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High energy emission from the center of our Galaxy.

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Employing data collected during the first 25 months observations by the Fermi -LAT, we describe and subsequently seek to model the very-high energy ($>$ 300 MeV) emission from the central few parsecs of our Galaxy. Using the combination of Fermi data on 1FGL J1745.6-2900 and HESS data on the coincident, TeV source HESS J1745-290, we show that the spectrum of the central gamma-ray source is flat at both low and high energies with a relatively steep spectral region inbetween. We model the gamma-ray production in the inner 10 pc of the Galaxy and examine cosmic ray (CR) proton propagation scenarios that reproduce the observed spectrum of the central source. We show that a model considering a transition from diffusive propagation of the CR protons at low energy to almost rectilinear propagation at high energies can well explain the spectral phenomenology. We find considerable degeneracy between different parameter choices which will only be broken with the addition of morphological information that gamma-ray telescopes cannot deliver given current angular resolution limits. We argue that a future analysis performed in combination with higher-resolution radio continuum data holds out the promise of breaking this degeneracy.

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1. Introduction

Over the past decade-and-a-half since the discovery by EGRET of a very high energy (VHE) gamma-ray source near the Galactic center (GC), there has been intense speculation as to what mechanism(s) are producing the observed emission. With the latest data, it is possible to place the center-of-gravity of the TeV point source within the central $\sim 6''$ of the Galaxy ([1]), leaving only a handful of possible sources. These include the central black hole itself, Sgr A* ([4, 14]); a plerion discovered within the central few arcseconds of the Galaxy ([13]), a putative "black hole plerion" produced by the wind from Sgr A* ([7]), and the diffuse ≤ 10 pc region surrounding Sgr A* ([5, 8, 9]).

Given the above background, we consider here the further insights now possible in light of the Fermi -LAT observations of the GC region. Employing data collected during the first 25 months' observations by the Fermi -LAT, we describe and subsequently seek to model the very high energy (>300 MeV) emission from the central few parsecs of our Galaxy. We analyse, in particular, the morphological, spectral and temporal characteristics of the central source, 1FGL J1745.6-2900, which coinsides positionally with HESS J1745-290. Significance maps based on the maximum likelihood test statistic (so-called TS maps) of the central part ($1.5^{\circ} \times 3.5^{\circ}$) of the Galaxy center as seen by Fermi are shown in Figure 1. Our analysis does not show statistically significant variability of 1FGL J1745.6-2900.

Remarkably, the data show a clear, statistically significant signal at energies above 10 GeV, where the Fermi -LAT has an excellent angular resolution comparable to the angular resolution of HESS at TeV energies. This makes meaningful the joint analysis of the Fermi and HESS data. The spectrum in 100 MeV–300 GeV energy range can be fitted by a power law with a slope of $\Gamma = 2.212 \pm 0.005$ and a flux normalization of $F = (1.39 \pm 0.02) \times 10^{-8}$ cm^{-2} s^{-1} MeV^{-1} at 100 MeV. We also attempted to split the spectrum into two different energy bands, and found that the fitted slope is equal to $\Gamma = 2.196 \pm 0.001$ in 300 MeV–5 GeV energy range, and $\Gamma = 2.681 \pm 0.003$ in 5 – 100 GeV energy range. Thus the slope of the Fermi spectrum above several GeV is significantly steeper than the spectrum reported by the HESS collaboration at TeV energies ($F_{\rm HESS} \sim E^{-2.1}$), ([2]).

With the spectral information from both Fermi and HESS in hand, we model below the production of gamma-rays from the inner GC due to hadronic interactions of protons accelerated within the central black hole and diffusing into the surrounding interstellar medium.

2. Modeling

As proposed in [5], a significant fraction of the protons accelerated near the black hole may enter the surrounding gaseous environment and initiate VHE gamma-ray emission through neutral pion production and subsequent decay. The efficiency of the process, and the energy spectrum of resulting gamma-rays depends not only on the protons' injection rate and the ambient gas density, but also on the speed of proton transport into the surrounding medium.

Given that the VHE emission detected by HESS and Fermi can be localized to within the central several arcminutes then, for a GC distance of $d \sim 8$ kpc, the linear size of the production region of VHE gamma-rays can be as large as 10 pc. Continuum X-ray and radio observations of

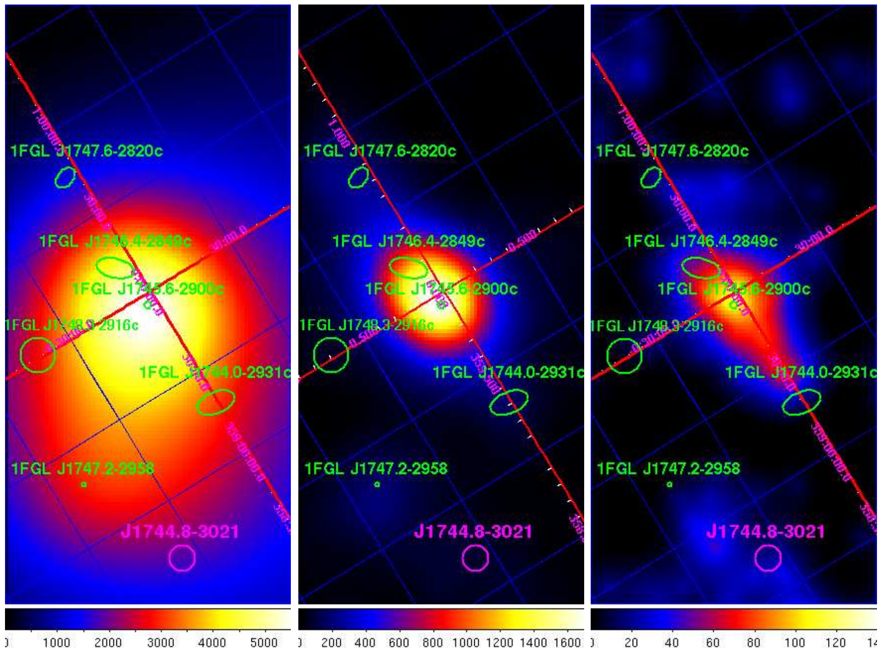

Figure 1: TS maps of the central part (1.5° × 3.5°) of the Galaxy center as seen by Fermi in 300 MeV – 3GeV, 3GeV–30 GeV and 30GeV–300 GeV energy ranges (left to right). Note that linear colour scheme has different maximum value in all cases varying from 5500 in the less energetic left picture to 140 in the most energetic right one. Source significance can be approximately estimated as a square root of TS.

the central 10 pc region of the Galaxy show a complex environment with many unique structures. For simplicity we assume here that the supermassive black hole in the center of our Galaxy is surrounded by a shell of a dense matter with a density, normalized to $n_H = 1000$ cm^{-3} at 1 pc radius, with either constant or $1/r^2$ radial dependence. The inner and outer radii of this shell are parameters in our model.

In the standard diffusion approximation the propagation of particles is described by the diffusion equation which, in the spherically symmetric case, reduces to the form:

$$\frac{\partial n}{\partial t} = \frac{D}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial n}{\partial r} + \frac{\partial}{\partial E}(bn) + Q, \tag{2.1}$$

where $n(r,t,E)$ is the space density of relativistic particles with energy E, at instant t being a distance r from the source; $b(e) = -dE/dt$ is the continuous energy loss rate; $Q(E,t)$ is the injection rate; and $D(E) = 10^{28}(E/1\mathrm{GeV})^{\beta}\kappa$ cm^2 s^{-1} is the energy-dependent diffusion coefficient. We have assumed here, for simplicity, that D is independent of r. Formally, the diffusion equation does not contain information on how fast a particle may propagate. Since Eq.(2.1) does not prevent an artificial "superluminal motion", we follow the phenomenological approach proposed by [6] to avoid this problem.

3. Discussion

The spectral properties of the VHE emission from the GC differs considerably from that at

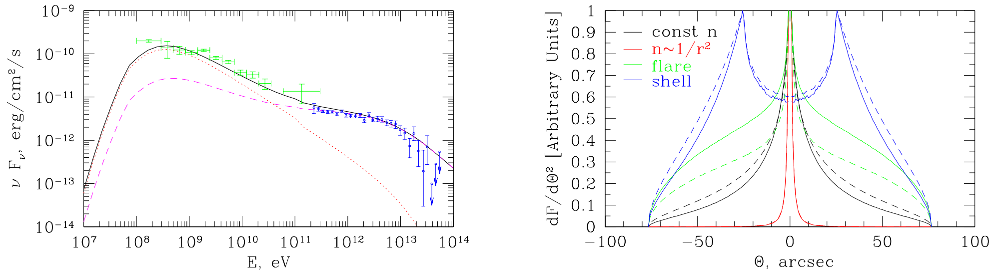

Figure 2: *left:*Combined Fermi (green points) and HESS (blue points) explained by superposition (black solid line) of a proton flare of 10 years duration happened 300 years ago (magenta dashed line) and a constant source that switched on 10^4 years ago (red dotted line). *right:*Brightness profile of the GC in 100MeV - 1GeV (solid lines) and 1GeV – 10GeV (dashed lines) energy ranges. $25''$ corresponds to 1pc.

lower energies: whilst the GC is known to be variable at X-rays and near-IR wavelengths, no variability has been detected either by HESS, or by Fermi. This seeming duality has a natural explanation if the low energy emission is generated very close to the central black hole, while the gamma-ray emission originates from a much larger region and is emitted during the diffusion of the relativistic protons through the interstellar medium surrounding the central black hole. In such a case, the very high energy emission would only reflect (with a delay) major flares originating from the central source. In this context, one should mention the morphological interpretation of the diffuse gamma-ray emission observed by HESS from the central 200 pc region of GC, which relates the positive detections of gamma-rays from giant molecular clouds in GC to a putative "proton" flare that occurred in Sgr A* in the past, 10,000 years ago or so ([3]).

The observations of reflected X-radiation from the cloud Sgr B2 located at a distance of 100 pc from Sgr A* suggests that about a hundred years ago there was an increase of X-ray luminosity of Sgr A* ([16, 17]). In our modeling, we checked that assuming different injection and diffusion parameters we are able to explain the data as a result of a constant injection of protons over a few hundreds years as well as 10000 yeras ([10]). Our model is able to self-consistently explain different spectral indices at GeV and TeV energies by the different effective escape velocities of the protons. While high energy protons, producing TeV photons, escape quasi-rectilinearly without spectral deformation, as, indeed, do the particles fully trapped at the lowest energies, the particles with intermediate energies are affected by diffusion, but not fully trapped and their spectrum becomes much steeper providing the transition between two extreme cases.

Recent monitoring of the Sgr B2 cloud with X-ray instruments shows flux variability on time scales of 10 years ([17]). This variability can be naturally interpreted as a measure of the flare duration. Although the X-ray luminosity and proton acceleration in Sgr A* should not necessarily correlate, it is interesting to explore also the scenario when we deal with a flare of proton acceleration and injection into the interstellar medium on timescales of years.

In Figure 2 we compare the spectra of gamma-ray emission resulting from realization of three different scenarios: (i) a proton flare of 10 years duration that occurred 300 years ago, (ii) a constant source that switched on 10^4 years ago, and (iii) a proton flare on top of the constant source, namely the superposition of (i) and (ii). To fit the data, we took the size of the gamma-ray emission region to be $R = 8$ pc, parameters of the diffusion coefficient $\beta = 0.65$, $\kappa = 1$, and initial proton spectrum of $Q(E) \propto E^{-2}\exp(-E/100\ \mathrm{TeV})$, with the proton injection rate of 1.9×10^{39}erg/s for the constant source and 1.9×10^{42}erg/s for the flare.

For this parameter set, the 10 years long flare happened 300 years ago cannot have a strong impact on the currently observed TeV spectrum, since most of the high energy protons from the flare have already escaped. On the other hand, the emission at GeV energies is produced by protons from the flare which are still trapped by diffusion in the gamma-ray production region. To explain the TeV data we need much slower diffusion or a fresh injection of protons, for example contributed from a very recent flare, or by the quasi-steady component of protons. Actually the form of TeV emission doesn't depend on the age of the source if it exceeds $t_{esc} = R/c \sim 30$years. The case of superposition (solid line) of the flare (dashed line) and persistent (dotted line) components of protons is shown in left panel of Figure 2. For the chosen parameters, the GeV energy range of gamma-rays is dominated by the flare component of protons, while the TeV gamma-rays are contributed mainly by protons from the persistent component.

Thus, we are able to reproduce the observed spectrum of gamma-rays in different ways. The total mass of the clouds incide the central zone needed to explain the observed spectrum turned out to be about $10^5 M_\odot$. It is interesting to note that this mass is in a good agreement with the masses of the molecular clouds within the central ($\sim$10 pc) zone [11]. The total energy required in relativistic protons currently trapped in the gamma-ray production region varies from 10^{49} to 10^{51} erg for different models. This energy can be injected in very different ways: in reality there has probably been a series of flares with different energetic signatures occurring throughout the life-time of the central source. Variability of the iron line in diferent molecular clouds support the idea of multiple flares in X-ray as well [15].

The observed spectral and temporal properties of the GC at various wavebands are not enough to constraint all the parameters in our model. Additional information can be extracted from the gamma-ray morphology of the inner arcminute region. The radial distribution of photons is highly dependent on the model parameters. Right panel of Figure 2 shows the brightness profile of the inner 3 pc after 10^4 years of the constant injection. In this figure different curves correspond to different model parameter sets in terms of the ambient matter distribution and injection. For all models in Figure 2, parameters were chosen so that the resulting integrated emission accurately reproduces the Fermi and HESS data, and the resulted profiles were normalized to the maximum value to aid comparison.

Geometrically, the black line represents the case of constant density and exhibits a broader profile at higher energies. If instead, one models the region with a density falling off proportional to a $n_H \propto 1/r^2$ profile, the resulting profiles are narrower and are represented by the red lines. The profile is more centrally peaked in the latter case, since the matter is more concentrated in the center and so the photon flux will originate mostly from this region.

The green lines show the profile created if, in addition to a constant source, there was also a 10 years flare which occurred 300 years ago. In order to match observational data in this case, a larger diffusion coefficient had to be assumed, which inevitability leads to a larger diffusion radius and – correspondingly – to a broader profile. Finally in Figure 2 we show the brightness profiles corresponding to a shell geometry. In this case the profile has a maximum at a radius of the inner

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shell (1 pc).

However, with the angular resolutions of the current space- and ground-based detectors, we cannot distinguish between the different radial profiles. Fortunately, such information can be recovered by observations of synchrotron emission of secondary electrons from decays of charged pions, accompanying the production of gamma-rays from decays of neutral muons. Since through this channel the electrons and gamma-rays are produced with similar energy distributions, we can connect directly the frequency of synchrotron photons of secondary electrons with the energy of the “genetically" connected gamma-rays:

$$\varepsilon \simeq 100 \left(\frac{B}{10^{-4}\ \mathrm{G}}\right)\left(\frac{E_\gamma}{1\ \mathrm{GeV}}\right)^2 \mathrm{MHz}. \tag{3.1}$$

Thus, in the first approximation, the morphology of the synchrotron radiation of "hadronic" origin should be similar to the morphology of GeV gamma-rays. While at sub-GHz frequencies, GC radio photons are attenuated by free-free absorption in dense HII regions between the GC and the Earth ([12]), the synchrotron emission at $\sim$ GHz frequencies arrives without significant attenuation. Therefore we anticipate that the new Fermi data combined with available radio measurements, could allow us to constrain significantly the parameter space of models positing that the GeV and TeV gamma-ray emission of the GC is due to hadronic interactions in the central few parsecs of GC. Analysis of the morphology of radio emission holds out particular promise here.

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