

A new GeV-TeV particle component and the barrier of cosmic-ray sea in the CMZ region

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The Galactic center is widely anticipated to be an important cosmic-ray source and the observations of some Imaging Atmospheric Cherenkov Telescopes did successfully reveal a new component of TeV-PeV cosmic rays in the vicinity of the Galactic center. This work reports the identification of GeV-TeV cosmic rays in the central molecular zone with the γ -ray observations of the Fermi-LAT. The spectrum and spatial gradient of the GeV-TeV source component are consistent with that measured by the Imaging Atmospheric Cherenkov Telescopes. The inferred cosmic-ray energy density in the central molecular zone region is, however, substantially lower than the so-called cosmic-ray sea component. Our finding is in support of the presence of a high energy particle accelerator at the Galactic center and strongly suggests a barrier that can effectively suppress the penetration of the particles from the cosmic-ray sea to the central molecular zone.

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1. Introduction

It is believed that in the Milky Way cosmic rays (CRs) could be accelerated by shocks in supernova remnants [1, and references therein] or massive star wind [2]. Those charged relativistic particles would then propagate diffusively in the Galactic magnetic field, possibly experiencing reacceleration, convection, spallation, and energy loss processes [3, 4]. This production and propagation process would lead to a large-scale, quasi-steady-state CR sea, which distributes relatively smoothly in the Galaxy, as supported by the Fermi-LAT observations [5–7].

However, in the proximity of a recent or currently active accelerator, the smoothly distributed CR sea would be overlaid with a new component of fresh CRs. Observations of such a fresh CR component will be very important in studying the acceleration, injection, and transportation processes of CRs. In the central molecular zone (CMZ) region, the High Energy Stereoscopic System (H.E.S.S.) and other Imaging Atmospheric Cherenkov Telescopes (IACTs) reveal a large amount of very-high-energy (VHE) CRs with a hard spectrum and a high density (a factor of ~ 10 times higher than that measured locally at the Earth), implying an injection of CRs by a source close to the GC [8–10]. Further studies [11–13] show that there is a gradient of the CR density profile, $\propto r^{-\alpha}$ ($\alpha \sim 1 - 1.2$), deduced from the γ -ray profile deconvolved the gas density in the CMZ. One attractive explanation is that Sagittarius A*, which might have been more active in the past, accelerated CRs up to PeV energies which diffuse outwards and collide with molecular gas to produce energetic γ -rays.

The search for a possible counterpart of the VHE component in the low-energy γ -ray band would be very important in revealing its nature [14, 15]. In the analysis, the so-called Galactic Center GeV excess [GCE; e.g., 16] that could be either from dark matter annihilation or a group of unresolved faint point sources like millisecond pulsars [17] may play an important role. Though this excess peaks at several GeV, at several tens of GeV it may be still bright enough to contaminate other emission signals [18, 19]. A dedicated morphological and spectral analysis of the Fermi-LAT data in the GC region, with proper consideration of the GCE component, is thus necessary to critically address the CR population in the most central region.

2. The setup of the Fermi-LAT data analysis

The Fermi-LAT data¹ of version P8R3 and class SOURCE are used in this analysis. We select the data recorded from August 4, 2008 to February 1, 2020. We select photons with energies higher than 8 GeV, which have a balance of a good angular resolution and a large enough statistics. To suppress the contamination from γ -ray generated by CR interactions in the upper atmosphere, photons collected at zenith angles larger than 90° are removed. Moreover, we adopt the specifications (DATA_QUAL>0) && (LAT_CONFIG==1) to select good quality data. We bin the data, from 8 GeV to 500 GeV, into 20 logarithmically distributed energy bins and 100×100 spatial bins with pixel size of 0.1° centered at the GC. We employ the binned likelihood analysis method to analyze the data with the FermiTools version 1.2.1. The instrument response function (IRF) adopted is P8R3_SOURCE_V2.

¹<https://fermi.gsfc.nasa.gov/ssc/data/access/>

The source model XML file is generated using the user contributed tool `make4FGLxml.py`² based on the 4FGL catalog [20, 21]. The spectrum of Sagittarius A* is modeled as a power-law instead of the default log-parabola spectrum. Two additional point sources, 3FHL J1747.2-2822 and 3FHL J1748.6-2816 which are not in the 4FGL source catalog `g11_psc_v23.xml`³ but in the 3FHL source catalog `g11_psch_v12.xml`⁴, are also added in our analysis.

We use the Galactic diffusion emission (GDE) modeled by the GALPROP software⁵ [22, 23] in this work, which gives different components of the diffuse emission individually. The result of model A as introduced in [24] is taken as our baseline GDE model. For systematics studies about the template tracing neutral pion decay, besides the mentioned GALPROP generated model, we also employ the Planck dust opacity map⁶ from [25] as an alternative, which traces the gas distributions without the uncertainty from the X_{CO} factor in the GALPROP related templates. The bremsstrahlung in our energy range is expected to be small and is thus neglected. The γ -ray emissions from the inverse Compton scattering of high energy electrons off the optical, infrared, and the cosmic microwave background are taken as another template. The third diffuse template is the isotropic background. Power-law spectra of these three diffuse templates are assumed, and both the normalizations and spectral indices are treated as free parameters in the likelihood fit. For the GCE component, we use a line-of-sight integration of $\rho^2(r)$, where $\rho(r) \propto r^{-1.28}$ as derived in [19], to model its spatial distribution, and again assume a power-law to model its spectrum. As shown in [19], the power-law spectrum is reasonable to describe the high-energy tail of the GCE.

3. CRs with low density in the CMZ

We single out the CMZ region [26] for studying CR properties near the GC region, and the rest is referred to as off-CMZ region. The spectral indices and normalizations of the CMZ and off-CMZ regions are independent in the fitting. The spectral index of the CMZ region is harder by 0.19 ± 0.07 than that, about 2.68, predicted in the GALPROP GDE model A, and the integrated energy flux is $(7.05 \pm 0.44) \times 10^{-5} \text{ MeV cm}^{-2} \text{ s}^{-1}$ from 8 GeV to 500 GeV. We find that the spectral index of the CMZ is consistent with that observed in the VHE γ -ray band ($2.32 \pm 0.05_{\text{stat}} \pm 0.10_{\text{sys}}$ and $2.28 \pm 0.03_{\text{stat}} \pm 0.20_{\text{sys}}$ by H.E.S.S. [11–13]), but is clearly harder than that expected from the CR sea interaction with the gas in the CMZ. Furthermore, the integrated flux is lower than that predicted from the CR sea interaction. Similar results have been obtained if we change the GALPROP template to the Planck template. Our results thus imply that there is a hard component in the CMZ which possibly coincides with the VHE component, and the CR density of the background sea component in the CMZ region should be suppressed.

Then we investigate the CR density distribution in the CMZ and off-CMZ directions. To enable a high enough spatial resolution of the gas distribution, we use the Planck dust opacity map as a tracer of the line-of-sight integral of the gas distribution. We split the Planck map into small segments, as shown in the left panel of Figure 1, with a width of 0.5 degrees except for the last one.

²<http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/>

³https://fermi.gsfc.nasa.gov/ssc/data/access/lat/10yr_catalog/

⁴<https://fermi.gsfc.nasa.gov/ssc/data/access/lat/3FHL/>

⁵<http://galprop.stanford.edu/>

⁶https://irsa.ipac.caltech.edu/data/Planck/release_2/all-sky-maps/maps/componentmaps/foregrounds/COM_CompMap_Dust-GNILC-Model-Opacity_2048_R2.01.fits

We model each segment with a power-law spectrum by fixing the spectral index, to be those derived above using the Planck template, which are 2.56 in the CMZ region, and 2.64 in the off-CMZ region. We fix all the parameters of point sources outside the CMZ to their fitting values as well and leave all other source parameters free. The CR densities (w_{CR} in eV/cm^3) in those segments can thus be estimated from the normalizations (and hence luminosities) of the γ -ray emission as

$$w_{\text{CR}}(E_{\text{CR}}) \approx 0.018 \left(\frac{\eta_N}{1.5} \right)^{-1} \times \left(\frac{L_\gamma(E_\gamma)}{10^{34} \text{ erg/s}} \right) \left(\frac{M}{10^6 M_\odot} \right)^{-1}, \quad (1)$$

where $E_{\text{CR}} \approx 10E_\gamma$ is the corresponding energy of CRs giving γ -ray energy of E_γ , η_N accounts for the correction from nuclei heavier than protons and is taken as 1.5 in this work, $L_\gamma(E_\gamma)$ is the γ -ray luminosity and M is the total mass of the gas in the segment which is estimated using the relation between the dust opacity and the column density for the Planck dust opacity map [27]. Using parameters for each segment derived in the fitting, the distribution of w_{CR} ($80 \text{ GeV} \leq E \leq 5 \text{ TeV}$) is shown in the right panel of Figure 1. It is very interesting to find that, for segments outside the CMZ, the CR density is almost a constant, which is consistent with the expectation of the CR sea in such a small region. The CR density in the CMZ, however, declines clearly with the distance to the GC, which is consistent with a gradient profile observed at the VHE band. The CR density in the CMZ is also generally smaller than that outside the CMZ.

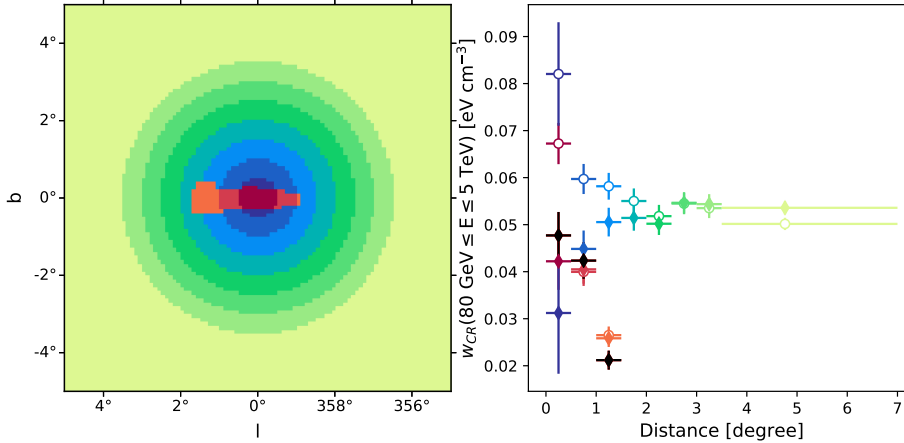


Figure 1: Left: The segment division of the GC region for the Planck map. Segments in the CMZ are marked in red to orange and segments in the off-CMZ region are marked in green to blue. Right: CR densities in different segments of the Planck map defined in the left panel, with same colors. Filled and open symbols represent results from fittings with and without the GCE, respectively. CR densities, inferred from analysis with the CS map, for segments within the CMZ are marked with black points, and they agree well with those derived from fitting with the Planck map.

4. The GeV-TeV counterpart of the new CR component discovered by the IACTs

The VHE observations of the new component in the GC show a power-law radial profile, $\propto r^{-\alpha}$, of the CR density with $\alpha = 1.10 \pm 0.12$ [11] and 1.2 ± 0.3 [13]. However, in the GALPROP GDE model the spatial gradient of CR densities in the very center region of the Galaxy is not properly modeled. Furthermore, the molecular hydrogen component used in GALPROP is traced with the CO emission, which may be strongly contaminated by the foreground and background emissions in the GC. The CS radio map [26] is expected to be a better tracer of the molecular component [11, 13]. Therefore we use a power-law function $r^{-\alpha}$ to parameterize the radial distribution of the CR density in the CMZ, and multiply its line-of-sight integral with the CS emission template to model the spatial distribution of the new component. The spatial template of the off-CMZ region is adopted as the GALPROP template. We scan α from 0.0 to 2.0 and we find that the Fermi-LAT data favors a non-zero value of α at a confidence level of 5.4σ . The fitting result is $\alpha = 1.35^{+0.06}_{-0.09}$, which is consistent with that derived in the VHE band, $\alpha = 1.2 \pm 0.3$ in [13] and $\alpha = 1.1 \pm 0.12$ in [11]. To visualize the radial dependence of the CR density and to investigate the dependence on the mass estimation with different observations, we derive the CR density in the CMZ region using the CS map without radial scaling divided into 3 segments again. We estimate the mass for each segments, using the relation between the total CS fluxes and the mass. As shown in the right panel of Figure 1, the CR densities in the 3 segments within the CMZ, inferred from the CS map, agree well those inferred from the Planck map.

We derive the spectral energy distributions (SED) of the new component in the CMZ region, using the CS $\propto r^{-1.35}$ template, and show the results in Figure 2. The γ -ray spectral index of the fitting in the whole energy band from 8 GeV to 500 GeV is 2.50 ± 0.08 , which is roughly consistent with that measured in the VHE band ($2.32 \pm 0.05_{\text{stat}} \pm 0.10_{\text{syst}}$ and $2.28 \pm 0.03_{\text{stat}} \pm 0.20_{\text{syst}}$ by H.E.S.S. [11, 12]). The γ -ray flux in the inner 150 pc ($\pm 1^\circ$) region is $(5.50 \pm 0.38) \times 10^{-5}$ MeV cm⁻² s⁻¹. Taking the mass of dense molecular clouds as $3 \times 10^7 M_\odot$ [26, 28] and $\eta_N = 1.5$, we obtain the CR density in the CMZ as $(4.5 \pm 0.3) \times 10^{-2}$ eV cm⁻³ from 80 GeV to 5 TeV, which is close to the local CR density, about 4.2×10^{-2} eV cm⁻³ at this energy range [29, 30]. And the proton density above 10 GeV, $(4.3 \pm 0.3) \times 10^{-12}$ cm⁻³ if the power-law spectrum still holds for energy down to 10 GeV, is a factor of a few smaller than the expectation, about 12×10^{-12} cm⁻³, of the CR sea in the GC region [31]. We also note that the derived proton density in the CMZ region in [31] is also lower than that from the prediction, and this supports our results.

5. Conclusions

Here, we report the re-analysis of the Fermi-LAT data in the CMZ region and the identification of a component of GeV-TeV CRs, which is likely the counterpart of the new TeV-PeV CR component discovered by the IACTs. This supports the presence of a high-energy particle accelerator at the GC. Unexpectedly, we further show that the inferred energy density from the background CRs in the CMZ region is clearly smaller than that from an extrapolation of the CR sea distribution. A natural explanation is that there is a barrier in the CMZ, maybe due to the strong magnetic field in such a region, that can effectively suppress the penetration of particles from outside to the CMZ.

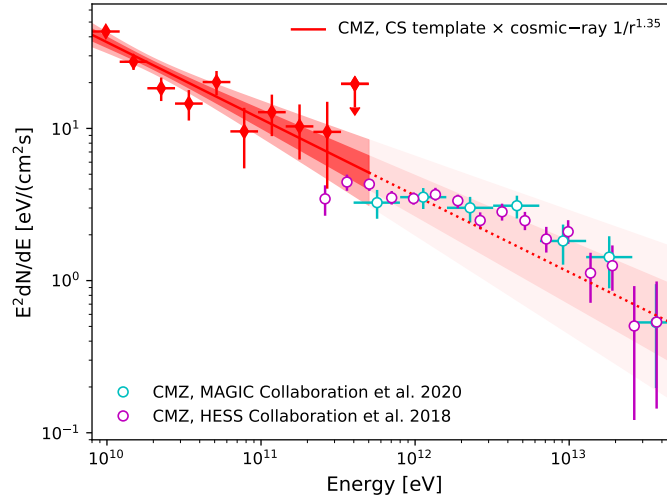


Figure 2: SED of CMZ component obtained using the Fermi-LAT data (red filled dots), compared with those measured by H.E.S.S. [11] and MAGIC [13]. The solid lines and associated bands show the best-fit power-law model and the 68% and 95% confidence ranges.

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