Diffuse Emission Models Confront the Galactic Center Excess

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Novel Cosmic-Ray Injection Models Confront the Galactic Center Gamma-Ray Excess

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At observations of the Milky Way Galactic Center (GC) have revealed a spherically symmetric, high concentration of GeV γ-rays extending to at least 10 kpc from the dynamical center of the galaxy. A

total of 45 GC γ-ray events of GeV γ-rays from the GC region. Recently, it has been noted that the GC emission and injection models employed in these studies have not

in a cosmic-ray injection rate far below that can be predicted by the injection rate with many properties determined in three-dimensions. In this study, we add a significant emi-

trate of the γ-ray excess. Specifically, we have determined the GC density drops considerably in the GC. In the case of the γ-ray excess, the mass density in models employing a

cosmic-ray injection rate at the GC and surrounding the GC. However, in models with a self-similar radial profile, the normalization to changes in the

cosmic-rays injected in the GC is not as resilient as cosmic-rays injected at the GC. Thus, we conclude that cosmic-ray injection in the GC is not a

Galactic Center excess. The normalization to changes in the injection rate is not as resilient as cosmic-rays injected at the GC. Thus, we conclude that cosmic-ray injection in the GC is not a
Template Fitting Analyses

Data
750 — 950 MeV
Best Angular Resolution Cut
10° x 10° ROI

pion-decay
bremsstrahlung
ICS
ICS-CMB
Point Sources
Dark Matter?
Two Separate Analysis Regions

**INNER GALAXY**
- Mask galactic plane (e.g. $|b| > 1^\circ$), and consider $40^\circ \times 40^\circ$ box
- Bright point sources masked at $2^\circ$
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
- **Background systematics controlled**

**GALACTIC CENTER**
- Box around the GC ($10^\circ \times 10^\circ$)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source
- **Bright Signal**
Powerful Evidence for the Excess

Previous analyses showed that the evaluation of the excess was:

1.) independent of ROI (Daylan et al.)

2.) independent of diffuse emission model (Calore et al.)

If these findings hold, then we can immediately start producing explanations for the excess: dark matter, MSPs, leptonic cosmic-ray outbursts, etc.
Cosmic-Rays are thought to be accelerated primarily by supernovae events.

Cosmic-Rays take about $10^8$ — $10^9$ years to escape the Milky Way magnetic field.

What we need is a catalog of all Galactic supernovae over the past billion years.
Diffuse Emission Modeling

Need tracers of current and past supernovae rate:
+ Observed SNR
+ Pulsars
+ OB Stars

All of these models observe relatively recent star formation events:
Pulsars (~30 Myr + 100 kyr), SNR (~30 Myr + 10 Myr), OB Stars (~30 Myr).

Cosmic-Ray propagation (~30 Myr + 100 Myr)
Cosmic-Ray Injection Sources

These models can then fail in two ways:

1.) Observational incompleteness

2.) Time variable injection

Interestingly the models used for these analyses have extremely small injection rates near the GC (in several cases identically 0).
Cosmic-Ray Injection in the GC

Why Is this Done?

1.) Want to fit a simple analytic form to a profile that peaks at 4 kpc.

2.) Small datasets mean error bars near GC are large.

3.) Model of GC is unimportant for cosmic-ray propagation studies.
Current Observations of GC

However, observations of the GC find intense star formation and many supernovae remnants.

e.g. 5-10% of the total galactic SFR rate occurs in the Central Molecular Zone (Longmore et al. 2012)
Excesses are not Limited to GeV Energies

Fermi data reveal giant gamma-ray bubbles

All-sky image in the 511 keV line after 5 years
**Solution:** Add a new cosmic-ray injection morphology tracing the molecular gas density.

**Observational Resilient:** Several tracers of molecular gas are sensitive to the galactic center region.

**Theoretically Motivated:** Molecular Gas is the seed of star formation, the Schmidt Law gives

\[ \Sigma_{SFR} \propto \Sigma_{\text{Gas}}^{1.4\pm.15} \]

Specifically we inject a fraction of cosmic-rays \( f_{\text{H}_2} \) following:

\[ Q_{\text{CR}}(\vec{r}) \propto \begin{cases} 0 & \rho_{\text{H}_2} \leq \rho_s \\ \rho_{\text{H}_2}^{n_s} & \rho_{\text{H}_2} > \rho_s \end{cases} \]
Cosmic-Ray Injection in the GC

Two features leap out immediately:

1.) Spiral Arms

2.) A bright bar in the Galactic Center
Adding a Molecular Gas Component

Adds a new, and significant, cosmic-ray injection component, in particular near the Galactic Center.

The cosmic-ray injection rate now matches observational constraints.
New Cosmic-Ray Injection models are added into a fully-3D realization of Galprop. XCO ratios are fitted in galactocentric rings in order to produce a full diffuse model (e.g. Ackerman et al. 2012).

New models for the 3D galactic gas density are also produced (Carlson 2015, to be submitted).
Steady State Cosmic-Ray Distribution
A Better fit to the Gamma-Ray Sky

1.) The addition of a new cosmic-ray injection template tracing the 3D H$_2$ density greatly improves the overall fit to the gamma-ray diffuse emission.

2.) This is an important point on its own, as it offers a new method for improving diffuse models for the gamma-ray sky.

3.) Technique will become more powerful with the introduction of 3D gas and dust maps in the near future.
A Better fit to the Gamma-Ray Sky

Fits are significantly improved, in particular in regions near the Galactic Center where there is significant kinematic gas information.
An Inner Galaxy Analysis of the GCE

**INNER GALAXY**

- Mask galactic plane (e.g. \( |b| > 2^\circ \)), and consider 40° x 40° box
- Energy dependent masking of bright point sources (following Calore et al. 2014)
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
  - Isotropic energy spectrum fixed via error bars in EGRB analysis (Fermi-LAT 2014)
  - Bubbles fixed via error bars from Su et al.

This creates an analysis with a large sidebands region, where the best fit normalization of the diffuse components is relatively independent of the NFW template.
Effect on the Gamma-Ray Excess

Adding cosmic-rays injection tracing the H2 density significantly decreases the overall normalization of the gamma-ray excess.

However, when dark matter is included, the best fit value of $f_{\text{H2}}$ is approximately 0.1
The Excess is Degenerate with $f_{H2}$

Models with no dark matter universally prefer $f_{H2} \sim 0.2$ for the $40^\circ \times 40^\circ$ region surrounding the GC.

Models with an NFW emission template prefer $f_{H2} \sim 0.1$.

The reduction in the normalization of the NFW template is $\sim 1.5$ for $f_{H2} \sim 0.1$, instead of a factor of 3 at $f_{H2} \sim 0.2$. 
The morphology of the gamma-ray excess is also affected, becoming flatter, and extended perpendicular to the Galactic plane for high values of $f_{\text{H2}}$. 
A Fermi Bubbles Component?

When the excess floats to the best fit morphological configuration, much of the excess intensity returns.

Most importantly, the over subtraction issue at low energies is fixed.
A Galactic Center Analysis of the GCE

- Examine 15° x 15° region surrounding the galactic center.
- No point source masking
- Use likelihood analysis, allowing the diffuse templates and point sources to float in each energy bin.

This creates an analysis with no sidebands region, where the NFW template normalization plays a critical role in determining the spectrum and normalization of diffuse components.
In this smaller region, the excess remains resilient to changes in diffuse emission modeling.
Intriguingly, this persists even when the inner 2° are masked - implying that analyses of small ROIs favors the excess.
Ellipticity in the GC Analysis

In the galactic center, spherical symmetry and a steep inner profile slope is still preferred by the data.
The deviations from typical NFW profiles are more extreme when the $|b| < 2^\circ$ is masked from the analysis, with a shallower emission profile preferred by the data.
The lack of cosmic-ray injection in the GC should still be slightly disturbing. Especially when we try to answer the question: “excess compared to what?”

On the other hand, it seems clear that we don’t have a final answer yet. An optimal diffuse model should remove or produce an excess that is consistent among all ROIs and analysis techniques.
Coming to a Conclusion

1.) We introduce a new astrophysical emission tracer which:
   a.) Improves the overall fit to the gamma-ray sky
   b.) Is degenerate with properties of the gamma-ray excess

2.) The effect on the gamma-ray excess depends on the technique employed. In signal dominated regions the NFW template produces significant emission, while in side-bands dominated regions, the excess is greatly diminished.

3.) For a preferred value of $f_{\text{H}_2} \sim 0.1$, the morphology of the excess is significantly altered, producing a more cored, and slightly elliptical morphology.

3.) This model space is not yet fully explored, new models of H2 gas near the GC may greatly improve our fits to the gamma-ray data. There is a clear path forward with enhanced gas observations.
Local Cosmic-Ray Flux

![Graph showing the local cosmic-ray flux for different particles as a function of kinetic energy.](image-url)
Changes in IG Spectra

![Graph showing changes in IG Spectra](image)
Changes in IG Spectra