MAGIC Gamma-ray Observations of the Perseus Galaxy Cluster

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Abstract: In order to detect the gamma-ray emission from cosmic ray (CR) interactions with the intra-cluster medium, the ground-based imaging Cherenkov telescope MAGIC conducted the deepest-to-date observational campaign targeting a galaxy cluster at very high-energies (≥ 100 GeV) and observed the Perseus cluster for a total of 85 hr during 2009–2011. The observations constrain the average CR-to-thermal pressure ratio to be 1–2% and the maximum CR acceleration efficiency at structure formation shocks to be < 50%. Alternatively, this may argue for non-negligible CR transport processes such as CR streaming and diffusion into the outer cluster regions. Additionally, assuming that the Perseus radio mini-halo is generated by secondaries created in hadronic CR interactions, the central magnetic field is limited to be > 4–9 µG. This range is well below the field strength inferred from Faraday rotation measurements and, therefore, the hadronic model remains a plausible explanation of the Perseus radio mini-halo. Following this successful campaign, MAGIC is continuing collecting data on Perseus.

Keywords: acceleration of particles, gamma rays, galaxy clusters, Perseus, MAGIC

1 Introduction
In the standard hierarchical model of structure formation, clusters of galaxies are the largest and latest objects to form through mergers of smaller galaxy groups. During these merger events, enormous amounts of energy — of the order of the final gas binding energy $E_{\text{bind}} \sim 3 \times (10^{61} - 10^{63})$ erg — are released through turbulence and collisionless shocks. This energy is dissipated on a dynamical timescale of about 1 Gyr and the corresponding energy dissipation rates are $L \sim (10^{45} - 10^{47})$ erg s$^{-1}$ (see [1] for a review). If only a small fraction of this energy is conveyed into non-thermal particles, the associated emission should be detectable in gamma-rays and could be used to decipher the history of structure formation.

Many galaxy clusters show large scale diffuse synchrotron radio emission in the form of so-called radio (mini-)halos which proves the existence of magnetic fields and relativistic electrons permeating the intra-cluster medium (ICM) [2]. Galaxy clusters should also be acceleration sites for relativistic protons and heavier relativistic nuclei, similarly to shocks within our Galaxy such as those in supernova remnants. Protons and heavier nuclei are accelerated more efficiently to relativistic energies with respect to electrons because of their higher masses. Therefore, we expected a ratio of the spectral energy flux of cosmic ray (CR) protons to CR electrons above 1 GeV of about 100 as it is observed in our Galaxy between 1–10 GeV [3]. CR protons also have cooling times that are longer than the age of the Universe, and hence can accumulate over the Hubble time in a galaxy cluster [4]. For typical gas density $n \sim 10^{-3}$ cm$^{-3}$ in galaxy clusters, the radiative cooling time of CR protons is much longer than the hadronic timescale, $\tau_{\text{pp}} \approx 30$ Gyr $\times (n/10^{-3}$ cm$^{-3}$)$^{-1}$, on which CR protons collide inelastically with ambient gas protons. This is the process in which we are primarily interested here as it generates charged and neutral pions that successively decay into synchrotron-emitting electrons/positrons and gamma-rays, respectively.

The Perseus cluster was selected for the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) observations as it is the most promising target for the detection of gamma-rays resulting from neutral pions produced in hadronic CR interactions with the ICM [5] [6] [7] [8]. This cluster of galaxies, at a distance of 77.7 Mpc ($z = 0.018$), is the brightest X-ray cluster with a luminosity in the soft X-ray band of $L_{\text{0.5-2.4 keV}} = 8.3 \times 10^{44}$ erg s$^{-1}$ [9]. It contains a massive cool core with high central gas densities of about 0.05 cm$^{-3}$ [10] and a luminous radio mini-halo with an extension of 200 kpc [11].
The MAGIC telescopes are two 17 m dish IACTs located at with a spectral index of about wobble mode, tracking positions 0 data sample consists of 84 due to non-optimal atmospheric conditions, and the final energies of interest here, i.e, above approximately 600 GeV, the Crab Nebula flux and the point spread function (PSF), defined as a 2-dimensional Gaussian, has a $\sigma \approx 0.06^\circ$. The Perseus cluster region was observed by the MAGIC telescopes from October 2009 to February 2011 for a total of about 99 hr [8, 13, 14]. Observations were performed in wobble mode, tracking positions 0.4° from the cluster center at low zenith angles (12°–36°). The data quality check resulted in the rejection of about 14 hr of data, mainly due to non-optimal atmospheric conditions, and the final data sample consists of 84.5 hr of effective observation time. The standard MAGIC stereo analysis chain was used for calibration and image cleaning [12].

Cosmological simulations suggest that the spectrum of CR-induced gamma-rays obeys a power-law, $F \propto E^{-\alpha}$, with a spectral index of about $\alpha \approx 2.2$ at the energies of interest here [5, 6]. The corresponding signal is extended. However, because of the dense gas in the cluster center, approximately 60% of the emission is coming from a region centered on NGC 1275 with a radius of 0.15°. NGC 1275 is a radio galaxy located at the center of Perseus and its emission is dominant below approximately 600 GeV with a spectral index of about 4 [14]. Therefore, we limit the analysis to energies above 630 GeV where the NGC 1275 signal is not detected. Figure 1 shows the significance skymap above 630 GeV. In contrast to NGC 1275, the spectrum of IC 310, another radio galaxy in the cluster, is very hard and remains detectable above 600 GeV [13]. IC 310 is $\sim 0.6^\circ$ (≈ 10 PSF) away from the cluster center and its highly variable emission does not leak into the signal region. Nevertheless, it can affect the background estimation and, therefore, we measure it with three off-source positions at 0.4° from the the camera center and > 0.28° away from IC 310 guaranteeing that there is no contamination.

As clear from Figure 1, we do not detect any gamma-ray emission coming from the center of the Perseus cluster above 630 GeV. Therefore, we derive integral flux upper limits (ULs) for several energy thresholds and for a spectral index of 2.2; we show them in Table 1. The ULs have been corrected to take into account the expected source extension comparing the fraction of the total events inside the signal region for a point-like source and for the expected CR-induced signal. Therefore, the ULs shown in Figure 2 can be compared with the theoretical expectations for the region within a radius of 0.15°. The UL estimation is performed using the Rolke method [15] with a confidence level of 95% and a total systematic uncertainty of 30%. The integral UL for energies above 1 TeV corresponds to the best sensitivity for sources with spectral index 2.2 and it is the most constraining value. Therefore, we will adopt the 1 TeV UL as reference value for the following discussion.

| $E_{\text{th}}$ [GeV] | $\sigma_{\text{LiMa}}$ PL | $N_{\text{UL}}$ PL | $F_{\text{PL}}$ UL | $F_{\text{UL}}$ |
|----------------------|-----------------|-----------------|-----------------|----------------|
| 630                  | 0.59            | 84.7            | 2.93            | 3.22           |
| 1000                 | 0.15            | 41.4            | 1.25            | 1.38           |
| 1600                 | 0.33            | 38.7            | 1.07            | 1.18           |
| 2500                 | 0.38            | 28.8            | 0.79            | 0.87           |

Table 1: Integral flux ULs $F_{\text{UL}}$ for a power-law gamma-ray spectrum with spectral index 2.2, above a given energy threshold $E_{\text{th}}$, in units of $10^{-13}$ cm$^{-2}$ s$^{-1}$. We show both the point-like (PL) and the 0.15° region cases. We also show the corresponding significance $\sigma_{\text{LiMa}}$ and ULs in number of events $N_{\text{UL}}$ (before applying the source extension correction).

3 Results and Discussion

In order to model the thermal pressure of the cluster, we adopt the measured electron temperature and density profiles of Perseus [10].

Considering a simplified analytical model that assumes a power-law CR momentum spectrum and a constant CR-to-thermal pressure ratio [16], we constrain this last quantity, $X_{\text{CR}} = P_{\text{CR}}/P_{\text{th}}$ (averaged within the virial radius of 2 Mpc), to be $< 0.77\%$ and 11.6% for $\alpha$ varying between 2.1 and 2.5. For a spectral index of 2.2, favored by simulations, we obtain $X_{\text{CR}} < 1.1\%$.

For a more realistic approach, we turn to cosmological hydrodynamical simulations and adopt the semi-analytical model developed by Pinzke & Pfrommer [6]. The normalization of the gamma-ray emission scales with the CR maximum acceleration efficiency at shocks. Motivated by recent observations and theoretical studies of supernova remnants, we assume that 50% of the dissipated energy at strong shocks is injected into CRs, while this efficiency rapidly decreases for weaker shocks.

These cosmological simulations only consider advective transport of CRs by turbulent gas motions which produces a centrally enhanced profile. However, CR transport phenomena, such as CR diffusion and streaming, flattens the CR radial profile, producing a spatially constant CR number density in the most extreme case [17, 18, 19]. This results in a bimodality of the CR spatial distribution, with most sensitivity (relaxed) cut (flat) CR density. As a consequence, relaxed clusters could have a reduced gamma-ray luminosity with respect to the simulation predictions.
In order to assess the biases associated with the insufficient numerical resolution of the simulations, as well as incompletely understood physical properties of the cluster plasma, we performed our analysis with two limiting cases bracketing the realistic case (see [5, 8] for details). In our optimistic CR model (simulation-based analytics with galaxies), we calculated the cluster total gamma-ray flux within a solid angle, while we cut the emission from individual galaxies and compact galactic-sized objects in our more conservative model (simulation-based analytics without galaxies). Figure 2 shows the corresponding spectrum for Perseus within an aperture of radius 0.15°. The MAGIC UL above 1 TeV falls below the flux level of the conservative model by 20%. Therefore, we find that X_Cr of the simulation-based analytical model have to be less than 1.6% within 0.15° (200 kpc). Assuming this spatial CR profile, we obtain a CR-to-thermal pressure ratio < 1.7% within the virial radius and < 5% within 20 kpc.

For the first time, the CR physics of galaxy clusters in the cluster central region at energies above 630 GeV where the significant excess of gamma-rays was detected from the radio mini-halo emission. The 4 Conclusions

MAGIC observed the Perseus cluster – the best target where to search for pion decays from CR hadronic interactions with the ICM – for a total of 85 hr between October 2009 and February 2011 [8]. This campaign represents the longest observation ever of a galaxy cluster at very high-energies (> 100 GeV) and resulted in the detection of the IC 310 [13, 21] and NGC 1275 [14, 22] radio galaxies. No significant excess of gamma-rays was detected from the cluster central region at energies above 630 GeV where the photon yield from NGC 1275 is negligible.

Using a simplified analytical approach, that assumes a power-law CR momentum spectrum and a constant CR-to-thermal pressure ratio, we can constrain X_Cr ≤ 0.8% and 12% for α varying between 2.1 and 2.5. For a spectral index of α = 2.2, favored by simulations, we find that X_Cr < 1.1%.

Adopting the simulation-based approach [6], we obtain X_Cr < 1.7%. This is a factor of 1.25 below the model and – for the first time – limits the underlying physics of the simulation distribution of CR electrons loses all its energy to synchrotron radiation for strong magnetic fields B > B_CMB [8], we can derive a minimum gamma-ray flux. This results to be a factor of 1.8 to 17.3 lower than our ULs for a spectral index between 2.1 ≤ α ≤ 2.5. The case of α = 2.2, as suggested by simulations, is shown in Figure 3. This is within the reach of future observations as the current MAGIC ULs are only a factor 3.2 higher.

We can turn this last argument around and use our gamma-ray ULs to derive a lower limit on the magnetic field value needed to explain the observed synchrotron radio emission within the hadronic scenario. The lower the gamma-ray limit, the higher the magnetic field needed to generate the radio emission.

First, we match the radio emission profile fixing the radial CR distribution for a given magnetic field model, B(r) = B_0 (n(r)/n(0))^{α_B}. We then require the gamma-ray flux from pion decays to match the MAGIC ULs, fixing the normalization of the CR distribution, and eventually obtain the lower limits on the magnetic field central value B_{0,min} shown in Table 2. They are in the 2–13 µG range for the values of α and α_B used in this study and suggested by radio observations. Both the thermal equipartition value in the center of Perseus, B_{eq,0} ≈ 80 µG, and Faraday rotation measurement (RM) estimates [20] are much higher than the magnetic field values obtained here. We therefore conclude that there is still considerable available phase space for the hadronic model as an explanation of the Perseus radio mini-halo emission.

4 Conclusions

MAGIC observed the Perseus cluster – the best target where to search for pion decays from CR hadronic interactions with the ICM – for a total of 85 hr between October 2009 and February 2011 [8]. This campaign represents the longest observation ever of a galaxy cluster at very high-energies (> 100 GeV) and resulted in the detection of the IC 310 [13, 21] and NGC 1275 [14, 22] radio galaxies. No significant excess of gamma-rays was detected from the cluster central region at energies above 630 GeV where the photon yield from NGC 1275 is negligible.

Using a simplified analytical approach, that assumes a power-law CR momentum spectrum and a constant CR-to-thermal pressure ratio, we can constrain X_{CR} < 0.8% and 12% for α varying between 2.1 and 2.5. For a spectral index of α = 2.2, favored by simulations, we find that X_{CR} < 1.1%.

Adopting the simulation-based approach [6], we obtain X_{CR} < 1.7%. This is a factor of 1.25 below the model and – for the first time – limits the underlying physics of the sim-
ulation. This could either indicate that the CR maximum acceleration efficiency at strong structure formation shocks is < 50% or may point to CR streaming and diffusion out of the cluster core region. This would lower the central $X_{\text{CR}}$ values and, correspondingly, the gamma-ray emission.

Adopting a strong magnetic field, $B \gg B_{\text{CMB}}$, everywhere in the radio-emitting region, we can estimate the minimum gamma-ray flux in the hadronic model of radio (mini-)halos. This is a factor of 2 to 18 below the MAGIC ULs for $\alpha$ varying between 2.1 and 2.5. For $\alpha = 2.2$, as suggested by simulations, the minimum gamma-ray flux is a factor of 3.2 lower than the MAGIC ULs, within the reach of future observations.

Finally, by matching the radio emission profile and requiring the pion-decay gamma-ray flux to match the MAGIC ULs, we obtain lower limits on the central magnetic field value in Perseus. The inferred values are $2 \mu G \leq B_{\text{0,min}} \leq 13 \mu G$ for the explored parameter space. Since this is smaller than recent field strengths estimates through Faraday RM studies in cool core clusters, the hadronic model is an interesting possibility for explaining the radio mini-halo emission.

This shows the potential of future gamma-ray observations of the Perseus cluster of galaxies to refine the parameters of the hadronic model, assessing its validity in explaining radio (mini)-halos. Indeed, the detection of the CR-induced gamma-ray emission could be within the reach of future observations. For this reason, MAGIC is extending this successful observation campaign and already accumulated additional 100 hr during 2012–2013.

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