Observation of the Perseus galaxy cluster with the MAGIC telescopes

SAVERIO LOMBARDI[1], FABIO ZANDANEL[2], PIERRE COLIN[3], MICHELE DORO[4], DOROTHEE HILDEBRAND[5], FRANCISCO PRADA[2] FOR THE MAGIC COLLABORATION, AND CHRISTOPH PFROMMER[6], ANDERS PINZKE[7]
[1] *Università di Padova and INFN, I-35131 Padova, Italy*
[2] *Instituto de Astrofísica de Andalucía (IAA-CSIC), E-18080 Granada, Spain*
[3] *Max-Planck-Institut für Physik, D-80805 München, Germany*
[4] *Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain*
[5] *ETH Zurich, 8093 Zurich, Switzerland*
[6] *Heidelberg Institute for Theoretical Studies (HITS), D-69118 Heidelberg, Germany*
[7] *UCSB, California, USA*

saverio.lombardi@pd.infn.it

Abstract: The MAGIC ground-based Imaging Cherenkov experiment observed the Perseus galaxy cluster for a total of about 25 hr between November and December 2008 in single telescope mode and for nearly 90 hr between October 2009 and February 2011 in stereoscopic mode. This survey represents the deepest observation of a cluster of galaxies at very high energies ever. It resulted in the detection of the central radio galaxy NGC 1275 and the head-tail galaxy IC 310. It also permits for the first time to put constraints on emission models predicting γ-rays from cosmic ray acceleration in the cluster and to investigate dark matter scenarios. Here, we will report the latest MAGIC results on these studies.

Keywords: Cluster of galaxies, Perseus, very high energy γ-rays, Cosmic rays, Dark Matter, MAGIC

1 Introduction

In the cosmological hierarchic clustering model [1], large-scale structures grow hierarchically through merging and accretion of smaller systems into larger ones, and thus clusters of galaxies are the latest objects to form. These astrophysical environments represent therefore the largest and most massive gravitationally bound systems in the Universe, with radii of few Mpc and total masses $M \sim (10^{14} - 10^{15}) M_{\odot}$, of which galaxies, gas, and dark matter (DM) contribute roughly for 5%, 15% and 80%, respectively (see e.g. [2, 3] for general overviews).
Cluster of galaxies are expected to be significant γ-ray emitters on the following general grounds. (i) Clusters are actively evolving objects and being assembled today, in the latest and most energetic phase of hierarchical structure formation [4], 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 [5, 6, 7]. (ii) Clusters are home of different types of energetic outflows of powerful sources such as radio galaxies [4] and supernova-driven galactic winds [8], and the intra-cluster medium (ICM) can function as an efficient energy reservoir. (iii) Clusters contain large amounts of gas with embedded magnetic fields – the ICM is known to be permeated by magnetic fields with strengths $B \sim 1 - 10$ μG [9] – often showing direct evidence for shocks and turbulence as well as relativistic particles [10]. Additionally, galaxy clusters present very large mass–to–light ratios and considerable DM overdensities, which are considered crucial for indirect DM searches [11, 12]. Despite the fact that they are not as near as other potential DM candidates, like for instance the dwarf spheroidal galaxies [13, 14, 15], the large DM masses of clusters could make them ideal laboratories for the search of emissions in the γ-ray regime from DM annihilation [11, 12] or decay [16]. However, the recently underlined very extended nature of the DM signal in clusters [11, 12] is a major issue for the current generation of Cherenkov telescopes.

2 The Perseus cluster and its observation with the MAGIC telescopes

The Perseus cluster, at a distance of 77.7 Mpc (z = 0.018), is the brightest X-ray cluster [17], hosting a massive cooling flow and a luminous radio mini-halo that fills a large fraction of the cluster core region [18]. 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 ICM protons requiring only a very modest fraction of a few percent of CR-to-thermal pressure [19].

The Perseus galaxy cluster was carefully chosen over other nearby clusters as it is the most promising target for the detection of γ-rays coming from the neutral pion decays result of the hadronic cosmic rays (CR) interactions with the ICM [20]. Moreover, the huge DM content of the cluster represents an additional strong motivation. Additionally, the central radio galaxy NGC 1275 is a very interesting GeV-TeV target, and hence it is a further reason for the observation of this cluster [21] at very high energies (VHE).

The MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) experiment consists of two 17 meter Imaging Air Cherenkov Telescopes (IACTs) located on the Canary Island of La Palma (28.8°N, 17.8°W), 2200 meters above the sea level. The MAGIC telescopes are currently the largest world-wide existing IACTs. Since fall 2009 the telescopes are working together in stereoscopic mode which ensures an excellent sensitivity of $\sim$0.8% of Crab Nebula flux above $\sim$250 GeV in 50 hr of observations and an analysis threshold of $\sim$50 GeV [22].

The MAGIC experiment conducted the deepest survey ever made at VHE of the Perseus cluster, collecting data both in single telescope mode ($\sim$25 hr of MAGIC-I observations, between November and December 2008 [21]) and in stereoscopic mode ($\sim$90 hr of observations, between October 2009 and February 2011). The data were taken during dark nights at zenith angles below 35° (which guarantees a low analysis energy threshold) in false-source tracking (wobble) mode [23], in which the pointing direction alternates every 20 minutes between different positions symmetrically offset by 0.4° from the source. The data analysis was performed using the standard MAGIC analysis and reconstruction software [24]. These observations resulted in the detection of VHE emission from the head-tail radio galaxy IC 310 [25] as well as the central radio galaxy NGC 1275 (ATel#2916). A discussion of these two discoveries is presented elsewhere in this conference [26].

3 Results and Discussion

3.1 MAGIC-I observations

MAGIC-I observations of the Perseus cluster took place during November and December 2008 resulting in a total effective time, after data selection, of 24.4 hr [21]. No significant excess was found in the data.

The integral flux upper limits computed for different energy thresholds and for a supposed power law spectrum with spectral index of -2.2, as expected for the CR induced γ-ray emission in the energies of interest here [20], are reported in Table 1. These upper limits are compared to the simulated flux of the γ-ray emission from decaying neutral pions that result from hadronic CR interactions with the ICM [20] in Figure 1. The upper limits are a factor of two above our conservative model implying consistency with the cluster cosmological simulations of [20], allowing to constrain the average CR-to-thermal pressure to $< 4\%$ for the cluster core region and to $< 8\%$ for the entire cluster. Using simplified assumptions adopted in earlier work, i.e. a power-law spectrum with an index of -2.1, and a constant CR-to-thermal pressure for the peripheral cluster regions while accounting for the adiabatic contraction during the cooling flow formation, we would limit the ratio of cosmic ray-to-thermal energy to $\mathrm{E_{CR}}/\mathrm{E_{th}} < 3\%$.

$\mathrm{E_{th}}$ [GeV]	Φ^{UL} [$\times 10^{-12}$ cm^{-2} s^{-1}]
100	6.55
130	6.21
160	6.17
200	5.49
250	4.59
320	3.36
400	1.83
500	1.39
630	0.72
800	0.65
1000	0.47

Table 1: MAGIC-I observation integral flux upper limits, at 95% confidence level, for a power-law γ-ray spectrum with spectral index of -2.2 above different energy threshold $\mathrm{E_{th}}$.

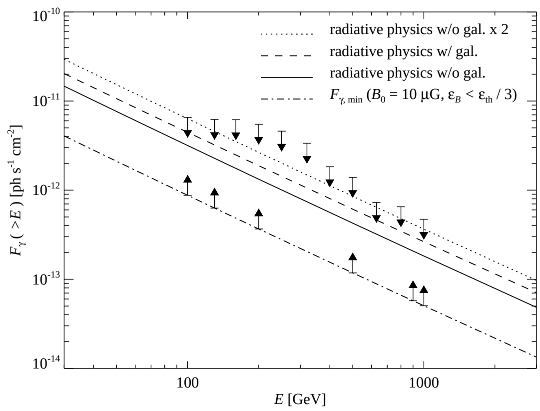

Figure 1: Comparison between the MAGIC-I observation integral flux upper limits (upper arrows) and the simulated integrated spectra of the CR induced γ-ray emission of the Perseus cluster [20]. The conservative model without galaxies (solid) is contrasted to the model with galaxies (dashed) and it is scaled with a factor of 2 so that it is just consistent with the upper limits obtained in [21] (dotted). Additionally shown is the minimum γ-ray flux estimated for the hadronic model of the radio mini-halo of the Perseus cluster (dash-dotted with arrows). Note that a non-detection of γ-rays at this level seriously challenges the hadronic model. See [21] for details.

The MAGIC-I data were also interpreted in terms of a potential DM annihilation emission [21]. The Perseus cluster DM density profile was modeled with a typical Navarro-Frank-White (NFW) profile [27] and the DM particle was assumed to be the *neutralino* within the mSUGRA scenario [28], considering one of the most optimistic value for the particle physics factor for the energies of interest here [29]. The resulting expected γ-ray flux above the energy threshold of 100 GeV is then $\Phi_{\rm DM,th} = 1.4 \times 10^{-16}$ cm^{-2} s^{-1}. The corresponding integral flux upper limit, computed for a generic DM annihilation spectrum modeled as a power-law with spectral index of -1.5, is $\Phi^{\rm UL}$(>100 GeV)$= 4.63 \times 10^{-12}$ cm^{-2} s^{-1}. This means that a boost in the flux of the order of 10^4 is needed to reach the predicted DM annihilation flux. This boost factor could come from different mechanisms (not taken into account in the calculation of $\Phi_{\rm DM,th}$) that may enhance the annihilation γ-ray flux notably, such as the presence of DM substructures [30, 31] and the Sommerfeld effect [32, 33].
However, the above results, obtained without considering the contribution of DM substructures, should be substantially revised after two recent works [11, 12] that highlighted the strong contribution of subhaloes, which make the DM density profile extremely flat up to large distances from the core for all clusters (1.2° in the case of Perseus).

3.2 Stereo observations

The MAGIC telescopes observed the Perseus galaxy cluster in stereoscopic mode between October 2009 and February 2011 for a total effective time, after data selection, of about 90 hr. The observation resulted in the detection of VHE emission from the head-tail radio galaxy IC 310 [25] as well as the central radio galaxy NGC 1275 (ATel$\#$2916) which are shown in the significance skymap above 150 GeV of Figure 2 (IC 310 and NGC 1275 discoveries are presented elsewhere in this conference [26]).
To investigate a possible signal from CR hadronic interactions, we limit the analysis to energies where the central radio galaxy NGC 1275 is not emitting, i.e. approximately above 600 GeV. This is shown in the θ^2 plot calculated from the overall stereo data sample in Figure 3. We conclude that no CR induced emission is detected at energies above 630 GeV, where we only observe background fluctuations. The preliminary integral flux upper limit above that energy and assuming a power law spectrum with spectral index of -2.2 is $\Phi^{\rm UL} = 0.3 \times 10^{-12}$ cm^{-2} s^{-1}.
With the nearly 90 hr of stereo observation, we are now able to significantly tighten the constraints on the CR-to-thermal pressure obtained with the MAGIC-I observation [21]. For the first time, we can put strong constraints on the hadronic model of radio mini-halo emission, potentially starting to probe the acceleration physics of CRs at structure formation shocks. In fact, using the preliminary integral flux upper limit above 630 GeV, we would be able to constrain a combination of the assumed acceleration efficiency and CR transport parameters in the conservative model *radiative physics without galaxies*, shown with a solid line in Figure 1. However, we caution that this upper limit is only a preliminary estimate. A publication is in preparation and will be available soon.

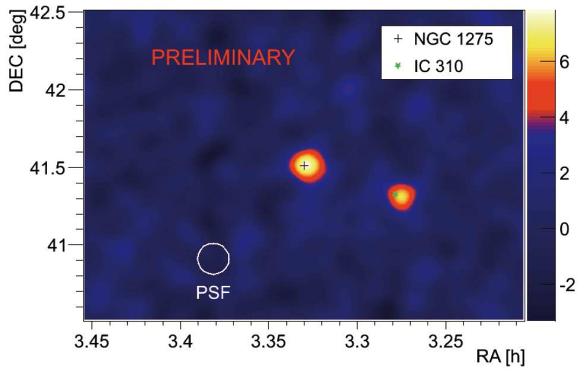

Figure 2: MAGIC stereo significance skymap of the Perseus cluster region above 150 GeV. For this map the overall stereo data sample of about 90 hr have been used. NGC 1275 is clearly detected at the center of the cluster (ATel$\#$2916) and IC 310 is also visible in the map [25].

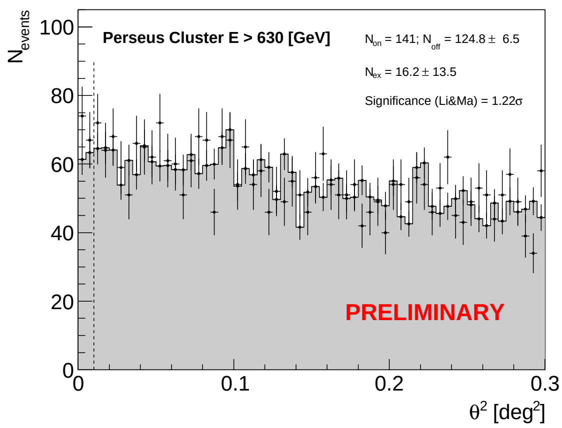

Figure 3: MAGIC stereo θ^2 plot above 630 GeV. The black points represent the *signal* while the gray shaded region is the *background*. The vertical dotted line represents the *signal region* where a point-like emission is expected. No significant γ-ray excesses are seen above that energy.

4 Summary

We present 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 (~90 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. Using simplified assumptions adopted in earlier work (i.e. a power-law spectrum with index of -2.1 and constant CR-to-thermal pressure for the peripheral cluster regions while accounting for the adiabatic contraction during the cooling flow formation) would allow us to limit the ratio of cosmic ray-to-thermal energy to $E_{\rm CR}/E_{\rm th} < 3\%$.
Stereo observations permit to significantly tighten the previous constraints. This is made possible due to the fact that detection of the central cluster radio galaxy NGC 1275 [26] does not affect the higher energies (in fact, no signal is detected above approximately 600 GeV). This enables us to start to probe the acceleration physics of CRs at structure formation shocks. The estimation and interpretation of the flux upper limits, however, are still ongoing and a corresponding paper is under preparation.

5 Acknowledgements

We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN, the Swiss National Fund SNF, and the Spanish MICINN is gratefully acknowledged. This work was also supported by the Marie Curie program, by the CPAN CSD2007-00042 and MultiDark CSD2009-00064 projects of the Spanish Consolider-Ingenio 2010 programme, by grant DO02-353 of the Bulgarian NSF, by grant 127740 of the Academy of Finland, by the YIP of the Helmholtz Gemeinschaft, by the DFG Cluster of Excellence "Origin and Structure of the Universe", by the DFG Collaborative Research Centers SFB823/C4 and SFB876/C3, and by the PolishMNiSzW-grant 745/N-HESSMAGIC/2010/0.

References

[1] Peebles, P. J. E. 1993, *Principles of physical cosmology*, Princeton University Press
[2] Sarazin, C. L. 1988, *X-ray emission from clusters of galaxies*, Cambridge University Press
[3] Voit, G. M. 2005, Reviews of Modern Physics, 77, 207
[4] Forman, W. *et al.* 2003, arXiv:astro-ph/0301476v1
[5] Sarazin, C. L. 2002, ASSL, 272, 1
[6] Miniati, F. 2003, MNRAS, 342, 1009
[7] Pfrommer, C. 2008, MNRAS, 385, 1242
[8] Völk, H. J., Aharonian, F. A. & Breidschwerdt, D. 1996, SSR, 75, 27
[9] Vogt, C. & Enßlin, T. A. 2003, A&A, 412, 373
[10] Feretti, L. 2003, ASP, 301, 143
[11] Sánchez-Conde, M. A. *et al.* 2011, arXiv:1104.3530v1
[12] Pinzke, A., Pfrommer, C. & Bergström, L. 2011, arXiv:1105.3240v1
[13] Albert, J. *et al.* 2008, ApJ, 679, 428
[14] Aliu, E. *et al.* 2009, ApJ, 697, 1299
[15] Aleksić, J. *et al.* 2011, arXiv:1103.0477v1
[16] Cuesta, A. J. *et al.* 2011, ApJL 726, L6
[17] Edge, A. C., Stewart, G. C. & Fabian, A. C. 1992, MNRAS, 258, 177
[18] Pedlar, A. *et al.* 1990, MNRAS, 246, 477
[19] Pfrommer, C. & Enßlin, T. A. 2004, A&A, 413, 17
[20] Pinzke, A. & Pfrommer, C. 2010, MNRAS, 409, 449
[21] Aleksić, J. *et al.* 2010, ApJ, 710, 634
[22] Carmona, E. *et al.* 2011, these proceedings
[23] Fomin, V. P. *et al.* 1994, Astropart.Phys., 2, 137
[24] Lombardi, S. *et al.* 2011, these proceedings
[25] Aleksić, J. *et al.* 2010, ApJL, 723, L207
[26] Hildebrand, D. *et al.* 2011, these proceedings
[27] Navarro, J. F., Frenk, C. S. & White, S. D. M. 1997, ApJ, 490, 493
[28] Chamseddine, A. H., Arnowitt, R. & Nath, P. 1982, Phys. Rev. Lett., 49, 970
[29] Sánchez-Conde, M. A. *et al.* , 2007, Phys. Rev. D, 76, 123509
[30] Kuhlen, M., Diemand, J. & Madau, P. 2008, ApJ, 686, 262
[31] Springel, V. *et al.* , 2008, MNRAS, 391, 1685
[32] Lattanzi, M. & Silk, J. 2009, Phys. Rev. D, 79, 083523
[33] Pinzke, A., Pfrommer, C. & Bergström, L. 2009, Phys. Rev. Lett., 103, 181302