Gamma-rays from possible disk component of dark matter

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Abstract. We consider a dark matter model with “active” component (annihilating or decaying), that forms a disk in the Galaxy. In this work we calculate gamma-ray flux from the galactic center for given model and compare it to the observations. It was found that predicted flux with model parameters obtained in our last analysis which did not take the data on gamma-ray flux from the center into account, agrees (does not exceed) observational one. Gamma-ray fluxes for the whole sky have been obtained and compared with existing data. Unfortunately existing data include contributions from all possible gamma-ray sources in a wide energy range, what requires respective special analysis. We adopted existing data in a simple way to compare with them and obtained qualitative agreement.

1. Introduction
It is suggested now a big variety of forms of dark matter (DM), many of which go beyond habitual concept of collisionless massive particles. These are self-interacting DM (e.g., \cite{1,4} and references therein), primordial black holes (e.g., \cite{5,9}), dark disk models \cite{10,13}, DM in the form of scalar field clumps (e.g. \cite{14}) and deformed extra dimensions \cite{15}, composite multicomponent DM \cite{16,19} and others. Many attempts to build DM model are trying with its help to explain other astrophysical problems. The observed anomaly in cosmic ray (CR) positrons is one of their subject, which we focus on.

The main difficulty in explaining the positron anomaly \cite{20} involving DM is a constraint coming from the isotropic diffuse gamma-ray background (IGRB) \cite{11,13,21,26}. We are developing a model that bypasses this restriction by assuming the presence of a dark matter disk in the Galaxy \cite{11,13}. In spite on postulating of disk existence, it may naturally account for annihilation enhancement due to Sommerfeld-Gamow-Sakharov effect \cite{27,29} or classical approach applicability \cite{30,31}.

In our previous work \cite{11}, all the parameters of the model were obtained by fitting the data on cosmic positrons \cite{32} and IGRB. In this paper, we show that the expected flux of gamma rays from the galactic center (GC) is compatible with the observation \cite{33}. We also compare the estimated gamma-ray fluxes for the whole sky to the measured ones \cite{21,22,34}.

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2. Gamma radiation from the disk of dark matter

In our model \cite{11,13} we assume that the dark matter is composed of a dominant “passive” component that forms the halo, and an “active” component, which gives a signal in CR and forms a disk. In this model, the active component of DM can decay or annihilate to one of three channels: $e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$. This is fairly conservative assumption as to final state radiation (FSR) production. One can assume more exotic model where double positron mode exists leading to two times suppression of FSR photon to positron yield ratio \cite{35,36}.

The parameters of considered here model are the mass of DM particles $M_X$, disk half-height $h$, annihilation (decay) branching ratios $Br_i \ (i = e, \mu, \tau; \sum Br_i = 1)$ and the rate of annihilation (decay) $j(\vec{s})$, defined as follows:

$$j(\vec{s}) = \begin{cases} \frac{\langle \sigma v \rangle}{4M_X^2} \rho^2(\vec{s}) & \text{(annihilation)}, \\ \frac{1}{\tau M_X} \rho(\vec{s}) & \text{(decay)}, \end{cases}$$

where $\langle \sigma v \rangle$ is the averaged over velocity annihilation cross section (for Dirac particles), $\tau$ is the lifetime of a particle in case of decay, $\rho(\vec{s})$ is the DM density at a given point $\vec{s}$ in the Galaxy.

The choice of model parameters at which the positron anomaly is described and there is no contradiction with data on IGRB and on gamma-ray flux from the GC, is performed by minimizing the following expression for the $\chi^2$:

$$\chi^2 = \sum_{i=1}^{k} \left( \frac{F(E_i, p) - F_{i, \text{exp}}}{\sigma_i} \right)^2 + \sum_{j=1}^{m} \theta \left( \Phi(E_j, p) - \Phi_{j, \text{exp}} \right) \left( \frac{\Phi(E_j, p) - \Phi_{j, \text{exp}}}{\sigma_j} \right)^2 + \theta \left( \Psi(E, p) - \Psi_{\text{exp}} \right) \left( \frac{\Psi(E, p) - \Psi_{\text{exp}}}{\sigma} \right)^2 \right. \right. \right.$$  

Here $i$ and $j$ denote indices of experimental points in AMS-02 and Fermi-LAT data respectively, $k$ and $m$ are the numbers of data points included in the analysis, $p$ denotes the set of model parameters listed above, $F(E_i, p)$, $\Phi(E_j, p)$ and $\Psi(E, p)$ are respectively the cosmic positron fraction, IGRB and the gamma-ray flux from the GC, predicted by the model, $F_{i, \text{exp}}$, $\Phi_{j, \text{exp}}$ and $\Psi_{\text{exp}}$ are the corresponding experimental values with $\sigma_{(i,j)}$ being the errors, and $\theta$ is the Heaviside step-function. Note that simultaneous accounting for all terms in equation (2) in the procedure of minimizing $\chi^2$ provides more flexible test criterion \cite{37}.

The gamma-ray flux is calculated as follows:

$$\Phi(E) = \frac{1}{4\pi \Delta \Omega} \int \frac{S(b, l)}{\Delta \Omega} \int d\cos(b) \int dl j(s, b, l) \sum_i Br_i f_i^j(E),$$

where $l$ and $b$ are the galactic longitude and latitude, $f_i^j(E)$ is the differential energy spectrum of prompt photons, produced in the $i$-th channel, $S(b, l)$ is the distance to the disk “border”, $\Delta \Omega$ is the solid angle.

In this paper we consider the case of annihilation; the case of decay does not differ fundamentally.

For dark disk the following density profile is used \cite{38}:

$$\rho(R, z) = \rho_0 e^{-R/R_c} e^{-z/z_c},$$

where $R$ and $z$ are the cylindrical galactic coordinates, $R_c = 7$ kpc, $z_c = 0.4$ kpc, and $\rho_0$ is the constant obtained from the condition $\rho_{loc} \equiv \rho(r_\odot = 8.5 \text{ kpc}) = 0.39$ GeV/cm$^3$. 

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Figure 1. The predicted gamma-ray flux at energy 100 GeV (left) and the ratio model/experiment (right) for the whole sky. $l$, $b$ denotes galactic longitude and latitude, respectively. Left panel shows $\log_{10}(f)$ with the flux $f$ given in MeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

In figure 1 the obtained gamma-ray map is shown. Left and right panels correspond to the pure theoretical flux and its ratio to the experimental one [21][22][34]. Experimental data represent full gamma-ray fluxes integrated in energy $E > 3$ GeV.

Since expected gamma-ray flux from the GC virtually coincides with experimental flux at $E \sim 100$ GeV, we rescale the whole map as the ratio:

$$\frac{\int_{3 \text{ GeV}}^{\infty} \Psi_{\text{exp}}(E)\,dE}{\int_{3 \text{ GeV}}^{\infty} \Psi(E)\,dE}. \quad (5)$$

In other words, with such rescaling, we get the ratio model/experiment (right panel in figure 1) equals one at the GC. Now if this value is greater (less) than one means that the theoretical flux (does not) exceed(s) the measured one at high energy (where model/experiment ratio is the highest). It is true under a rough assumption that the energy spectra shape does not change in angle coordinates. Note that black spots in the right panel of figure 1 correspond to point-like gamma-ray sources.

As one can see from figure 1, the ratio model/experiment is around one by varying from GC to poles within just one order of magnitude, while the model and experimental fluxes solely change within 5–7 orders of magnitude. From one side, such comparison result favours the model, but from other side, it means that more refined analysis is required to verify the model.

3. Conclusion

In this work we continue the development of the dark matter model with a disk component in the Galaxy, which can explain the positron anomaly without contradiction to data on gamma radiation. Earlier we compared prediction with IGRB, which represents the flux averaged over high latitudes with exclusion of known sources contribution. Here we take into account data on gamma-ray flux from the GC and all other galactic coordinates but including all contributions and integrated over wide energy range (except GC). Our adopting the presented data in a simple way allowed to compare model predictions and experimental data. On the basis of such comparison one may conclude that the model does not explicitly contradict to data and that more refined analysis is required to verify the model.
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