

Prospects for gamma-ray observations of Hercules cluster

V. V. Voitsekhovskiy*

Taras Shevchenko National University of Kyiv, Glushkova ave., 4, 03127, Kyiv, Ukraine

Galaxy clusters are the largest and most massive gravitationally bound objects in the large-scale structure of the Universe. Due to keV temperatures of virialized gas in the intracluster medium and presence of cosmic rays (CR), galaxy clusters are effective sources of thermal X-ray radiation and non-thermal leptonic (synchrotron) radio emission. Galaxy clusters are also store-rooms for hadronic CR, but non-thermal hadronic gamma-ray emission (mainly, due to pp collisions and subsequent pion decay) from galaxy clusters has not been detected yet. In this work we present the simulation of the expected non-thermal hadronic gamma-ray and neutrino emission from the dominant part of Hercules cluster (A2151) and estimated a perspective of detection of this emission by existing (Fermi-LAT, LHASSO, IceCube) and planned (CTA, IceCube-Gen2) ground-based and space-based detectors.

Key words: gamma-rays: galaxies: clusters, neutrinos, galaxies: clusters: intracluster medium

INTRODUCTION

Galaxy clusters (GCs) are the largest virialized structures in the Universe at the present cosmological time $t_0 = 13.8$ Gyr (i.e. redshift $z_0 = 0$) [27]. The growth of initial density fluctuations due to gravitational instability led to the formation of the main elements of large scale structure: sheet-like structures bordered by low density voids and filaments connected to the high-density nodes – galaxy clusters and superclusters [24]. The total gravitational mass $M_{cl} \sim 10^{14} - 10^{15} M_\odot$ of GCs contains dominant fraction of dark matter (about 80% of mass) and much smaller fraction of baryonic matter ($\sim 15\%$ of mass in intracluster medium (ICM) gas and $\sim 5\%$ of mass in stars/galaxies) [4, 7, 13]. Virial temperature of ICM plasma $k_B T \sim GM_{cl} m_p / R_{cl}$ in GCs with typical size $R_{cl} \sim 2 - 3$ Mpc is of the order of $1 - 10$ keV, and therefore GCs are luminous sources of thermal X-ray emission with typical luminosities $L_X \sim 10^{44} - 10^{46}$ erg s $^{-1}$.

The formation of gravitationally bound and virialised GCs is long-lasting violent process of main halo collapse and substructures' merger, that is often not completed yet. Most clusters have not fully relaxed yet and accretion and merger processes are still ongoing. Magnetohydrodynamic (MHD) flows in ICM and in active galactic nuclei (AGN), which are rich in shock waves, accelerate cosmic rays efficiently and enhance/generate magnetic fields in ICM. In observed $B_{cl} \sim 1 - 10 \mu\text{G}$ GC magnetic

fields the time of diffusive escape of CR from GCs $t_{\text{diff}} \sim R_{cl}^2 / D(E)$ is of order or larger than the age of Universe for typical value of diffusion coefficient $D(E) \sim 10^{28} (E/10 \text{ GeV})^{0.5} \text{ cm}^2 \text{ s}^{-1}$. As a result, GCs are effective store-rooms for accelerated CR [7] and therefore, GCs are expected to be promising sources of non-thermal leptonic (synchrotron) as well as of hadronic radio emission (mainly, due to pp collisions and subsequent neutral pion decay) [18, 23].

Indeed, a non-thermal synchrotron radio emission within MHz–GHz range from relativistic electrons ($E_e \sim 10$ GeV) in clusters' magnetic fields $\nu_{syn} \sim 4(B_{cl}/1 \text{ e}\mu\text{G})(E_e/10 \text{ GeV})^2$ GHz is widely presented in observations of GCs [26], but non-thermal gamma-ray emission from GCs has not been detected yet [1, 28].

Both non-thermal radio- and thermal X-ray emission supplemented by data of *Planck* thermal Sunyaev-Zel'dovich (SZ) effect give a valuable information about dark/baryon matter distribution and physical processes in ICM of GCs [2]. In our work we have carried out a modelling of non-thermal hadronic gamma-ray and neutrino emission from Abell cluster A2151 (a dominant part of Hercules cluster) and estimate prospects for gamma-ray observations of A2151 by existing and planned (Fermi-LAT, LHASSO, IceCube, CTA, IceCube-Gen2) ground-based and space-based detectors. For calculation we used code MINOT [2] and Λ CDM cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ [21].

*v.v.voitsekhovskiy@gmail.com

HERCULES CLUSTER

The nearby ($z = 0.0367$) Hercules supercluster is one of the most massive structures in the local Universe. It is composed by three Abell clusters: A2151 (the Hercules cluster), A2147 and A2152 [6]. The most prominent GC A2151 with mass $M_{200} = 4.00 \times 10^{14} M_{\odot}$ and size $R_{200} = 1.45$ Mpc includes three subclusters and shows the sign of ongoing collapse and merger processes [3]. In addition, there are seven galaxies with active nuclei in the central part of A2151, including a pair of interaction galaxies NGC 6050 and IC 1179.

In this paper we consider that GC A2151 contains nearly 360 galaxies and its optical center has coordinates $RA = 241.34^{\circ}$ and $DEC = 17.75^{\circ}$ [3]. As was mentioned about this cluster demonstrates a significant division into three substructures: bright central bimodal subclump A2151C and two fainter A2151E and A2151N. Based on *Chandra* and *XMM-Newton* observations, A2151C also can be divided into two substructures — bright central A2151C(B) and fainter lateral A2151C(F) [25]. According to state of the art sensitivity of current γ -ray detectors, only A2151C has a chance to be detected. In our work we present the analysis of this problem and future prospects for gamma-ray studies of A2151C.

Physical conditions and spherically-symmetric dark/baryonic matter distribution in ICM of GC are determined mainly from two global GC parameters — its total mass M_{cl} and size R_{cl} . There are several types of characteristic masses that we have usually used in the modelling. The first one is the mass M_{500} enclosed inside the radius R_{500} , where the mean density (i.e. averaged on the volume) exceeds the critical density by 500 times ($\rho/\rho_{crit} = 500$). This relation can be presented by the following equation:

$$M_{500} = \frac{4\pi}{3} 500 \rho_{crit} R_{500}^3 \quad (1)$$

The second characteristic mass is the total mass M_{tot} of GC, which can be expressed as $M_{tot} = M_{HSE}/(1 - b_{HSE})$, where M_{HSE} is the hydrostatic mass derived from the hydrostatical equilibrium and $b_{HSE} \sim 0.2$ is the hydrostatic mass bias [20, 22]. The spatial distribution of gas mass fraction in GC $f_{gas}(r)$ is determined as the ratio of the gas mass $M_{gas}(r)$ and the total mass $M_{tot}(r)$ like $f_{gas}(r) = M_{gas}(r)/M_{tot}(r)$.

Gas electron density profile $n_e(r)$ is an important parameter for estimating gamma-ray emission, because of its proportionality to total gas density $n_{gas}(r)$, that describes the intensity of proton-proton interactions. There are several theoretical models to describe $n_e(r)$, particularly the analytical beta

model [10] which was used in this work:

$$n_e(r) = n_{e,0} \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta_{dens}/2} \quad (2)$$

where $n_{e,0}$ is the normalisation factor, r_c is the core radius of density distribution and β_{dens} is the density index.

In addition to $n_e(r)$ thermal gas pressure also plays a valuable role, because it allows to normalize the number of CR. Electron thermal pressure $P_e(r)$ is often described by Generalized Navarro Frank White (GNFW) profile [16], an improved version of the earlier Navarro Frenk White profile (NFW) [17]. Universal pressure profile (UPP) for electrons $\mathbb{P}_e(r)$ depends on four parameters: the normalization factor P_0 , the scale radius $r_p = R_{500}/c_{500}$ (c_{500} is the concentration parameter for the region bounded by R_{500}), and three power indices a_p , b_p , c_p , which denote distribution slope for different spatial regions ($r < r_s$, $r \approx r_s$ and $r > r_s$, respectively):

$$\mathbb{P}_e(r) = P_0 \left(\frac{r}{r_p} \right)^{-c_p} \left(1 + \left(\frac{r}{r_p} \right)^{a_p} \right)^{(c_p - b_p)/a_p} \quad (3)$$

In order to describe physical processes in particular GC, it is necessary to multiply UPP Eq. (3) by several scale factors as $P_e(r) = \mathbb{P}_e(r) \times P_{500} \times F_{500}$. P_{500} is the characteristic pressure [5, 16], which can be determined by mass and cosmological parameters:

$$P_{500} = 1.65 \times 10^{-3} E(z)^{8/3} \cdot \left(\frac{M_{500}}{3 \times 10^{14} h_{70}^{-1} M_{\odot}} \right)^{2/3} h_{70}^2 \quad (4)$$

F_{500} is the corrective factor, which makes modification by mass due to the self-similarity of GC and can be presented in the following form:

$$F_{500} = \left(\frac{M_{500}}{3 \times 10^{14} h_{70}^{-1} M_{\odot}} \right)^{0.12} \quad (5)$$

where $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$, $h_{70} = h/0.70$, and $E(z) = H(z)/H(0)$ or $E^2(z) = \Omega_M(1+z)^3 + \Omega_{\Lambda}$.

For ICM with hydrogen $X = 0.725$, helium $Y = 0.270$ and heavy elements' mass fraction $Z = 1 - X - Y = 0.005$ the mean molecular weights are $\mu_{gas} = 0.60$, $\mu_e = 1.15$ using which we can express the pressure, density and temperature of ICM gas through the pressure and number density of ICM electrons [2]:

$$P_{gas}(r) = (\mu_e/\mu_{gas}) P_e(r), \quad (6)$$

$$\rho_{gas}(r) = (\mu_e/\mu_{gas}) m_H n_e(r) \quad (7)$$

$$k_B T_{gas}(r) = \mu_{gas} m_H [P_{gas}(r) / \rho_{gas}(r)] \quad (8)$$

The distribution of magnetic field follows the matter distribution [8, 14]. Based on magnetic freezing conditions the spatial distribution of the magnetic field can be expressed proportional to some power η_B of density profile $B(r) = B_0(n_e(r)/n_{e,0})^{\eta_B}$. The normalisation factor B_0 is set to $5 \mu\text{G}$, which is a typical value for GCs measured for Coma cluster from Faraday rotation data [8].

The spatially-energetic distribution of CR are composed of nuclei (mainly protons, $i = p$) and electrons ($i = e_1$ for primary ICM electrons and $i = e_2$ for secondary electrons produced in inelastic collisions) in ICM and can be divided into the product of energetic and spatial distributions as:

$$\frac{dN_i(E, r)}{dE} = A_i f_i(E) \phi_i(r) \quad (9)$$

At the same time, ICM protons and electrons accelerating on shock waves inside GCs acquire the power law distribution by energies. In particular, the classic power law with exponential cut-off energy spectrum, which we use in this work:

$$f_i(E) = A_i \times \left(\frac{E}{E_{0,i}} \right)^{-\alpha_i} \exp \left(-\frac{E}{E_{cut,i}} \right) \quad (10)$$

where α_i is the spectral index, and cut-off occurs at energies $E_{cut,i}$ ($i = p, e_1$). The normalization factor A_i is determined by the ratio of CR energy and thermal energy inside sphere with radius $r = R_{500}$, and can be calculated as $X_{CR,i,th} = U_{CR,i}(R_{500})/U_{th}(R_{500})$, where U_{CR} and U_{th} are CR and thermal energy, respectively. Typical values are $X_{cr,p,th} \approx 0.02 - 0.10$, $X_{cr,e,th} \approx 0.0001 - 0.001$. The spatial distribution of CR in ICM is related to the gas distribution and usually approximated by power law dependence:

$$\phi_i(r) = \left(\frac{n_e(r)}{n_e(0)} \right)^{\eta_{CR,i}} \quad (11)$$

Additional important parameter for analysis of GC properties is the truncation radius R_{trunc} , which is used to denote physical boundaries of the region containing the entire GC volume (i.e the outside density drops to zero). At this distance from center of GC there is a discontinuity in thermodynamic parameters, which indicates the region of accretion shock radius, where kinetic energy of accretion is converted into thermal energy [11]. The size of this region depends on characteristic radius $R_{trunc} = 3R_{500}$.

GAMMA-RAY AND NEUTRINO EMISSION OF A2151

Characteristics of thermal and non-thermal emission of GCs are determined by the spatial distribution of matter (dark and baryonic), magnetic fields and CR (leptonic and hadronic components) inside ICM. To recover these distributions we can use observational data in thermal X-ray emission and CMB distortions due to the thermal SZ effect. For instance, we can recover the spatial distribution of partial pressure of electrons $P_e(r)$ and of the total pressure of baryonic gas $P_{tot}(r)$ inside ICM. According to equations presented in the previous section we can retrieve distributions of the magnetic field and CR inside ICM.

Recent work [25] presents new observational results for thermal X-ray emission and thermodynamic parameters of ICM plasma for brightest subclumps A2151CB and A2151CF in GC A2151. We used corresponding parameters of ICM in subclumps A2151CB and A2151CF for modelling of their gamma-ray and neutrino emission (see Table 1). Based on these data we calculated the normalization factor P_0 for the pressure profile using Eq. (3) (its value is denoted by * in Table 1). Other parameters of the pressure distribution were taken from [19]. To take into account the gamma-ray flux absorption by the interaction with an extragalactic background light (EBL) [9] we used Python package `ebtable`¹.

Using parameters of GC and CR presented above as input ones we use open access Python language-based software MINOT² (Modelling the Intracluster medium (Non-)thermal content and Observable prediction Tools). MINOT simulates the intracluster diffuse thermal and nonthermal broad-band (from radio- to gamma-ray) and neutrino emission and produces the multiwavelength observation spectra, profiles, fluxes, and images for the radio (synchrotron), X-ray (thermal Bremsstrahlung), gamma-ray (inverse Compton and hadronic processes), and neutrino (hadronic processes) messengers [2].

Main results of gamma-ray and neutrino emission for A2151CB and A2151CF subclumps are presented in Fig. 1-5. The most promising case of CTA-detection corresponds to hard CR spectrum with spectral index $\alpha_p < 2$. In particular, Fig. 1 demonstrates the expected gamma-ray flux from the central brightest subclump A2151CB for $\alpha_p = 1.5$ and for three values of the cluster mass – the average mass and $\pm \Delta m$ in Table 1. Meantime, there is no significant increase in flux due to more compact CR distribution, the result of the magnification of $\eta_{CR,p}$ twice is shown in Fig. 2.

To compare different models of CR distribution in ICM we simulated the gamma-ray flux for three values of spectral index (see Fig. 3 and 4). As we

¹<https://github.com/me-manu/ebtable/>

²<https://github.com/remi-adam/minot>

can see, there is a possibility for CTA to detect the brightest subclump A2151CB in the case of the hard CR spectrum, while A2151CF shows relatively low flux for all CR distribution models (see Fig. 4). The calculated neutrino flux for the brightest subclump A2151CB together with IceCube discovery potential at significance level 5σ is presented in Fig. 5 and shows that neutrinos do not suffer from energy losses unlike photons due to EBL absorption. This fact can make neutrino emission a good probe for GC in the future.

CONCLUSIONS

Due to a long time necessary for cosmic rays diffusion escape, GCs should be luminous extragalactic sources of neutrino and non-thermal gamma-rays, but such emission has not been detected yet. Using the recent data from [25] of thermal X-ray emission for brightest subclumps A2151CB and A2151CF in GC A2151 we have performed the modelling of non-thermal hadronic gamma-ray and neutrino emission of these subclumps using MINOT code [2]. Assuming the typical parameters of cosmic ray distribution (the cosmic ray proton to thermal energy ratio $X_{CR,p} \approx 0.04-0.06$, spectral index of proton power-law energy spectrum $\gamma = 2.5$) our simulations showed that both non-thermal hadronic gamma-ray and neutrino emission of subclumps A2151CB and A2151CF remain still undetected by existing and future detectors. At the same time, the back reaction of 7 galaxies with active nuclei in subclumps A2151CB and A2151CF and other unaccounted sources of cosmic rays (e.g. merging and accretion flows, turbulence etc) can increase up to $X_{CR,p} \approx 0.1$ and provide harder spectral index $\gamma = 1.5 - 2.0$. In such case, brighter subclump A2151CB can be detected by CTA at 5σ level. The hard cosmic ray spectrum can be respective for the strong flux of neutrinos that can be very promising for detection in future neutrino detectors (like IceCube-Gen2 etc). In addition, neutrino fluxes do not attenuate from the interaction with the EBL (like gamma-rays do), and therefore there are good possibilities to detect PeV-neutrinos in case of GCs – cosmic PeVatrons with hard ($\gamma < 2.0$) spectra.

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Table 1: Simulation parameters for subclumps A2151CB and A2151CF.

Global Parameters	A2151CB	A2151CF
z	0.0368	0.0368
M_{500} , [$10^{13} M_{\odot}$]	9.08 ± 5.24	3.01 ± 2.11
R_{500} , [kpc]	$803.38^{+113.18}_{-172.13}$	$566.09^{+89.09}_{-158.26}$
R_{trunc} , [kpc]	2410.15	1698.28
helium mass fraction	0.2735	0.2735
metallicity	0.0153	0.0153
abundance	0.43	0.13
hydrostatic mass bias	0.2	0.2
$X_{cr,p} = U_{cr,p}/U_{th}$ inside R_{500}	0.1	0.1
$X_{cr,e1} = U_{cr,e1}/U_{th}$ inside R_{500}	0.01	0.01
$E_{p,min}$, [GeV]	1.21	1.21
$E_{p,cut}$, [TeV]	30	30
$E_{p,max}$, [TeV]	10^6	10^6
Spectral index α_p (Model)	1.5 (PLEC)	1.5 (PLEC)
$E_{e1,min}$, [keV]	511	511
$E_{e1,break}$, [GeV]	—	—
$E_{e1,cut}$, [TeV]	10^6	10^6
$E_{e1,max}$, [TeV]	10^6	10^6
Spectral index α_{e1} (Model)	2.3 (PL)	2.3 (PL)
Density CR _p model: $n_{CR,p}(r) \propto n_e(r)^{\eta_{CR,p}}$	$\eta_{CR,p} = 1.0$	$\eta_{CR,p} = 1.0$
Density CR _{e1} model: $n_{CR,e}(r) \propto n_e(r)^{\eta_{CR,e}}$	$\eta_{CR,e} = 1.0$	$\eta_{CR,e} = 1.0$
Pressure gas model (GNFW):	$P_0 + PUP$	$P_0 + PUP$
P_0 , [keV/cm ³]	0.009*	0.0077*
a_p	1.33	1.33
b_p	4.13	4.13
c_p	0.31	0.31
c_{500}	1.81	1.81
Density gas model (beta)		
n_0 , [cm ⁻³]	0.00875	0.0049
r_c , [kpc]	19.35	10.43
β_{dens}	0.38	0.28
Magnetic field		
B_0 , [μ G]	5	5
η_B	2/3	2/3

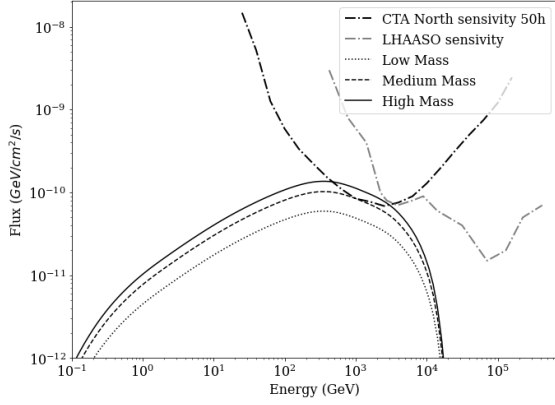


Fig. 1: Spectral flux from A2151CB for three values of cluster mass M_{500} and $M_{500} \pm \Delta m$. Other parameters were taken as in Table 1.

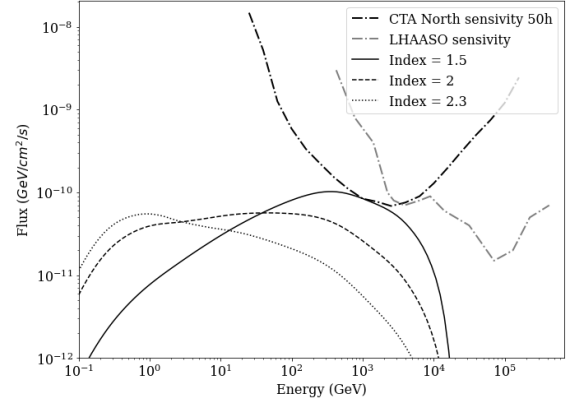


Fig. 2: Spectral flux from A2151CB for three values of spectral index. CRs distribution $CR_p \propto n_e(r)^2$. Other parameters were taken as in Table 1.

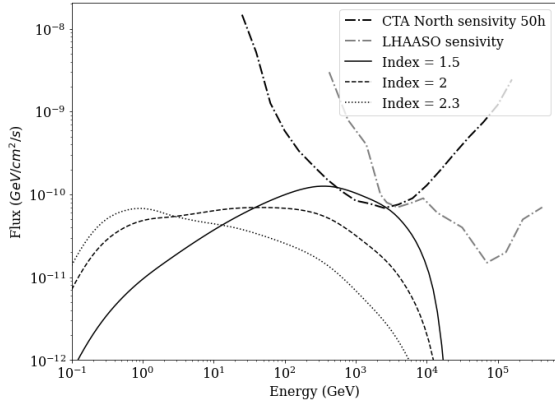


Fig. 3: Spectral flux from A2151CB for three values of spectral index. Other parameters were taken as in Table 1.

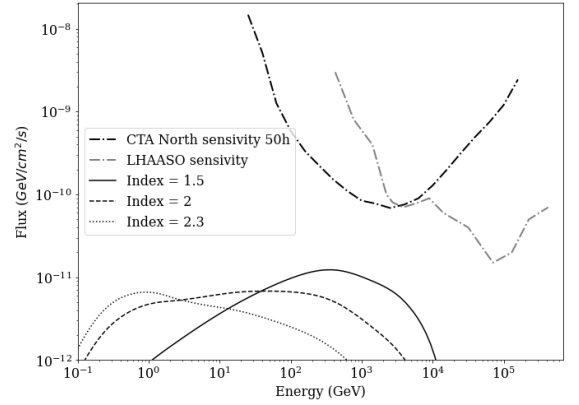


Fig. 4: Spectral flux from A2151CF for three values of spectral index. Other parameters were taken as in Table 1.

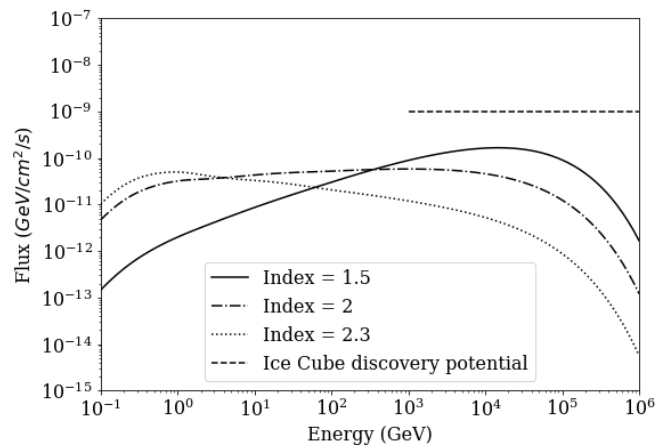


Fig. 5: Neutrino flux from the brightest subclump A2151CB with IceCube 5σ discovery potential at 1–1000 TeV [12].