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On a Possible Origin of the Gamma-ray Excess around the Galactic Center

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Abstract: Recent observations of gamma rays with the Fermi Large Area Telescope (LAT) in the direction of the inner galaxy revealed a mysterious excess of GeV. Its intensity is significantly above predictions of the standard model of cosmic rays (CRs) generation and propagation with a peak in the spectrum around a few GeV. Popular interpretations of this excess are that it is due to either spherically distributed annihilating dark matter (DM) or an abnormal population of millisecond pulsars. We suggest an alternative explanation of the excess through the CR interactions with molecular clouds in the Galactic Center (GC) region. We assumed that the excess could be imitated by the emission of molecular clouds with depleted density of CRs with energies below $\sim$10 GeV inside. A novelty of our work is in detailed elaboration of the depletion mechanism of CRs with the mentioned energies through the "barrier" near the cloud edge formed by the self-excited MHD turbulence. This depletion of CRs inside the clouds may be a reason for the deficit of gamma rays from the Central Molecular Zone (CMZ) at energies below a few GeV. This in turn changes the ratio between various emission components at those energies and may potentially absorb the GeV excess by a simple renormalization of key components.

Keywords: dark matter; gamma-ray excess; galactic center

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1. Introduction and Motivation

The physical nature of dark matter (DM) remains one of the biggest puzzles in modern physics despite the extensive searches for DM with colliders, direct detectors and indirect observations. The latter comprises the searches of various CR particles (see, e.g., [1]) and emissions from DM annihilation or decay, particularly in gamma rays (e.g., [2] part V). Possible gamma-ray signals from DM may in turn have two different spectral types: wideband continuum and narrow lines from annihilation directly into photons. The latter would represent a very pristine signature of DM, since such spectral features are not expected from any other astrophysical processes. Searches for narrow lines in the Fermi-LAT data were not successful so far—only upper limits were derived; see, e.g., [3]. This justifies a motivation to develop new gamma-ray telescopes with better spectroscopic capabilities. One such project, GAMMA-400, is being developed in Russia now [4]. It is expected to have better sensitivity to narrow spectral lines around GC in the energy range of $\sim$(0.1–100) GeV in comparison with Fermi-LAT due to better energy resolution. This and other aspects of DM searches by GAMMA-400 are described in detail in [5].

There is less ignorance when it comes to the searches for continuum signals from DM annihilation or decay: already a while ago, a significant excess of gamma rays around GC was firmly identified (e.g., [6]). It is difficult to explain such diffuse excess by phenomenological models of emission from CRs, described, e.g., in the monographs [7,8] and implemented in sophisticated numerical codes such as GALPROP [9,10].

The excess is spherically symmetric, visible up to $\sim 10^\circ$ from GC and peaks around 2 GeV. It can be well fitted by annihilating WIMPs with the mass of several decades of

GeV, the annihilation cross-section around the thermal value, and steep density profile (e.g., [11,12]). However, alternative explanations through various astrophysical mechanisms indeed exist. Thus, the excess can be caused by the unusual population of ∼1000-millisecond pulsars in the Galactic bulge—e.g., [13]. The pulsar interpretation is probably considered to be the most plausible at present. Other astrophysical interpretations include the emission from molecular clouds, the base of Fermi bubbles, a CR burst in the past etc. Furthermore, in our opinion, the secondary emissions from millisecond pulsars, produced by inverse Compton and bremsstrahlung of $e^{\pm}$ ejected by pulsars, also deserve an attention. Thus, the DM interpretation is challenged by both its own systematics (e.g., Calore et al. [14]) and the existence of many competing opportunities.

Almost all of the mentioned opportunities were challenged at some point by a non-trivial observational fact: abnormal excessive emission was identified in other regions of the galactic plane [15]. This may indicate that the excess source is concentrated around the galactic plane rather than around GC. This in turn supports the molecular cloud (MC) origin of the excess originally proposed in [16], since the clouds indeed reside along all the plane. This creates a motivation to investigate this interesting opportunity further, which comprises the subject of our work. The next section describes in detail our model of CR interaction with MCs, which may modify the MC emission spectra through a peculiar way leading to the imitation of some excessive emission at GeV energies.

2. Modeling the CR Interaction with Molecular Clouds

The authors de Boer et al. [16] found that the GC excess is correlated with the distribution of MCs. They tested two hypothesis of the GeV-excess: the real excess hypothesis assuming the excess is caused by DM annihilation, and the seeming excess hypothesis assuming that the "GeV-excess" is related to a hypothetical depletion of gamma rays from MCs below ≈2 GeV, as it is directly observed in the Central Molecular Zone (CMZ). The authors [16] did not model in details the origin of the emission depletion below 2 GeV, however stated that it is most likely caused by a magnetic cutoff of cosmic rays in MCs. We have developed the latter idea further.

Generally speaking (see, e.g., [15,16]) the hadronic gamma-ray emission is presented by the two components: π^0 gamma-ray emission from the diffuse gas around the GC and π^0 gamma-ray emission from MCs. The investigation by [16] showed that the derived spatial distribution of the emission from MCs correlated nicely with the molecular hydrogen (traced by CO) distribution. Moreover, they found that the gamma-ray emission in the direction on the GC is fully determined by the MC component, where a huge mass of $5 \times 10^7 M_{\odot}$ of molecular hydrogen is concentrated, while other components have a minor effect there. de Boer et al. [16] speculated that this 2 GeV spectral bump is formed due to depletion of the density of CRs with certain energies inside the clouds.

Ivlev et al. [17] and Dogiel et al. [18] abandoned the phenomenological model of CR propagation and conducted more realistic non-linear simulations of gamma-ray emission from MCs, which naturally produces the "GeV excess" through the "MHD-barrier", which reflects CRs with energies $\lesssim$10 GeV and does not allow them to penetrate into the clouds. We assumed that the apparent GeV excess does not have a real source but rather can be explained through an unaccounted modification of MC spectra at certain energies and overall renormalization of the spectra of all emission components. MC spectra gets depleted below few GeV due to a self-excited MHD turbulence by CRs, when the density of CRs inside the cloud is depleted by magnetic fluctuations around the MCs. A flux of CRs propagating through the diffuse ionized gas can excite self-generated magnetic fluctuations (MHD waves). As for the required renormalization of the emission components, it is not large, taking into account that the overall intensity of the GC excess does not exceed ≈10% of the total gamma-ray intensity within 10° from GC (see, e.g., [15]). Such renormalization by ≈10% could be made relatively easily accounting for the systematic uncertainties related to the gas emissivity. Let us discuss now in detail our model of the modification of MC spectra.

The following system of nonlinear kinetic equations describes processes of CR penetration into MCs (see details of the equations in [17]) in one-dimensional approximation. The spectrum of CRs $f(z,E,t)$ and the spectrum of magnetic fluctuations W are described by

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial f}{\partial z} - v_A f\right) + \frac{\partial}{\partial p}\left(\frac{dp}{dt}f\right) \tag{1}$$

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left(\frac{W}{T_{\rm nl}}\right) - \frac{\partial}{\partial z}(v_a W) + \Gamma W - \nu W\,. \tag{2}$$

where p is the particle momentum, the spatial diffusion coefficient

$$D \simeq \frac{vB^2}{6\pi^2 k^2 W}\,, \tag{3}$$

Γ is the frequency of CR collisions with the background gas, v_A is the Alfvenic velocity, the rate of stream instability excited by CR is

$$\Gamma(k,z) \simeq \pi^2 \frac{e^2 v_A}{m_p c^2 \Omega} pvD\frac{\partial f}{\partial z}\,, \tag{4}$$

$(\partial/\partial k)(W/T_{\rm nl}(k))$ describes the nonlinear cascade of magnetic fluctuations and ν describes waves damping due to ion-neutral friction.

The flux of CRs $S(E) = v_A f - D\frac{\partial f}{\partial z}$ propagating through the envelope and entering the dense interior of the cloud is derived as (see Equations (1) and (2))

$$S(E) = \frac{v_A f_{IS}(E)}{1 - \delta e^{-\eta_0(E)}} \tag{5}$$

where

$$\eta_0(E) = v_A \int\limits_0^H \frac{dz}{D(E,z)}\,, \tag{6}$$

H is the size of the envelope, and f_{IS} is the CR spectrum in the the interstellar medium. Coordinate $z = 0$ corresponds to the boundary between ISM and the envelope, while $z = H$ corresponds to the conditional boundary between the envelope and the dense interior. The parameter $\delta < 1$ in Equation (5) describes opacity of the cloud and depends on its column density N_H (see [18] for details).

The expression for η_0 can be estimated from a balance of the growth rate between MHD wave excitation and damping rates due to ion-neutral collisions, $\Gamma = \nu$, which leads to the following equation for η_0:

$$1 - \delta e^{-\eta_0(E)} \propto \delta v p f_{IS}(E)\,. \tag{7}$$

Since $\delta < 1$ and $f_{IS}(E)$ decreases with energy quite steeply, there is a certain value of $E = E_{ex}$, where $\eta_0(E_{ex}) = 0$. Furthermore, at higher energies the balance can no longer be maintained. This threshold energy, E_{ex}, is a boundary between range of free penetration into the cloud core and the range of self modulated CRs. At sufficiently high energies, $E > E_{ex}$, the CR flux is not affected by MHD-turbulence and converges to the regime of the free-streaming (since $\eta_0 = 0$ and $D \to \infty$).

Within the range of wave excitation by CRs, $E < E_{ex}$, the spectrum of MHD fluctuations is provided by excitation-damping balance described by Equation (7). As a result, below $\sim E_{ex}$, a universal spectrum of CRs $f_p(E) \propto E^{-1}$ is formed inside the dense regions of MCs. This spectrum is independent of external parameters outside the cloud. Above $\sim E_{ex}$, the spectrum in the core is the same as in the intercloud medium:

$$f_p(E) \propto \begin{cases} E^{-1}, & \text{if } E \lesssim E_{ex}\,, \\ E^{-\gamma_p}, & \text{if } E \gtrsim E_{ex}\,, \end{cases} \tag{8}$$

where γ_p is the spectral index of the CRs spectrum in the intercloud medium of the CMZ.

Self-excited MHD turbulence may also impact the gamma-ray emission produced by relativistic electrons, since relativistic protons and electrons interact with turbulence in the same way. This is also very relevant for GeV excess interpretations, since the bremsstrahlung and inverse Compton emission from relativistic electrons may comprise a significant part of the total emission intensity in the GC region (see, e.g., [15,19]). Hence any minor modifications of those emission components may have a big impact on the GC excess amplitude and spectrum.

Even if the intensity of bremsstrahlung from electrons is lower as compared to the emission from proton–proton collisions, the energy break in the spectrum of bremsstrahlung emission is expected to be located at higher energies. Therefore visible effect of CRs self-modulation on bremsstrahlung emission should appear at much lower column densities.

To illustrate the potential influence of self-generated MHD turbulence on the observed spectra of gamma-ray emission we showed in Figure 1 spectra of proton–proton emission $\left(\frac{dN}{dE}\right)_{pp}$ and electron bremsstrahlung emission $\left(\frac{dN}{dE}\right)_{br}$ from the particles inside the cloud. For comparison, we displayed the experimental data points of the GeV excess taken from Ackermann et al. [15].

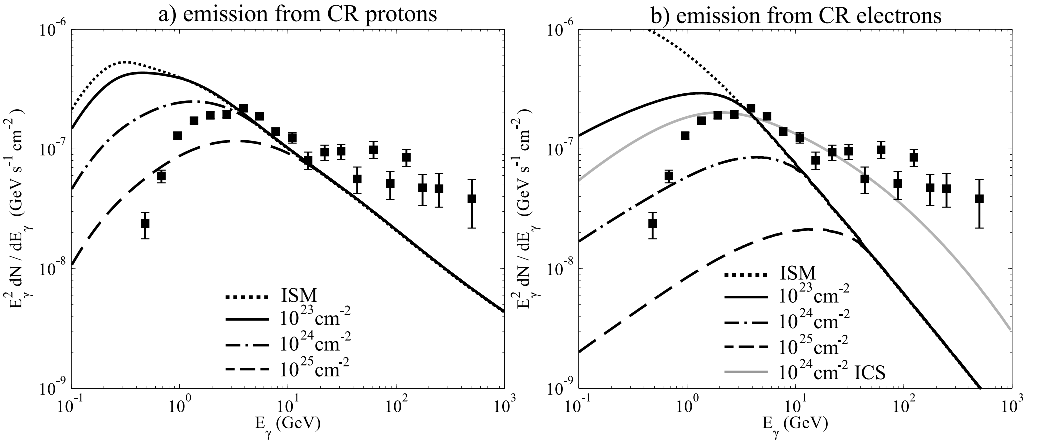

Figure 1. Gamma-ray emission from particles inside the clouds for different values of the cloud column density. (**a**) Emission from relativistic protons. (**b**) Bremsstrahlung emission from relativistic electrons. ICS emission due to scattering of optical photons is also displayed for comparison. The data points represent the GC excess spectrum according to Ackermann et al. [15].

We used the following expressions to calculate the gamma-ray emission spectra:

$$\left(\frac{dN}{dE_\gamma}\right)_i = \frac{M_i c}{4\pi R_{GC}^2 m_p} \int dE\, f_j(E) \left(\frac{d\sigma(E, E_\gamma)}{dE_\gamma}\right)_i, \tag{9}$$

where i stands for either pp or br and j is either p in the case of proton–proton interactions or e in the case of electron bremsstrahlung. M is the total mass of of clouds emitting gamma rays, $R_{GC} = 8$ kpc is the distance to the galactic center, and m_p is the mass of the proton. The differential cross section of the photon production in proton–proton interactions is taken from Kafexhiu et al. [20], and the bremsstrahlung cross section is from Blumenthal and Gould [21].

Equation (9) assumes that the CR spectrum does not change significantly throughout the cloud. This assumption is based on the fact that clouds absorb only a small portion of the penetrating relativistic protons and electrons and that their density is therefore almost constant in the dense regions of the clouds. CR spectra experience significant spatial variations in the diffuse envelope, where the modulation process takes place. However, the mass of that envelope is negligible as compared to the total mass of the cloud, and gamma-ray emission from this envelope can be ignored.

We did not implement any spatial modeling of the gamma rays in the current work. The main reason was that, to produce a correct spatial distribution of the gamma-ray emission, we need to know how clouds with different masses and different column densities are distributed in the galaxy. Indeed, for each cloud, there should be a specific value of E_{ex}, and therefore, to get a correct spectral shape, we need to integrate over the distribution of all values of E_{ex}. We intend to do this in the future; however, here we only want to show possible effects of the CR modulation on the gamma-ray spectrum.

We assumed that the CR density in the GC is the same as local CR density [22] and took the analytical forms of CR spectra from Ivlev et al. [23]. We considered four representative values of the cloud column density: 0 (marked in Figure 1 as ISM), 10^{23}, 10^{24}, and 10^{25} cm^{-2}, which, according to Dogiel et al. [18], correspond to the following values of E_{ex}: 0, 3.4, 12, and 43 GeV. These column densities can be observed in the following clouds. $N_{H_2} = 10^{23}$ cm^{-2} corresponds to the average column density of CMZ [24] or to the envelope of Sgr B2 [25]. $N_{H_2} = 10^{24}$ cm^{-2} and $N_{H_2} = 10^{25}$ cm^{-2} correspond to the moderate-density region and core of Sgr B2, accordingly [25]. One should notice, however, that Sgr B2 is one of the most massive molecular clouds in the galaxy; therefore, column density as high as 10^{24}–10^{25} cm^{-2} should be considered as a rare occurrence.

The parameters of the ISM were taken as follows: magnetic field strength is $B = 10$ µG, and the diffuse gas density is $n = 10$ cm^{-3} [24,26]. We note that exact value of the magnetic field strength is uncertain, especially in the central regions of the galaxy; however, its value does not affect the value of E_{ex} significantly. Similarly to Ivlev et al. [17], we assumed that the most abundant ion in the envelope is C^+, with density of 3×10^{-3} cm^{-3}. The corresponding value of the Alfven velocity in the envelope is $v_A = 10^7$ cm/s.

To reproduce the curves shown in Figure 1 we need the following values of the total mass. For proton–proton collisions it is equal to $M_{pp} = 2 \times 10^8 M_\odot$ and for the electron bremsstrahlung it equals $M_{br} = 2 \times 10^9 M_\odot$. These values exceed the total mass of CMZ and even the mass of the galactic circumnuclear disk (CND) [24]. The reason for this discrepancy may be due to the influence of the local clouds along the line of sight. Indeed, we assumed that all molecular clouds are located at the distance of $R = 8$ kpc and ignored the contribution of clouds that are located in the vicinity. In the case of electrons, we can also argue that their density in the galactic center is much higher than their local density [19].

We also plotted the ICS emission from the modulated spectrum of electrons due to the scattering of soft photons with energy of 1 eV. To calculate this, we used Equation (9), where we replaced factor $\frac{M}{m_p}$ with εV. Here, ε is the average energy density of soft photons in the galaxy and V is the total volume involved in the emission. The differential cross section of the ICS emission is taken from Blumenthal and Gould [21].

If we assume that $\varepsilon = 10$ eV·cm^{-3} [27], we need the volume to be equal to $V = 7 \times 10^{65}$ cm^3 to match the data points and assuming that the region is spherical with a radius of about $r = 2$ kpc. This is larger than the size of the the CMZ and CND; however, we can argue that soft photon density is much higher in the central regions of the galaxy.

As one can see from Figure 1, modulation of CR flux due to self-generated turbulence indeed produces the deficit of gamma-ray photons at the required energies below several GeV. Thus, our model is able to justify the explanation of GC excess (see [16]).

One can assume that the analysis performed by, e.g., Ackermann et al. [15] used standard assumptions (incorporated by GALPROP) to calculate the emissivity of MCs and did not take into account self-modulation of the CRs. Therefore, they overestimated the intensity of all the key emission components coming from MCs: hadronic due to proton–proton interactions, and bremsstrahlung and ICS from electrons at energies below several GeV.

Although the intercloud diffuse gas emissivity in our model is not modified, the modification of the part of total emission coming from MCs is potentially able to change the ratio of all components significantly. The deficit of gamma-ray intensity from MCs below several GeV would require in turn an increase in the GC excess intensity at those energies in order to preserve the whole balance. The GC excess brightening at low energies in turn would make its spectrum more monotonous, i.e., less bumpy. Furthermore, this kind of power-law spectrum is then relatively easy to “absorb” into the overall diffuse gas or point sources (both resolved and unresolved) spectra, which have the similar shape close to a power law, by their slight renormalization towards higher levels. Such procedure would remove the GC excess as a separate emission component merging the former with the known components.

Finally, we would like to notice that our model curves in Figure 1 are not intended to fit the GC excess directly. They only illustrate that reasonable parameter values for MCs and ISM are able to produce the spectral break in intensity of MCs at an energy near the GC excess peak, allowing the excess below this energy to “brighten” up to the state (ideally) where the whole excess spectrum is close to a monotonous power law.

3. Conclusions and Discussion

We elaborated the mechanism of the modification of emission spectra of MCs, which, according to [16], can fit the mysterious GeV excess around GC. Our mechanism represents a viable alternative to other possible excess explanations such as annihilating DM, millisecond pulsars, etc. In order to investigate the nature of the GC excess further and finally establish its exact source, the astrophysical community needs in new high-quality gamma-ray data. Thus, we crucially need to increase angular and energy resolutions of our instruments around the energies $E_\gamma \sim$1 GeV with respect to capabilities of Fermi-LAT. This will allow us to conduct the resolved imaging of the CMZ region [18] and better discriminate the spectra of various emission components there. At the same time, we still cannot exclude the DM origin of the excess. Hence, further investigations may eventually lead to DM discovery. This is why we have great expectations from the currently planned new gamma-ray telescopes: *GAMMA-400* [5], *e-ASTROGAM* [28], *AMEGO* [29], and others.

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