SEARCH FOR DIFFUSE GAMMA-RAY EMISSION FROM GALAXY CLUSTERS WITH THE CHERENKOV TELESCOPE ARRAY

R. Adam[1] and the CTA consortium

Abstract. Galaxy clusters represent the last step of the formation of large-scale structures in the Universe. They are both useful cosmological probes and unique astrophysical laboratories. The clusters grow by accretion of surrounding structures and from the merging of subclusters, in very energetic events, eventually forming a diffuse gas phase made of a hot thermal component, but also leading to particle acceleration up to very high energies. One of the key science projects of the Cherenkov Telescope Array (CTA), the next generation array of imaging atmospheric Cherenkov telescopes, being built in La Palma (Spain) and Paranal (Chile), consists of the first unambiguous measurement of the diffuse gamma-ray emission associated with the interaction between the cluster cosmic rays protons and the thermal gas. Prospects for probing such a signal using CTA are discussed and we highlight what can be learned about cluster physics from such observations.

Keywords: Galaxy clusters, Intracluster medium, cosmic-rays, gamma-rays

1 Introduction

Galaxy clusters are the largest virialized structures in the Universe with masses up to 10^{15} M$_\odot$ (Voit 2005). The properties of their intracluster medium (ICM) are shaped by the hierarchical growth of structures through mergers and accretion. These dynamic events not only convert kinetic energy into heat but can also accelerate cosmic rays in the ambient magnetic fields (Brunetti & Jones 2014). Additionally, galaxies within these clusters may contribute to cosmic ray generation through active galactic nuclei (AGN) feedback and star formation processes (Fabian 2012).

Recent radio observations have provided direct evidence for the presence of cosmic ray electrons and magnetic fields in galaxy clusters (van Weeren et al. 2019). These observations have revealed various types of radio sources, including radio halos associated with cluster mergers and mini-halos in more relaxed clusters. Galaxy clusters are also expected to store cosmic ray protons (CRp) and heavier nuclei, injected into the ICM via various mechanisms. These CRp can interact with the thermal gas to produce gamma-ray emission (Dennison 1980; Blasi & Colafrancesco 1999), involving high-energy secondary electrons contributing to cluster-scale radio emission. Current theoretical models propose (re)acceleration of emitting electrons by turbulence and shocks, with the role of secondary electrons being debated. Cosmological simulations predict gamma-ray emissions but are subject to uncertainties in acceleration and transport physics (Enßlin et al. 2011; Brunetti & Jones 2014), emphasizing the importance of studying gamma-ray emissions from galaxy clusters.

The search for diffuse gamma-ray emissions from galaxy clusters has continued for over two decades (e.g., Reimer et al. 2003; Ackermann et al. 2014; Ahnen et al. 2016), but definitive detections are still pending, although some hints of a signal have been obtained towards the Coma cluster (Xi et al. 2018; Adam et al. 2021; Baghmanyan et al. 2022). Non-detections have constrained the CRp to thermal energy ratio to a few percent, challenging our understanding of these processes in the ICM, particularly when combined with radio data. Strict gamma-ray limits have also ruled out pure hadronic models for nearby radio halos and tested models involving the reacceleration of secondary particles, contributing to our comprehension of cosmic ray processes in galaxy clusters (Brunetti et al. 2017; Adam et al. 2021).

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[1] Laboratoire Lagrange, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Blvd de l'Observatoire, CS 34229, 06304 Nice cedex 4, France

The Cherenkov Telescope Array (CTA) is the next-generation ground-based gamma-ray observatory[*], offering exceptional sensitivity across a wide energy range (20 GeV to 300 TeV) and improved angular resolution (Cherenkov Telescope Array Consortium et al. 2019). CTA will operate from two locations, La Palma and Paranal, enabling observations of a significant portion of the sky. Its primary goals include the study of cosmic rays and dark matter. CTA will play a crucial role in searching for diffuse gamma-ray emissions from galaxy clusters, with one of the key projects focusing on the Perseus cluster, a promising target for such observations.

The Perseus cluster is a massive ($M_{500} \simeq 6 \times 10^{14}$ M$_\odot$) nearby (redshift $z = 0.017$) cluster with a dense core, with characteristics of a relaxed cool-core cluster. It hosts a radio mini-halo (e.g., Miley & Perola 1975; Gendron-Marsolais et al. 2020). Two cluster member AGNs, NGC 1275 and IC 310, have been identified as variable gamma-ray emitters (Abdo et al. 2009; Neronov et al. 2010). NGC1275 is the central galaxy and is associated with X-ray cavities, indicating significant feedback in the cluster center. Several other radio galaxies in the cluster were not detected in gamma rays but may still contribute to cosmic-ray injection into the ICM. The Perseus cluster is a prime target for gamma-ray searches due to its mini-halo in a very dense location, which concentrates hadronic collisions and secondary particle production. The cluster proximity implies that CTA can resolve the diffuse emission efficiently. Previous searches for gamma-ray emission in the Perseus cluster yielded no detection, setting upper limits on the cosmic-ray to thermal pressure ratio of about 1-2% (Ahnen et al. 2016).

Here, we summarize the current status of the study of the sensitivity of CTA to detect diffuse gamma-ray emission induced by cosmic rays from the Perseus cluster. The dark matter analysis was already discussed in Pérez-Romero & Consortium (2022) and the full analysis can be found in Cherenkov Telescope Array Consortium et al. (2023).

2   Modeling the diffuse gamma-ray emission

2.1   Modeling framework

The production of diffuse gamma-ray emission is expected due to the hadronic interaction between CRp and the thermal gas. We utilize the MINOT code (Adam et al. 2020), which calculates various observable ICM properties based on user-defined cluster conditions. Therefore we model the thermal gas density ($n_{\mathrm{gas}}(r)$) and pressure ($P_{\mathrm{gas}}(r)$), which provide the target particles and the thermal energy, respectively. Given the thermal gas model, we compute the X-ray and Sunyaev-Zel'dovich observables, which we use in combination with literature data (Churazov et al. 2003; Urban et al. 2014; Planck Collaboration et al. 2016), to calibrate the thermal model parameters. The thermal component is accurately described from the core to the outskirts and its uncertainties are negligible compared to the uncertainties associated with the non-thermal component. We consider the particle interactions to compute the gamma-ray production, but also the secondary cosmic-ray electrons. Assuming different models for the magnetic field strength profile, we compute the diffuse synchrotron emission arising from these electrons. The CRp population is modeled as a function of energy E (or momentum p) and radius r as

$$\frac{dN_{\mathrm{CRp}}}{dpdV}(E,r) = A_{\mathrm{CRp}} \; p^{-\alpha_{\mathrm{CRp}}} \; n_{\mathrm{gas}}(r)^{\eta_{\mathrm{CRp}}}, \tag{2.1}$$

where the normalization A_{CRp} is related to the parameter X_{CRp}, i.e. the CRp to thermal energy fraction within the characteristic radius R_{500}. The two other parameters are η_{CRp} and α_{CRp}, the spatial scaling with respect to the gas density and the spectral index of the CRp.

2.2   Calibration of the model parameters

The three model parameters, X_{CRp}, η_{CRp} and α_{CRp}, were estimated assuming two different scenarii. In the first scenario, we use the numerical simulation prediction (e.g., Pinzke & Pfrommer 2010) to set our model parameters to $X_{\mathrm{CRp}} = 10^{-2}$, $\eta_{\mathrm{CRp}} = 1$ and $\alpha_{\mathrm{CRp}} = 2.3$, i.e. the baseline model. In the second scenario, we assume that all the relativistic electrons arise from the same hadronic interactions that produce the gamma-rays, i.e. the (optimistic) pure hadronic model. We use the radio data from Pedlar et al. (1990); Gitti et al. (2002) to fit our model parameters and fix them to the best-fit values in the latter case.

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[*]https://www.cta-observatory.org/

3   Simulation, analysis and results

3.1   Sky model and CTA simulations

In order to simulate CTA-like data to be analyzed, we constructed a sky model by considering the two cluster scenarios discussed above. The two AGNs NGC 1275 and IC 310 were included according to MAGIC observations assuming low-state emission (Aleksić et al. 2014; Ahnen et al. 2016). We also included the instrumental background using the standard instrument response function[†]. The event simulations were performed accordingly using the `ctools` software (Knödlseder et al. 2016), for 300h of observing time.

3.2   Analysis and results

We first analyze the simulations to test the upper limits that will be obtained by CTA, in the cluster parameter space, in the case of non-detection. This is done by performing a likelihood fit to the data to set an upper limit on the normalization X_{CRp}, given η_{CRp} and α_{CRp}. The limits are reported in the right panel of Figure 1. CTA will improve the current MAGIC constraints by about an order of magnitude. We can also observe that in the case of non-detection, the pure hadronic scenario will be ruled out.

   We then reconstruct the spectrum and profile of the cluster assuming our two different scenarios (Figure 1, left panel, in the case of the pure hadronic model). We can see that in optimistic cases, CTA will be capable of constraining accurately both the spectrum and the profile of the cluster, which are related to the acceleration and transport physics of cosmic rays, although we note significant degeneracy between X_{CRp} and α_{CRp}.
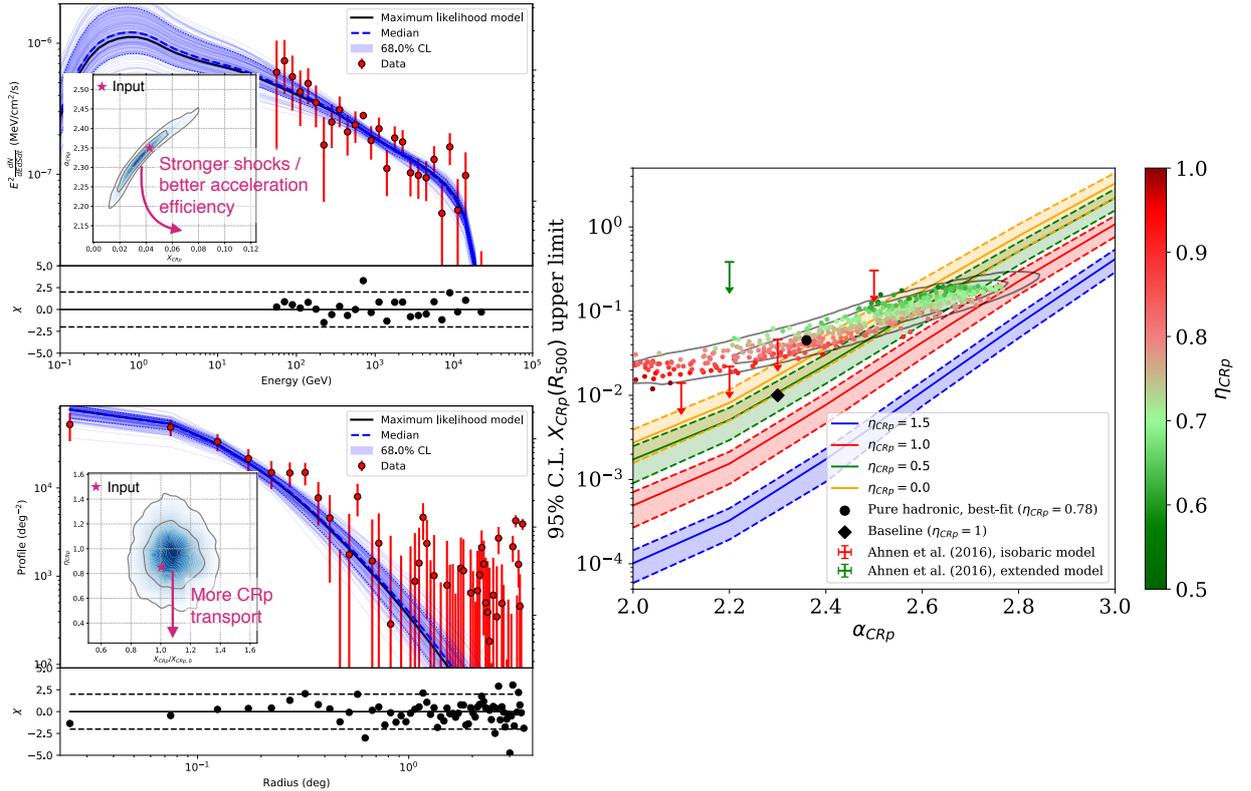

Fig. 1. Left: constraints on the spectrum (top) and profile (bottom) expected in the case of the best-fit pure hadronic model. **Right**: upper limits expected in the case of non-detection. The scattered points show the constraints on the pure hadronic model parameters, with colors indicating the value of η_{CRp}, and the black point giving the best-fit model.

[†]Available at `https://zenodo.org/record/5163273#.Y5nebbKZNQ0`.

4   Conclusions

In this study, we investigated the sensitivity of CTA to detect diffuse gamma-ray emissions from the Perseus galaxy cluster. We considered contributions from cosmic rays. The contribution from dark matter annihilation/decay has already been discussed elsewhere (Pérez-Romero & Consortium 2022) and the full analysis can be found in Cherenkov Telescope Array Consortium et al. (2023).

We developed a model for gamma-ray emissions induced by CRp using the MINOT software. This model incorporated information about thermal gas pressure and density, magnetic field strength, and the spatial and spectral distribution of CRp. We calibrated these components based on existing literature data. CRp parameters were calibrated for different scenarios, including a baseline and pure hadronic model. Additionally, we considered the background sky, accounting for two point sources that would impact CTA observations. Lastly, we assessed CTA's sensitivity to detect diffuse gamma-ray emissions.

Our main findings regarding gamma-ray emission are as follows. 1) The pure hadronic model, calibrated with existing radio data, suggests about 5% of CRp energy relative to thermal energy within R_{500}, with uncertainties mainly due to limited radio data coverage and magnetic field uncertainties. 2) CTA is expected to improve current limits on the CRp content in the Perseus cluster by about one order of magnitude, reaching a constraint of around 3×10^{-3} within R_{500} in a standard scenario. 3) Assuming the pure hadronic model, CTA should detect the diffuse emission from the ICM with high significance, providing precise constraints on the CRp spectral index and spatial distribution. Thus, the CTA observations of Perseus will address key questions about particle acceleration and transport mechanisms in the ICM.

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