 | 7.2 | 2.32 | $7 \times 10^6$ |
| C             | $1.14 \times 10^{-4}$ | 2.20 | 7.2 | 2.32 | $7 \times 10^6$ |
| N             | $9.18 \times 10^{-6}$ | 2.20 | 7.2 | 2.35 | $7 \times 10^6$ |
| O             | $1.27 \times 10^{-4}$ | 2.20 | 7.2 | 2.37 | $7 \times 10^6$ |
| Ne            | $1.62 \times 10^{-5}$ | 2.20 | 7.2 | 2.30 | $7 \times 10^6$ |
| Mg            | $3.45 \times 10^{-6}$ | 2.20 | 7.2 | 2.36 | $7 \times 10^6$ |
| Si            | $1.91 \times 10^{-5}$ | 2.20 | 7.2 | 2.30 | $7 \times 10^6$ |
| Fe            | $1.82 \times 10^{-5}$ | 2.20 | 7.2 | 2.31 | $7 \times 10^6$ |

Table II. Injection parameters of different source components.

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