ISSN 1063-7788, Physics of Atomic Nuclei, 2018, Vol. 81, No. 3, pp. 373–378. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © A.E. Egorov, A.M. Galper, N.P. Topchiev, A.A. Leonov, S.I. Suchkov, M.D. Kheymits, Yu.T. Yurkin, 2018, published in Yadernaya Fizika, 2018, Vol. 81, No. 3, pp. 360–365.

ELEMENTARY PARTICLES AND FIELDS
Experiment

Detactability of Dark Matter Subhalos by Means of the GAMMA-400 Telescope

A. E. Egorov[1)*], A. M. Galper[1),2)], N. P. Topchiev[1)], A. A. Leonov[1),2)], S. I. Suchkov[1)], M. D. Kheymits[2)], and Yu. T. Yurkin[2)]

Received November 14, 2017

Abstract—The potential of the planned GAMMA-400 gamma-ray telescope for detecting subhalos of mass between 10^6 $M_\odot$ and 10^9 $M_\odot$ in the Milky Way Galaxy that consist of annihilating dark matter in the form of weakly interacting massive particles (WIMPs) is studied. The inner structure of dark matter subhalos and their distribution in the Milky Way Galaxy are obtained on the basis of respective theoretical models. Our present analysis shows that the expected gamma-ray flux from subhalos depends strongly on the WIMP mass and on the subhalo concentration, but that it depends less strongly on the subhalo mass. Optimistically, a flux of 10 to 100 ph per year in the energy range above 100 MeV can be expected from the closest and most massive subhalos, which can therefore be thought to be detectable sources for GAMMA-400. Because of the smallness of fluxes, however, only via a joint analysis of future GAMMA-400 data and data from other telescopes would it become possible to resolve the inner structure of the subhalos. Also, the recent subhalo candidates 3FGL J2212.5+0703 and J1924.8−1034 are considered within our model. Our conclusion is that these sources hardly belong to the subhalo population.

DOI: 10.1134/S1063778818030110

1. INTRODUCTION AND MOTIVATION

Although dark matter (DM) in the Universe was discovered more than 80 years ago, its physical nature remains one of the most fundamental unresolved problems in modern astrophysics. There are many DM candidates but weakly interacting massive particles (WIMPs) in the form of neutralinos still remain the most probable and natural candidate (see, for example, [1]). As well known, these supersymmetric particles may undergo self-annihilation, producing highly energetic Standard Model particles, such as photons, electrons, and protons [1]. This process proceeds vigorously in regions where the DM concentration is high and could manifest itself via the emission of annihilation products. This is quite a promising approach to discovering WIMP and its physical parameters or, at least, to setting limits on these parameters. Such indirect DM searches are being vigorously performed in all astrophysical objects that could in principle contain DM: from the Sun to galaxy clusters. Such objects of interest include DM subhalos in the dark halo of the Milky Way Galaxy. An N-body simulation of DM halos reliably predicts the presence of a hierarchical substructure within them in the form of subhalos having masses in a very broad range extending down to about 10^{-6} $M_\odot$ [1]. Specifically, modern N-body models (see, for example, [2]) are able to resolve several tens of thousand subhalos within a Milky Way—sized halo. The most massive subhalos are expected to be dwarf satellites of the Milky Way (MW). A simulation also shows [3] that less massive subhalos of mass below 10^7 or 10^8 $M_\odot$ do not contain a luminous gas or a stellar component. However, such halos could be rather close and be bright gamma sources because of DM annihilation. At the same time, one-third of gamma sources in the 3FGL Fermi-LAT catalog have not been associated with any sources in different ranges of the spectrum [4]. These unidentified sources could in fact be DM subhalos. In summary, one can expect the following valuable subhalo properties making it possible to identify unambiguously subhalo radiation as photons from annihilating dark matter: (i) Subhalos emit virtually no radiation other than that from DM annihilation. (ii) This emission is absolutely stable, featuring no variability in time. (iii) All subhalos have the same predictable spectrum. (iv) They have a nearly isotropic distribution on the sky. (v) In contrast to typical astrophysical objects, such as blazars, they can be resolved as extended sources.

Thus, DM subhalos is an object of great interest for DM searches. A profound investigation of sub-

[1)]Lebedev Physical Institute, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 119991 Russia.
[2)]National Research Nuclear University MEPhI, Kashirskoe sh. 31, Moscow, 115409 Russia.
[*]E-mail: eae14@yandex.ru

halo detectability by means of gamma-ray telescopes, such as Fermi-LAT, has been performed earlier (for example, [3]). However, the conclusion at which the authors of that investigation arrived is not optimistic: Fermi-LAT is able to detect about one subhalo over the whole sky and to resolve spatially less than one subhalo as an extended object. At the same time, several research groups have already studied catalogs of pointlike gamma-radiation sources for the presence of subhalo candidates in them (see, for example, [5]). This resulted in revealing two interesting candidates, J2212.5+0703 and J1924.8−1034, in the 3FGL Fermi-LAT catalog [5–7]. Their exact nature is still the subject of lively discussions. Section 4 of our present article is devoted to this issue.

Also, the problem of assessing the potential of future gamma-ray telescopes for the detection of DM subhalos is urgent at the present time (see, for example, [8]). The main objective of our present study is to explore the detectability of subhalos with GAMMA-400, which is a new gamma-ray telescope currently being designed and which is planned to be launched around 2025 [9, 10]. This telescope will possess unique energy and angular resolutions. They are expected to be at a level of 1% and 0.01°, respectively, at an energy of about 100 GeV. These features are substantially better than those characteristic of Fermi-LAT. Thus, GAMMA-400 would possibly possess a high potential for detecting subhalos and for resolving their inner structure. In turn, this would pave the way toward obtaining deeper insight into DM nature. Also, we may expect interesting results from a joint analysis of GAMMA-400 data and data from other telescopes, including Fermi-LAT and proposed e-ASTROGAM [11]. In the present analysis, it is assumed that DM is constituted by neutralinos exclusively.

2. SIMULATION OF THE SUBHALO POPULATION

Here, we make use of the elaborate model of the subhalo population in the MW Galaxy from [3]. The authors of [3] performed an N-body simulation of MW halos of two types—that which contains only cold DM (CDM) and that which contains CDM together a baryon component. They did not reveal any significant difference between the results in these two cases. The mass range of subhalos that are resolvable in this simulation is $\sim(10^6-10^{11})\ M_\odot$. Here, we focus on the subhalo-mass range of $(10^6-10^9)\ M_\odot$, since, according to [3], all heavier subhalos contain stars; therefore, they are formally dwarf satellites. Of course, the boundary between subhalos and dwarfs involves a substantial degree of arbitrariness since these are objects of the same nature. Here, however, we do not dwell on signals from dwarfs—that is, the most massive subhalos—postponing their analysis to our future studies. As for subhalos of mass in the range of $10^6-10^9\ M_\odot$, the analysis reported in [3] predicts about 4000 such objects in MW under the assumption of a typical mass distribution, $dN/dM \sim M^{-1.9}$.

Relying on the results obtained in [3], we will now describe briefly basic properties of subhalos and the DM distribution in them. The DM density distribution within a subhalo is approximated by the Einasto profile

$$\rho(r) = \rho_s \exp\left(-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right), \quad (1)$$

where r is the distance from the subhalo center; r_s and ρ_s are the characteristic scales of the subhalo radius and density, respectively; and $\alpha = 0.16$. Figures 2 and 10 in [3] illustrate the resulting dependence of the radius r_s on the subhalo mass. One can see that these radii exhibit a rather broad spread of values for each mass. It is important to study this uncertainty in detail since, as will be seen below, gamma-ray fluxes from subhalos depend strongly on r_s. In this context, we decided to compare the results of the simulation with real data on the mass distribution within dwarf MW satellites. For this purpose, we used the results obtained in [12, 13], where the authors reproduced the mass (that is, DM, since one can disregard the stellar and gas masses) distributions in known dwarfs on the basis of observations of their kinematics. This comparison revealed that, by and large, the results reported in [3] reproduce dwarfs to a reasonable degree of precision. However, we noticed the following systematic trend: on average, the dwarfs have r_s values smaller than those predicted by the simulation—upon plotting the dwarfs in Fig. 2 from [3], one can see that they lie near the lower boundary of the cloud of points from the simulation. In this situation, we took the M_{SH} dependence of r_s in the form exhibited by real dwarfs as a realistic mean expectation—it corresponds to minimum values of r_s from the simulation in [3]. This dependence was approximated in the form

$$\log(r_s/\mathrm{kpc}) = 0.441 \log(M_{200}/M_\odot) - 4.10, \quad (2)$$

where M_{200} is the virial subhalo mass—that is, the mass within the sphere with average density $200\rho_{\mathrm{crit}}$. As a matter of fact, r_s specifies the subhalo-concentration parameter $c_{200} \approx r_{200}/r_s$, which affects strongly the gamma-ray flux from DM of the whole subhalo. The higher the concentration, the higher the flux, which depends quadratically on the DM density. Therefore, it is important to study the dependence of the gamma-ray flux on the uncertainty in the concentration model. For this purpose, we have considered, in addition to mean model specified by Eq. (2), the extreme cases of the maximum and minimum possible fluxes: these are the maximum possible r_s in the form of the middle (blue) line in Fig. 2 [3], which are approximately twice as great as mean r_s (2), and the minimum possible ones, which are one-half as large as mean r_s. The maximum values of r_s are approximated by the equation

$$\log(r_s/\mathrm{kpc}) = -0.111 \log^2(M_{200}/M_\odot) + 2.11 \log(M_{200}/M_\odot) - 10.0. \quad (3)$$

This choice of range for the possible values of r_s is not accidental: it approximately corresponds to the range of measurement uncertainties in r_s for real dwarfs according to [12].

In order to calculate the gamma-ray flux, it is also necessary to specify the distance to subhalos. This is done with the aid of Fig. 10 in [3]. Naturally, we have considered subhalos closest to the observer—they are so close that their number over the whole sky is about unity in each mass interval of width about one order of magnitude. We deduced the following approximation of the distance as a function of the mass of such subhalos:

$$\log(d_{\min}/\mathrm{kpc}) = 0.0505 \log^2(M_{200}/M_\odot) - 0.556 \log(M_{200}/M_\odot) + 2.76. \quad (4)$$

This monotonic dependence yields $d_{\min}(10^6\ M_\odot) = 17$ kpc and $d_{\min}(10^9\ M_\odot) = 70$ kpc.

3. RESULTS—FLUXES AND ANGULAR SIZE OF SUBHALOS

The gamma-ray flux in the energy range $[E_{\min}...E_{\max}]$ within the solid angle $\Delta\Omega$ can be calculated by the well-known formula

$$F_\gamma(\Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\int\limits_{E_{\min}}^{E_{\max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma \times \int\limits_{\Delta\Omega}\int_{\mathrm{l.o.s.}}\rho^2(\mathbf{r})dl d\Omega', \quad (5)$$

where m_χ is the neutralino mass, $\langle\sigma v\rangle$ is the annihilation cross section, and dN_γ/dE_γ is the spectrum of photons produced in one annihilation event (according to calculations based on the studies reported in [14–16]). The double integral on the right of the multiplication sign in expression (5) is the so-called J factor. The spectrum of the gamma rays being considered depends substantially on the annihilation channel (that is, on primary annihilation products), which is a priori unknown. In view of this, we follow common practice, examining two representative channels: $\chi\chi \to b\bar{b}$ and $\chi\chi \to \tau^+\tau^-$. It is noteworthy that, in the most general case, the DM density $\rho(r)$ in expression (5) should include the contribution of the substructure within a subhalo in addition to the smooth component in (1). However, the substructure effect can increase the total signal from subhalos by not more than 10% (see Fig. 7 in [17]), which is beyond the accuracy of our estimations. Therefore, we disregard this effect.

Table 1. Annihilation cross sections chosen according to [18] for calculating gamma-ray fluxes from subhalos

m_χ, GeV	$\langle\sigma v\rangle(b\bar{b})$, cm^3/s	$\langle\sigma v\rangle(\tau^+\tau^-)$, cm^3/s
10	5×10^{-27}	4×10^{-27}
100	3×10^{-26}	3×10^{-26}
1000	2×10^{-25}	8×10^{-25}

By substituting the dependences in (1)–(4) into expression (5), we have calculated the expected fluxes of gamma rays for representative neutralino masses and neutralino-annihilation channels. The results are given in Fig. 1 ($E_\gamma > 100$ MeV). The annihilation cross section for each mass value was taken to be maximum possible with allowance for the current constraints obtained by the Fermi-LAT Collaboration on the basis of observations of 15 dwarf MW satellites [18] (see Table 1). We have also calculated the fluxes for the various subhalo-concentration models described in Section 2. Figure 1 shows that the flux depends rather weakly on the subhalo mass, decreasing as the mass decreases. Thus, the highest mass subhalos are the brightest, even though they are the most remote. The probability for detecting subhalos of mass below $10^6\ M_\odot$ (which are not resolvable individually within the model considered in [3]) is low. As might have been expected, the dependence on the concentration is substantially stronger—upon going over from one concentration model to another, fluxes change by about one order of magnitude. The mass of the DM particle also plays a significant role: as the mass increases, fluxes decrease very fast despite the growth of the annihilation cross section (see Table 1). It is also noteworthy that the tau-leptonic annihilation channel provides substantially lower fluxes in relation to the hadronic channel. For specific combinations of model parameters, the flux may reach 10 to 100 photons per year (we assume a normal incidence of photons to the detector), in which case this class of objects is potentially detectable with the GAMMA-400 telescope. The expected effective area of the detector was taken to be $A = 4000$ cm^2.

Figure 2*a* shows the spectrum of gamma rays from a massive subhalo for various masses of the DM particle and various annihilation channels. It

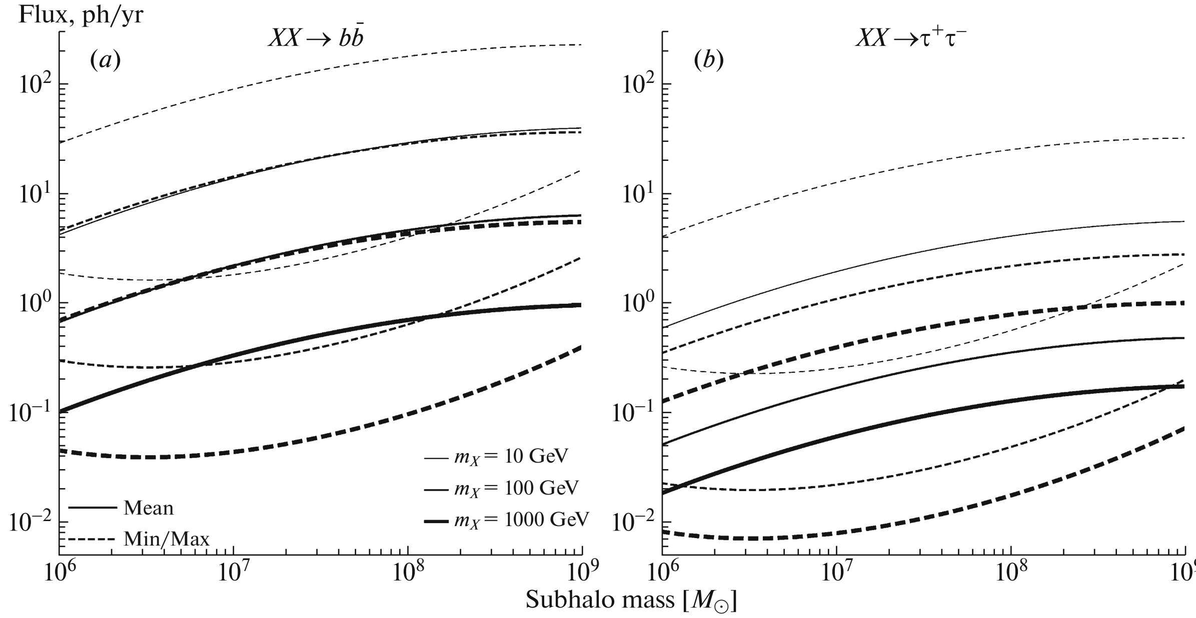

Fig. 1. Flux of gamma rays with energy above 100 MeV from the closest subhalos as a function of their mass for two representative annihilation channels. The lines of different thickness correspond to different values of the neutralino mass: 10, 100, and 1000 GeV. The solid lines represent the results obtained on the basis of the mean realistic subhalo-concentration model, while the dashed lines stand for their counterparts in the extreme cases of the minimum and maximum possible concentrations. For each mass, the annihilation cross section was set to the maximum possible value compatible with the Fermi-LAT limits from the observations of dwarfs [18] (see Table 1). The effective detector area is 4000 cm^2 (for more details, see Sections 2 and 3).

is noteworthy that the $b\bar{b}$ channel dominates over the $\tau^+\tau^-$ channel at low energies and vice versa at high energies ($E_\gamma \gtrsim 0.1 m_\chi$). That example of the distribution of the subhalo surface brightness in the range between 10 and 100 GeV which is optimal for detection is given in Fig. 2*b* along with the respective point spread function (PSF) for our instrument. We see that the subhalo brightness curve goes well above PSF within some angular-distance range before undergoing fusion with the isotropic sky background (we consider the case that is optimistic for detection and in which the subhalo being considered lies at high galactic latitudes). Thus, the convolution of the subhalo brightness distribution with PSF would be substantially different from that for a pointlike source, making it possible in principle to resolve the inner structure of the subhalo being considered and to discriminate it reliably from objects of a different class. However, the flux of photons from the whole subhalo in the above energy range is as low as about one photon per year, and this will prevent the accumulation of a sufficiently vast data sample for photons. A change in the energy range would not be helpful either, since the GAMMA-400 angular resolution decreases sharply at lower energies [10]. This problem could possibly be solved by combining future data from GAMMA-400 with data from other telescopes, such as Fermi-LAT and e-ASTROGAM, and by performing a joint analysis of these data. This would permit synthesizing the spatial image of a subhalo.

4. J2212.5+0703 AND J1924.8−1034 CANDIDATES FOR DM SUBHALOS FROM THE 3FGL CATALOG

As was mentioned in Section 1, the authors of [5–7] asserted that, in the 3FGL catalog of sources, there are two subhalo candidates—J2212.5+0703 and J1924.8−1034. They are likely to be extended objects of angular radius about 0.1°. Their spectrum is well described in terms of DM annihilation through the channel $\chi\chi \to b\bar{b}$ at a neutralino mass in the range of $m_\chi \approx 20$–40 GeV. The authors of [6, 7] assumed a thermal annihilation cross section of $\langle\sigma v\rangle \approx 3 \times 10^{-26}$ cm^3/s in their fits to the spectrum of signals from the candidates. We would like to indicate that this cross-section value is overly large for the above masses of the DM particle—Fermi-LAT limits [18] allow cross sections that are severalfold smaller. We rescaled the required J-factor values reproducing the measured fluxes from these objects by employing realistic values for the annihilation cross section and found that $J \geqslant 5 \times 10^{20}$ GeV^2 cm^{-5}. All known dwarf satellites have $J \lesssim 10^{20}$ GeV^2 cm^{-5} [20]. Thus, we see that the subhalo candidates require

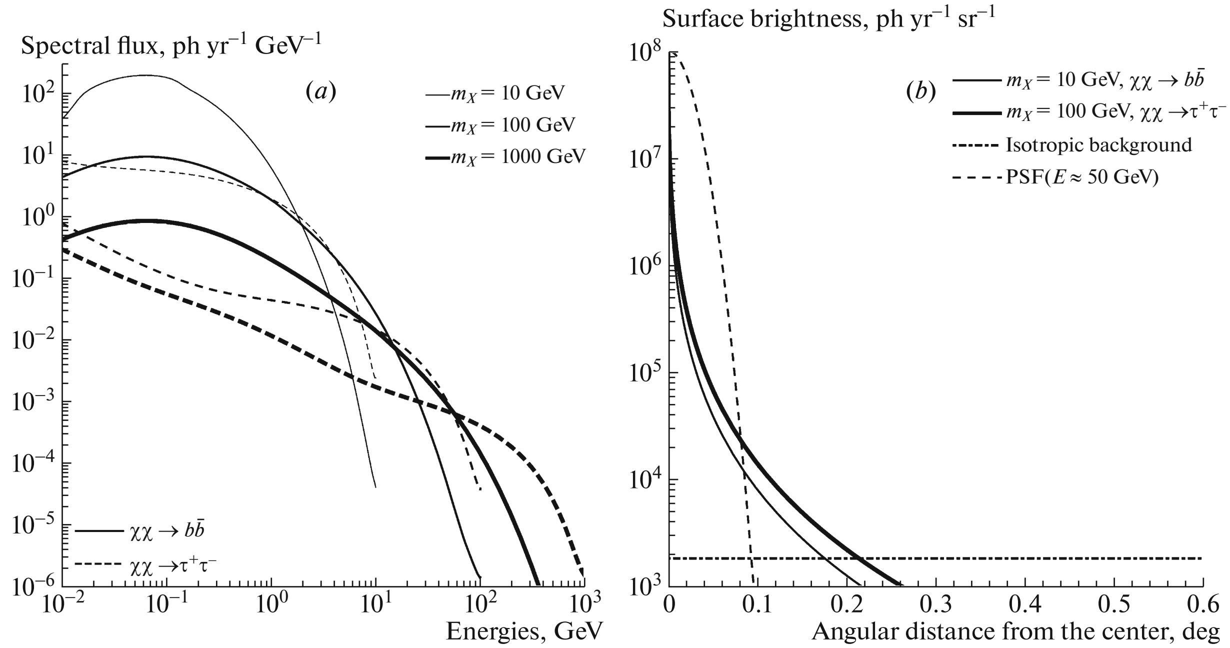

Fig. 2. (*a*) Spectra of a nearby subhalo with mass $10^9\ M_\odot$ for various neutralino masses and various annihilation channels. The annihilation cross section was chosen in just the same way as for Fig. 1, and the mean realistic model was assumed for the DM subhalo concentration. (*b*) Example of the surface-brightness distribution for the case of a nearby subhalo with mass $10^9\ M_\odot$ in the energy range from 10 to 100 GeV. The model of the high subhalo concentration was chosen. This model provides a flux of approximately one photon per year in the above energy range. The dashed line stands for an approximate telescope point spread function. The horizontal line represents the brightness of the isotropic sky background according to Fermi-LAT data from [19]. The right boundary of the graph (at about 0.6°) corresponds to the distance $r = r_s$ for the subhalo being considered.

anomalously high values of J. The absence of a substantial stellar population in such objects seems highly improbable. The only possibility for them to be dark is that they are light subhalos situated extremely close to the observer. We fitted the distances to such subhalos to the measured gamma-ray flux from them. In doing this, we took two representative mass values for the subhalo candidates—$10^6\ M_\odot$ and $10^9\ M_\odot$. For these values, we obtained distances of, respectively, about 1 and 10 kpc (which are approximately identical for the two objects being considered). These distances contradict sharply the dependence in (4). Also, this contradiction can be seen more clearly from Fig. 10 in [3]: in 100 simulations of MW, no subhalo was discovered at distances smaller than about 12 kpc. Thus, the candidates under discussion do not pass either of the two simple tests—that in the J factor and that in the distance to them. On this basis, we are inclined to think that the candidates in question are typical astrophysical sources, each consisting of two sources on very close lines of sight. This possibility was also admitted in [5–7]. It is indirectly confirmed by the fact that the analysis of observational data revealed a slight deviation of the object images from a circular shape.

5. CONCLUSIONS AND DISCUSSION

We have assessed the detectability of DM subhalos in MW Galaxy with the planned GAMMA-400 gamma-ray telescope. For this purpose, we first developed a model of DM density distributions within subhalos and spatial subhalo distributions in the MW Galaxy for subhalos in the mass range of 10^6–$10^9\ M_\odot$, relying on the results reported in [3]. This made it possible to calculate gamma-ray fluxes from subhalos and the morphology of subhalos for various values of DM and subhalo parameters (see Figs. 1 and 2). We can formulate the following brief conclusions: (i) The integrated gamma-ray flux from subhalos depends rather weakly on the subhalo mass, but it depends rather strongly on the DM concentration and on the mass of the DM particle. The most massive subhalos are the brightest. (ii) For the neutralino mass that is the most realistic at the present time (about 100 GeV) and the thermal annihilation cross section, we can expect the existence of several objects on the whole sky that produce a gamma-ray flux of about 10 photons per year, with the result that such subhalos are detectable in principle with the GAMMA-400 gamma-ray telescope even in the case of rather heavy DM particles. (iii) Because of the smallness of gamma-ray fluxes, it is hardly possible to resolve the inner structure of subhalos. However, this obstacle could possibly be sidestepped by combining and jointly processing future data from GAMMA-400 with data from other telescopes. (iv) In our opinion, the J2212.5+0703 and J1924.8−1034 candidates for DM subhalos in the 3FGL catalog are likely to be classical binary astrophysical sources.

Thus, DM subhalos are an interesting object from the point of view of DM searches by means of the GAMMA-400 gamma-ray telescope. A further study of this class of objects and an analysis of the possibilities for detecting DM in dwarf MW satellites and for setting limits on the properties of DM on this basis are planned.

ACKNOWLEDGMENTS

This work was supported by the Space Research Council of Russian Academy of Sciences and by the Roscosmos State Corporation for Space Activities.

REFERENCES

1. *Particle Dark Matter: Observations, Models and Searches,* Ed. by G. Bertone (Cambridge Univ. Press, Cambridge, 2010).
2. E. Charles, M. Sánchez-Conde, B. Anderson, R. Caputo, A. Cuoco, M. di Mauro, A. Drlica-Wagner, G. A. Gomez-Vargas, M. Meyer, L. Tibaldo, M. Wood, G. Zaharijas, S. Zimmer, M. Ajello, A. Albert, L. Baldini, et al., Phys. Rep. **636**, 1 (2016); arXiv: 1605.02016.
3. F. Calore, V. de Romeri, M. Di Mauro, F. Donato, and F. Marinacci, Phys. Rev. D **96**, 063009 (2017); arXiv: 1611.03503.
4. F. Acero, M. Ackermann, M. Ajello, A. Albert, W. B. Atwood, M. Axelsson, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, A. Belfiore, R. Bellazzini, E. Bissaldi, R. D. Blandford, E. D. Bloom, J. R. Bogart, et al., Astrophys. J. Suppl. Ser. **218**, 23 (2015); arXiv: 1501.02003.
5. B. Bertoni, D. Hooper, and T. Linden, J. Cosmol. Astropart. Phys. **5**, 049 (2016); arXiv: 1602.07303.
6. Y.-P. Wang, K.-K. Duan, P.-X. Ma, Y.-F. Liang, Z.-Q. Shen, S. Li, C. Yue, Q. Yuan, J.-J. Zang, Y.-Z. Fan, and J. Chang, Phys. Rev. D **94**, 123002 (2016); arXiv: 1611.05135.
7. Z.-Q. Xia, K.-K. Duan, S. Li, Y.-F. Liang, Z.-Q. Shen, C. Yue, Y.-P. Wang, Q. Yuan, Y.-Z. Fan, J. Wu, and J. Chang, Phys. Rev. D **95**, 102001 (2017); arXiv: 1611.05565.
8. T.-L. Chou, D. Tanoglidis, and D. Hooper, arXiv: 1709.08562.
9. A. M. Galper, O. Adriani, R. L. Aptekar, I. V. Arkhangelskaja, A. I. Arkhangelskiy, M. Boezio, V. Bonvicini, K. A. Boyarchuk, Yu. V. Gusakov, M. O. Farber, M. I. Fradkin, V. A. Kachanov, V. A. Kaplin, M. D. Kheymits, A. A. Leonov, F. Longo, et al., Adv. Space Res. **51**, 297 (2013); arXiv: 1201.2490.
10. N. P. Topchiev, A. M. Galper, V. Bonvicini, O. Adriani, I. V. Arkhangelskaja, A. I. Arkhangelskiy, A. V. Bakaldin, S. G. Bobkov, M. Boezio, O. D. Dalkarov, A. E. Egorov, M. S. Gorbunov, Y. V. Gusakov, B. I. Hnatyk, V. V. Kadilin, V. A. Kaplin, et al., EPJ Web. Conf. **145**, 06001 (2017).
11. A. De Angelis, V. Tatischeff, M. Tavani, U. Oberlack, I. Grenier, L. Hanlon, R. Walter, A. Argan, P. von Ballmoos, A. Bulgarelli, I. Donnarumma, M. Hernanz, I. Kuvvetli, M. Pearce, A. Zdziarski, A. Aboudan, et al., Exp. Astron. **44**, 25 (2017); arXiv: 1611.02232.
12. G. D. Martinez, Mon. Not. R. Astron. Soc. **451**, 2524 (2015); arXiv: 1309.2641.
13. A. Geringer-Sameth, S. M. Koushiappas, and M. Walker, Astrophys. J. **801**, 74 (2015), 1408.0002.
14. http://www.marcocirelli.net/PPPC4DMID.html.
15. M. Cirelli, G. Corcella, A. Hektor, G. Hütsi, M. Kadastik, P. Panci, M. Raidal, F. Sala, and A. Strumia, J. Cosmol. Astropart. Phys. **3**, 051 (2011); arXiv: 1012.4515.
16. P. Ciafaloni, D. Comelli, A. Riotto, F. Sala, A. Strumia, and A. Urbano, J. Cosmol. Astropart. Phys. **3**, 019 (2011); arXiv:1009.0224.
17. Á. Moliné, M. A. Sánchez-Conde, S. Palomares-Ruiz, and F. Prada, Mon. Not. R. Astron. Soc. **466**, 4974 (2017); arXiv:1603.04057.
18. M. Ackermann, A. Albert, B. Anderson, W. B. Atwood, L. Baldini, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, E. Bissaldi, R. D. Blandford, E. D. Bloom, R. Bonino, E. Bottacini, T. J. Brandt, J. Bregeon, et al., Phys. Rev. Lett. **115**, 231301 (2015); arXiv:1503.02641.
19. https://fermi.gsfc.nasa.gov/ssc/data/access/.
20. A. Albert, B. Anderson, K. Bechtol, A. Drlica-Wagner, M. Meyer, M. Sánchez-Conde, L. Strigari, M. Wood, T. M. C. Abbott, F. B. Abdalla, A. Benoit-Lévy, G. M. Bernstein, R. A. Bernstein, E. Bertin, D. Brooks, D. L. Burke, et al., Astrophys. J. **834**, 110 (2017); arXiv: 1611.03184.