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LETTER TO THE EDITOR

New limit on high Galactic latitude PeV γ-ray flux from Tibet ASγ data

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ABSTRACT

The Tibet ASγ collaboration has recently reported the detection of γ-rays with energies up to Peta-electronvolt from parts of the Galactic plane. We note that the analysis of γ-ray flux by the Tibet-ASγ experiment also implies an upper bound on the diffuse γ-ray flux from high Galactic latitudes ($|b| > 20°$) in the energy range between 100 TeV and 1 PeV. This bound is up to an order of magnitude stronger than previously derived bounds from GRAPES3, KASCADE, and CASA-MIA experiments. We discuss the new Tibet-ASγ limit on the high Galactic latitude γ-ray flux in the context of possible mechanisms of multi-messenger (γ-ray and neutrino) emission from nearby cosmic ray sources, dark matter decays, and the large-scale cosmic ray halo of the Milky Way.

Key words. gamma rays: diffuse background – cosmic rays

1. Introduction

Diffuse GeV–TeV γ-ray flux from the sky is dominated by emission from interactions of cosmic rays in the interstellar medium (Ackermann et al. 2012; Acero et al. 2016; Lipari & Vernetto 2018; Neronov & Semikoz 2020). In the energy range below several hundred Giga-electronvolts, high Galactic latitude diffuse flux also has a sizeable contribution from extragalactic sources, but this contribution vanishes at higher energies because of the effect of absorption of extragalactic γ-rays during their propagation through the intergalactic medium (Gould & Schréder 1967; Franceschini et al. 2008).

High Galactic latitude flux has been measured up to several Tera-electronvolts in energy by the *Fermi*/LAT telescope (Neronov & Semikoz 2020). It is dominated by emission from the local interstellar medium, but can also contain contributions from nearby very extended sources (Neronov et al. 2018; Bouyahiaoui et al. 2019). The diffuse emission from the local interstellar medium has two main contributions: from interactions of cosmic ray protons and atomic nuclei and from inverse Compton emission by cosmic ray electrons. The modelling of these two components suggests that pion decay flux from interactions of protons and nuclei dominates over the inverse Compton flux in this part of the sky (Lipari & Vernetto 2018). The inverse Compton flux above several Tera-electronvolts is further suppressed by the decrease in the interaction cross section in the Klein-Nishina regime and by the softening of the cosmic ray electron spectrum above Tera-electronvolt (Aharonian et al. 2008; Adriani et al. 2018; Ambrosi et al. 2017).

At even higher energies, diffuse γ-ray flux has been measured from parts of the sky by extensive air shower (EAS) arrays MILAGO, HAWC, and ARGO-YBJ (Abdo et al. 2008; Bartoli et al. 2015; Abeysekara et al. 2017a). In this energy range, emission from the Galactic plane generally follows the powerlaw extrapolation of the lower energy flux (Neronov & Semikoz 2020), as expected from the flux produced by the cosmic rays with a powerlaw spectrum. No measurements of the γ-ray flux at high Galactic latitudes have been reported so far. In the absence of detection, the EAS experiments have previously reported upper bounds on the all-sky γ-ray flux, assuming its near isotropy. The tightest reported bounds in the 1 PeV range are from the KASCADE (Apel et al. 2017) and CASA-MIA (Chantell et al. 1997) experiments. At somewhat lower energies in the 0.01−0.1 PeV range, the best bounds come from the GRAPES3 EAS experiment (Minamino et al. 2009) and the HEGRA Cherenkov telescope array (Aharonian et al. 2002). The γ-ray flux at 100 TeV can be produced by cosmic ray protons and nuclei of energies far above 100 TeV in the energy range of the 'knee' of the cosmic ray spectrum. The measurement of the γ-ray flux in this energy range can thus yield information on the nature of the knee and on the location and properties of nearby cosmic accelerators boosting particle energies beyond 1 PeV, the so-called pevatrons. If the particles responsible for the γ-ray emission are protons and atomic nuclei, the 1 PeV γ-ray emission from the pevatrons is accompanied by the emission of neutrinos, with comparable luminosity and spectral characteristics. The detection of the 0.1−1 PeV diffuse γ-ray flux can thus be used to constrain the Galactic component of the astrophysical neutrino flux (Aartsen et al. 2013) of uncertain origin.

The Tibet-ASγ experiment has recently reported detection (rather than an upper bound) of diffuse emission from the Galactic plane in the energy range up to 1 PeV (Amenomori et al. 2021). The better sensitivity of Tibet-ASγ and higher energy reach, compared to MILAGRO, HAWC, and ARGO-YBJ, can be explained by its more efficient suppression of background EAS produced by protons and atomic nuclei. The supplementary material for the Tibet-ASγ publication shows the efficiency of the suppression of the charged cosmic ray background reaching the $\sim 10^{-6}$ level of the all-particle cosmic ray flux at 1 PeV. The Tibet-ASγ detection of the Galactic plane can be used to constrain the population of cosmic ray electrons (Fang & Murase 2021) and cosmic ray protons and nuclei (Koldobskiy et al. 2021) in the Galactic disk.

In what follows we note that the Tibet-ASγ analysis has another important implication: it constrains the γ-ray flux from the sky outside the Galactic plane. An upper limit on the high Galactic latitude flux from the Tibet-ASγ measurements and explore its implications for models of high-energy particle acceleration in the Milky Way and for the models of super-heavy dark matter.

2. Tibet-ASγ limit on the high Galactic latitude γ-ray flux

The Tibet-ASγ array achieves a high efficiency of rejection of the cosmic ray proton and nuclei background due to a large size muon detector. Hadronic EASs are typically muon-rich, whereas γ ray- and electron-induced showers are muon-poor. Discriminating between a γ-ray and an electron as well as a proton and a nuclei EAS becomes progressively more efficient with increasing energy because of larger muon statistics. This is shown in Fig. 1 which compares the efficiency of hadronic EAS background rejection in Tibet ASγ to that of HAWC (Abeysekara et al. 2017b) and LHAASO (Wu et al. 2019). The blue curve in Fig. 1 shows the efficiency of the selection of the γ-ray EASs for the same cut selection that suppresses the hadronic EAS background down to the black curve level (Amenomori et al. 2021).

Figure 1 shows that starting from 30 TeV, the background suppression of Tibet ASγ experiments starts to be better than that of HAWC. This is explained by the absence of a muon detector in HAWC. Similarly to Tibet ASγ, the LHAASO experiment (Bai et al. 2019), which is now under way, will use muon detectors for gamma-hadron separation. This explains a similar energy dependence of LHAASO and Tibet ASγ background suppression efficiencies.

The non-negligible fraction of the EAS that are not rejected by the cuts on 'gamma-like' events can, in principle, be real γ-ray events. It is, however, not possible anymore to distinguish the remaining hadronic EAS from the real γ-ray EAS based on the EAS parameters. The presence of real γ-ray events from a specific astronomical source can be spotted by comparing the statistics of events coming from the source direction with that for events from other directions on the sky. This has been done in the analysis of Amenomori et al. (2021), leading to the detection of the signal from the Galactic plane.

Comparing of the 'on-source' and 'off-source' event statistics is, however, not possible for the source spanning a large part of the sky because there is no 'off-source' region in this case. It might still be possible to detect sources in this regime if the observed event statistic shows an excess compared to the expectations based on the known hadronic cosmic ray spectrum and the efficiency of rejection of the hadronic cosmic rays derived from Monte-Carlo modelling of detector performance. In the absence of such modelling, only upper limits on the γ-ray flux from the large sky region can be derived, assuming that all the events remaining after the cuts are possible γ rays.

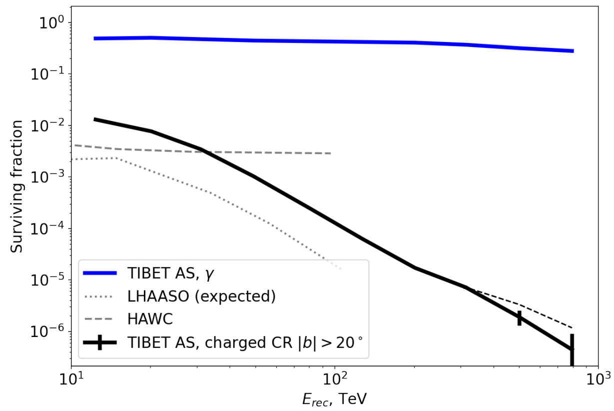

Fig. 1. Surviving fraction of proton and nuclei EAS in Tibet ASγ experiment after γ-ray-like event selection (Amenomori et al. 2021). The dashed black line shows the upper limit on the total number of surviving γ-ray-like events in the $|b| > 20°$ region. The blue line shows the efficiency of the selection of the γ-ray EAS. For comparison, grey dashed and dotted lines show the efficiencies of the suppression of the hadronic EAS background in HAWC (Abeysekara et al. 2017b) and LHAASO (Wu et al. 2019).

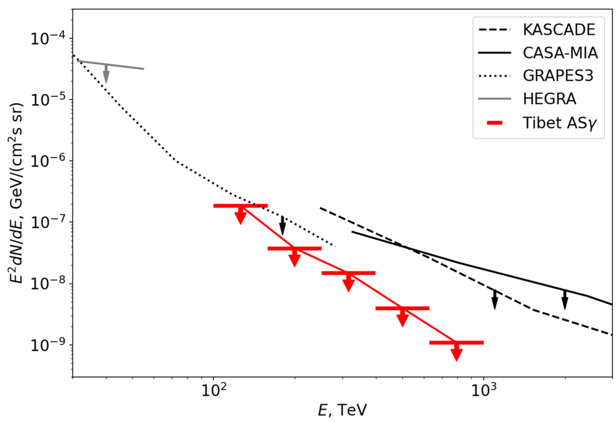

Fig. 2. Tibet ASγ limit on high Galactic latitude γ-ray flux derived from Amenomori et al. (2021), compared to previously reported limits from KASCADE (Apel et al. 2017), CASA-MIA (Chantell et al. 1997), GRAPES3 (Minamino et al. 2009), and HEGRA (Aharonian et al. 2002) experiments.

This approach gives the upper limit on the γ-ray flux in the sky region $|b| > 20°$ shown in Fig. 2. To derive this upper limit, we used the measurement of the all-particle cosmic ray flux by the Tibet ASγ experiment (Amenomori et al. 2019) multiplied by the surviving event fraction of hadronic EASs and divided by the efficiency of the selection of γ-ray EASs. The last two bins have been corrected for the effect of low statistics on the surviving signal. The derived limits thus correspond to the same 719-day live time as in Amenomori et al. (2021).

Figure 2 provides a comparison of the upper limit on the diffuse flux from the sky region $|b| > 20°$ with previously reported regions on the sky-averaged γ-ray flux. One can see that in the 0.3−1 PeV energy range, the limit derived from Tibet ASγ data is an order of magnitude better than previous limits from KASCADE (Apel et al. 2017) and CASA-MIA (Chantell et al. 1997) experiments. At lower energies, the Tibet ASγ limit is comparable to that from the GRAPES3 experiment (Minamino et al. 2009).

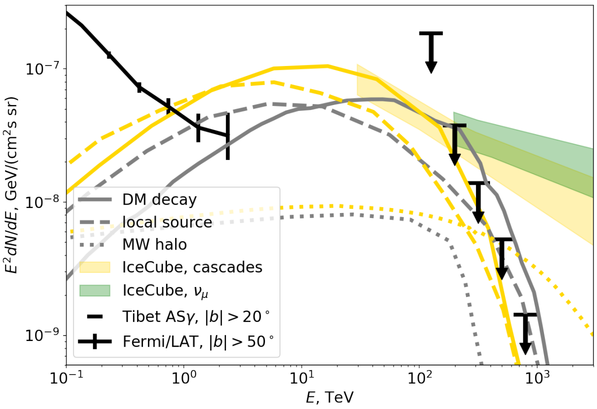

Fig. 3. Tibet ASγ limit on high Galactic latitude γ-ray flux compared to *Fermi*/LAT measurements at lower energies from Neronov & Semikoz (2020) and to model predictions of neutrino (yellow lines) and γ-ray (grey lines) fluxes for the local cosmic ray source (Bouyahiaoui et al. 2020) (dashed lines), dark matter decay (Neronov et al. 2018) (solid), and 100 kpc scale halos of the Milky Way (Recchia et al. 2021) (dotted). Yellow and green areas show the astrophysical neutrino spectrum measurement in cascade (Aartsen et al. 2020) and muon (Stettner 2019) channels.

3. Implications of the revised bound

An improvement to the upper limit on the diffuse γ-ray flux from the high Galactic latitude region, provided by the Tibet ASγ experiment, can be used to probe a range of models of γ-ray and neutrino emission from particle acceleration processes and dark matter in the Milky Way. Figure 3 shows a comparison of the new upper limit in the 0.1−1 PeV range with measurement of the high Galactic latitude flux in the region $|b| > 50^\circ$ with *Fermi*/LAT at the energies below 3 TeV (Neronov & Semikoz 2020) and with IceCube measurements of the astrophysical neutrino flux in muon (Stettner 2019) and cascade (Aartsen et al. 2020) channels.

The astrophysical muon neutrino flux measured above 200 TeV has a harder powerlaw spectrum which is shown by the green shaded range (Aartsen et al. 2016; Stettner 2019). Its overall energy flux is lower than the isotropic diffuse γ-ray flux measured by *Fermi*-LAT below 1 TeV (Fermi-LAT Collaboration 2016). This is consistent with a possibility that both the Peta-electronvolt energy scale neutrinos and Giga-electronvolt range γ-rays are produced by the same extragalactic source population (Murase et al. 2013). Blazars are possible candidates for γ-ray and neutrino sources and they provide a major contribution to the high-energy part of *Fermi* LAT diffuse γ-ray background (Abdo et al. 2010; Neronov & Semikoz 2012; Di Mauro et al. 2014; Fermi-LAT Collaboration 2016). However, γ-ray bright blazars do not offer a major contribution of IceCube muon neutrino flux (Aartsen et al. 2017; Neronov et al. 2017). Gamma-ray loud blasars still can provide up to 20% of total muon neutrino flux according to Giommi et al. (2020). A piece of evidence for a significant contribution from radio-brightest blazars has been reported recently (Plavin et al. 2020, 2021). Otherwise, non-blazar active galactic nuclei (AGN) (Smith et al. 2021) and ultra-high energy cosmic ray sources (Kachelrieß et al. 2017) can contribute to the neutrino flux. Uncertainties regarding the modelling of the extragalactic neutrino source populations still leave a possibility that part of the neutrino flux comes from the local Galaxy. The new Tibet-ASγ bound derived above severely limits a possible Galactic component of the neutrino flux in the Peta-electronvolt energy range. Figure 3 shows that no more than 10% of the neutrino flux above 1 PeV detected from the high Galactic latitude region can come from the region within 10 kpc around the Solar System. The γ-ray flux from larger distances is attenuated by the effect of pair production on the cosmic microwave background. The mean free path of PeV γ-rays with respect to the pair production is $\lambda_{\gamma\gamma} \simeq 10$ kpc (Gould & Schréder 1967). If as of yet uncertain source(s) of high Galactic latitude neutrino flux is(are) situated at the distances $D \gtrsim 2\lambda_{\gamma\gamma}$ for which $\exp(-D/d_{\gamma\gamma}) \lesssim 0.1$, the γ-ray flux accompanying the neutrino flux can still be suppressed down to the level of the Tibet-ASγ bound.

The astrophysical neutrino flux has also been detected at lower energies in the 'cascade' channel, down to ∼10 TeV, where it appears to have a softer spectrum (Aartsen et al. 2020; Abbasi et al. 2021) shown by the yellow range in Fig. 3. Its spectral properties suggest that it is produced in proton-proton or nuclei-nuclei interactions, rather than $p-\gamma$ interactions that are typically characterised by an energy threshold in the range above 100 TeV and the hard neutrino spectrum below the threshold energy. In this case the soft neutrino spectrum is expected to extend down to the 1 GeV range. It has been suggested that the softer spectrum neutrinos have a Galactic origin (Neronov et al. 2014; Neronov & Semikoz 2016a,b). However, a large signal from the Galactic plane is inconsistent with arrival directions of neutrino events (Albert et al. 2018), suggesting that the latter come from either hidden extragalactic sources (Murase et al. 2016) or from galactic sources distributed away from the Galactic plane (Taylor et al. 2014; Kachelrieß et al. 2018a). In this last case one should see the unavoidable diffuse γ-ray background at high galactic latitudes. Figure 3 shows that *Fermi*/LAT high latitude flux and IceCube astrophysical neutrino energy fluxes are in fact comparable (albeit sampled in different energy ranges). This suggests that a common process producing neutrinos and γ rays may indeed provide non-negligible contribution to both γ-ray and neutrino diffuse fluxes. The new Tibet-ASγ limit at 100 TeV still does not rule out the possibility of the existence of a γ-ray flux at the level of neutrino flux up to the 100 TeV range.

Several models for the common process generating a high Galactic latitude neutrino and γ-ray fluxes have been proposed, including the possibility of local cosmic ray sources (Kachelrieß et al. 2015, 2018b; Neronov et al. 2018; Bouyahiaoui et al. 2019, 2020), the decay of super-heavy dark matter particles (Berezinsky et al. 1997; Feldstein et al. 2013; Esmaili & Serpico 2013; Neronov et al. 2018; Kachelrieß et al. 2018a), as well as a large-scale cosmic ray halo of the Milky Way galaxy (Taylor et al. 2014; Kalashev & Troitsky 2016; Blasi & Amato 2019; Recchia et al. 2021). These models have been previously constrained by the *Fermi*/LAT and IceCube data, but not by the γ-ray data in the IceCube energy range. The new Tibet ASγ upper bound on the high Galactic latitude flux starts to constrain these models. In particular, predictions of the model of γ rays from dark matter particle decays by Neronov et al. (2018) exceed the Tibet ASγ limit. The model can be made consistent with Tibet ASγ data only if the mass of the dark matter particle is lower than $M_{\rm DM}c^2 < 3$ PeV. The local source model is not yet constrained, but its prediction is right at the Tibet ASγ upper bound on the γ-ray flux.

Even though the large-scale halo model has been initially proposed as an explanation for the astrophysical neutrino signal (Taylor et al. 2014), its flux has been strongly constrained by the *Fermi*/LAT measurement of the isotropic γ-ray background, so that the neutrino flux from the halo is far below the measured astrophysical neutrino flux (Recchia et al. 2021). As such, the model is also consistent with the Tibet ASγ data.

Measurements of the diffuse γ-ray flux at a high Galactic latitude will be crucially improved by LHAASO (Wu et al. 2019). The potential of LHAASO is clear from Fig. 1 which shows that LHAASO's efficiency in suppressing the hadronic EAS background will be 6 times lower than that of Tibet ASγ. This should a substantial improvement to the upper bound or detection of the signal in 0.3−1 PeV range where the Tibet ASγ bound is close to the model predictions and where the maximal possible flux level is close to the level of the neutrino flux.

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