Galactic Center Observations with CTAO LST-1

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Abstract. Very-high-energy gamma-ray observations of the central part of the Milky Way Galaxy allow for morphological study of cosmic-ray propagation around the supermassive black hole Sgr A*. An interpretation of the diffuse gamma-ray component, which spans a few hundred parsecs in longitude, is the PeVatron scenario: the spectral energy distribution follows a power law up to a few tens of TeV, with a spatial distribution that is aligned with the central molecular zone and accelerated cosmic rays that propagate in the vicinity of Sgr A*. Nevertheless, differences in the findings of earlier studies persist among current-generation telescopes, each offering different interpretations based on different analytical approaches. The MAGIC telescopes for example presented a hint of a presence of a spectral turnover at around 20 TeV, possibly in tension with the PeVatron scenario. We analyzed Galactic Center data taken by the Large-Sized Telescope prototype (LST-1) for the Cherenkov Telescope Array Observatory (CTAO), the next-generation project of a ground-based gamma-ray observatory currently under commissioning. Despite the limited sensitivity due to the current monoscopic observation, the relatively wide field of view and the large-zenith-angle observation technique allow LST-1 to study the diffuse emission in the TeV range. In this contribution, we will report the current status of studies of the Galactic Center diffuse emission by including our results from LST-1 observations.

1 Introduction

The Galactic Center (GC) region is home to a variety of particle accelerators, namely the supermassive black hole, supernova remnants, and pulsar wind nebulae. Notably, the region is believed to supply a significant portion of accelerated particles. From TeV gamma-ray observations of the inner ~200 pc region, H.E.S.S. derived a cosmic ray (CR) spatial profile that peaks towards Sagittarius A* (Sgr A*) along the Galactic longitude [1]. The study also reported a power-law energy spectrum of the diffuse gamma-ray emission, resulting in a

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lower bound of the CR spectral cut-off of 2.9 (0.6) PeV at a 68% (90%) confidence level. These morphology and spectrum align with the scenario that Sgr A* was more active in the past 10^6-10^7 years and acted as a source of PeV CRs. In addition, HAWC detected UHE gamma rays from the GC region, yielding a power-law spectrum that extends from 6 TeV to 114 TeV [2]. This finding also supports the hadronic PeVatron scenario. However, the diffuse gamma-ray spectrum observed with HAWC is measured to be much softer (index of $-2.88 \pm 0.15_{\mathrm{stat}} - 0.1_{\mathrm{sys}}$) than the spectra reported by other Imaging Atmospheric Cherenkov Telescopes (IACTs), which estimated the index ranging roughly between −2 and −2.4 [1, 3–5]. Furthermore, the MAGIC telescopes suggested a 2σ hint of a presence of the spectral cut-off at around 20 TeV for the diffuse emission along the Galactic ridge, possibly in tension with the simple PeVatron scenario [4]. Such differences in the findings of earlier studies persist and have not been well understood.

The Cherenkov Telescope Array Observatory (CTAO) is a next-generation IACT observatory for VHE gamma-ray astronomy. In 2018, the Large-Sized Telescope prototype (LST-1) was inaugurated at the CTAO northern site in the Roque de los Muchachos Observatory on the Canary Island of La Palma (28°N, 18°W) [6]. In parallel with ongoing commissioning, LST-1 has been taking science data of several gamma-ray sources, including the GC region.

At the LST-1 site, the GC culminates at a zenith distance of $\sim 58°$ in the horizontal coordinates. LST-1 is thus required to perform the large zenith angle observations, which generally enhances the high-energy (typically above 1 TeV) sensitivity at the sacrifice of the energy threshold increased to $\mathcal{O}(100)$ GeV [7]. Also, in comparison with other IACT systems in the northern hemisphere, the relatively wide field of view of LST-1 (~ 4.5 deg in diameter) allows for a more homogeneous sensitivity across the region where the diffuse emission from the Galactic ridge is distributed. Hence, despite the currently limited sensitivity due to the monoscopic observations when compared with the future array, LST-1 already provides a comparable, or rather better, view towards the diffuse emission in the GC region than the current-generation telescopes. This study revisits the previous findings of the diffuse emission, using data from the first LST-1 campaign towards the GC.

2 Observation and Data Analysis

In this work, we used a total of ∼39-hour data after selections, from LST-1 observations of the GC in the so-called wobble mode with two offset angles of 0.5 deg or 0.7 deg (for operational reasons) for Sgr A*. For the analysis, Monte-Carlo (MC) simulations were densely performed along the GC trajectory to mitigate the MC/data discrepancy. Observations and MC simulations were then consistently processed with the official software `cta-lstchain` [6]. Developing `pybkgmodel`, a suite of tools for residual background modeling [8], we evaluated the background with the exclusion-map method [9]. On modeling signals, using standard tools included in `gammapy` [10, 11], we performed a spatially resolved spectral fit of predefined models to the data.

This study used four gamma-ray source models, in line with the previous study performed with the MAGIC telescopes [4]: point-like sources at the position of Sgr A*, G0.9+0.1, and the Arc; and the diffuse emission component along the Galactic ridge, as follows. The spectral models for Sgr A* and the diffuse emission were assumed to be power laws with exponential cut-offs, while the other sources were modeled with simple power laws. All parameters (amplitudes, spectral indices, and cut-offs) of these models were jointly fitted through the 3D (energy and galactic longitude/latitude) likelihood, for which the Cash statistics is adopted [12]. A detection significance was calculated by the likelihood ratio with and without a component or parameter, according to the Wilks' theorem [13].

Consistent with the previous studies [3, 4], the spatial model of the diffuse component was calculated as resulting from an inelastic *p*-*p* interaction between the central dense gas and the CRs propagating from Sgr A*. The target gas mass was estimated by the $C^{32}S$ (CS) J = 1–0 line emission from radio observations [14]. The CR density was modeled by a radial function $r^{-\alpha}$, where r is the physical distance from Sgr A*.

3 Results

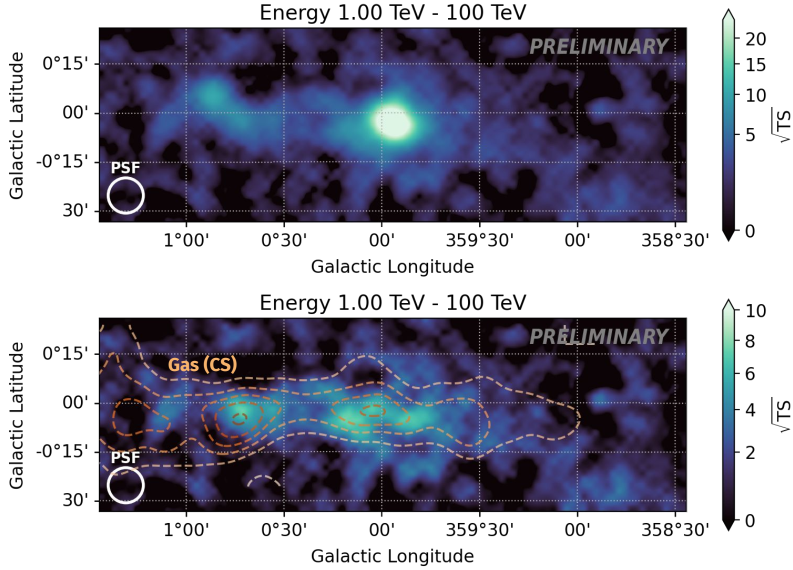

Figure 1. Sky map of the GC obtained with the LST-1 observations. The maps are smeared with a 0.06-deg Gaussian kernel. The circle at the bottom left corner shows a 68% containment radius. *Top*) Sky map in units of significance. *Bottom*) Sky map with the best-fit models of Sgr A* and G0.9+0.1 subtracted. The contours show the integrated and smeared gas map, estimated from the CS molecules [14].

The top panel of Figure 1 presents a clear gamma-ray image of the GC region obtained with LST-1. After subtracting the two bright point-like sources (i.e. Sgr A* and G0.9+0.1), the bottom panel of Figure 1 highlights that the gamma-ray diffuse emission is spatially well associated with the gas along the longitude. At energies between 398 GeV and 100 TeV, the detection significances for Sgr A*, G0.9+0.1, and the diffuse component were 31σ, 13σ, and 20σ, respectively. Remarkably, LST-1's wide field of view enables to obtain a higher significance of the diffuse component than that obtained by the other northern IACT arrays, despite having less than half the observing time.

The best-fit CR radial profile index was estimated to be $\alpha \sim 1.1$, which is consistent with the quasi-constant diffusion from Sgr A*. In agreement with the previous studies [1, 4], the spectral and morphological characteristics of the diffuse component can be reasonably associated with ultra-relativistic hadronic CRs colliding with the dense gas. However, similarly to the result from the MAGIC telescopes [4], we also obtained a 2.8σ hint of the spectral cut-off at $\sim$ 30 TeV in the diffuse component.

In summary, we have obtained the diffuse component morphology that is consistent with the previous studies, with a preference for the presence of a spectral curvature. To gain a more definitive understanding, we will continue to collect GC data, and more comprehensively discuss the diffuse component, making full use of the clearly detected signals.

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