A novel analytical model of the magnetic field configuration in the Galactic Center explaining the diffuse gamma-ray emission

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Motivation:

- In April 2016 the H.E.S.S. Collaboration reported the detection of a high energy diffuse gamma-ray flux in the Galactic Center from some GeV up to tens of TeV
- No significant allusion to a cut-off

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Semi-analytical model

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Semi-analytical model
- Diffusion with Kolmogorov spectrum
- spatially and energy dependent continuous loss and source distribution
- static and spherically symmetric
- injection at the center
- Proton-proton interaction

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Motivation:

Open questions:
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Open questions:

- How many sources are sufficient for the observation?
- How much energy is necessary?
- What is the impact of the ambient conditions?
Problem:

- Larger discrepancies at:
  1. higher longitudes
  2. lower energies
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- dominant horizontal magnetic field
- additional sources?
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Move away from semi-analytical approximation
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A novel model of the magnetic field configuration and strength in the Galactic Center
Problem:

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- dominant horizontal magnetic field
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Move away from semi-analytical approximation

A novel model of the magnetic field configuration and strength in the Galactic Center

Accurate modeling of the gas distribution
Gas distribution

An accurate 3D distribution has not been modeled yet!
Gas distribution

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New model
Gas distribution

An accurate 3D distribution has not been modeled yet!
Can be split into 3 components:

New model

3. molecular clouds
Gas distribution

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\[ \log\left(\frac{n}{1 \text{ cm}^{-3}}\right) \]

\[ n_{IC}/\text{cm}^{-3} \]

\[ 200. \]

\[ 150. \]

\[ 100. \]

\[ 50.0 \]

\[ 0.00 \]

\[ -70. \]

\[ -180. \]

-40.  40.

\[ z \text{ in pc} \]

\[ Y \text{ in pc} \]

Sgr B2

Dust ridge A-F

Sgr A*

Sgr D

Sgr C

X

Y

Z

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Magnetic Field in the GC

Status of research:

[Unger & Farrar, EPJWC, 210, 4005, 2019]

[Jaffe et al., MNRAS, 431, 683, 2013]
Magnetic Field in the GC

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lack in the Galactic Center
Magnetic Field in the GC- GBFD19

- Variation range between ~1e-5 G and ~5e-3G
- **Large-scale** magnetic field in the GC initially **poloidal**
- Then, inside **molecular clouds** were sheared out **horizontally**
Magnetic Field in the GC- GBFD19

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Has not been modeled yet!
Magnetic Field in the GC - GBFD19

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- **Large-scale** magnetic field in the GC initially **poloidal**
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Has not been modeled yet!

Can be split into 2 components:

1. **Poloidal:**
   - Intercloud medium (ICM) → large scale field
   - Non-thermal filaments (NTFs) → local field

2. **Horizontal:**
   - Dense molecular clouds (MCs) → local field

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Poloidal field

From Ferrière et al. (2014) we consider Model C (FT14-C)
Poloidal field

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analytical and divergence-free
Poloidal field

From Ferrière et al. (2014) we consider Model C (FT14-C)}

analytical and divergence-free

\[
\mathbf{B}^C = \begin{pmatrix}
B_r \\
B_\phi \\
B_z
\end{pmatrix} = \begin{pmatrix}
\frac{2 a z}{(1+a z^2)^3} \\
0 \\
\frac{1}{(1+a z^2)^2}
\end{pmatrix} \cdot B_1 \cdot e^{-r/L} \cdot \frac{1}{(1+a z^2)}
\]
Poloidal field

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$$\mathbf{B}^C = \begin{pmatrix} B_r \\ B_\phi \\ B_z \end{pmatrix} = \begin{pmatrix} \frac{2 a z}{(1+a z^2)^3} \\ 0 \\ \frac{1}{(1+a z^2)^2} \end{pmatrix} \cdot B_1 \cdot e^{-r/L} \cdot \frac{1}{(1+a z^2)}$$

$a$ ➔ opening of field lines away from the z-axis
$L$ ➔ exponential scale length
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From Ferrière et al. (2014) we consider Model C (FT14-C)}

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0 & \frac{1}{(1+a z^2)} & 0 \\
\frac{1}{1+a z^2} & 0 & \frac{1}{(1+a z^2)^2}
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\(a \rightarrow\) opening of field lines away from the z-axis

\(L \rightarrow\) exponential scale length

\(B_1 \rightarrow\) normalization factor

\(\) \{ \rightarrow\) observation

\) \{ \rightarrow\) geometry
Horizontal field

Starting with Euler’s potentials:

$$\vec{B} = \vec{\nabla} \alpha \times \vec{\nabla} \beta$$
Horizontal field

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analytical and divergence-free
Horizontal field

Starting with Euler’s potentials:

\[ \vec{B} = \vec{\nabla} \alpha \times \vec{\nabla} \beta \]  

analytical and divergence-free

Consider the zonal plane:  

\[ B_z = 0 \quad \beta = 1 \]
Horizontal field

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\vec{B} = \begin{pmatrix} B_r \\ B_\phi \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r} \frac{\partial}{\partial \phi} \alpha \\ -\frac{\partial}{\partial r} \alpha \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r} \frac{\partial \alpha}{\partial \psi} \frac{\partial \psi}{\partial \phi} |_r \\ \frac{\partial \alpha}{\partial \psi} \frac{\partial \psi}{\partial r} |_\phi \\ 0 \end{pmatrix}
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\[ \left| \frac{B_r}{B_\phi} \right| = \frac{1}{r} \cdot \frac{dr}{d\phi} \bigg|_{\psi, \rho} = \eta \]  
depends on the MC characteristics
Horizontal field

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\[ \psi = \phi \pm \eta^{-1} \ln \left( \frac{r}{\rho} \right) \quad \frac{\partial \alpha}{\partial \psi} = \rho \cdot B_r(\psi) \]
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\[ \psi = \phi \pm \eta^{-1} \ln (r/\rho) \]

\[ \partial \alpha/\partial \psi = \rho \cdot B_r(\psi) \]

we define: \( B_r(\psi) = B_1 \cdot \cos(\psi) \cdot h(z) \)
Horizontal field

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net magnetic flux=0

\( h(z) \) is arbitrary
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\[ B_{\text{tot}} = B_{IC}^C + \sum_{i=1}^{8} B_{NTF,i}^C + \sum_{i=1}^{12} B_{MC,i} \]

\[ h(z) \text{ is arbitrary} \]
Magnetic Field in the GC - GBFD19

Magnetic field strength in μG

0.0  2.0e+03  4.0e+03  6.0e+03  8.0e+03  1.0e+04

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log₁₀(n/1 cm⁻³)

Sgr B2  Radio Arc  NTFs

Sgr A*

Z in pc

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$\log_{10}(n/1cm^{-3})$

0.0  1.0  2.0  3.0  4.0  5.0
Magnetic Field in the GC - GBFD19

Colored data from [Nishiyama et al., APJ Letters, 712, L23, 2010]
Impact on CR propagation

This work

[Jansson & Farrar, APJ, 757, 14, 2012]
Impact on CR propagation

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Summary and conclusion

- A centrally located source is not easily sufficient for the observed gamma-ray emission
- **GBDF19:**
  - could explain the diffuse gamma-ray emission caused by a single centralized source
  - is strong in non-thermal filaments and molecular clouds
  - is compatible with polarization data and corresponds to the observations
  - has a significant impact on the longitudinal profiles of CR propagation
  - can be combined with any other Galactic B-field models
- The 3D gas distribution and **GBDF19** make a more accurate calculation accessible for the GC investigators
Backup slides

- Proton as primary cosmic-rays injected from SgrA* at the origin
- spherically symmetric description
- diffusion dominated scenario is favored
- spatial and energy dependent source
- energy dependent continuous loss
For the first time:
  - we include a spatially dependent term in the hadronic pion production interaction term

\[ -D_0 \gamma^\nu \frac{2}{r} \frac{\partial}{\partial r} n(r, \gamma) - D_0 \gamma^\nu \frac{\partial^2}{\partial r^2} n(r, \gamma) - \frac{\partial}{\partial \gamma} b(r) \gamma^{1+\mu} n(r, \gamma) = Q(r, \gamma) \]

Solution:

\[ n(r, \gamma) = \gamma^{-1-\mu} \int \int \frac{r_0^{\frac{3}{2}} H[r - r_0] \cdot H[\gamma_0 - \gamma]}{\sqrt{4\pi \cdot D_0 \cdot b_0 \cdot r_c^2}} \cdot \frac{\gamma_0^{\mu+2\nu}}{\sqrt{\frac{\gamma^\nu - \gamma_0^\nu}{\nu}}} \cdot \exp \left( -\frac{D_0}{4\nu \cdot b_0 \cdot r_c^2} (\gamma^\nu - \gamma_0^\nu) \right) \cdot \exp \left( -\frac{\log(\sqrt{r_0})^2 \cdot b_0 \cdot r_c^2}{D_0 \cdot (\gamma^\nu - \gamma_0^\nu)} \right) - \exp \left( -\frac{\log(\sqrt{r_0})^2 \cdot b_0 \cdot r_c^2}{D_0 \cdot (\gamma^\nu - \gamma_0^\nu)} \right) \cdot Q(r_0, \gamma_0) \, dr_0 \, d\gamma_0 \]
Backup slides

**Graph 1:**
- **x-axis:** $E_r$ in eV
- **y-axis:** $dN/dE_r$
- **Legend:**
  - $E_r = 10^{10}$ - $10^{15}$ eV
  - $L_y(r,E>1\ TeV)$ $\alpha = 2.2$
  - HESS
  - $L_y(r,10 GeV < E < 0.3 TeV)$ $\alpha = 2.2$
  - Fermi

**Graph 2:**
- **Title:** Pacman
- **Legend:**
  - pacman
  - IV
  - V
  - VI
  - VII

**Graph 3:**
- **Legend:**
  - H.E.S.S
  - $+0.4$
  - $+0.2$
  - $0.0$
  - $-0.2$
  - $-0.4$

**Graph 4:**
- **Legend:**
  - $0.0$
  - $-0.25$
  - $-0.50$
  - $-0.75$
  - $-1.00$
  - $-1.25$

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\[ \bar{B}_{MC}^{r>r'} = \beta \cdot \left( \pm \eta^{-1} \frac{R}{r+b} \begin{array}{cc} \frac{R}{r} \\ 0 \end{array} \right) \]
\[ \bar{B}_{MC}^{r<r'} = \beta \cdot \frac{R}{r'} \left( \frac{3r}{r'} - \frac{2r^2}{r'2} \right) \left( \pm \frac{r}{\eta(r+b)} \left( 1 + \frac{6(r-r')}{2r-3r'} \left( \frac{1}{\cos(\pm v(r)+m\phi)} \right) \right) \right) \]
\[ B_{\text{tot}} = B_{IC}^C + \sum_{i=1}^{8} B_{NTF,i}^C + \sum_{i=1}^{12} B_{MC,i} \]
Backup slides

Magnetic field strength in μG

Y in pc

X in pc

Z in pc

Y in pc

Z in pc

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