Massive Argon Space Telescope (MAST): a concept of heavy time projection chamber for γ-ray astronomy in the 100 MeV — 1 TeV energy range

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Abstract

We explore the concept of liquid Argon time projection chamber (TPC) for γ-ray astronomy in the 100 MeV — 1 TeV energy range. We propose a basic layout for such a telescope called MAST. Using a last-generation rocket such as Falcon Heavy, it is possible to launch a detector with the effective area and the differential sensitivity about one order of magnitude better than the Fermi-LAT ones. At the same time, the MAST concept allows for an excellent angular resolution, 3–10 times better than the Fermi-LAT one depending on the energy, and good energy resolution (∼ 20 % at 100 MeV and 6–10 % for the 10 GeV – 1 TeV energy range). We show that such a telescope would be instrumental in a broad range of long-standing astrophysical problems.

Keywords: primary γ-rays, space γ-ray telescopes, time projection chambers

1. Introduction

The Large Area Telescope (LAT) onboard the Fermi mission have proved to be a great success of γ-ray astronomy. In particular, Fermi-LAT detected about three thousand sources above 4σ significance, put upper limits on the dark matter (DM) annihilation cross section from observations of dwarf spheroidal galaxies, measured the extragalactic γ-ray background (EGRB) implying constraints on ultra-high energy cosmic ray and neutrino sources, as well as on annihilating DM models, constrained the flux and spectrum of the extragalactic background light (EBL). Additionally, Fermi-LAT data may be used to put constraints on the extragalactic magnetic field (EGMF) parameters.

Further progress in γ-ray astronomy would require a new instrument with improved sensitivity, angular and energy resolution, and wide energy coverage range. The fast development of astronautics and the reduction of prices on transportation services in space would soon allow for the launching of a very heavy γ-ray telescope with the mass up to 30–40 t. In this paper we propose a concept of a γ-ray telescope filled with pure liquid Argon and operating as time projection chamber (TPC) called MAST (an abbreviation from “Massive Argon Space Telescope”).

Many possible designs of TPC space-based γ-ray detectors filled with noble gases, sometimes in condensed phase, were considered before. However, most of these were designed for polarimetric observations in the MeV-GeV energy range. In this paper we show, for the first time, that the idea to use a liquid noble gas TPC transcends the above-mentioned task, and is useful for a wider energy range, from 100 MeV up to 1 TeV, and potentially even above 1 TeV. The present paper is organized as follows. In Sect. 2 we describe the basic geometry of the proposed instrument. In Sect. 3 we present the expected dependence of the effective area, angular and energy resolution vs. primary energy and calculate the point-like source differential sensitivity. After a brief discussion in Sect. 4 we conclude in Sect. 5. All graphs in this paper were produced with the ROOT software.

2. The basic geometry of the MAST telescope

A simplified scheme of MAST is shown in Fig. 1. The direction of a primary γ-ray, assuming normal incidence, is shown by magenta arrow. The detector with the overall

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dimension,\textsuperscript{2} \(L \times L \times D\) with \(L = 400 \text{ cm}\) consists of the two main modules, namely, a tracker (thickness \(D_t = 50 \text{ cm}\)) and a calorimeter (thickness \(D_c = 110 \text{ cm}\)), so that \(D = D_t + D_c\). Both modules are supposed to be filled with liquid argon (density \(\rho = 1.4 \text{ g/cm}^3\) and radiation length \(X_\gamma = 14 \text{ cm}\), see Tables 2.1 and 2.6 of \textsuperscript{[29]}). The total sensitive mass of the MAST telescope is \(M = \rho \cdot L^2 D = 35.8t\), still within the capabilities of the Falcon Heavy rocket.\textsuperscript{3} Assuming the orbit similar to that of the Fermi mission (565 km \times 565 km \times 25.5° \textsuperscript{1}), we estimate the maximal payload of the Falcon Heavy rocket for this orbit to be \(\approx 0.7 \cdot 63.8 t = 44.7 t\)\textsuperscript{4}.

The tracker, in turn, consists of \(N_t = 50\) layers (only two of these layers are shown in Fig. 1). The thickness of each layer is \(\Delta t = 1 \text{ cm}\). A uniform electric field \(E_t = 3 \text{ kV/cm}\) normal to the layers permeates the tracker medium (denoted as horizontal blue arrow in Fig. 1). All layers of the tracker are equipped with a readout device with the longitudinal sampling \(l_t = 100 \mu m\) in both dimensions collecting ionization electrons (two of these readouts are shown in Fig. 1) by horizontal hatching.

The calorimeter is a single volume split by a cathode leaf and permeated by a uniform electric field \(E_c = 500 \text{ V/cm}\) (denoted as vertical blue arrow in Fig. 1) directed normally to the symmetry axis of the telescope (denoted as horizontal dashed line in Fig. 1). The calorimeter has two readouts on its walls with the longitudinal sampling \(l_c = 1 \text{ mm}\) (shown in Fig. 1) by vertical hatching.

3. The performance of the MAST telescope

Below we neglect the passive material of the detector (“dead material”) and consider only \(\gamma\)-ray events with conversion vertex in the first 36 layers of the tracker; thus, the effective thickness of the tracker is \(36 \text{ cm} = D_t - X_\gamma\). We also neglect saturation of the detector at high radiation energy densities. Additionally, following \textsuperscript{22} we assume that the reconstruction is 100 % effective. We consider only \(\gamma\)-ray conversion in the nuclear field. Events due to primary \(\gamma\)-ray conversion on atomic electrons (“triplet events”) may yield some additional information.

3.1. Effective area

We estimate the effective area of the MAST telescope for normal incidence using two equivalent approaches as follows:

\[
A(E) = L^2 \left( 1 - \exp \left( -\mu_p(E) \rho (D_t - X_\gamma) \right) \right) = \\
L^2 \left( 1 - \exp \left( -\sigma_p(E) n (D_t - X_\gamma) \right) \right),
\]

\textsuperscript{2}In what follows we assume the rectangular box shape for simplicity.

\textsuperscript{3}The maximal payload to the 185 km \times 185 km \times 28.5° low Earth orbit amounts to 63.8 t \textsuperscript{[15, 30]}

\textsuperscript{4}For the Fermi mission, out of 4450 kg total mass, only 3997 kg is the payload, while 1002 kg is reserved for a dry bus and 351 kg for propellant \textsuperscript{[33]}, hence the factor of 3997/4450=0.7

where \(\mu_p \text{ [cm}^2/\text{g}]\) is the pair mass attenuation coefficient as a function of the primary \(\gamma\)-ray energy \(E\), \(\sigma_p \text{ [cm}^2]\) is the pair production cross section, and \(n \text{ [cm}^{-3}]\) is the concentration of Argon atoms. The effective area of MAST calculated following the latter approach with \(\sigma_p\) according to \textsuperscript{Geant4} \textsuperscript{[32, 33, 34]} Physics Reference Manual \textsuperscript{[35]} (version 10.4, Subsection 6.5.1, equation 6.4)\textsuperscript{5} is presented in Fig. 2 (top-left) in comparison with the same quantity for Fermi-LAT \textsuperscript{[1]} and for the projected \(\gamma\)-ray telescopes ADEPT \textsuperscript{25} and e-ASTROGAM \textsuperscript{36}. The relative difference between the values of \(A\) calculated with the two above-mentioned approaches is less than 3 % in the 10 MeV - 100 GeV energy range.

3.2. Angular resolution

The single-photon angular resolution (68 % containment radius) was estimated as follows:

\[
\sigma_\theta = \sqrt{\frac{1}{4} \sum_{i=1}^{4} \sigma_{\theta_i}^2},
\]

\textsuperscript{5}We assumed \(\sigma_p = \text{const} \text{ at } E > 8.7 \text{ GeV} \).
single-track angular resolution component due to multiple scattering, $\sigma_3$ is the so-called “kinematical limit”, and $\sigma_4$ is the contribution from the uncertainty of the secondary electron and positron momentum absolute value measurement (for a discussion of pair production kinematics relevant for $\gamma$-ray telescopes see e.g. [37, 38]).

Following [23, 24],

$$\sigma_1 = \frac{2\sigma_d}{L} \sqrt{\frac{3}{N + 3}}$$

(3)

and

$$\sigma_2 = \frac{(2\sigma_d)^{1/4} l_t^{1/8}}{X_{0}^{3/8}} \left( \frac{p_0}{p} \right)^{3/4},$$

(4)

where $L$ is the tracking length, $N = L/\Delta_t$ is the number of samplings, and $p_0 = 13.6$ $MeV/c$. The spatial resolution $\sigma_d$ is limited mainly by the longitudinal sampling $l_t$ and the spatial extension of charge carrier cloud (which, in turn, is defined by the diffusion process, see eq. (3.4) of [29]):

$$\sigma_d = \sqrt{\frac{l_t^2}{12} + \frac{K_D \Delta_t}{v_d}}.$$  

(5)

Here $K_D = 16$ [cm$^2$/s] [39] (Fig. 10) is the perpendicular diffusion coefficient and $v_d = 2.6 \times 10^5$ [cm/s] [39] (Fig. 7) is the charge carrier drift velocity (see also [40, 41, 42, 43] and [29] for discussion).

The kinematical limit $\sigma_3$ is due to the fact that the recoil nucleus is very hard to register. We assume that the recoil nucleus is not seen. The kinematical limit $\sigma_3$ was calculated according to [44] with correction of [45] using tables for the Argon atomic form-factor presented in [46].

Finally, an uncertainty in electron ($p_-$) and positron ($p_+$) momenta absolute value measurement translates into some uncertainty of the reconstructed primary $\gamma$-ray direction. This contribution to the angular resolution ($\sigma_4$) was estimated with a dedicated Geant4 (version 4.10.04.p02)
application by calculating a change in the reconstructed pair direction $\vec{p}_e + \vec{p}_\gamma$ assuming true MC momenta values in the first case and equal distribution of the momenta between the electron and the positron in the second case.

The result of our calculation for the full angular resolution $\sigma_\theta$ is shown in Fig. 2 (top-right) in comparison with the same quantity for other $\gamma$-ray instruments, namely e-ASTROGAM [36], AdEPT [23], CTA [17] (see also [18]), H.E.S.S. [49, 51] (for MAGIC [51, 52] and VERITAS [53, 54] the angular resolution is qualitatively similar and not shown to avoid confusion of the graph; for a discussion of the point spread function of imaging atmospheric Cherenkov telescopes see [55]), Fermi-LAT [1], GRAINE, GAMMA-400 [57]. For these $\gamma$-ray telescopes, we take the results on the angular resolution presented by the authors at face value. We note that $\sigma_\theta$ for MAST and e-ASTROGAM is comparable, notwithstanding the two-order difference in cascades inside the model of the section. We simulated the development of electromagnetic interactions between the electron and the positron in the second case.

3.3. Energy resolution

The energy resolution was estimated with the same Geant4 application that was used in the previous subsection. We simulated the development of electromagnetic cascades inside the model of the MAST detector for five values of the primary $\gamma$-ray energy ($E = 100$ MeV, $1$ GeV, $10$ GeV, $100$ GeV, $1$ TeV) and recorded all the tracks of cascade electrons above the energy threshold of $10$ MeV. The critical energy for Argon is $\approx 33$ MeV for $e^-$ and $\approx 32$ MeV for $e^+$. The primary energy was reconstructed as follows: 1) using the integral over the cascade curve at $E \leq 100$ GeV as the energy estimator and 2) by normalizing to the following analytical expression for the cascade curve (see eq. (33.36) in [59]) at $E = 1$ TeV:

$$\frac{dE}{dt} = C_0 b^a t^{a-1} e^{-bt} \frac{1}{\Gamma(a)},$$  \hspace{1cm} (6)

where $a$, $b$, and $C_0$ are the free parameters of the fit, $t$ is the thickness in radiation lengths, and $\Gamma$ denotes the gamma function. For the case of $E = 100$ GeV and the first energy estimation method we introduced an additional correction to the estimated value of the primary energy depending on the depth of the shower’s maximum. Using a simple linear correction, we were able to improve the resulting relative energy resolution $\epsilon_E$ from $11.4\%$ to $8.6\%$. For the case of $E = 1$ TeV we excluded $\approx 3\%$ of cascades which revealed fitting problems.

The dependence of $\epsilon_E$ on $E$ is shown in Fig. 2 (bottom-left) in comparison with the Fermi-LAT energy resolution [1]. We note that it appears possible to estimate the primary energy with a reasonable accuracy both at the low-energy region ($E = 100$ MeV–$1$ GeV), as well as at the high-energy region ($E = 100$ GeV–$1$ TeV), notwithstanding a relatively high critical energy in Argon (compared to the tungsten calorimeter of Fermi-LAT) and a relatively low depth of the MAST calorimeter that amounts to $11.4$ radiation lengths. The details of this primary energy estimation procedure will be published elsewhere. Moreover, the results of [60] indicate that a several-fold improvement in the energy resolution is achievable in the energy range of $0.5$–$5$ GeV.

3.4. Differential sensitivity

Finally, we estimated the differential sensitivity of the MAST telescope for point-like sources following the approach of [23] and assuming four bins per decade of energy, the threshold significance of $5\sigma$, and the effective area and angular resolution as described above. We also require at least ten events in every energy bin. The EGRB with the spectrum in the form $dN/dE = C_0 E^{-\gamma} \exp(-E/E_c)$ and $(C_0 = 7.8 \times 10^{-8}$ MeV$^{-1}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$, $\gamma = 2.26$, $E_c = 233$ GeV) (model C of [6]) was assumed as the background in this calculation. The resulting differential sensitivity for ten years of observation is shown in Fig. 2 (bottom-right) in comparison with the same quantity for Fermi-LAT, H.E.S.S., and CTA according to [61]. The $MAST$ sensitivity is shown for two options: “the survey mode” when the source is seen only a fraction of $\eta = 0.17$ (solid curve) and “the pointing mode” when $\eta = 1$ (dashed curve). We note that a preliminary version of this result was presented in [62] for different detector parameters.

4. Discussion

Calculations made in the previous section show that the MAST $\gamma$-ray telescope could achieve a significant improvement over presently operating and projected space-based $\gamma$-ray detectors in terms of the effective area and differential sensitivity, at the same time retaining excellent angular resolution and reasonable energy resolution. We note that the huge (total mass $68$ kt) liquid Argon detectors of the DUNE project [63] are presently in development. After the successful operation of the ICARUS experiment [19], this once more proves that the liquid Argon TPC is an extremely cost-effective technique.

Possible astrophysical tasks for the MAST instrument include, but are not confined to the EBL [64, 65, 12, 66] and EGMF [13, 14] measurement (for a review see [67, 68]), the study of the $\gamma$-ray – neutrino connection in blazars [69, 70, 71, 72, 73], observations of neutron star mergers [74, 75], the search for $\gamma$-rays from black hole mergers [76, 77], $\gamma \rightarrow ALP$ oscillation [78] in active galactic nuclei spectra [79, 80, 81, 82, 83, 84, 85], Lorentz invariance violation search [86, 87, 88] (see, however, [89]), and DM annihilation or decay signatures search [90, 10, 11]. Detailed investigation of the MAST sensitivity to these processes is beyond the scope of the present paper. Preliminary
estimates obtained with intergalactic cascade calculation techniques developed in [90, 91, 92] show a good sensitivity to the EGMF strength down to 10 aG and coherence length of 1 kpc (see also [38]). The results of this study will be published elsewhere. Finally, we note that MAST could represent an excellent low-energy counterpart for ground-based γ-ray detectors such as CTA [17] and LHAASO [39, 40].

5. Conclusions

In this paper we considered a concept of a γ-ray telescope called MAST based on heavy time projection chamber (TPC) filled with liquid Argon. Estimates of the effective area, angular resolution, energy resolution, and differential sensitivity show a great potential of such an instrument in a wide range of γ-astronomical tasks. We conclude that constructing and operating the MAST detector could facilitate a significant advance in astroparticle physics.

Acknowledgements

This work was supported by the Russian Science Foundation (RSF) (project No 18-72-00083). We are greatly indebted to Dr. D. Bernard for very helpful discussions.

References

[1] W. B. Atwood, A. A. Abdo, M. Ackermann, W. Atchous, et al., ApJ 697 (2) (2009) 1071–1102. doi:10.1088/0004-637x/697/2/1071
[2] F. Acero, M. Ackermann, M. Ajello, W. B. Atwood, et al., Phys. Rev. Lett. 104 (10) (2010) 101101. doi:10.1103/physrevlett.104.101101
[3] M. Ackermann, M. Ajello, B. Anderson, W. Atwood, et al., Phys. Rev. Lett. 115 (23) (2015) 231301. doi:10.1103/physrevlett.115.231301

[15] [link] https://www.spacex.com/falcon-heavy
[16] D. Nygren, Proceedings of The 1974 PEP Summer Study 5-30 Aug 1974, Berkeley, California.
[17] J. N. Marx, D. R. Nygren, Physics Today 31 (10) (1978) 46–53. doi:10.1063/1.2949775
[18] C. Rubbia, CERN-EP-INT-77-08.
[19] C. Rubbia, M. Antonello, P. Aprili, B. Baibissnov, et al., JINST 6 (07) (2011) P07011–P07011. doi:10.1088/1748-0221/6/07/p07011
[20] [link] http://www.ccefe.ac.uk/MAST.aspx
[21] E. Aprile, A. Bolotnikov, D. Chen, R. Mukherjee, NIM A 327 (1) (1993) 216–221. doi:10.1016/0168-9002(93)91464-t
[22] E. Aprile, A. Curioni, K. Giboni, M. Kobayashi, et al., NIM A 593 (3) (2008) 414–425. doi:10.1016/j.nima.2008.05.039
[23] D. Bernard, NIM A 701 (2013) 225–230. doi:10.1016/j.nima.2012.10.023
[24] D. Bernard, NIM A 713 (2013) 76–77. doi:10.1016/j.nima.2013.03.005
[25] S. D. Hunter, P. F. Bloser, G. O. Depaola, M. P. Dion, et al., Astropart. Phys. 59 (2014) 18–28. doi:10.1016/j.astropartphys.2014.04.002
[26] G. Caiando, B. Rossi, F. Longo, G. Fiorillo, et al., POS (Neutel) 2013 (2014) 067.
[27] P. Gros, S. Amano, D. Attiè, P. Baron, et al., Astropart. Phys. 97 (2018) 10–18. doi:10.1016/j.astropartphys.2017.10.008
[28] R. Brun, F. Rademakers, NIM A 389 (1-2) (1997) 81–86. doi:10.1016/j.nima.2008.05.039
[29] E. Aprile, A. E. Bolotnikov, A. Bolozdynya, T. Doke, Noble Gas Detectors. Wiley-VCH Verlag GmbH & Co. KGaA, 2006. doi:10.1002/9783527610020
[30] [link] URL http://www.spacecraftunichreport.com/falcon.html
[31] [link] URL http://space.skyrocket.de/doc_stat/glast.htm
[32] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, et al., NIM A 506 (3) (2003) 250–303. doi:10.1016/j.nima.2002.06.023
[33] J. Allison, K. Amako, J. Apostolakis, H. Araujo, et al., IEEE Transactions on Nuclear Science 53 (1) (2006) 270–278. doi:10.1109/tns.2006.869826
[34] J. Allison, K. Amako, J. Apostolakis, P. Arce, et al., NIM A 835 (2016) 186–225. doi:10.1016/j.nima.2016.05.125
[35] [link] URL http://geant4-userdoc.web.cern.ch
[36] A. De Angelis, V. Tatischeff, I. Grenier, J. McEnery, et al., Astropart. Phys. 34 (2) (2010) 106–115. doi:10.1016/j.astropartphys.2010.06.003
[37] G. B. Gelmini, O. Kalashev, D. V. Semikoz, JCAP 2012 (01) (2012) 044-044. doi:10.1088/1475-7516/2012/01/044
[38] The Fermi LAT collaboration, JCAP 2015 (09) (2015) 008. doi:10.1088/1475-7516/2015/09/008
[39] O. Kalashev, M. Kuznetsov, Phys. Rev. D 94 (6) (2016) 063535. doi:10.1103/physrevd.94.063535
[40] T. Cohen, K. Murase, N. L. Rodd, B. R. Safdi, et al., Phys. Rev. Lett. 119 (2) (2017) 021102. doi:10.1103/physrevlett.119.021102
[41] M. Ackermann, M. Ajello, A. Allafort, P. Schady, et al., Science 338 (6111) (2012) 1190–1192. doi:10.1126/science.1227160
[42] A. Neronov, I. Vovk, Science 328 (5974) (2010) 73–75. doi:10.1126/science.1184192
[43] M. Ackermann, M. Ajello, L. Baldini, J. Ballet, et al., ApJ Supplement Series 237 (2) (2018) 32. doi:10.3847/1538-4365/aacdf7
