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First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

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We report, for the first time, the long-awaited detection of diffuse gamma rays with energies between 100 TeV and 1 PeV in the Galactic disk. Particularly, all gamma rays above 398 TeV are observed apart from known TeV gamma-ray sources and compatible with expectations from the hadronic emission scenario in which gamma rays originate from the decay of π^0's produced through the interaction of protons with the interstellar medium in the Galaxy. This is strong evidence that cosmic rays are accelerated beyond PeV energies in our Galaxy and spread over the Galactic disk.

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Introduction.—The cosmic-ray energy spectrum has approximately a power-law shape $dN/dE \propto E^p$ in an energy region between 10^{10} and 10^{20} eV [1]. One of the most prominent features of the spectrum is the so-called knee at 4×10^{15} eV (= 4 PeV), where the spectrum steepens with its power-law index changing from $p = -2.7$ to -3.1 [2,3]. In a scenario most widely accepted, cosmic rays are accelerated up to PeV energies by energetic objects in our Galaxy, such as supernova remnants, and well confined in the Galaxy up to the knee energy by the Galactic magnetic field [4,5], although source objects and acceleration mechanisms are still under discussion. To confirm the theory predicting the Galactic origin of the PeV cosmic rays, therefore, it would be conclusive to experimentally identify the objects in our Galaxy, called "PeVatrons," which are accelerating cosmic rays up to PeV energies.

In recent decades, high-energy gamma-ray observations have been utilized to identify cosmic-ray sources by detecting the arrival direction of gamma rays produced by cosmic rays, because gamma rays travel straight from the source free from the magnetic deflection. Through the hadronic interaction with ambient matters, PeV cosmic rays produce neutral pions which decay into gamma rays with energies as high as 100 TeV [6–8]. Recently, the ground-based Cherenkov telescopes and air shower (AS) arrays observed gamma rays with energies up to a few tens of TeV from more than 100 sources in the Galaxy [9–11]. The Tibet ASγ [12] and high altitude water cerenkov (HAWC) experiments [13] also detected gamma rays beyond 100 TeV from a few sources which are very good candidates of PeVatrons. However, there has been no conclusive evidence for the cosmic-ray PeVatron reported so far.

Gamma-ray telescopes on board satellites, such as the EGRET and *Fermi*-LAT, have precisely observed diffuse gamma rays from the Galactic disk in an energy range $0.1 < E < 100$ GeV [14,15]. The gamma-ray distribution is extended more than a few degrees in Galactic latitude, similar to the distribution of interstellar gas. The measured spectra are now established to be dominated by emissions from the interaction of cosmic rays including electrons with interstellar gas and magnetic field in this energy region [15]. In the higher energy range, the Milagro experiment reported TeV diffuse gamma-ray emissions from the Cygnus region in the Galactic disk [16], while the astrophysical radiation with ground-based observatory at Yangbajing (ARGO-YBJ) experiment reported diffuse gamma rays with $0.35 < E < 2$ TeV extended over Galactic longitude (l) between $25° < l < 100°$ [17]. Overall, their observed fluxes are consistent with the standard *Fermi*-LAT model for the diffuse Galactic emission. At the highest energy region, the Chicago air shower array - Michigan muon array (CASA-MIA) experiment presented the upper limits of Galactic diffuse gamma rays with 140 TeV $< E <$ 1.3 PeV [18].

In this Letter, we report on the detection of diffuse gamma rays with 100 TeV $< E <$ 1 PeV from the Galactic disk with the Tibet air shower array and muon detector array (Tibet AS + MD array) and present evidence for PeV cosmic rays being accelerated and confined in the Galaxy.

Experiment.—In order to observe high-energy gamma rays with high sensitivity, we started a new hybrid experiment using the surface AS array combined with the underground water-Cherenkov-type muon detector array at Yangbajing (90.522 °E, 30.102 °N; 4300 m above sea level) in Tibet, China. The AS array, covering a large area of 65 700 m^2, precisely measures the arrival direction and energy of each primary cosmic ray, while the underground muon detector array, with a detection area of 3400 m^2 beneath the AS array, measures the number of muons in each AS. Because an AS induced by a gamma ray contains many fewer muons than an AS induced by a primary cosmic ray in the atmosphere, the muon detector array enables us to efficiently discriminate cosmic-ray background events from gamma-ray signals [19]. Based on this technique, we suppressed more than 99.9% of cosmic-ray background events above 100 TeV and succeeded in detecting unprecedentedly high-energy gamma rays from the Crab Nebula. For more details, please see [12].

Data analysis.—The energy and arrival direction of each gamma ray are reconstructed using the AS particle density and timing recorded at each scintillation detector composing the AS array. The angular resolution (50% containment) is estimated to be approximately 0.22° and 0.16° for 100 and 400 TeV gamma rays, respectively. The pointing accuracy has been estimated to be less than 0.06° from the observation of the Crab Nebula as described in the Supplemental Material of our previous Letter [12].

To estimate the gamma-ray energy, we use S50 defined as the particle density detected in an AS surface detector (ρ) at a perpendicular distance of 50 m from the AS axis in the best-fit Nishimura-Kamata-Greisen (NKG) function [20]. The energy resolutions with S50 are roughly estimated to be 20% and 10% for 100 and 400 TeV, respectively. The absolute energy scale uncertainty was estimated to be 12% from the westward displacement of the Moon's shadow center due to the geomagnetic field [21]. The live time of the dataset is 719 days from February 2014 to May 2017, and the average effective detection time for the Galactic plane observation is approximately 3700 h at the zenith angle less than 40°. The data selection criteria are the same in our previous work [12] except for the muon cut condition. According to the CASA-MIA experiment, the marginal excess along the Galactic plane in the sub-PeV energies is 1.63 σ, and the fraction of excess to cosmic-ray background events is estimated to be approximately 3×10^{-5} [18]. In order to search for signals with such a small excess fraction, we adopt a tight muon cut in the present analyses requiring for gamma-ray-like events to satisfy $\Sigma N_\mu < 2.1 \times 10^{-4}\,(\Sigma\rho)^{1.2}$ or $\Sigma N_\mu < 0.4$, where ΣN_μ is the total number of muons detected in the underground muon detector array. This is just one order of magnitude tighter than the criterion used in our previous work [12]. The cosmic-ray survival ratio with this tight muon cut is experimentally estimated to be approximately 10^{-6} above 400 TeV, while the gamma-ray survival ratio is estimated to be 30% by the MC simulation. The comparison between the cosmic-ray data and the MC simulation is described in Fig. S1 in Supplemental Material [22].

Results and discussion.—Figure 1 shows arrival directions of gamma-ray-like events in (a) $100(=10^{2.0}) < E < 158(=10^{2.2})$ TeV, (b) $158(=10^{2.2}) < E < 398(=10^{2.6})$ TeV, and (c) $398(=10^{2.6}) < E < 1000(=10^{3.0})$ TeV, remaining after the tight muon cut. It is seen that the observed arrival directions concentrate in a region along the Galactic plane (see also Fig. 2). Particularly in Fig. 1(c), 23 gamma-ray-like events are observed in $|b| < 10°$ which we define as the on region ($N_{\rm ON} = 23$), while only ten events are observed in $|b| > 20°$ which we define as the off region ($N_{\rm OFF} = 10$). Since the total number of events before the tight muon cut is 8.6×10^6, the cosmic-ray survival ratio is estimated to be 1.2×10^{-6} in $|b| > 20°$ above 398 TeV. We use $N_{\rm OFF}$ in $|b| > 20°$ to estimate the number of cosmic-ray background events, because the contribution from extragalactic gamma rays in $E > 100$ TeV is expected to be strongly suppressed due to the pair-production interaction with the extragalactic background light. The mean free path lengths for the pair production for 100 TeV and 1 PeV are a few megaparsecs and 10 kpc, respectively [29].

Since the ratio (α) of exposures in on and off regions is estimated to be 0.27 by the MC simulation with our geometrical exposure, the expected number of background events in the on region with $|b| < 10°$ is $N_{\rm BG} = \alpha N_{\rm OFF} = 2.73$, and the Li-Ma significance [30] of the diffuse gamma rays in the on region is calculated to be 5.9 σ. The number of events and the significances in each energy bin are summarized in Table S1 in Supplemental Material [22].

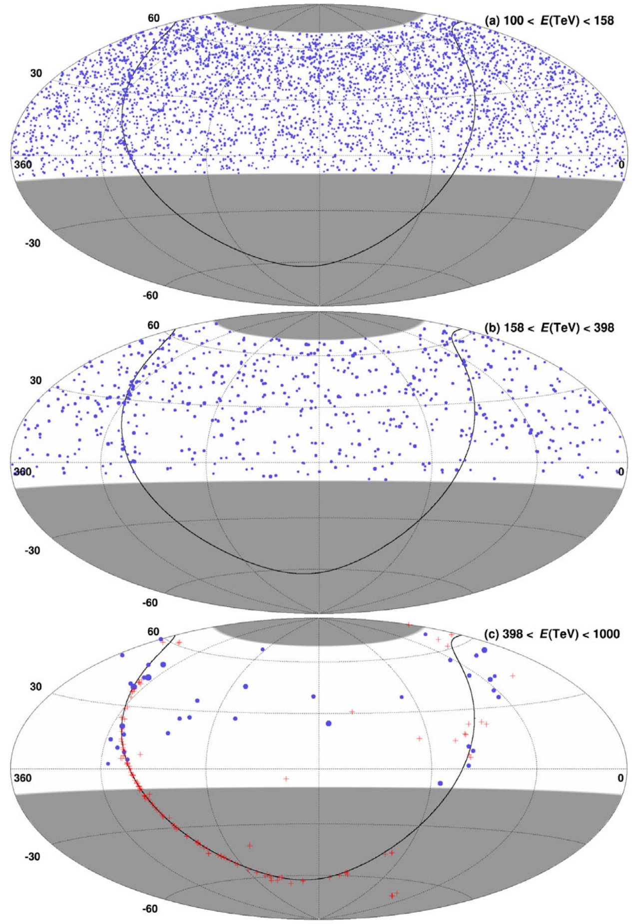

FIG. 1. The arrival direction of each gamma-ray-like event observed with (a) $100 < E < 158$ TeV, (b) $158 < E < 398$ TeV, and (c) $398 < E < 1000$ TeV, respectively, in the equatorial coordinate. The blue solid circles show arrival directions of gamma-ray-like events observed by the Tibet AS + MD array. The area of each circle is proportional to the measured energy of each event. The red plus marks show directions of the known Galactic TeV sources (including the unidentified sources) listed in the TeV gamma-ray catalog [9]. The solid curve indicates the Galactic plane, while the shaded areas indicate the sky regions outside the field of view of the Tibet AS + MD array.

The observed distribution of the number of muons for $E > 398$ TeV after the muon cut is consistent with that estimated from the gamma-ray MC simulation as shown in Fig. S2 in Supplemental Material [22]. The highest-energy $957(^{+166}_{-141})$ TeV gamma ray is observed near the Galactic plane, where the uncertainty in energy is defined as the quadratic sum of the absolute energy-scale error (12%) and the energy resolution [12]. Solid circles in Fig. 2 display $N_{\rm ON} - N_{\rm OFF}$ as a function of b in (a) $100 < E < 158$ TeV, (b) $158 < E < 398$ TeV, and (c) $398 < E < 1000$ TeV. The concentration of diffuse gamma rays around the Galactic plane is apparent particularly in Fig. 2.

In order to estimate contribution from the known gamma-ray sources, we searched for gamma-ray signals

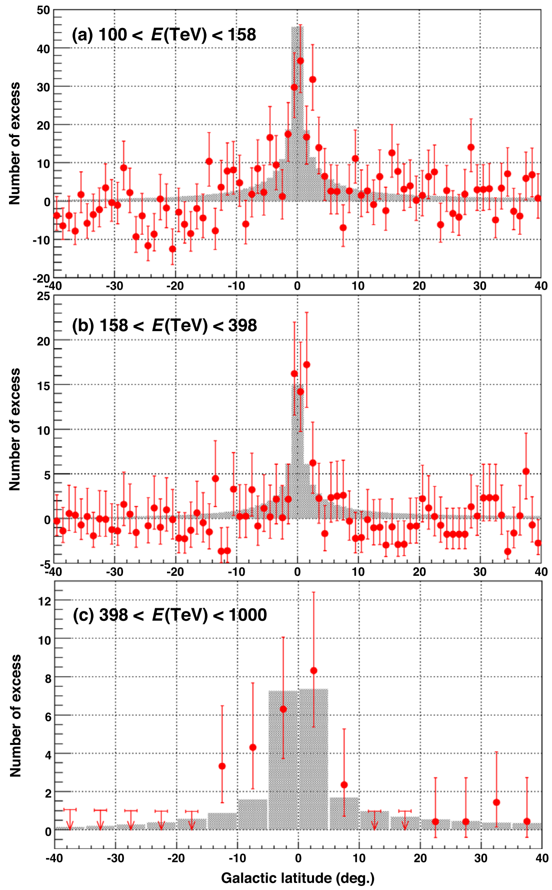

FIG. 2. Gamma-ray excess counts as a function of Galactic latitude with (a) $100 < E < 158$ TeV, (b) $158 < E < 398$ TeV, and (c) $398 < E < 1000$ TeV. The excess count is calculated from the observed event number after subtracting the estimated background event number (see the text). The Galactic longitude of the arrival direction in each figure is integrated across our FOV (approximately $22° < l < 225°$). The solid circles show the experimental data, while the shaded histograms display the model profile [8] rebinned in every (a),(b) 1° and (c) 5° of the Galactic latitude. The downward arrows show upper limits of excess at 68% confidence level. The number of excess in the model, which is independent of energy, is normalized to the observed number within $|b| < 5°$.

above 100 TeV from the direction of the selected 60 Galactic sources (excluding the extragalactic-type sources but including the unidentified sources) listed in the TeV source catalog [9] within $|b| < 5°$ in our field of view (FOV). We used a search window with a radius of 0.5° centered at each source direction, which contains more than 90% of gamma-ray events, as shown in Fig. S3 in Supplemental Material [22]. Since the source extensions of the HAWC sources above 56 TeV were typically around 0.3° [13], the search window radius 0.5° is appropriate to exclude most of the contributions from such extended sources to diffuse gamma rays. Stacking 60 sources, we found 37 gamma-ray-like events within search windows against 8.7 background events, which corresponds to

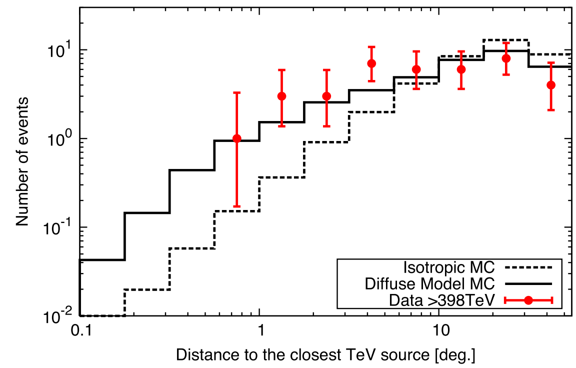

FIG. 3. The distribution of the angular distance between the arrival direction of each observed gamma-ray-like event with $E > 398$ TeV and the direction of its closest known TeV source listed in the TeV gamma-ray catalog [9]. The red solid circles show the observed data, while the dashed and solid histograms display the MC results expected from the isotropic event distribution and the diffuse gamma-ray model [8], respectively, to be observed with our geometrical exposure.

6.8 σ above 100 TeV, while the number of all excess within $|b| < 5°$ (N_{excess}) is 253.5. The fractional source contribution ($N_{\mathrm{point}} = 37 - 8.7 = 28.3$) to the diffuse component ($N_{\mathrm{diffuse}} = N_{\mathrm{excess}} - N_{\mathrm{point}} = 225.2$) is estimated to be 13% above 100 TeV.

We also searched for gamma-ray signals within a search window centered at each direction of 38 gamma-ray-like events in $E > 398$ TeV, but we found no significant signal above 10 TeV. This implies that these 38 events are orphan gamma rays as is expected from the diffuse gamma-ray scenario, although the existence of unknown sporadic or weak steady sources with very hard spectra in each direction cannot be ruled out.

Figure 3 shows the distribution of angular distance between each of 38 gamma-ray-like events in $E > 398$ TeV and its closest Galactic TeV source. Surprisingly, there is no gamma-ray excess near the known TeV sources. Such high-energy gamma rays which originate from PeV electrons should be produced near the sources, due to significant energy loss via the synchrotron radiation in the magnetic field around the source. The observed gamma rays are, therefore, hard to interpret in the leptonic scenario. The gamma-ray emission by electrons will be also significantly suppressed above 100 TeV due to rapid decrease of inverse-Compton (IC) cross section by the Klein-Nishina effect.

Recently, Lipari and Vernetto [8] developed a model capable of successfully reproducing the diffuse gamma-ray or neutrino flux observed in 0.1 GeV $< E <$ 10 PeV, by utilizing relevant cosmic-ray nuclei and electron spectra, interstellar gas distribution, soft photon field, gamma-ray and neutrino production processes, and absorption effects in the Galaxy. They tested two different models named the space-independent and space-dependent models. The cosmic-ray spectrum in the first model is assumed to be identical everywhere in the Galaxy, while the spectrum in the second model is assumed to be harder in the central region of the Galaxy than that at Earth as indicated by the observed spectral index of Galactic diffuse gamma rays in $0.1 < E < 100$ GeV. This kind of scenario was also discussed elsewhere [31]. Both models can reproduce the observed flux and spatial distribution of arrival directions by *Fermi*-LAT in the GeV energy region. The predicted gamma-ray spectrum above 1 GeV is also dominated by the contribution from the hadronic interaction between the interstellar matter and cosmic rays. It was concluded that the contribution to the diffuse gamma rays from the IC scattering and bremsstrahlung by relativistic electrons is less than 5% compared with the hadronic process above 100 TeV, considering the steep electron and positron spectra with $p = -3.8$ measured by high energy stereoscopic system (H.E.S.S.) [32], dark matter particle explore (DAMPE) [33], and calorimetric electron telescope (CALET) [34]. Another model [35] showed the IC scattering contribution in the low Galactic latitude is negligible above 20 TeV.

Gray histograms in Fig. 2 show the prediction of the space-independent model [8]. It is seen that the distribution in Figs. 2(a) and 2(b) is overall consistent with the model prediction. The distribution in Fig. 2(c) observed in $398 < E < 1000$ TeV looks broader than that in Figs. 2(a) and 2(b), but it is also statistically consistent with the prediction rebinned in every 5° of the Galactic latitude (b).

Figure 4 shows the observed differential energy spectra of diffuse gamma rays, compared with the model predictions by Lipari and Vernetto [8] in which gamma-ray spectra are calculated in (a) $25° < l < 100°$ and (b) $50° < l < 200°$ along the Galactic plane, each in $|b| < 5°$. The measured fluxes by the Tibet AS + MD array are summarized in Table S2 in Supplemental Material [22]. These fluxes are obtained after subtracting events within 0.5° from the known TeV sources, and the systematic error of the observed flux is approximately 30% due to the uncertainty of absolute energy scale [21]. We corrected time variation of detector gain at each detector based on the single-particle measurement for each run. The time variation of gamma-ray-like excess above 100 TeV in $|b| < 5°$ is stable within approximately 10%. It is seen that the measured fluxes by the Tibet AS + MD array are compatible with both the space-independent and space-dependent models based on the hadronic scenario. As a leptonic model, it is proposed that gamma-ray halos induced by the relativistic electrons and positrons from pulsars explain the Galactic diffuse gamma rays above 500 GeV [36]. However, the gamma-ray flux predicted by this model has an exponential cutoff well below 100 TeV and is inconsistent with the observation by Tibet AS + MD array [see Fig. 4(a)].

The observed flux in the highest-energy bin in $398 < E < 1000$ TeV looks higher than the model prediction, but it is not inconsistent with the model when the statistical and systematic errors are considered. Above 398 TeV, the total number of observed events is ten in each of $25° < l < 100°$ and $50° < l < 200°$, which includes the Cygnus region around $l = 80°$. Interestingly, four out of ten events are detected within 4° from the center of the Cygnus cocoon, which is claimed as an extended gamma-ray source by the ARGO-YBJ [37] and also proposed as a strong candidate of the PeVatrons [38], but not taken into account in the model [8]. If these four events are simply excluded, the observed flux at the highest energy in Fig. 4 better agrees with model predictions.

The high-energy astrophysical neutrinos are also a good probe of the spectrum and spatial distribution of PeV cosmic rays in the Galaxy [39,40]. According to Lipari and Vernetto [8], the diffuse gamma-ray or neutrino fluxes predicted near the Galactic Center ($|l| < 30°$) by the space-dependent model are more than 5 times higher

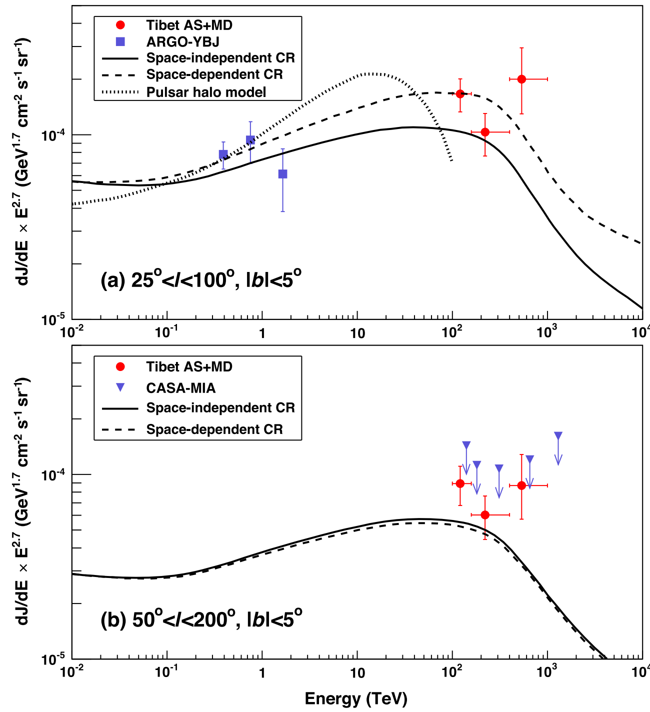

FIG. 4. Differential energy spectra of the diffuse gamma rays from the Galactic plane in the regions of (a) $|b| < 5°$, $25° < l < 100°$ and (b) $|b| < 5°$, $50° < l < 200°$, respectively. The solid circles show the observed flux after excluding the contribution from the known TeV sources listed in the TeV gamma-ray catalog [9], while the solid and dashed curves display the predicted energy spectra by the space-independent and space-dependent models by Lipari and Vernetto [8], respectively (see the text). The dotted curve in (a) shows the flux predicted by a leptonic model [36] in which gamma rays are induced by relativistic electrons and positrons from pulsars. Solid squares in (a) and triangles with arrows in (b) indicate the flux measured by ARGO-YBJ [17] and the flux upper limit by the CASA-MIA experiment [18], respectively. The error bar shows 1σ statistical error.

than that predicted by the space-independent model in $100\ \mathrm{TeV} < E < 10\ \mathrm{PeV}$. Therefore, the gamma-ray and neutrino observations in the Southern hemisphere will also play important roles to understand or constrain the spatial distribution of PeV cosmic rays in the Galaxy. Probing PeV diffuse gamma rays and neutrinos from the large-scale structures, such the Fermi bubble [41] and the possible dark matter halo in the Galaxy [42,43], will be also interesting.

Conclusions.—We successfully observed the Galactic diffuse gamma rays in $100\ \mathrm{TeV} < E < 1\ \mathrm{PeV}$ by the Tibet AS + MD array. Particularly, in the energy region above 398 TeV, we found 23 gamma-ray-like events against 2.73 background events, which corresponds to 5.9 σ statistical significance, in $|b| < 10°$ in our FOV. The highest energy of the observed gamma ray is $957(^{+166}_{-141})$ TeV, which is nearly 1 PeV. The gamma-ray distribution is extended around the Galactic plane apart from known Galactic TeV gamma-ray sources. We also found no significant signal above 10 TeV in directions of 38 gamma-ray-like events above 398 TeV, which implies that these events are orphan gamma rays as is expected from the diffuse gamma-ray scenario. The measured fluxes are overall consistent with recent models assuming the hadronic cosmic-ray origin. These facts are hard to interpret with the leptonic cosmic-ray origin, indicating that sub-PeV diffuse gamma rays are produced by the hadronic interaction of protons, which are accelerated up to a few PeV energies (or possibly ∼10 PeV) and escaping from the source, with the interstellar gas in our Galaxy. Hence, we conclude that the PeVatrons inevitably exist in the present and/or past Galaxy accelerating cosmic rays which spread in the Galaxy being well confined around the Galactic disk.

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