Ultra-high-energy diffuse gamma-ray emission from cosmic-ray interactions with surrounding medium

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ABSTRACT

The diffuse $\gamma$-ray spectrum at sub-PeV energy region has been measured for the first time by the Tibet-\textsuperscript{AS}$\gamma$ experiment. It will shed new light on the understanding of 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-\textsuperscript{AS}$\gamma$ 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.

1. INTRODUCTION

The Galactic diffuse $\gamma$-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 $\pi^0$ 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 (Strong et al. 2007). This model can consistently describe most of the DGE data below 100 GeV and the locally observed results of CRs (Strong et al. 2004; Zhang et al. 2010; Ackermann et al. 2012), 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 (Ackermann et al. 2012). 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 (Abdo et al. 2007, 2008; Bartoli et al. 2015). Particularly, in the Cygnus region, the Milagro observation identified an excess (Abdo et al. 2007) compared with the CR propagation model tuned to account for the low-energy DGE (Strong et al. 2004). Some fresh sources in such a region may explain the excess (Bi et al. 2009; Guo et al. 2016a). Very recently, the DGE in the Galactic plane above 100 TeV energies was for the first time measured by the Tibet-\textsuperscript{AS}$\gamma$ experiment (Amenomori et al. 2021), which has attracted wide attention for possible physical discussion (Kimura et al. 2021; Dzhatdoev 2021; Fang & Murase 2021; Liu & Wang 2021; Qiao et al. 2021; Huitemeyer 2021; Esmaili & Serpico 2021; Koldobskiy et al. 2021; Bouyahiaoui et al. 2021; Dzhappuev et al. 2021; Li & Ma 2021; Tibaldo et al. 2021; Nath Maity et al. 2021). The Tibet-\textsuperscript{AS}$\gamma$ 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 (Amenomori et al. 2021; Liu & Wang 2021; Qiao et al. 2021).

In this work, we propose that the interactions between CRs and the medium around the sources may result in the high fluxes of the ultra-high-energy (UHE) DGE measured by Tibet-\textsuperscript{AS}$\gamma$. The energy spectra of CRs are harder before they diffuse out, and thus such in-
teractions become more and more important with the increase of energies. 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 mostly up-to-date measurements of DGE and CRs, and find a consistent description of these new data.

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 (Abeysekara et al. 2017) and the spatial variations of the CR intensities and spectral indices from Fermi-LAT observations (Yang et al. 2016; Acero et al. 2016). The spatially-dependent propagation (SDP) model was also proposed to explain the observed hardenings of CRs (Tomassetti 2012, 2015; Feng et al. 2016; Guo et al. 2016b; Liu et al. 2018; Guo & Yuan 2018; Tian et al. 2020), and also the large-scale anisotropies with the help of a nearby source (Liu et al. 2019; Qiao et al. 2019; Yuan et al. 2021).

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

$$D_{xx}(r, z; R) = D_0 F(r, z) \frac{\delta(r, z)}{\delta(r, z)} ,$$

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 (Tian et al. 2020). 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 $D_{pp} D_{xx} = 4 p^2 v_A^2$ where $v_A$ is the Alfvén velocity, $p$ is the momentum, and $\delta$ is the rigidity dependence slope of the diffusion coefficient (See & Ptuskin 1994). The numerical package DRAGON is used to solve the propagation equation of CRs (Evoli et al. 2017). For energies smaller than tens of GeV, the fluxes of CRs are suppressed by the solar modulation effect. We use the force-field approximation (Glesson & Axford 1968) to account for the solar modulation.

2.2. Background source distribution

Supernova remnants (SNRs) are widely expected as likely sites for the acceleration of CRs, in which the charge particles are accelerated to a power-law distribution through the diffusive shock acceleration. The spatial distribution of SNRs are approximated as an axisymmetric form, which can be parameterized as

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

where $r_\odot = 8.5$ 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 (Case & Bhattacharya 1996). 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 $R$

$$q(R) = q_0 \left\{ \begin{array}{ll}
\left(\frac{R_{br1}}{R_0}\right)^{\nu_2} \left(\frac{R}{R_{br1}}\right)^{\nu_2}, & R \leq R_{br1} \\
\left(\frac{R}{R_0}\right)^{\nu_2}, & R_{br1} < R \leq R_{br2} \\
\left(\frac{R_{br2}}{R_0}\right)^{\nu_2} \left(\frac{R}{R_{br2}}\right)^{\nu_3} \exp \left[-\frac{R}{R_c}\right], & R > R_{br2}
\end{array} \right. ,$$

where $q_0$ is the normalization factor, $\nu_{1,2,3}$ are the spectral indices, $R_{br1,2}$ are break rigidities, $R_c$ is the cutoff rigidity, and $R_0$ is a reference rigidity.

2.3. Local pulsar and local SNR

At TeV energies, CREs originate from sources within ~ 1 kpc around the solar system (Yuan & Feng 2018). 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 (Mertsch 2011; Bernard et al. 2012; Fang et al. 2017). The contribution of nearby sources to CREs has been studied in the past works (see e.g., (Serpico 2012; Di Mauro et al. 2014; Liu et al. 2017; Fang et al. 2018)). In this work, we assume a nearby pulsar to account for the positron excess above ~ 20 GeV. The propagation of CREs injected instantaneously from a point source is described by a time-dependent propagation equation (Atoyan et al. 1995). The injection rate as a function of time and rigidity is assumed to be

$$Q_{psr}(R, t) = Q_{psr}^0(t) \left(\frac{R}{R_0}\right)^{-\gamma} \exp \left[-\frac{R}{R_c}\right] ,$$
where $\mathcal{R}_c^{\pm}$ is the cutoff rigidity of its accelerated CREs. A continuous injection process of electron and positron pairs with injection rate proportional to the spindown power of the pulsar is assumed, i.e.,

$$Q_{0}^{\text{par}}(t) \propto \frac{q_{0}^{\text{par}}}{\tau_0(1 + t/\tau_0)^n}, \quad (5)$$

where $\tau_0$ is a characteristic time scale of the decay of the spindown (Kawanaka et al. 2010; Yin et al. 2013).

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 (Zhang et al. 2021). The injection process of the SNR is approximated as burst-like. The source injection rate is assumed to be the same as Eq. (4) but with

$$q_0^{\text{SNR}}(t) = q_0^{\text{SNR}} \delta(t - t_0), \quad (6)$$

where $t_0$ is the time of the supernova explosion. The propagated spectrum from the local pulsar and SNR is thus a convolution of the Green’s function and the time-dependent injection rate $Q_0(t)$ (Atoyan et al. 1995)

$$\varphi(r, \mathcal{R}, t) = \int_{t_0}^{t} G(r - r', t - t', \mathcal{R})Q_0(t')dt'. \quad (7)$$

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 assumed to convert to accelerate CRs, the total energy of supernova explosion is estimated to $\sim 3.7 \times 10^{51}$ erg.

2.4. 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

$$Q_{\text{sec}, j} = \sum_{i=p, He} \int_0^{+\infty} dE_i \cdot v \left\{ n_H \frac{d\sigma_{i+H \to j}}{dE_j} + n_{He} \frac{d\sigma_{i+He \to j}}{dE_j} \right\} Q_i(E_i), \quad (8)$$

where $n_{H, He}$ is the number density of hydrogen and helium, $d\sigma_{i+H \to j}/dE_j$ 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

$$Q_{B,j} = \sum_{i=C, N, O} (n_H \sigma_{i+H \to j} + n_{He} \sigma_{i+He \to j}) vQ_i(E). \quad (9)$$

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

3. RESULTS

3.1. Spectra of CR nuclei

The left panel of Fig. 1 shows the proton spectrum expected from the model, compared with the measurements (Aguilar et al. 2015; Yoon et al. 2017; An et al. 2019; Hörandel 2003). The model parameters for different source components are given in Table 1. 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 (Alemanno et al. 2021). In the right panel of Fig. 1 we show the total spectrum of high-abundance nuclei, compared with the data (Hörandel 2003). For the parameters we adopt, the knee of the all-particle spectrum is mainly due to the spectral cutoff of protons and helium nuclei from the background SNRs.

3.2. Diffuse $\gamma$ rays

The DGE is produced through three major processes: decay of $\pi^0$ produced in $pp$-collisions, ICS and bremsstrahlung of CREs. 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 (Bartoli et al. 2015) and Tibet-AS$\gamma$ (Amenomori et al. 2021) 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 Qiao et al. (2021). 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. Here, the trapped time of accelerated CRs around the source regions is estimated to be about $5 \times 10^5$ years for the Galactic gas density distribution as adopted in DRAGON. This time may be shorter if some of the sources were located in denser molecular medium. Note that at very high energies ($E \gtrsim 100$ TeV), the absorption of $\gamma$ rays due to pair production with ISRF becomes important (Zhang et al. 2006), which leads to a reduction of the DGE spectrum, as shown by the solid line.

3.3. Ratios of $B/C$ and $\bar{p}/p$
proton spectrum

![Graph showing proton spectrum](image)

**Fig. 1.** The spectra of protons (left) and all particles (right). The measurements of proton spectra are from AMS-02 (Aguilar et al. 2015), CREAM (Yoon et al. 2017), and DAMPE (An et al. 2019). The all-particle spectrum is taken from the normalized result of Hörandel (2003).

![Graph showing diffuse γ-ray spectra](image)

**Fig. 2.** Diffuse γ-ray spectra from the model calculation, compared with the measurements by ARGO-YBJ (Bartoli et al. 2015) and Tibet ASγ (Amenomori et al. 2021).

The same process to produce secondary γ rays will generate simultaneously secondary Boron nuclei and antiprotons. The results of the B/C and the 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 \( E \gtrsim 100 \text{ GeV} \) for γ 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.

### 3.4. 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. The results are given in Fig. 4. Model parameters of electrons are also given in Table 1. For the total CRE spectra, we give two groups of parameters according to the fittings to the H.E.S.S. (H.E.S.S. collaboration et al. 2017) and DAMPE (DAMPE Collaboration et al. 2017) 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.

4. 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-ASγ 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-ASγ. 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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