PROCEEDINGS OF SCIENCE

Increased Support for a New Millisecond Pulsar Population in the Galactic Bulge

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Almost a decade after its discovery, the Galactic center gamma-ray excess remains puzzling. Although the spectral characteristics of this signal can be explained by either dark matter emission or a new population of millisecond pulsars, the spatial morphology of the excess is the key to separating the two theories. This contribution presents the results of a recent study that uses cutting-edge models for interstellar gas, inverse Compton emission, and stellar mass models to reanalyze the Galactic center excess. A strong correlation is observed between the Fermi GeV excess's spatial morphology and the Galactic bulge stars, supporting the millisecond pulsar hypothesis.

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1. Introduction

Our incomplete understanding of the astrophysical background, especially that in the Milky Way's center, limits our ability to search for new physics with gamma-ray telescopes. Despite this limitation, Fermi-LAT data from the Galactic center (GC) show an excess [1–7] of extended GeV gamma rays that is not easily explained by known astrophysical sources.

This GC excess (GCE) might be explained by the emission of GeV-scale dark matter particles (e.g., [1, 4, 7–11]) or by a new population of millisecond pulsars [4, 6, 12, 13]. Although the predicted spectrum of either of these hypothetical sources is degenerate, their spatial morphologies are expected to be quite different [14]. Recent studies [15–20] demonstrated that there is a correlation [1] between the spatial morphology of the GCE and that of Galactic bulge stars in the Galactic center. The nature of the Fermi GeV excess would be fully clarified if these results are confirmed with realistic (good-fitting in an absolute sense) Galactic diffuse emission models (GDE).

As part of this contribution (see Ref. [23] for in-depth discussions), we present a much improved model for the GDE in the inner Galaxy and evaluate how this impacts the GCE's characteristics. Our results confirm previous findings that stellar mass in the Galactic bulge (e.g., Ref [15–17]) better matches the GCE's spatial morphology than dark matter templates.

2. Methods

In comparison to previous studies, our new GDE model[2] for the Galactic center region contains numerous substantial improvements. First, our atomic hydrogen model is based on explicit radiation-transport modeling of line, absorption, and continuum emission [23], allowing a more realistic representation of hydrogen distribution in the GC. Second, our inverse Compton (IC) templates reproduce the state-of-the-art templates recently constructed by the GALPROP team [24]. As pioneered by the Fermi collaboration [25], we have divided these two components of the GDE into Galactocentric rings so that they have the flexibility to accommodate for negative/positive residuals present in the data. Third, we used bleeding-edge models for the stellar bulge [18] and Fermi bubbles [17]. Figure 1 shows residual maps for the atomic hydrogen distribution in the GC. The hydrogen gas maps are constructed by subtracting the standard hydrogen gas maps in Ref. [26] from our new hydrodynamic hydrogen models. Observed differences between the old and new models can be attributed to a variety of factors: (i) hydrodynamic gas maps are based on smoothed particle hydrodynamic simulations, whereas standard ones are based on circular orbits of gas, (ii) the new gas maps account for continuum emission and absorption lines, but the standard ones do *not*, and (iii) we allow for the hydrogen excitation temperature to vary along the longitudinal and latitudinal directions (in Galactic coordinates), whereas the standard maps assume a constant excitation temperature across the Galaxy [26]. An interesting finding was that our new GDE model significantly outperformed the previous generation of hydrodynamic gas models [15, 17, 27], as well as the standard gas templates [28].

The spectra of the different interstellar gas ring templates are presented in Fig. 2. As can be seen, each ring's spectra show a marked hadronic/bremsstrahlung-like behavior, demonstrating the

[1]Though we note that Refs. [21, 22] have claimed different results.
[2]Our GDE model is publicly available at https://doi.org/ 10.5281/zenodo.6276721

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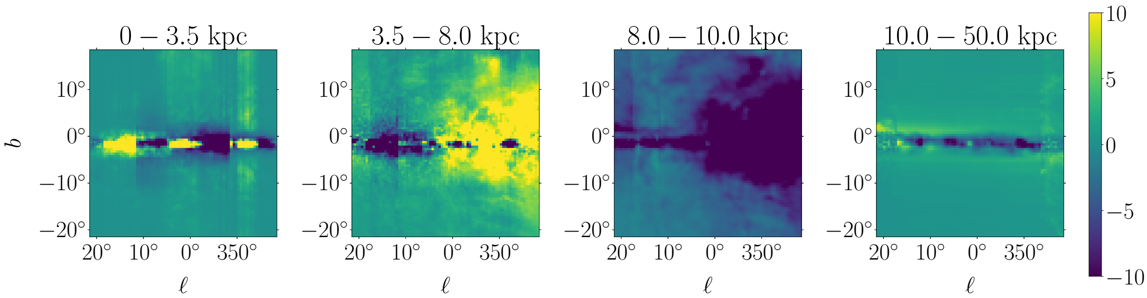

Figure 1: Residual atomic hydrogen maps ($\mathrm{H}I_{\mathrm{hydrodynamic}} - \mathrm{H}I_{\mathrm{interpolated}}$) in units of $10^{20}\mathrm{cm}^{-2}$, where $\mathrm{H}I_{\mathrm{hydrodynamic}}$ refers to the new hydrodynamic gas maps introduced in Ref. [23], and $\mathrm{H}I_{\mathrm{interpolated}}$ to the standard gas maps widely used in the community (e.g., Ref. [28]). The new hydrodynamic gas maps account for continuum emission and absorption, allow for the hydrogen excitation temperature to vary with l and b, and do *not* assume circular orbits for the motion of interstellar gas.

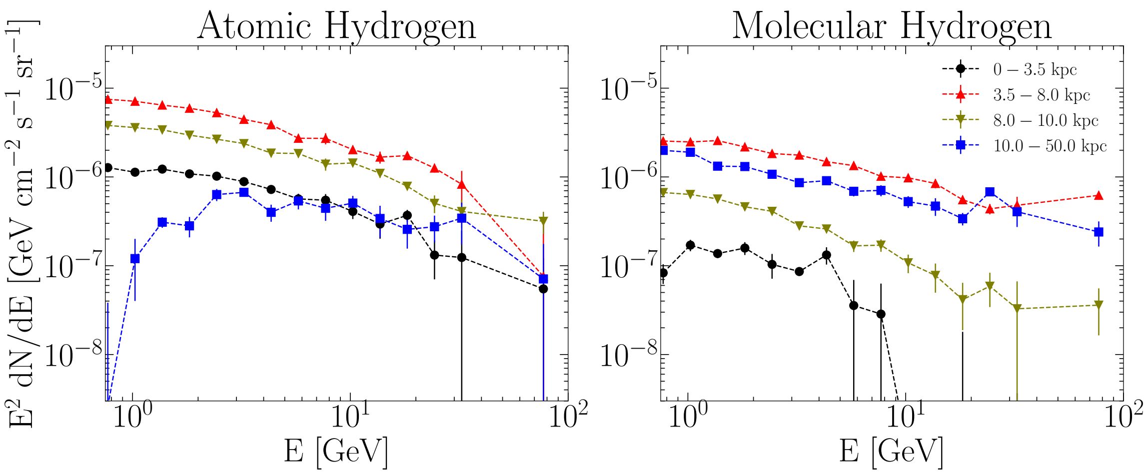

Figure 2: Spectra of the different interstellar annular gas templates included in the fit. See Fig. 1 and Fig. 5 in Ref. [23] for further details. These were obtained using a bin-by-bin analysis technique [15, 19] with which we agnostically reconstruct the spectra of each template based solely on their spatial morphology. The left panel shows the spectra for atomic hydrogen and the right panel the spectra of the molecular hydrogen, assumed to be traced by Carbon monoxide (CO) [15]. Both appear physically plausible and stable.

adequacy of the subdivision we adopted in our pipeline. We presented the total gas-correlated spectra for our region of interest in Fig. 13 of Ref. [23].

3. Results

We calculated the statistical significance of different templates for the GCE by running maximum-likelihood procedures separately for each energy bin (this bin-by-bin method is described in Ref. [23]). Specifically, we considered four classes of dark matter (DM) profiles, and two maps tracing the distribution of stars in the inner Galaxy (as described in the Appendix of Ref. [23]). Each new source's statistical significance is calculated by computing ΔTS as shown in Eq. 2.5 of [17], and noting that each additional template has 15 degrees of freedom. Table 1 displays the results of our statistical tests for different combinations of templates. Using this procedure, we

Baseline model	Additional source	ΔTS	Significance
Base	Cored ellips.	0.0	0.0 σ
Base	Cored	0.1	0.0 σ
Base	BB	282.2	15.3 σ
Base	NFW ellips.	647.2	24.2 σ
Base	NFW	807.1	27.3 σ
Base	NB	1728.9	40.8 σ
Base+NB	Cored ellips.	0.1	0.0 σ
Base+NB	Cored	0.7	0.0 σ
Base+NB	NFW ellips.	1.0	0.0 σ
Base+NB	NFW	3.4	0.2 σ
Base+NB	BB	261.0	14.7 σ
Base+NB+BB	NFW ellips.	0.1	0.0 σ
Base+NB+BB	Cored ellips.	0.4	0.0 σ
Base+NB+BB	Cored	0.7	0.0 σ
Base+NB+BB	NFW	2.6	0.1 σ

Table 1: Statistical significance of the GCE templates for the H*I* maps with varying $T_{\rm exc}$. The Base model comprises the new hydrodynamic gas maps introduced in this work (divided in four concentric rings), dust correction maps, inverse Compton maps, the 4FGL point sources, and templates for the Fermi Bubbles, Sun, Moon, Loop I, and isotropic emission (see the Appendix of Ref. [23]). Additional sources considered in the analysis are: Nuclear bulge (NB) [29], boxy bulge (BB) [18], NFW profile with $\gamma = 1.2$, cored dark matter [30], and ellipsoidal versions of these (see Fig. 3 in [19]). Note that as usual, all dark matter model templates are squared as is appropriate for pair-pair annihilation.

find that the data strongly supports the inclusion of the Nuclear Bulge (NB) template first, followed by the Boxy Bulge (BB). In line with previous analyses [15–17, 19, 20], we find that once the ROI model includes both the NB and BB templates, none of the DM templates that have been considered in the literature are needed.

4. Conclusions

With high significance, we were able to improve the fit to the diffuse gamma-ray emission detected by *Fermi*-LAT. Based on our new GDE model, we are able to estimate the statistical significance of the different spatial templates that have been proposed for the GCE, and we confirm that the stellar template is significantly preferred over the DM-like template. After the stellar templates are included, the data no longer shows any DM-like signal, whether cuspy or cored. Several tests for systematic issues are conducted, and the result is robust to variations in various parameters, such as the excitation temperature of atomic hydrogen.

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