PROCEEDINGS OF SCIENCE

Cosmic Rays Interacting with Molecular Clouds in the Galactic Center

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The High-Energy Stereoscopic System (H.E.S.S.) has detected diffuse TeV emission correlated with the distribution of molecular gas along the 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 Ridge [1]. An alternative, steady-state model explaining all three data sets (TeV, GeV, and radio) invokes purely leptonic processes [2]. 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 Ridge. We also show that a range of single-zone, steady-state models are able to explain all three spectral data sets. Large gas densities equal to the volumetric average in the region can be accommodated by an energy independent diffusion or streaming based steady-state model.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

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PoS(ICRC2015)902

1. Introduction

The High Energy Stereoscopic System (H.E.S.S.) collaboration [1] reported the discovery of diffuse TeV emission from the innermost part of the Galactic Center (GC) region. These gamma rays are localized over a ridge like area defined by Galactic longitude $|l| < 0.8^\circ$ and latitude $|b| < 0.3^\circ$. Morphological analysis of the data shows a close correlation between gamma-ray emission and molecular gas present in the region, known as the central molecular zone (CMZ). This is a strong indication that the gamma rays originate in cosmic-ray (CR) interactions with interstellar matter (and thus have a volumetric emissivity proportional to the density of CRs and that of target material).

Ref. [1] proposed a model for the TeV Ridge emission in which a single flare injection of CR protons occurring near the super-massive black hole Sgr A* or the young supernova remnant Sgr A East could plausibly explain the observed TeV flux density.

Steady-state models for the TeV Ridge have also been proposed [2–4]. In these models there is continual emission of CRs into the CMZ with multiple sources distributed within the CMZ rather than a single emission event at the GC.

Several groups, using data from the Fermi large area telescope (Fermi-LAT), have identified an extended GeV source of gamma rays in the GC region [5–16]. It has been confirmed that this GeV extended source is best fitted by the combination of a spherically-symmetric template (radius $\sim 1^\circ$) and a ridge-like template resembling the CMZ in the inner ~ 200 pc of the GC [13]. For the spherical component, the square of a generalized Navarro-Frenk-White (NFW) profile with inner slope of 1.2 provides a good fit, and for the GeV Ridge component, a template based on the H.E.S.S. residuals or 20-cm continuum radio emission map provides a satisfactory fit. The spectrum of each template is not significantly affected in the combined fit and are consistent with previous single-template fits. The statistical independence of these two GeV extended sources allows us to robustly extract spectral and spatial GeV gamma-ray information from the Ridge. There have been three main proposals for the origin of the spherically symmetric emission: an unresolved population of millisecond pulsars, dark matter pair annihilation, and CRs interacting with the interstellar medium and radiation field. Some examples of recent articles discussing the pros and cons of the different proposals are [13–15, 17–28].

In this conference proceedings, we provide a summary of Ref. [29]. We focus on understanding the GeV and TeV Ridge component, while, at the same time, accounting for the spherically symmetric generalized NFW component and modeling its spectrum empirically with a best-fit log parabola parametric form.

For the Ridge template, we revisit the non-steady-state hadronic model and demonstrate that diffuse GeV-TeV gamma-rays radiation as well as radio continuum emission from the Ridge can be explained by a flare-like injection of high energy protons in the surrounding dense gas environment. We also update the steady-state models of [3] to include the GeV Ridge data.

2. Diffuse GeV data from the Ridge region

If high-energy gamma rays from H.E.S.S. Ridge TeV source are produced by the decay of neutral mesons (mostly π^0's) resulting from hadronic interactions of CRs with interstellar matter, it is plausible that the GeV and TeV emission from the Ridge source 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 H.E.S.S. field.

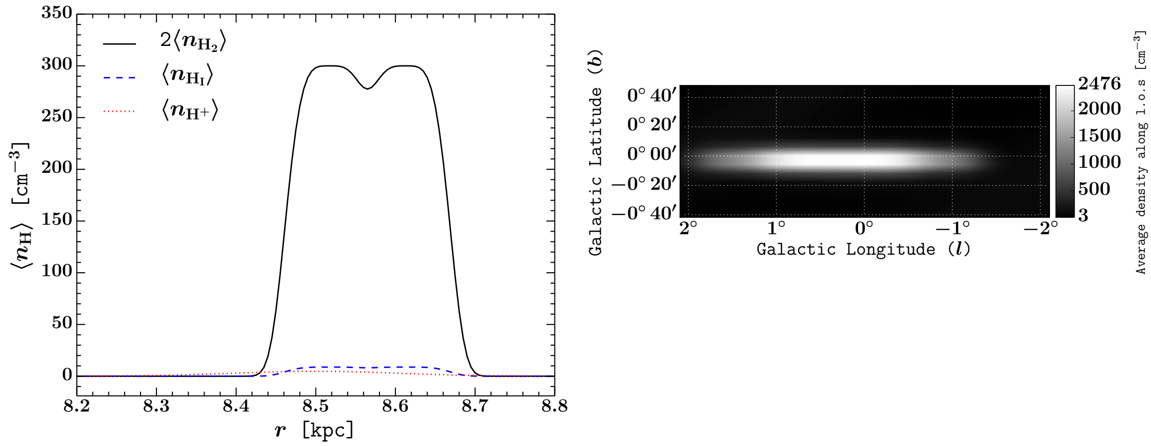

Figure 1: Panels shown are obtained from data taken from [30]. Left: Average densities of interstellar gas as functions of distance (r) along the line of sight passing between us and the GC; Molecular hydrogen is shown with a black solid line, atomic hydrogen with a blue dashed line and ionized hydrogen 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.

3. Gas Density Maps of the inner 200 parcecs region of the Galactic Center

In order to perform realistic simulations of hadronic gamma-ray emission from the GC a detailed knowledge of the spatial distribution of interstellar gas in the region is necessary. Here, we employ the model of [30], valid for the innermost 3.0 kpc of our Galaxy. This 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. 1 illustrates the variation of the column densities of molecular, atomic and ionized gases. The most abundant material in our region of interest is molecular hydrogen $\langle n_{H_2}\rangle$. This component forms a Galactic structure known as the CMZ—an asymmetric layer of predominantly molecular gas that encompasses the region defined by $-1.5^\circ \lesssim l \lesssim 2.0^\circ$ and $|b| \leq 0.3^\circ$ around Sgr A*.

4. Multiwavelength Modeling

The origin of extended gamma-ray emission from the direction of the 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 H.E.S.S., these observations can be well explained by more than one mechanism [2–4]. Interestingly, the H.E.S.S. 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 [2, 13] 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.

We assume here, for simplicity, that $D(E)$ is independent of position, and given by $D(E) = 10^{28}\left(\frac{E}{1\,\mathrm{GeV}}\right)^{\beta} \times \kappa$ where β and κ are free parameters. For the initial spectrum of protons $Q[E_g(E,t)]$ we use a power-law with an exponential cutoff $Q[E_g(E,t)] = K\left(\frac{E_g}{1\,\mathrm{GeV}}\right)^{-\Gamma}\exp\left(-\frac{E_g}{100\,\mathrm{TeV}}\right)$ where K is a normalization constant, Γ is the spectral slope. Both K and Γ are left free in our parameter estimations. 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 with the three dimensional spatially varying gas map $\langle n_H \rangle$ we obtained from [30]. 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 [12].

4.1 Synchrotron emission from $e^{\pm}$ of hadronic origin

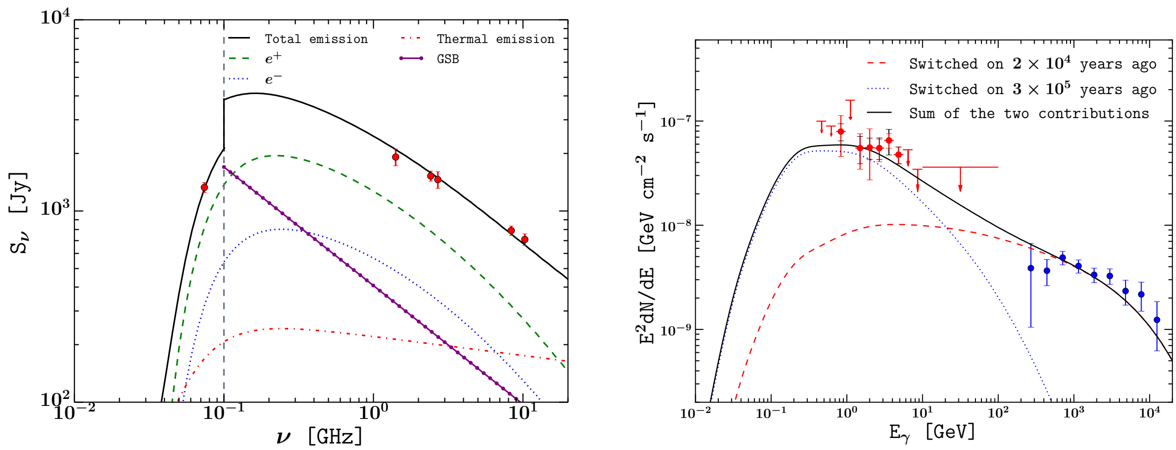

Figure 2: H.E.S.S. Ridge region spectrum for the best-fitting, non-steady-state, Kolmogorov-type turbulence, hadronic scenario. The model consists of two independent flares that might have occurred 2×10^4 and 3×10^5 years ago and lasted for approximately 10 years. Fitted parameters are summarised in Table 1. We assume the gas maps provided in [30]. Data are from H.E.S.S. diffuse [1], Ridge Fermi-LAT [13] and radio observations [3]. 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 [3]. 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.

	$\Gamma_{\rm GeV}$	$\Gamma_{\rm TeV}$	$E_{\rm total,GeV}[10^{50}$ erg]	$E_{\rm total,TeV}[10^{50}$ erg]	$B[\mu$G]	Free-free [Jy]	$\Gamma_{\rm GSB}$
Mean	1.9 ± 0.1	1.8 ± 0.3	120^{+50}_{-60}	1.5 ± 1.0	400 ± 300	150 ± 50	0.6 ± 0.1
Best fit	2.0	1.8	150	1.5	200	180	0.6

Table 1: Propagation parameters obtained from the full broad-band spectral observations. The column corresponding to χ^2 is obtained from the fit to spectra shown in Fig. 2. The GSB provides an effective extra radio data-point. The mean values are obtained from marginal distributions assuming a non-negative prior for all parameters. The errors correspond to the 68% confidence intervals.

For the Ridge environment, we have a total average hydrogen density of $\overline{\langle n_H \rangle} = 109.3$ cm^{-3} [30] and, as we show below, our fit to the radio data suggests an average magnetic field $B = 200\ \mu$G.

5. Results

5.1 Non-steady-state Model

The main results of the non-steady-state model are shown in Fig. 2 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 3×10^5 and 2×10^4 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 2×10^{52} and 2×10^{50} erg each. The latter is a reasonable match for a single supernovae remnant, 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_0), only the total injected energy affects the predicted gamma-ray spectrum. Details of our best-fit parameters are provided in Table 1.

In Fig. 2 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.

As a consistency check, we also evaluated the TS value of the GeV spatial map obtained from our non-steady-state model predictions using the Fermi-Tools software package [1]. These results are shown in Table 2.

5.2 Steady State Results

We find two very satisfactory parameter regimes that can be broadly described as:

(i) ~GeV dominantly primary electron bremsstrahlung, ~TeV dominantly hadronic emission, and radio dominantly primary electron synchrotron, with a large gas density;

[1] `http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/`

Model	$2\log(\mathscr{L}/\mathscr{L}_{\rm base})$	$\rm dof_{base}-dof$
Base	0	0
Base+20 cm template	176	3
Base+H.E.S.S. residual template	149	3
Base+Best-fitting two-flare model template	194	6

Table 2: The likelihoods evaluated in compiling the above table are maximized with a broad band analysis using the Fermi Tools. Alternatives models of the GC in the 200 MeV−100 GeV energy range are listed. Base=2FGL+"bgkA"+"New point source" −"the Arc"−Sgr B+Spherically symmetric source. 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 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 [12].

(ii) ∼GeV *and* ∼TeV dominantly hadronic emission, and radio dominantly primary electron synchrotron with high gas density and slow escape (approaching thick target limit).

We remark in passing that we have also found a class of solutions with ∼GeV *and* ∼TeV dominantly hadronic emission and radio dominantly *secondary* electron synchrotron but these require very strong magnetic fields and are somewhat statistically disfavoured by the fitting procedure so we do not pursue them further here. Also, there are ∼GeV *and* ∼TeV dominantly hadronic emission, and radio dominantly primary electron synchrotron with low gas density and fast escape (consistent with a wind) solutions. However, due to large degeneracies between the gas density and other parameters, in this article we just consider the gas density giving by the [30] of $\overline{\langle n_H \rangle} = 109.3$ $\rm cm^{-3}$ for the Ridge region for both the steady-state and non-steady-state cases.

6. Conclusions

We have examined steady-state and non-steady-state models of the Ridge gamma-ray excess emission. We found that a flare model from the GC provides an acceptable fit to the TeV, GeV and radio data, provided the diffusion coefficient is energy independent. However, if Kolmogorov-type turbulence is assumed to inform the diffusion coefficient, we found that two flares are needed, one for the TeV data (occurring approximately 10^4 years ago) and an older one for the GeV data (occurring approximately 10^5 years ago).

We also found that the flare models we investigated do not fit the spherically symmetric GeV excess as well as the usual generalized NFW spatial profile, but are better suited to explaining the Ridge excess. This is due to the ridge like morphology of the CMZ gas distribution.

We also found that, assuming distributed injection, a range of steady-state models are able to explain the GeV, TeV, and radio data for the excess Ridge-like emission but classes of solution with a floating gas density were poorly constrained. Fixing the gas density at a high value equal to the volumetric average value we find good solutions that, because of fast escape, have to be interpreted as energy-independent diffusion or streaming of the escaping cosmic rays *through* the gas (rather than escape of particles *in* gas advected away on a wind). Consistent with previous

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work, we robustly find that the magnetic field had to be at least an order of magnitude larger than in the local ISM for all models considered.

Acknowledgments

OM was 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 TOOLS [2], MINUIT2 [31] and SCIPY [32].

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