Cosmic-Ray Models of the Ridge-Like Excess of Gamma Rays in the Galactic Center

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8 October 2014

ABSTRACT
The High-Energy Stereoscopic System (HESS) has detected diffuse TeV emission correlated with the distribution of molecular gas along the Galactic Ridge at the Galactic Center. Diffuse, non-thermal emission is also seen by the Fermi large area telescope (Fermi-LAT) in the GeV range and by radio telescopes in the GHz range. Additionally, there is a distinct, spherically symmetric excess of gamma rays seen by Fermi-LAT in the GeV range. A cosmic ray flare, occurring in the Galactic Center, 10^4 years ago has been proposed to explain the TeV Galactic Ridge (Aharonian et al. 2006). An alternative, steady-state model explaining all three data sets (TeV, GeV, and radio) invokes purely leptonic processes (Yusef-Zadeh et al. 2013). We show that the flare model from the Galactic Center also provides an acceptable fit to the GeV and radio data, provided the diffusion coefficient is energy independent. However, if Kolmogorov-type turbulence is assumed for the diffusion coefficient, we find that two flares are needed, one for the TeV data (occurring approximately 10^4 years ago) and an older one for the GeV data (approximately 10^5 years old). We find that the flare models we investigate do not fit the spherically symmetric GeV excess as well as the usual generalized Navarro-Frenk-White spatial profile, but are better suited to explaining the Galactic Ridge. We also show that predominantly hadronic steady-state models are able to explain all three data sets. Additionally, we investigate how the flare and steady-state models may be distinguished with future gamma-ray data looking for a spatial dependence of the gamma-ray spectral index.

Key words: (ISM:) cosmic rays — gamma rays: theory — gamma rays: observations — Galactic Center

1 INTRODUCTION

The High Energy Stereoscopic System (HESS) collaboration (Aharonian et al. 2006) reported the discovery of diffuse TeV emission correlated with the distribution of molecular gas along the Galactic Ridge at the Galactic Center. Diffuse, non-thermal emission is also seen by the Fermi large area telescope (Fermi-LAT) in the GeV range and by radio telescopes in the GHz range. Additionally, there is a distinct, spherically symmetric excess of gamma rays seen by Fermi-LAT in the GeV range. A cosmic ray flare, occurring in the Galactic Center, 10^4 years ago has been proposed to explain the TeV Galactic Ridge (Aharonian et al. 2006). An alternative, steady-state model explaining all three data sets (TeV, GeV, and radio) invokes purely leptonic processes (Yusef-Zadeh et al. 2013). We show that the flare model from the Galactic Center also provides an acceptable fit to the GeV and radio data, provided the diffusion coefficient is energy independent. However, if Kolmogorov-type turbulence is assumed for the diffusion coefficient, we find that two flares are needed, one for the TeV data (occurring approximately 10^4 years ago) and an older one for the GeV data (approximately 10^5 years old). We find that the flare models we investigate do not fit the spherically symmetric GeV excess as well as the usual generalized Navarro-Frenk-White spatial profile, but are better suited to explaining the Galactic Ridge. We also show that predominantly hadronic steady-state models are able to explain all three data sets. Additionally, we investigate how the flare and steady-state models may be distinguished with future gamma-ray data looking for a spatial dependence of the gamma-ray spectral index.

Key words: (ISM:) cosmic rays — gamma rays: theory — gamma rays: observations — Galactic Center

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originates from the same population of CR particles. This suggests that extended emission should be detectable at GeV energies. It is expected that analyses of the GeV counterpart of this TeV source will help to single out the emission mechanisms producing high energy photons from the HESS field.

2.1 GeV γ-ray observations of the Galactic Ridge

The Fermi-LAT telescope detects γ-rays from 20 MeV to more than 300 GeV using particle physics technology (Atwood et al. 2009). This instrument operates most of the time in continuous sky-survey mode, observing the entire sky every ~3 hours. We accumulated Pass-7 data taken within a squared region of $7^\circ \times 7^\circ$ centred on Sgr A* in the first 45 months of observations over the period August 4, 2008 – June 6, 2011. We kept only the SOURCE class events, which have a high probability of being photons of astrophysical origin. In order to limit the contamination from the Earth’s atmospheric γ-ray emission, we selected events with measured arrival directions within 100$^\circ$ of the local zenith, taken during periods when the LAT rocking angle was less than 52$^\circ$. The angular resolution of Fermi-LAT depends on the photon energy, improving as the energy increases (Atwood et al. 2009).

We also only selected events between 200 MeV – 100 GeV without making any distinction between Front and Back events. Below 200 MeV the angular resolution is poor and source confusion could introduce a large bias, whereas above 100 GeV it is limited by low photon statistics. The sources spectra was computed using a binned likelihood technique (Nolan et al. 2012) with the pyLikelihood analysis tool$^1$ and the energy binning was set to 24 logarithmic evenly spaced bins.

2.2 Fermi-LAT analysis methods

The spatial and spectral features of a source are intrinsically correlated. An inaccurate spatial model would affect the source spectra and vice versa. In Macias & Gordon (2014) some of us showed evidence for an extended γ-ray-emitting source that is the GeV counterpart of diffuse emission detected by HESS and some radio telescopes (Aharonian et al. 2006), Crocker et al. 2011, Yusel-Zadeh et al. 2013). The fit included all 2FGL (Nolan et al. 2012) point-sources present in the region of interest as well as standard diffuse Galactic and isotropic extra-galactic models gal2yearp7v6.fits and iso_p7v6source.txt respectively.

Macias & Gordon (2014) performed a set of maximum likelihood fits using templates for the Galactic Ridge source. Either a 20-cm map (Yusel-Zadeh et al. 2013) or a HESS residuals (Aharonian et al. 2006) map were used. Although it was found that the best fit model results from a combination of the 20-cm map with point sources “the Arc” (2FGL J1746.6-2851c) and “Sgr B” (2FGL J1747.3-2825c), it is possible that these two point sources also result from the interaction of CRs with molecular gas and so as to maximize the Galactic Ridge signal, they were not included (Yusel-Zadeh et al. 2013, Macias & Gordon 2014).

Macias & Gordon (2014) confirmed evidence for a spherically symmetric extended source, whose spectrum and morphology is

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1 Pass-7 data has been superseded by reprocessed Pass-7 (PAS7-REP). However, 193 weeks of Pass-7 data are still available at http://heasarc.gsfc.nasa.gov/FTP/fermi/data/lat/weekly/p7v6/photons/

http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/
consistent both with emission from millisecond pulsars or dark matter annihilation. Most prominent is the fact that the spatial extension and spectrum of the Galactic Ridge source was shown to be robustly independent of the spherical γ-ray source. Although, additional complications due to systematic uncertainties in the Galactic diffuse emission model (Nolan et al. 2012), the analysis in Macias & Gordon (2014) assessed such systematic uncertainties concluding that these are in the vicinity of 20%. For this work we use similar analysis methods and assume the same estimates for the systematic uncertainties in the Galactic diffuse emission model.

Since the 2FGL catalog (Nolan et al. 2012) was constructed with 2 years of data, while our dataset comprises almost 4 years, we searched for additional point sources within the ROI by constructing maps of residual significance after subtracting all known sources in the region. This was done with the gttsmap tool, a specialized routine provided with the Fermi analysis software that computes test statistic (TS) images. The TS gives a measure of the significance of adding a source to a model, defined as $TS = 2\log(L_1/L_0)$ where $L_1$ is the likelihood, and the subscripts 0 and 1 refer to the original model and a model with an additional source, respectively. We illustrate in Fig. 1 the adequacy of the astrophysical model used here once two new faint point-sources plus the Galactic Ridge and spherical extended source are included.

We performed a curvature analysis (Nolan et al. 2012) intended to determine whether the Galactic Ridge spectrum can be fitted with a power law or needs a curved spectrum such as a broken power law. We found that the broken power-law spectrum is preferred at about 7σ significance.

We also extracted the γ-ray spatial distribution from the Galactic Ridge by performing a longitudinal analysis that mirrors the one done by the HESS collaboration for the same site (Aharonian et al. 2006). We obtained a residual counts map of the Galactic Ridge in the energy range 0.2 – 100.0 GeV by subtracting out all of our best-fitting sources from the raw counts map, except for the 20 cm map source. The background level was estimated using events from the regions $0.8^\circ < |b| < 1.5^\circ$ and is somewhat longitude dependent. Counts obtained at each different bin, 0.2° wide, were thus background subtracted.

Figure 2. Panels shown are obtained from data taken from Ferriere et al. (2007). Left: Average densities of interstellar gas as functions of distance (r) along the line of sight passing between us and the Galactic Center; Molecular hydrogen is shown with a black solid line, atomic hydrogen with a blue dashed line and ionized hydrogen atoms with a red dotted line. Right: Total space-averaged density of interstellar hydrogen nuclei along the line of sight of the innermost 3 kpc.

Figure 3. Proton energy-loss time-scales ($E/dE$) in the Galactic Ridge region. The total average hydrogen density used for this calculation is $\langle n_H \rangle = 109.3$ cm$^{-3}$ (Ferriere et al. 2007). This also assumes a kinetic temperature of 5000 K.

3 GAS DENSITY MAPS OF THE INNER 200 PARSECS REGION OF THE GALACTIC CENTER

In order to perform realistic simulations of hadronic γ-ray emission from the Galactic Center a detailed knowledge of the spatial distribution of interstellar gas in the region is necessary. Here, we employ the model of Ferriere et al. (2007), valid for the innermost 3.0 kpc of our Galaxy. That model provides three-dimensional (3D) hydrogen space-averaged densities maps that best fits the observational data while being entirely consistent with theoretical predictions. This will prove pivotal to our present study as it enables us to create fully 3D CR propagation simulations.

Fig. 2-left illustrates the radial variation of the column densities of molecular, atomic and ionized gases. The most abundant material in our region of interest is molecular hydrogen ($n_H$). This component forms a Galactic structure known as the CMZ—an asymmetric layer of predominantly molecular gas that encompasses the region...
defined by $-1.5^\circ \leq l \leq 2.0^\circ$ and $|b| \leq 0.3^\circ$ around Sgr A*. The right hand side panel of Fig. [2] is obtained by computing the mean value of the total gas density

$$\langle n_H \rangle = 2\langle n_H^+ \rangle + \langle n_H^- \rangle,$$

(1)

along the line of sight direction. From this we can thus expect that one or more CR accelerators injecting protons into the medium will generate (given an appropriate choice of diffusion parameters) $\gamma$-ray distributions that approximately follow the density of interstellar gas displayed in Fig. [2].

4 MULTIWAVELENGTH MODELING

The origin of extended $\gamma$-ray emission from the direction of the Galactic Ridge is not yet firmly established. Despite the fact that the region of emission ($|l| < 0.8^\circ$, $|b| < 0.3^\circ$) and spectra have been detected with great accuracy by HESS, these observations can be well explained by more than one mechanism (Crocker et al. 2011; Yusef-Zadeh et al. 2013; Macias & Gordon 2014). Interestingly, the HESS team interpreted the breakdown in the correlation between the diffuse TeV emission and the molecular hydrogen density as an indication of a non-steady-state phenomena. Such a model however must be carefully evaluated for consistency in light of recent measurements (Yusef-Zadeh et al. 2013; Macias & Gordon 2014) at lower energies. Here we revisit the non-steady-state $\gamma$-ray production scenario related to past activity of Sgr A* or possibly supernova remnants in its immediate vicinity.

4.1 Computation of $\gamma$-ray and $e^\pm$ spectra in a non-steady-state Hadronic emission model

Liu et al. (2006) argued that protons interacting resonantly with turbulent electromagnetic fields in the accretion torus of Sgr A* can undergo stochastic acceleration. A significant fraction of these protons will be significantly decelerated and can undergo stochastic acceleration. A significant fraction of these protons will be significantly decelerated and can undergo stochastic acceleration. A significant fraction of these protons will be significantly decelerated.

We describe the spatial and energy distribution of protons at a given time (Aloisio et al. 2009) by

$$\frac{dn_p(E,r)}{dE} = \frac{1}{4\pi r^2} \int_{\xi_{\text{min}}}^{\xi_{\text{max}}} d\xi \frac{\xi}{\alpha(E,\xi)} \frac{\alpha(E,\xi)}{K_1(\alpha(E,\xi))} \exp \left[ -\frac{\alpha(E,\xi)}{\sqrt{1 - \xi^2}} \right] \left[ \text{cm}^{-3} \text{eV}^{-1} \right],$$

(2)

where $K_1(x)$ is the modified Bessel function, $c$ the speed of light, $E_\text{g}$ is the generation (or initial) kinetic energy of a proton, $E$ is the cooled proton kinetic energy at time $t$ and $Q[\bar{E}_g(E,t)]$ is the injection spectrum.

For convenience, the dimensionless variable $\xi = r/c \tau$ is substituted for the time $t$. The integration limits corresponding to our flare scenario are

$$\xi_{\text{min}} = \frac{r}{c\tau_0} \quad \text{and} \quad \xi_{\text{max}} = \text{Min} \left[ \frac{r}{c(\tau_0 - \Delta t)} \right].$$

(3)

where $\tau_0$ represents the time that has lasted since the source switched on and $\Delta t$ corresponds to the duration time of the flare event.

The dimensionless function $\alpha(E,\xi)$ in Eq. (2) is defined as follows

$$\alpha(E,\xi) = \frac{c^2}{2\Gamma |E_g(E,t)|}$$

with

$$\lambda(E,\xi) = \int_{E}^E \frac{dE'}{b(E')} D(E'),$$

(4)

where $D(E)$ is the diffusion coefficient. Also, the total energy loss rate of CR protons, given by

$$b(E) = -\frac{dE}{dt},$$

(5)

is mainly due to pion production, Coulomb losses and ionization interactions. In this section, we consider full energy loss expressions provided in Eq. (5.3.58) of Schlickeiser (2002). Making use of these explicit functions for $b(E)$, the generation energy $E_g(E,t)$ can be readily computed by integrating Eq. (4). We display in Fig. [3] the relevant time-scales in which proton energy losses are significant.

We assume here, for simplicity, that $D(E)$ is independent of position, and given by

$$D(E) = 10^{26} \left( \frac{E}{10^9 \text{G}} \right)^{1.5} \cm^{-2} \text{s}^{-1},$$

(6)

where $\beta$ and $\kappa$ are free parameters. For the initial spectrum of protons $Q[\bar{E}_g(E,t)]$ we use a power-law with an exponential cutoff

$$Q[\bar{E}_g(E,t)] = K \left( \frac{E}{10^9 \text{G}} \right)^{-\Gamma} \exp \left( -\frac{E}{10^9 \text{G}} \right),$$

(7)

where $K$ is a normalization constant, $\Gamma$ is the spectral slope. For our calculations, we actually used an exponential cut-off power law in momentum as that is the generic prediction from shock acceleration. But in practice we found this only makes a negligibly small change compared to having an exponential cut-off in kinetic energy as employed by Chernyakova et al. (2011). Both $K$ and $\Gamma$ are left free in our parameter estimations. We note that in Eq. (2) of Chernyakova et al. (2011) there is a typo in that the injection spectrum should depend on the generation rather than the observed energy.

Figure 4. Total loss time scale ($\tau_{E^{-\pm}}$) for electrons and positrons in the Galactic Ridge region ($\langle n_H \rangle = 109.3 \cm^{-3}$ and $B = 119 \mu G$). Energy losses considered in this work are: ionization, bremsstrahlung, synchrotron and inverse Compton.

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Finally, the differential emissivity of secondary particles (photons, electrons, or positrons) resulting from collisions between a distribution of injected protons \( dn_p(E,r)/dE \) (as obtained in Eq. (2)) into ambient hydrogen of Galactic Ridge average density \( \langle n_H \rangle = 109.3 \text{ cm}^{-3} \) is calculated as

\[
q_{\gamma,e^\pm}(E,r) = c \langle n_H \rangle \int_0^{\infty} dE' \int_0^{\infty} ds q_{\gamma,e^\pm}(E',r) \frac{d\sigma_{\gamma,e^\pm}(E,E')}{dE} \left[ \text{secondaries eV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \right],
\]

where \( d\sigma_{\gamma,e^\pm}(E,E')/dE \) is the differential cross-section which we are taking to be non-zero only for kinematically allowed energies. This is provided by Kamata et al. (2006) in the form of interpolating functions for several different final state particles. The actual spectrum of secondaries is then obtained by integrating the source function along the line of sight and over the angular area (\( \Delta\Omega \)) of the Galactic Ridge

\[
\frac{dn_{\gamma,e^\pm}(E)}{dE} = \int_{\Delta\Omega} ds \int_{0}^{\infty} d\Omega' \int_{0}^{\infty} d\Omega'' q_{\gamma,e^\pm}(E',r) \left[ \text{secondaries eV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \right],
\]

where we use the conventional coordinates transformation

\[
r = \sqrt{R_0^2 - 2xR_c \cos(b) \cos(l) + s^2},
\]

with \( s \) varying along the line-of-sight path, \( b \) and \( l \) the Galactic coordinates and \( R_c = 8.5 \text{ kpc} \) is the distance from the solar system to the Galactic Center.

As we have seen, the \( \gamma \)-ray emission is proportional to the pion production rate, and because the lifetime of pions is extremely short, the location of the \( \gamma \)-ray emission is essentially that of the proton scattering. To construct the spatial morphology of our \( \gamma \)-ray predictions, we first multiply the three dimensional proton distribution (Eq. (2)) with the three dimensional spatially varying gas map \( \langle n_H \rangle \) we obtained from Ferriere et al. (2007). We then take the resulting three dimensional distribution and perform line of sight integrations from the solar system position to construct the two dimensional map of the predicted spatial morphology for the \( \gamma \)-ray maps that were tested against GeV and TeV data. Our methods for performing the GeV spatial fits are explained in Gordon & Macias (2013).

4.2 Synchrotron emission from \( e^\pm \) of Hadronic origin

For the Galactic Ridge environment, we have a total average hydrogen density of \( \langle n_H \rangle = 109.3 \text{ cm}^{-3} \) (Ferriere et al. 2007) and, as we show below, our fit to the radio data suggests an average magnetic field \( B = 119 \mu \text{G} \).

In our non-steady-state hadronic emission model, synchrotron radiation at a frequency of \( \sim 1 \text{ GHz} \) will be generated by secondary leptons of energy \( E_{\nu} \sim 1 \text{ GeV} \) (see appendix of Macias & Gordon (2014)). As discussed later, we consider our diffusion coefficient in the Galactic Ridge environment to be \( D(E) = 10^{28} (E/1 \text{ GeV})^{0.2} \text{ cm}^{2} \text{ s}^{-1} \). Using \( t_{\text{los}} = E/\gamma D(E) / \tau \), we find that the diffusive transport scale \( \langle A \rangle \) (Aharonian 2004) is given by \( 2D(E) t_{\text{los}}^2 \) and \( \sim 50 \text{ pc} \sim 5 \text{ pc} \) is the upper limit in radius of our region of interest. Based on this comparison, we neglect the diffusive transport in our estimation and can thus solve the diffusion equation in the thick target limit (Crocker et al. 2007):

\[
\frac{dn_{\nu,e^\pm}(E,r)}{dE} = \int_0^{\infty} dE' \int_0^{\infty} d\Omega' q_{\nu,e^\pm}(E',r) \frac{d\sigma_{\nu,e^\pm}(E,E')}{dE} b_{\nu}(E),
\]

where \( q_{\nu,e^\pm}(E',r) \) is given by Eq. (8) and \( b_{\nu}(E) = -dE_{\nu}(E)/dt \) is the total energy loss rate of electrons, which is calculated using the formulas presented in Delahaye et al. (2010) and plotted in Fig. 4. We take into account energy losses due to ionization, bremsstrahlung, synchrotron and inverse Compton (IC). We also assume that electrons and positrons suffer identical energy losses and neglect electron positron annihilation.

The power per frequency of emitted synchrotron radiation for a single electron with energy \( E = m_e c^2 \) is (Schlickeiser 2002):

\[
P_{\nu}(v,E) = \frac{\sqrt{3}}{2} E^2 \sin^2 \frac{\alpha}{2} \frac{m_e c^2}{e} F(x) \text{ erg s}^{-1} \text{ Hz}^{-1},
\]

where \( \alpha \) is the electron charge in statocoulombs, \( \alpha \) is the pitch angle and \( x = v/\nu c \). The quantities \( \nu c \) and \( F(x) \) are defined as

\[
\nu c = \frac{3}{2} \frac{m_e c^2}{e} \frac{\sin \alpha}{2} \text{ and } F(x) = x \int_{x}^{\infty} K_5/3(\xi) d\xi,
\]

where \( K_5/3(\xi) \) is the modified Bessel function of order 5/3 and we assume \( B_{\gamma} = 0.78 B_{\gamma} \) (Crocker et al. 2007). Finally, we calculate the non-thermal synchrotron radio emission \( S_{\nu} \), for a given distribution of secondary leptons by using the following expression:

\[
S_{\nu} = \int_0^{\infty} ds dE P_{\nu}(v,E) \frac{dn_{\nu,e^\pm}(E,r)}{dE / dE},
\]

4.3 Fitting procedure

Our approach is to find the set of parameters that best describes the broad-band extended emission from the Galactic Ridge region. Specifically, we use a minimization procedure to determine the model parameters describing the injection spectrum of protons and time of occurrence of the tentative supernovae explosions (or flare events from Sgr A*) giving rise to the CR population responsible for the extended emission from the region. Such a CR accelerator is assumed to be located at the Sgr A* position in our analysis. We set the diffusion coefficient parameters in Eq. (6) to \( \kappa = 1 \), which is typical for cosmic-ray diffusion in the galactic disk (Aharonian & Neronov 2005), and \( \beta = 0.3 \) to have Kolmogorov diffusion. The value of \( \kappa \) is statistically degenerate with the flare age \( t_0 \) as from Eq. (3) it can be seen that the diffusive transport scale is given by \( R_{\text{diff}} = \lambda (1/2) \gamma \) and \( \lambda \approx t_0 \). The required value of \( R_{\text{diff}} \) is determined by the Galactic Ridge morphology. However, as this in turn is limited by the molecular-gas distribution, the data only give a lower limit \( R_{\text{diff}} > 5 \text{ pc} \times 8.5 \text{ pc} = 119 \text{ pc} \). This implies our values for \( t_0 \) are lower limits, as a larger \( t_0 \) will not affect the spatial morphology. The lower limit on \( t_0 \) can be changed by making the corresponding changes in \( \kappa \) to preserve \( R_{\text{diff}} \). Aharonian et al. (2006) found that CRs with a Gaussian morphology and a standard deviation of 0.8° gave a good fit to the TeV data. We chose our flare ages so as that both our GeV and TeV flares resulted in CRs with a similar Gaussian distribution. This gave similar results to basing the flare age on setting \( R_{\text{diff}} = 119 \text{ pc} \) for a typical energy range of the flare.

In order to fit the radio data with our non-steady-state model, we also take into consideration thermal emission from the very complex environment of the Galactic Ridge. We assume a superposition of the thermal component with a spatially mixed non-thermal contribution given by Eq. (14). Our calculations account for free-free absorption following the methods described at length in Crocker et al. (2011) and the supplementary material of Crocker et al. (2010). In short, the observed flux density in the model is given by

\[
F = \Delta\Omega \{ S_{\text{NT}} \exp[-t] + B(T) (1 - \exp[-t]) + S_{\text{GB}} \}.
\]

where \( B(T) \) is Planck’s function at the temperature \( T \) and \( \Delta\Omega \) is
Figure 5. Top panel: HESS Galactic Ridge region spectrum for the best-fitting, non-steady-state, Kolmogorov-type turbulence, hadronic scenario. The model consists of two independent flares that might have occurred $2 \times 10^4$ and $3 \times 10^5$ years ago and lasted for approximately 10 years. Fitted parameters are displayed in Table 1. We assume the gas maps provided in Ferriere et al. (2007). Data are from HESS diffuse (Aharonian et al. 2006), Galactic Ridge Fermi-LAT (Macias & Gordon 2014) and radio observations (Crocker et al. 2011). We display modeled synchrotron emission from CR electrons and positrons of hadronic origin at radio wavelengths. Total radio emission is the combination of thermal and non-thermal emission, both of which are affected by free-free absorption. We also include a Galactic synchrotron background (GSB) component for $\nu > 0.1$ GHz to account for foreground and background (Crocker et al. 2011). Notice, that the unphysical step at 100 MHz is explained by the fact that the first datum is interferometric and does not receive a contribution from the large angular scale, line-of-sight GSB emission. Bottom panel: Confidence regions generated from the data and models shown in the top panel. The thermal contribution at 2 GHz is computed as a percentage of the total emission, $\tau_{ff}^0$ and is defined in Eq. (16). The white cross shows our best-fit values for these parameters.

Table 1. Best-fitting propagation parameters obtained from the full broad-band spectral observations. The column corresponding to $\chi^2_{\text{GeV}} + \chi^2_{\text{TeV}}$ is computed as the $\chi^2$ obtained from the fit to spectrum shown in top-panel of Fig. 5.

| Model       | $\Gamma$ | $Q_{\text{total}}$ [erg] | $t_0$ [years] | $\chi^2_{\text{GeV}} + \chi^2_{\text{TeV}}$ | dof |
|-------------|----------|--------------------------|---------------|---------------------------------------------|-----|
| GeV flare   | 2.0      | $4 \times 10^{52}$       | $3 \times 10^5$|                                             | 13  |
| TeV flare   | 1.8      | $2 \times 10^{50}$       | $2 \times 10^4$|                                             | 21-6=15|

The Galactic Ridge solid angle. We left the normalization $\tau_{ff}^0$ of the optical depth, which is defined as follows

$$\tau(\nu) = \tau_{ff}^0 \left(\frac{\nu}{0.325 \text{ GHz}}\right)^{-2.1},$$

(16)
as a floating parameter. Also, the Galactic synchrotron background (GSB) is modeled as

$$S_{\text{GSB}} = \frac{710}{\Delta \Omega} \left(\frac{\nu}{408 \text{ MHz}}\right)^{-\gamma_{\text{GSB}}} \text{Jy sr}^{-1}$$

(17)
The fitting procedure to the radio data also included an extra parameter related to the relative contribution of thermal and non-thermal
Corrected excess counts

Excess counts

Galactic Latitude ($b$)

□ 20
□ 40
□ 60
□ 80
□ 100
□ 120
□ 140
□ 160
□ 180
□ 200
□ 220
□ 240
□ 260
□ 280
□ 300
□ 320
□ 340
□ 360
□ 380
□ 400
□ 420
□ 440
□ 460
□ 480

Figure 6. Brightness profile of the Galactic Ridge in 0.2 – 100.0 GeV (left column) and 0.27 – 12.5 TeV (right column) energy ranges for our best-fitting non-steady-state hadronic model. See Sec. 5 for a description of the models. Top panel: Two-dimensional distributions of γ-ray emission from our best fit GeV flare (left) and TeV flare (right) models. Below each 2D counts map we display its corresponding longitudinal profile. Bottom panel: Gamma-ray counts versus longitude. The background level was estimated using events from the regions 0.8° < |b| < 1.5°. Counts obtained at each different bin, 0.2° wide, are background subtracted. The red dashed histograms show the density of molecular gas as obtained from Ferriere et al. [2007], the red solid curve shows target gas as traced by CS emission [Aharonian et al. 2006]. The blue histograms show the longitudinal distribution of photons as predicted by our model at the two different energy ranges. For comparison we show the best-fit obtained in [Aharonian et al. 2006] with a green-dashed line.

| $B$ [μG] | Thermal amplitude at 2.42 GHz [%] | $\chi^2_{\text{GSB}}$ | $\chi^2_0$ | $\chi^2_{\text{radio}} + \chi^2_{\text{GSB}}$ | dof |
|----------|-------------------------------|-------------------|-----------|--------------------------------|-----|
| 197 ± 27 | 23 ± 14                        | 0.69 ± 0.12       | 0.049 ± 0.12 | 0.13                         | 7-4-3 |

Table 2. Best fit values obtained in the radio analysis for the magnetic field $B$, thermal amplitude at 2.42 GHz, spectral index $\Gamma_{\text{GSB}}$ and normalization $\varepsilon_0^{\text{gamma}}$. The best fit spectra and corresponding data are shown in the top left panel of Fig. 5. The GSB provides an effective extra radio data-point.

emission. Namely, we calculate the thermal contribution at 2.417 GHz as a percentage of the total emission, and allowed it to vary accordingly. For the black body radiation spectrum we assume a kinetic temperature of 5000 K.

We also fit the non-steady-state model to the γ-ray spectrum and spatial γ-ray distribution in the GeV – TeV energy range. The full broad-band fit is obtained via the numerical minimization algorithm MINUIT [James & Roos, 1975]. The global $\chi^2$ function entered to the minimization routine is given by

$$\chi^2 = \chi^2_{\text{radio}} + \chi^2_{\text{GSB}} + \chi^2_{\text{GeV}} + \chi^2_{\text{TeV}},$$

where the parameters over which we minimize the $\chi^2$ are: $\varepsilon_0^{\text{gamma}}$ defined in Eq. (16), the amplitude of thermal emission, $\varepsilon_0^{\text{GSB}}$ introduced in Crocker et al. [2011] ($\chi^2_{\text{GSB}} = (\varepsilon_{\text{GSB}} - 0.695)^2/0.12^2$), the magnetic field $B$, and the time of occurrence $t_0$ of the flare event. Also minimized over were $\kappa$ and $\Gamma$ which are the injection spectrum of protons (See Eq. (17)). Notice however, that instead of the normalization $K, we report the more convenient parameter the total emission energy, $Q_{\text{total}} \equiv \int_0^\infty E dQ(E)$. Here $Q_0 = \int_{0}^{t_{\text{flare}}} E dQ(E)$ is the injection luminosity. In practice, we set the lower limit of the integral to 0, but as $Q$ is a power law in momentum space, for that range, it makes a negligible difference if one rather has a power law in kinetic energy and integrates with a lower limit of $m_{\text{proton}}$.

5 STEADY-STATE FITS

We also perform fits to the broadband spectrum of the Galactic Ridge in the steady-state limit. We try to find self-consistent descriptions of the in situ, steady-state, non-thermal proton (for simplicity we
neglect heavier ions) and electron populations in the Ridge and the environmental parameters describing the Ridge ISM such that the radiation from these populations reproduces the spectral data. We assume that the non-thermal particles are injected into the Ridge ISM as power laws in momentum whereupon they undergo the energy loss and transport processes that shape their steady-state distributions. As for the non-steady-state modelling, for CR protons, energy losses are via ionisation at low energy and hadronic \((pp)\) collisions at high energies. For electrons, energy losses are from low to high energy ionisation, bremsstrahlung, and synchrotron/inverse Compton emission (IC). Transport is assumed to be energy-independent consistent with the evidence for the existence of a large-scale outflow from the region; the wind velocity (or, equivalently, energy-independent escape time) is also a parameter of our fitting. Because, in our single zone model, we also impose the constraint that mass loss in the outflow be no more than \(0.5 \, M_\odot/\text{yr}\) (consistent with global constraints, see Crocker 2012), however, we find that our fitting prefers a very slow outflow so that the steady-state, non-thermal particle distributions are practically calculated in the thick target limit.

Figure 7. Broadband spectral energy distribution (SED) of the Galactic Ridge for the steady-state bremsstrahlung solution. Left Panel: Radio flux density spectrum of the Galactic Ridge for the bremsstrahlung solution. Curves are: dashed black: primary electron synchrotron; short dashed (red) secondary electron synchrotron; solid (purple): primary + secondary synchrotron; dash dotted (black): primary + secondary synchrotron neglecting free-free absorption; solid with triangles (green): GSB; solid with triangles upside down (brown): free-free emission; and solid (black) total emission. Note that the lowest frequency (74 MHz) datum is interferometric, having been obtained with the VLA which is insensitive to the spatially slowly-varying contribution of the GSB on the size scales of the Galactic Ridge solid angle. This is why the GSB (and its contribution to the total flux density over the solid angle) is displayed with an unphysical cutoff at 100 MHz. Right Panel: Dashed curves are for primary electron emission and dotted are for secondary electron emission; hadronic gamma-rays are shown as the dot-dashed (brown) curve; solid curves show total non-thermal emission. The \(\sim \text{GeV}\) data are dominantly ascribed to primary electron bremsstrahlung (long dashed green) with a subdominant IC primary contribution (long dashed red). The \(\sim \text{TeV}\) data are dominantly ascribed to hadronic emission, mostly neutral pion decay following \(pp\) collisions.

Figure 8. Broadband spectral energy distribution (SED) of the Galactic Ridge for the steady-state bremsstrahlung solution when the gas density is fixed to \(\langle n_H \rangle = 109.3 \, \text{cm}^{-3}\). Curves are as given in the caption to Fig. 7.
Radiation accompanying the loss processes listed above is self-consistently calculated to compare against the broadband spectral data on the region though note that we do not seek to reproduce morphological data with this fitting. Hadronic collisions lead to the production of charged mesons (in addition to the neutral mesons whose decay is responsible for γ-ray emission) generating final-state electrons and positrons; the radiation from these ‘secondary electrons’ is self-consistently calculated in our fitting. To calculate IC cooling and emission, we assume an energy density for the interstellar radiation field of 90 eV cm$^{-3}$; (see Crocker 2012, Crocker et al. 2011 for more details). The other parameters controlling cooling processes are the magnetic field amplitude (controlling synchrotron emission) and gas density (controlling ionisation, bremsstrahlung, and pp losses); these parameters are left floating for the fitting process.

Other floating parameters in the fit are: the spectral index of the GSB which contributes to the line-of-sight radio flux density over the Ridge’s solid angle; the free-free (thermal bremsstrahlung) flux density at 10 GHz (from which we can self-consistently calculate the free-free absorption at lower frequencies); the normalization at 1 TeV (in cm$^{-3}$ s$^{-1}$ eV$^{-1}$) and the spectral index, $\gamma_p$, of the freshly-injected CR protons; and the normalization of the freshly-injected electrons at 1 TeV relative to that of the protons ($\kappa_{ep}$). Note that we have explored allowing the electrons and protons’ injection distributions to have independent spectral indices but, given the fitting prefers them to be very similar, we set $\gamma_e = \gamma_p \equiv \gamma$.

Altogether there are 8 fitting parameters and 28 data points (6 radio data points, 12 Fermi points, 9 HESS points, and a data point which is the expectation for the spectral index of the GSB), implying 20 degrees of freedom unless otherwise noted.

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Figure 9. Broadband SED of the Galactic Ridge for the steady-state $\pi^0$ solution. Curves are as given in the caption to Fig. 7.

Figure 10. Broadband SED of the Galactic Ridge for the steady-state $\pi^0$ solution when the gas density is fixed to $\langle n_H \rangle = 109.3$ cm$^{-3}$ and $\kappa_{ep} = 0.004$. Curves are as given in the caption to fig. 7.
6 RESULTS

6.1 Non-steady-state Model

The main results of the non-steady-state model are shown in Fig. 5 and Fig. 6 where we reproduce the observed broadband radiation spectrum as well as the spatial $\gamma$-ray distribution (at GeV and TeV energies) with two flares from the central source. It is interesting to note that, very likely, there have been a series of flares with different energetic properties occurring throughout the lifetime of Sgr A*. Our fit preferred a model in which the impulsive events tentatively occurred $3 \times 10^5$ and $2 \times 10^4$ years ago for the GeV and TeV flares respectively. The total energy required to inject relativistic protons capable of accounting for the extended radiation from the region were $4 \times 10^{52}$ and $2 \times 10^{50}$ erg each. The latter is a reasonable match for a single supernovae remenant, the former is not, so presumably would require a burst event from the super-massive black hole. The duration of both flares was chosen to be 10 years, however, as long as the flare duration is much less than the flare age ($t_f$), only the total injected energy affects the predicted $\gamma$-ray spectrum. Details of our best-fit parameters are provided in Table 1 and Table 2.

In the top panel of Fig. 5 we show that it is possible to fit the entire $\gamma$-ray domain with hadronic photons resulting from the scattering of protons with hydrogen gas in giant molecular clouds. The same interaction process produces charged mesons (mainly $\pi^\pm$) whose subsequent decay creates a non-thermal population of relativistic electrons and positrons. The synchrotron light emitted by such particles, in conjunction with thermal emission from the region, give an acceptable fit to the data over the radio band. Confidence level intervals for some of our model parameters are shown in the bottom panel of the same Fig. 5.

The parameters of our model are also constrained by additional information extracted from the spatial morphology of the $\gamma$-rays in the Galactic Ridge. In the top panel of Fig. 6 we show a two-dimensional representation of our best-fitting $\gamma$-ray spatial distribution. In the bottom panel of Fig. 6 predictions of our model are shown with blue histograms. The red dashed histograms show the averaged gas distribution obtained from maps provided by Ferriere et al. (2007), while red continuous line are taken from CS line emission observations (Aharonian et al. 2006). Visual inspection shows that gas maps in Ferriere et al. (2007) are consistent with the one used by Aharonian et al. (2006) but of lower resolution. The fact that maps in Ferriere et al. (2007) are coarser than the CS maps, explains why our model fails to account for the dip at $l \simeq +0.3^\circ$ in bottom-right panel. The same argument can be applied to explain a deficit in $\gamma$-rays at $l \simeq +1.5^\circ$ in bottom-left panel of Fig. 5. We thus note that a more detailed gas map of the Galactic Ridge will very likely improve to an acceptable range the quality of the spatial fit for the non-steady-state model.

As a consistency check, we also evaluated the TS value of the GeV spatial map obtained from our non-steady-state model predic-
6.2.1 GeV bremsstrahlung solution

This solution (see Fig.[7] and Table[5], for which $\chi^2_{\text{min}}/\text{dof} = 13.0/20$, is similar to that previously found by Yusef-Zadeh et al. [2013].

Consistent with previous work (Crocker et al. 2010) we find this fit (and the others) prefers a strong magnetic field in the 100 $\mu$G range, specifically 57 $\mu$G for this case, and a gas density of $\langle n_H \rangle = 26$ cm$^{-3}$. Note that this fitted gas density is smaller than the volumetric average in the region (see Sec. 3).

Largely due to the restriction on the mass flux from the region, we find a negligible wind speed for this fit (and the others) implying the observed spatial distribution of the emission must be due to the spatial distribution of the sites of particle acceleration; prima facie it is not unreasonable that the projected surface density of particle acceleration sites, presumably related to star formation processes, is correlated with the molecular gas column. Given a plethora of evidence that for a nuclear outflow with a speed $\gtrsim 100$ km/s e.g. (Crocker et al. 2011), this modeled wind speed is unphysically small and reflects either the inadequacy of a single zone model (i.e., in reality, there is a large dynamic range of different ISM phases with different temperatures and densities and the hot plasma phase may be swiftly outflowing even if the denser phases – which dominate the hadronic $\gamma$-ray production – are not) and/or there is significant further acceleration of the outflow at heights further from the plane than we currently model.

We impose the constraint $\kappa_{\text{p}} \leq 1$ which is saturated in this case: i.e., there is an equal differential number density of protons and electrons being injected at 1 TeV.

Given the assumed momentum power law form of the injection spectra, $\kappa_{\text{p}} \rightarrow 1$ together with the fitted spectral index $\gamma = 2.28$ implies a larger power in freshly injected electrons than protons, specifically $L_e = 2.1 \times 10^{37}$ erg/s and $L_p = 9.6 \times 10^{36}$ erg/s where we integrate down to 100 MeV in proton and electron kinetic energy (where ionisation losses start to become very strong).

We explored the effects of freezing the gas density in the fit to the measured value (Ferriere et al. 2007) of $\langle n_H \rangle = 109.3$ cm$^{-3}$ for the Galactic Ridge region. We find this to be an equally consistent solution. See Fig.[8] and Table[5].

| Model | $2\log(\mathcal{L}/\mathcal{L}_{\text{base}})$ | $\text{dof}_{\text{base}} - \text{dof}$ |
|-------|-----------------|-----------------|
| Base (2FGL+“bgkA”+“New point source”−“the Arc”−Sgr B+Spherically symmetric source) | 0 | 0 |
| Base+20 cm template | 176 | 3 |
| Base+HESS residual template | 149 | 3 |
| Base+Best-fitting two-flare model template | 194 | 6 |

Table 3. The likelihoods evaluated in compiling the above table are maximized with a broad band analysis using the Fermi Tools. Alternatives models of the Galactic Center in the 200 MeV−100 GeV energy range are listed. Each point source in the model has degrees of freedom (dof) from its spectrum and two extra dof from its location. The spectra for the Galactic Ridge templates are modeled by a broken power law, except for our two-flare model template, where we use the deduced $\gamma$-ray spectrum. In our two-flare model, the relevant dof are the two flare-ages and the two sets of injection spectrum parameters. While the spectra for the “spherically symmetric source” templates are modeled by a log parabola which has enough flexibility to mimic a good fitting dark matter or unresolved millisecond pulsars spectra (Gordon & Macias 2013).

| Template | $N_0$ [photons MeV$^{-1}$ cm$^{-2}$ s$^{-1}$] | $\Delta N_0$ [photons MeV$^{-1}$ cm$^{-2}$ s$^{-1}$] | $\gamma$ | $\delta \gamma$ |
|----------|---------------------------------|-----------------|--------|--------|
| Core | $3.5 \times 10^{-12}$ | $0.5 \times 10^{-12}$ | 2.33 | 0.06 |
| Edges | $2.1 \times 10^{-12}$ | $0.3 \times 10^{-12}$ | 2.43 | 0.07 |

Table 4. Best fit power-law ($dN/dE = N_0(E/E_0)^{-\gamma}$) parameters obtained from a likelihood analysis performed on the regions defined in the left panel of Fig. [17]. Errors are statistical only and were computed with the FERMI-TOOLS software.

6.2.2 GeV $p\bar{p}$ solution

Perturbing the initial starting points for the $\chi^2$ minimisation, we find a different but statistically equally good solution ($\chi^2_{\text{min}}/\text{dof} = 13.0/20$) wherein the majority of the $\sim$GeV flux density is ascribable to hadronic emission (neutral meson decay following $pp$ collisions, $p\bar{p}$ for brevity; See Fig.[3]).

ISM parameters are $B = 53$ $\mu$G, a very low gas density $\langle n_H \rangle = 3.4$ cm$^{-3}$, spectral indices of the injection proton and electron distributions are $\gamma = 2.4$, and $\kappa_{\text{p}} = 0.14$. With these parameters we find $L_e = 1.2 \times 10^{37}$ erg/s and $L_p = 2.8 \times 10^{37}$ erg/s. See Table[5].

Similarly we studied the impact of freezing the parameters $\langle n_H \rangle = 109.3$ cm$^{-3}$ and $\kappa_{\text{p}} = 0.004$. Again we find an acceptable fit to the data which requires a magnetic field amplitude about one order of magnitude higher than when we leave all parameters free to vary. See Fig.[10] and Table[5].

3 http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/
6.2.3 Secondary synchrotron solution

For both cases given above we find a very large power going into freshly-accelerated electrons relative to that going into protons.

Such a regime is quite different to that usually inferred from individual supernova remnants or the Galaxy-at-large (e.g., Thompson et al. 2006, 2007) where \( L_e \lesssim 0.1 L_p \) (where \( L_e \) is the luminosity going into freshly accelerated particles of type \( x \)).

If physical, such a large electron power must be connected to the unusual conditions in the Galactic Center environment.

For instance, the requisite electron acceleration might be associated with magnetic field reconnection occurring in the non-thermal radio filaments (Yusef-Zadeh et al. 1982) found uniquely in this region.

If this is the case, however, it remains unexplained why the fitting prefers \( \gamma_e \simeq \gamma_p \) with a value for the injection spectral index typical with expectation for first-order Fermi acceleration at astrophysical shocks.

Given the unusual parameter regime, we have also explored whether restricting \( \kappa_p \) to the expectation (Bell 1978) that it satisfy \( \kappa_p \sim (m_p/m_e)^{1/2} \); this choice implies equal total numbers of electrons and protons in the momentum power-law injection distributions and gives \( L_e \lesssim 0.1 L_p \) for \( \gamma \) close to 2 (see Fig. 11).

With this restriction, the number of degrees of freedom in the fitting is reduced to 19. We find, again, a statistically-satisfactory fit with \( \chi^2_{\text{min}}/\text{dof} = 15.1/19 \). ISM parameters are: a strong magnetic field \( B = 270 \mu \text{G} \), a low gas density \( n_H = 9.3 \text{ cm}^{-3} \), and spectral indices of the injection proton and electron distributions is \( \gamma = 2.5 \). With these parameters we find \( L_e = 1.2 \times 10^{36} \text{ erg/s} \) and \( L_p = 8.2 \times 10^{37} \text{ erg/s} \). See also Table 5.

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**Table 5.** Best fit parameter values obtained for five different solutions of the steady-state model for the Galactic Ridge region.

| Model                         | \( B \) [\( \mu \text{G} \)] | \( \gamma_{\text{NSB}} \) | \( \gamma_p \) | Normalization of protons at 1 TeV \( \text{cm}^{-3} \text{s}^{-1} \text{eV}^{-1} \) | \( \kappa_p \) | \( v_{\text{wind}} \) [\( \text{cm s}^{-1} \)] | \( \langle n_H \rangle \) [\( \text{cm}^{-3} \)] | \( \frac{L_p}{\text{erg s}^{-1}} \) | \( \frac{L_e}{\text{erg s}^{-1}} \) | \( \chi^2_{\text{min}}/\text{dof} \) |
|-------------------------------|-------------------------------|---------------------|-----------------|------------------------------------------------|----------------|---------------------|-------------------|----------------|----------------|--------------------|
| Bremsstrahlung solution       | 57.3                          | 2.29                | 6.3             | 2.90 \times 10^{-39}                             | 1.000         | 1.0 \times 10^9     | 26.0               | 348.9          | 9.6 \times 10^{36} | 2.1 \times 10^{37} | 13.0/20            |
| Bremsstrahlung solution with \( \langle n_H \rangle \) fixed | 116.1                         | 2.32                | 6.5             | 2.35 \times 10^{-39}                             | 0.849         | 1.6 \times 10^7     | 109.3              | 315.6          | 8.8 \times 10^{36} | 1.8 \times 10^{37} | 11.7/21            |
| \( \pi^0 \) solution          | 53.3                          | 2.43                | 6.4             | 4.92 \times 10^{-39}                             | 0.137         | 1.0 \times 10^5     | 3.4                | 435.7          | 2.8 \times 10^{37} | 1.2 \times 10^{37} | 13.0/20            |
| \( \pi^0 \)-solution with \( \langle n_H \rangle \) and \( \kappa_p \) fixed | 2370.2                         | 2.45                | 5.2             | 3.69 \times 10^{-39}                             | 0.004         | 2.4 \times 10^5     | 109.3              | 382.4          | 2.4 \times 10^{37} | 3.4 \times 10^{35} | 17.7/22            |
| Secondary synchrotron         | 280                           | 2.46                | 5.8             | 1.24 \times 10^{-38}                             | 0.004         | 1.2 \times 10^9     | 9.3                | 441.1          | 8.2 \times 10^{37} | 1.2 \times 10^{36} | 15.1/21            |

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**Figure 13.** Flare model proposed by the HESS collaboration (Aharonian et al. 2006). The model consists of a single flare that might have occurred \( \sim 10^4 \) years ago and lasted for approximately 10 years. We use the gas maps provided in Ferrerie et al. (2007). Note that the HESS team assumed an energy independent diffusion coefficient. Radio data is well fitted by synchrotron emission resulting from secondary CR electrons and positrons. For this case, the best fit magnetic field amplitude was \( B = 425 \mu \text{G} \).

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7 DISCUSSION AND CONCLUSIONS

In this section, we discuss four different proposals for the Galactic Ridge \(\gamma\)-ray data: A flare event from the Galactic Center with energy independent diffusion, two flare events from the Galactic Center with Kolmogorov diffusion, a continuous emission from the Galactic Center, and a steady-state model with emission occurring throughout the Galactic Ridge with convection dominating over diffusion of the CRs.

We used the formalism of Aloisio et al. (2009), which was recently utilized by Chernyakova et al. (2011), Linden & Profumo (2012), Linden et al. (2012) in the point-source analysis of HESS J17452–290. Indeed, if we compute the expected cosmic-ray density distribution from the Galactic Ridge using similar parameters to those obtained in Aharonian et al. (2006) but assuming constant injection of relativistic protons (instead of the flare emission used in Aharonian et al. (2006)), we find a good fit to the diffuse \(\gamma\)-ray data. As can be seen in Fig. 12, a continuous emission from the Galactic Center produces a more peaked spatial profile compared to a flare event.

In this sense, a constant injection model should be better suited to explain the point source nature of Sgr A* (Chernyakova et al. 2011, Linden et al. 2012). An excessively peaked profile, for the HESS Galactic Ridge, from the Galactic Center was also found for a constant source model by Wommer et al. (2008), which used an approach based on simulating the trajectories of individual protons. However, as discussed above, our analysis does show that if a flare model is considered, a single CR accelerator located in the Galaxy Center can consistently explain the broad band diffuse photon data from the Galactic Ridge.

Notice that our flare models neglect diffusive reacceleration throughout the Galactic Ridge. The time scale of this acceleration is \(t_{\text{acc}} = D/v_\text{A}^2\), where \(D\) is the spatial diffusion coefficient and \(v_\text{A}\) is the Alfvén velocity. Using an Alfvén velocity of 30 km/s (Schlickeiser 2002) gives \(t_{\text{acc}} \approx 10^7\) years for \(E \sim 1\) GeV. This justifies neglecting reacceleration, in our case, as our GeV producing flare happened \(3 \times 10^5\) years ago. A similar calculation for our TeV flare also justifies neglecting reacceleration throughout the Galactic Ridge.

7.1 Single flare versus multiple flares model

In Aharonian et al. (2006) the \(\sim\)TeV diffuse spectrum and spatial \(\gamma\)-ray distribution was explained with a single impulsive injection of CR protons occurring near the dynamical center of the Milky Way Galaxy. Their fit preferred a set of parameters for which the CR density is described by a Gaussian distribution (centered on Sgr A*) with a dependence on distance to the Galactic Center given by the standard deviation \(\sigma = 0.8\) kpc. They estimated that a central source of age \(\sim 10\) kyr and energy independent diffusion coefficient \(D = \eta \times 1 \times 10^{28}\) cm\(^2\) s\(^{-1}\), where \(\eta \leq 1.0\), can account for the observed morphology and spectrum of the TeV-\(\gamma\)-rays. In view of more recent measurements of diffuse radio emission (Crocker et al. 2011, Yusef-Zadeh et al. 2013) and GeV-\(\gamma\)-rays (Yusef-Zadeh et al. 2013, Macias & Gordon 2014) from the same region, it is not immediately obvious whether this model would still be adequate at a multiwavelength level.

We reproduced the results reported by Aharonian et al. (2006) and evaluated the goodness of fit for the HESS, Fermi-LAT and radio data. We found this model to have an acceptable fit (p-value > 0.001) to the full data set \(\chi^2_{\text{min}}/\text{dof} = 23.3/20\), see Fig. 13. Best fit diffusion parameters are: A diffusion coefficient \(D = 3 \times 10^{28}\) cm\(^2\) s\(^{-1}\), a total energy injection of \(Q_{\text{total}} = 1.0 \times 10^{51}\) erg (for a flare duration of \(\Delta t = 10\) years) and an initial time \(t_0 = 10^4\) years. This is about an order of magnitude more energy than reported by Aharonian et al. (2006). It’s possible that the mismatch is due to a different assumed value of \(n_0\) which will affect the needed normalization of the injection spectrum. In our case, the total energy injection is similar to the total energy emission of a typical supernova remnant. Unless there was a very high efficiency of cosmic-ray generation, our estimate may be better explained by a burst event from the supermassive black hole. Assuming the gas maps in Ferriere et al. (2007) we found for the ISM a strong magnetic field amplitude \(B = 425\) \(\mu\)G.

We used the radio data compilation from Crocker et al. (2011) rather than the radio data from Yusef-Zadeh et al. (2013). The difference between the two is that the latter presents background subtracted fluxes. We prefer to marginalize over the background so as to account for the additional uncertainty. The data in Yusef-Zadeh et al. (2013) also do not include the 5% systematic error associated with absolute calibration, although this could easily be added.

For the single flare model, the CR spatial density distribution in the \(\sim 0.2 - 100.0\) GeV and 0.2 – 12.5 TeV energy bands is the same because the diffusion coefficient is taken to be energy independent. In principle, the energy losses are energy dependent, but as can be seen from Fig. 14 the energy-loss time scale is much greater than the diffusion time scale, typically \(\tau_{\text{diff}} \approx 0.5\) kyr. Therefore, energy losses are not a significant factor for our single flare fit.

Notice that the diffusion coefficient may well be energy dependent, as for example in the case of a Kolmogorov spectrum of turbulence. The impact of assuming a Kolmogorov energy-dependent diffusion \(D(E)\) on the resulting \(\gamma\)-ray spectra is demonstrated in Fig. 5. The most salient feature is that, for this case, a single CR-injection event fails to explain all the observations. We are thus required to invoke a model consisting of the superposition of two flares.

It is instructive to understand why a single impulsive event cannot be accommodated to the diffuse Galactic Ridge \(\gamma\)-rays when the diffusion coefficient is a function of energy: For the best fit parameters in Table 1 our \(2 \times 10^4\) year old flare cannot have a strong impact on the observed GeV \(\gamma\)-ray distribution, since most of the \(\sim\)GeV protons from the flare are still trapped in the surroundings of the central source, i.e. \(R_{\text{diff}} = \sqrt{2\pi}(1\text{ GeV}, 2 \times 10^4\text{ years}) \approx 50\) pc. On the other hand, the \(3 \times 10^5\) year old flare cannot explain the TeV data because most of the very-high-energy protons have left the region. Fig. 14 illustrates how even if we harden sufficiently the injection...
Figure 15. Brightness profile of the Galactic Ridge in $0.2 - 100.0$ GeV energy range for the flare model with a Kolmogorov spectrum ($\kappa = 1.0$ and $\beta = 0.3$). The injection spectrum is described by an exponential cut-off in momentum with slope $\Gamma = 2.0$. We display burst events of increasing age for which the fluxes are normalized to the maximum. The resolution of every map is $0.1^\circ \times 0.1^\circ$ and no smoothing was applied to the images.
spectrum of protons, the fit cannot be ameliorated. This indicates that we need a fresher injection of protons to explain the TeV-$\gamma$-rays.

7.2 Resolving the spatial extension of the flare model

As can be seen from Fig. [15] a $t_0 = 2.5$ kyr or younger flare results in a relatively spherical morphology. This results from the CRs not yet reaching the CMZ boundary. We now consider the prospect that a $t_0 = 2.5$ kyr or younger flare could explain the Galactic Center spherically symmetric extended source in addition to the Galactic Ridge.

The spatial morphology resulting from a flare depends primarily on the flare age and the diffusion coefficient. To test the spatial morphology of the flare independently of the flare spectrum, we model the flare spectrum with a broken power-law of the form

$$\frac{dN}{dE} = N_0 \times \begin{cases} \left( \frac{E}{E_b} \right)^{-\gamma} & \text{if } E < E_b \\ \left( \frac{E}{E_b} \right)^{-\gamma} & \text{otherwise} \end{cases}$$

where $N_0$ is a normalization constant and $E_b$ is the break energy. This could always be generated provided sufficient flexibility was allowed in the flare injection spectrum.

The results of this analysis are shown in Fig. [15]. A full Fermi-tools analysis was done for each flare age. Both the flare template and the Galactic Center spherically symmetric extended source template were included. As can be seen, there is no choice of flare age which relevantly affects the significance of the spherically extended source. This inability of our flare models to describe the spherically symmetric extended source is probably due to a mismatch in the radial fall-off and extension of the younger flares ($t_0 \leq 2.5$ kyr) relative to the spherically symmetric source which requires a fall off of flux like $r^{-2.4}$ out to at least $1^\circ$ [Gordon & Macias 2013], while the older flares under consideration produce an excessively ridge-like morphology. The improvement in the flare fit levels off at $t_0 \sim 3 \times 10^5$ yr as then the CRs have reached the edges of the CMZ.

7.3 Non-steady-state versus steady-state model

In the steady-state model CR particles are, in principle, convected away from the Galactic Ridge region by supernovae and stellar winds (Crocker et al. 2011), a mechanism that can be assumed as energy-independent. As discussed above, however, our assumption of a single zone puts a restriction on the wind speed such that the steady-state model is practically calculated in the thick-target limit. In either circumstance, however, a distinctive prediction of this model is that particle transport does not alter the slope of the steady-state model is practically calculated in the thick-target winds (Crocker et al. 2011), a mechanism that can be assumed away from the Galactic Ridge region by supernovae and stellar winds (Crocker et al. 2011).

Contrastingly, in the non-steady-state scenario, at a fixed distance and time since a CR injection event, one expects higher-energy CRs to arrive first so the spectrum is hardened with respect to the injection distribution.

In the left panel of Fig. [17] we divide our region of interest in three sectors: the core is defined by Galactic longitude $-0.4^\circ \leq l \leq 0.4^\circ$ (red box in Fig. [17]) and the edges by $0.4^\circ \leq l \leq 0.8^\circ$ and $-0.8^\circ \leq l \leq -0.4^\circ$ (white boxes). We calculate the $\gamma$-rays in each of these areas and average the spectrum at the edges (see Fig. [17] (Right)). The spectra height are normalized to fit the data so as to make their comparison convenient. As can be seen, the current data are not accurate enough to distinguish the two scenarios. Better photon statistics in the $1 - 100$ GeV range are needed to be able to single out CR diffusion imprints in the $\gamma$-ray data.

Figure 16. Fermi-tools test statistic (TS) values for the Galactic Center spherically symmetric source (red solid line) and several flare models (black dashed line) of different ages (see also Fig. [15]). Note that each flare template was included in addition to the spherical source. The blue shaded region encloses the TS values obtained for the Galactic Ridge using a 20 cm map or the HESS residuals map (Macias & Gordon 2014). The green dotted line displays the best fit age ($t_0 = 3 \times 10^5$ years) of the GeV flare obtained from our bin-by-bin spectral analysis and shown in Table [4].

We also searched for spectral evidence of diffusion processing in the Fermi-LAT data using the Fermi-TOOLs analysis software. We created normalized map templates of the regions shown in Fig. [14] and modeled the GeV-$\gamma$-ray spectrum with a power-law formula. The spectral index of the diffuse $\sim$GeV emission from the core is $2.33 \pm 0.06$ and from the edges $2.43 \pm 0.07$ (see Table [4]). The diffusion steepening of the CRs is therefore not currently significant. However, as can be seen from Fig. [14] future GeV data has the potential to detect this or to rule it out. Such observations could also potentially be used to distinguish between the energy-independent diffusion scenario proposed by Aharonian et al. (2000) and the Kolmogorov diffusion two-flare model we have discussed in this article.

ACKNOWLEDGMENTS

OM is supported by a UC Doctoral Scholarship. RMC is the recipient of an Australian Research Council Future Fellowship (FT110100108). SP is supported in part by the US Department of Energy under Contract DE-SC0010107-001. RMC thanks Casey Law for helpful discussions. This work makes use of Fermi Science Tools4, MINUIT2 (James & Roos 1975) and SCiPY (Jones et al. 2001).

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Figure 17. Spatial variation of the SED along the plane of the Galactic Ridge: Left: Background subtracted diffuse TeV-γ-rays image as seen by HESS (Aharonian et al. 2006). The red box encloses the core of the region defined by \(-0.4^\circ \leq l \leq 0.4^\circ\), \(|b| \leq 0.3^\circ\) and white boxes the edges \(0.4^\circ \leq l \leq 0.8^\circ\), \(|b| \leq 0.3^\circ\) and \(-0.8^\circ \leq l \leq -0.4^\circ\), \(|b| \leq 0.3^\circ\). Right: Displayed are the predictions of the non-steady-state model (with Kolmogorov diffusion) for the γ-ray spectra in the regions defined in the left panel. On the spectrum, the edges are computed as the mean of the spectrum at both ends.

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