Observation of the Perseus cluster of galaxies with the MAGIC telescopes

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The MAGIC telescopes performed a deep observation of the central region of the Perseus galaxy cluster in stereoscopic mode between October 2009 and February 2011. The nearly 85 hr of collected data (after quality selection) represent the deepest observation of a cluster of galaxies at very high energies (VHE, \(E > 100\) GeV) ever. The survey resulted in the detection of VHE \(\gamma\)-ray emissions from its central galaxy NGC 1275 and from the radio galaxy IC 310. In addition, the deep survey also permits for the first time to constrain emission models predicting VHE \(\gamma\)-rays from cosmic-ray acceleration in the cluster. In this contribution we report the latest MAGIC results concerning these topics.

I. INTRODUCTION

Clusters of galaxies are the latest objects to form in the Universe and represent the largest and most massive gravitationally bound systems, with radii of few Mpc and total masses \(M \approx (10^{14} - 10^{15}) M_\odot\), of which galaxies, gas, and dark matter (DM) contribute roughly for 5%, 15%, and 80% respectively (see e.g. [1] for a general overview).

Clusters of galaxies are very complex astrophysical environments, where a significant amount of very high energy (VHE, \(E > 100\) GeV) \(\gamma\)-ray emission is expected on the following general grounds. (i) Clusters are actively evolving objects and they should dissipate energies of the order of the final gas binding energy through merger and accretion shocks as well as turbulences, which are also likely to accelerate non-thermal electrons and protons to high energies [2]. (ii) Clusters are home of different types of energetic outflows of powerful sources such as radio galaxies [3] and supernova-driven galactic winds [4]. (iii) Clusters contain large amounts of gas with embedded magnetic fields often showing direct evidence for shocks and turbulence as well as relativistic particles [5]. Furthermore, galaxy clusters are characterized by very large mass–to–light ratios and considerable DM over-densities, and hence they could be considered as interesting targets for the search of emissions in the \(\gamma\)-ray regime from DM annihilation [6, 7] or decay [8]. However, the recently underlined very extended nature of the DM signal in clusters [6, 7] represents a major issue for the current generation of Cherenkov telescopes. The Perseus cluster, at a distance of 77.7 Mpc (\(z = 0.018\)), is the brightest X-ray cluster [9], hosting a massive cooling flow and a luminous radio mini-halo that fills a large fraction of the cluster core region [10]. The radio mini-halo is well explained by the hadronic scenario where the radio emitting electrons are produced in hadronic CR proton-proton interactions with intra-cluster medium (ICM) protons [11]. Additionally, the Perseus cluster hosts two very interesting objects, that have been recently detected at high energy (HE, \(100\) MeV \(< E < 100\) GeV) by Fermi–LAT, and at VHE by MAGIC, namely the two radio galaxies NGC 1275 and IC 310.

NGC 1275 is the central galaxy of the Perseus cluster and is of great interest due to its possible “feedback” role in the cluster environment (e.g. [12]), and for physics studies of relativistic outflows. Its classification varies between different papers and catalogues, and the complex structure of NGC 1275 including surrounding filaments leads to a peculiar morphology.
IC 310 is classified as head-tail radio galaxy, a type of active galactic nuclei only occurring in dense galaxy clusters [14], like the Perseus cluster. In 1999, it was suggested that IC 310 could be a dim blazar because of the absence of strong emission lines and the spectral indices on radio and X-ray measurements [15]. Later on it was also shown that the X-ray emission may originate from the central active galactic nucleus of a BL Lac-type object [16].

II. THE MAGIC TELESCOPES AND THE OBSERVATIONS OF THE PERSEUS CLUSTER

The MAGIC experiment consists of two 17 m dish Imaging Air Cherenkov Telescopes (IACTs) located on the Canary Island of La Palma (2200 m a.s.l.). The MAGIC telescopes are currently the largest existing IACTs. Since the end of 2009 the telescopes are working together in stereoscopic mode which ensures an excellent sensitivity of 0.8% of Crab Nebula flux above ~ 300 GeV in 50 hr of observations, and a trigger energy threshold of 50 GeV [17]. The angular and energy resolution at 100 GeV are 0.1° and 20% respectively. The stereoscopic observations improved the sensitivity achieved with the single telescope observations by a factor of ~2 for energies above few hundreds of GeV, and a factor ~3 for lower energies down to the threshold, which allows us to extend the observations carried out by the Fermi–LAT detector up to the TeV scale and without energy gaps. The Perseus galaxy cluster was carefully chosen over other nearby clusters as it is the most promising target for the detection of γ-rays originating from the neutral pion decays result of the hadronic cosmic-rays (CR) interactions with the ICM [18]. Additionally, the central radio galaxy NGC 1275 is a very promising GeV-TeV target [19, 20]. Hence it represents a good reason for the observation of this cluster at VHE.

The MAGIC experiment conducted the deepest survey ever made at VHE of the Perseus cluster, collecting data in both single telescope mode (~25 hr of MAGIC-I observations between November and December 2008) [21] and stereoscopic mode (~85 hr of observations between October 2009 and February 2011) [22, 23]. The source was observed in the false source tracking (wobble) mode [24], with data equally split in different pointing positions located symmetrically at 0.4° from NGC 1275, in order to ensure optimum sky coverage and background estimates. The survey was carried out during dark time at low zenith angles (from 12° to 36°), which guaranteed the lowest energy threshold. The analysis of the data was performed using the standard MAGIC software [25], taking advantage (for the stereoscopic data) of newly developed analysis routines [17, 27]. These observations resulted in the discovery of IC 310 [28] and NGC 1275 as VHE γ-ray emitters, as shown in figure 1.

III. MAGIC-I OBSERVATION OF THE PERSEUS CLUSTER

The Perseus galaxy cluster was observed by the MAGIC-I telescope for a total observation time (after data selection) of 24.4 hr during November – December 2008. No significant excess was found in the data [22]. The integral flux upper limits (at 95% confidence level) were compared to the simulated flux of the γ-ray emission from decaying neutral pions that result from hadronic CR interactions with the ambient gas in the Perseus cluster [11], allowing to constrain the average CR-to-thermal pressure to < 4% for the cluster core region and to < 8% for the entire cluster (see figure 2).

IV. STEREOSCOPIC OBSERVATIONS OF THE PERSEUS CLUSTER

The Perseus galaxy cluster region was observed by the MAGIC telescopes (in stereoscopic mode) during two distinct campaigns. The first one was carried out between October 2009 and February 2010, for a total observation time of 45.3 hr. This survey resulted in the discovery of the radio galaxy IC 310 as VHE emitter [28]. The latest campaign (total observation time of 53.6 hr), which resulted in the discovery of NGC 1275 at VHE (ATel#2916) [24], was performed between August 2010 and February 2011. The whole stereoscopic data sample (~85 hr after
data selection) was used to investigate a possible signal from CR hadronic interactions. For this purpose, the analysis was restricted to energies where the central radio galaxy NGC 1275 is not emitting \([22]\), i.e. approximately above 600 GeV. No CR induced emission is detected above those energies, and the preliminary integral flux upper limit above 1 TeV (at 95% confidence level) are about a factor \(\sim 3\) more constraining that those achieved with the MAGIC-I mono observation. This permits to significantly tighten the previous constraints, and to start to probe the acceleration physics of CR at structure formation shocks. The estimation and interpretation of the flux upper limits are ongoing and the corresponding paper is under preparation \([24]\).

A. Discovery of VHE emission from IC 310

The radio galaxy IC 310 (redshift \(z=0.019\)) is located at a distance of 0.6° from the cluster’s central galaxy, NGC 1275. The source has been discovered in 2010 by the Fermi-LAT detector at HE \([28]\) and by MAGIC at VHE \([28]\). The combined MAGIC and Fermi–LAT spectrum is consistent with a flat spectral energy distribution stretching without a break over more than 3 orders of magnitude in energy (2 GeV - 7 TeV), as shown in figure 3. The spectrum at VHE measured by MAGIC has a spectral index of \(\Gamma = -2.00 \pm 0.14\), and the mean flux above 300 GeV, between October 2009 and February 2010, is \(F_\gamma = (3.1 \pm 0.5) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}\). Hints of week to year time-scale variability were seen in the MAGIC data (see figure 3).

B. Discovery of VHE emission from NGC 1275

The central cluster radio galaxy NGC 1275 was first detected in the HE \(\gamma\)-ray regime by the Fermi–LAT detector \([19]\), during the first four months of all-sky-
angular distance between the arrival direction of the events and the nominal source position [31]) of the signal coming from NGC 1275 and of the background (estimated from 3 distinct regions), for energies above 100 GeV. An excess of 521.9 ± 80.5 events, corresponding to a 6.6σ significance (calculated according to the equation 17 in [32]) was found. The observed flux is estimated to be ∼2.5% of the Crab Nebula flux above 100 GeV, and it decreases rapidly with energy. No signal is detected approximately above 600 GeV. A dedicated paper concerning this discovery is in preparation [23].

V. CONCLUSIONS

We presented the results achieved so far from the deep survey of the Perseus cluster of galaxies at VHE carried out by the MAGIC experiment, both in mono (∼25 hr) and stereo (∼85 hr) data taking mode. Mono observations permitted to constrain the average CR-to-thermal pressure to < 4% for the cluster core region and to < 8% for the entire cluster [22]. The implications of the significantly tighter upper limits from the stereo observations are currently under investigation and will be published in a forthcoming paper [24]. The stereoscopic observation of the Perseus cluster resulted on the discovery of two VHE γ-ray sources: the radio galaxy IC 310 [28], which is characterized by a flat spectrum in the GeV to TeV range with hints of year to week time-scale variability, as well as the central cluster radio galaxy NGC 1275 (ATel#2916) [23] which has been detected below 600 GeV, thanks to the excellent sensitivity of the MAGIC stereoscopic system in that energy range.

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