New results from HESS observations of galaxy clusters

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***Abstract*. Clusters of galaxies are believed to contain a significant population of cosmic rays. From the radio and probably hard X-ray bands it is known that clusters are the spatially most extended emitters of non-thermal radiation in the Universe. Due to their content of cosmic rays, galaxy clusters are also potential sources of VHE (>100 GeV) gamma rays. Recently, the massive, nearby cluster Abell 85 has been observed with the H.E.S.S. experiment in VHE gamma rays with a very deep exposure as part of an ongoing campaign. From the non-detection of Abell 85 with H.E.S.S. upper limits on the total energy of hadronic CRs in the cluster are calculated. If the cosmic-ray energy density follows the large scale gas density profile, the limit on the fraction of energy in these non-thermal particles with respect to the total thermal energy of the intra-cluster medium is 8% for this particular cluster. This implies a meaningful constraint on current models.**

***Keywords*: gamma-ray observations; galaxy clusters; Abell 85**

I. Introduction

Galaxy clusters, the most massive gravitationally bound systems in the Universe, are the spatially most extended emitters of non-thermal radiation in the Universe. Radio observations show most significantly the presence of accelerated electrons in these systems [1], [2]. Additionally, it is also expected that clusters contain a significant population of hadronic cosmic rays since they act as storehouses for hadronic cosmic rays. Due to their spatial extension and due to the presence of magnetic fields in the μG range, clusters confine and accumulate cosmic ray protons with energies of up to $\sim 10^{15}$ eV which were accelerated in the cluster volume [3], [4].

Cosmic rays can be accelerated at several sites in galaxy clusters. These sites can be divided into external and internal sources of cosmic rays. In external mechanisms large-scale shock waves connected to cosmological structure formation are accelerators of non-thermal particles [5], [6], [7]. Particles can also be accelerated by turbulence in the intra-cluster medium(ICM) generated by major sub-cluster merger events (e.g. Brunetti et al. [8]). In internal mechanisms processes launched by the cluster galaxies lead to production of cosmic rays. Supernova remnant shocks and galactic winds have the ability to produce high-energy particles [3]. Additionally, active galactic nuclei (AGNs) can distribute non-thermal particles in the cluster volume [9], [10], [11].

A component of high energy particles should result in gamma-ray emission in galaxy clusters (see e.g. [12] for a recent review). Both cosmic ray protons and nuclei and cosmic ray electrons have the ability to generate gamma rays. Hadronic cosmic rays can produce gamma rays through inelastic collisions with thermal protons and nuclei as targets and subsequent π^0 decay [13], [3]. Alternatively, leptonic cosmic rays with sufficiently high energies can up-scatter cosmic microwave background (CMB) photons to the gamma-ray range in inverse Compton processes [14], [15], [16].

Despite the arguments for potential gamma-ray emission given above, no galaxy cluster has firmly been established as a gamma-ray source. Upper limits have been inferred from EGRET observations for a number of prominent galaxy clusters [17]. In the very-high energy gamma-ray range (VHE, E $>$ 100 GeV) upper limits have been reported for several clusters by the *Whipple* [18] and *H.E.S.S.* collaboration [19], [20].

II. The H.E.S.S. experiment

The observations were performed with the H.E.S.S. telescope array, consisting of four imaging atmospheric Cherenkov telescopes located at the Khomas highlands in Namibia. See [21] for a description of the system. It has a field of view of $\sim 5^\circ$ and observes in the VHE gamma-ray regime. The whole system is well suited to study galaxy clusters since due to its large field of view, H.E.S.S. can detect extended sources and it is expected that clusters feature extended VHE gamma-ray emission.

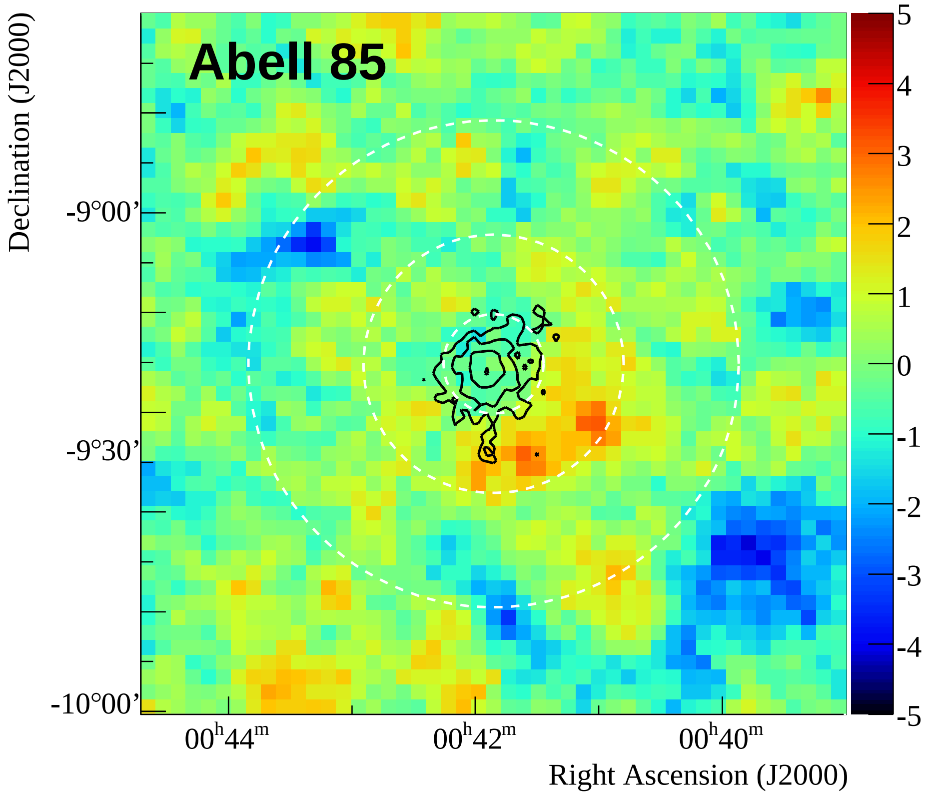

Fig. 1. Sky map of Abell 85 obtained with H.E.S.S. The black contours are from ROSAT PSPC X-ray observations. The dashed circles show radii of 0.4 Mpc, 1 Mpc and 1.9 Mpc. For details see main text.

III. Target Abell 85

The target clusters were selected in terms of optimal detectability, position and distance for an observation with H.E.S.S. Promising targets of this kind should be located on the southern hemisphere and at a redshift not larger than z $\sim$ 0.06, since more distant objects suffer substantial absorption from extragalactic background light. Furthermore, there should be no blazar at the location of the cluster which could superpose potential VHE emission of the galaxy cluster. In this paper the results of observations of the galaxy cluster Abell 85 with the H.E.S.S. experiment are presented. Abell 85 is a nearby (z = 0.055) massive and hot (T $\approx$ 7 keV) galaxy cluster with a complex morphology[22], [23]. It hosts a colling core at its center. In cooling core clusters, the central gas density is large enough that the radiative cooling time due to thermal X-ray emission of the intracluster gas is shorter than the age of the galaxy cluster. Additionally, it shows two sub-clusters merging with the main cluster which is quite uncommon for a cooling core cluster. Presumably the merging sub-clusters have not reached the central region of the main cluster and have therefore not disrupted the existing cooling core [22].

IV. Results

Abell 85 has been observed with H.E.S.S. for 32.5 hours live time of good quality in October and November 2006 and in August 2007. The mean zenith angle of the observations was 18° which resulted in an energy threshold of 460 GeV. H.E.S.S. standard data analysis was performed using different geometrical size cuts to account for the extended nature of the target [20]. The integration radii are chosen according to characteristic length scales of the density profile of the ICM, which acts as the target material for hadronic gamma-ray production. None of the probed regions showed a significant gamma-ray excess and hence upper limits have been derived (see Fig. 1). For obtaining the upper limits the approach of Feldman & Cousins [24] assuming a spectral index of the emission of -2.1 was used. The first region for which an upper limit has been calculated is the high gas density core region. For a radius of 0.1° (0.4 Mpc at the object) around the cluster center a flux upper limit of F (>460 GeV) $< 3.9 \times 10^{-13}$ ph. cm^{-2} s^{-1} has been found. As a next area, a radius of the size of the detected thermal X-ray emission of the cluster of 0.49° (1.9 Mpc) has been investigated. Here the upper limit in VHE gamma-ray flux is F (>460 GeV) $< 1.5 \times 10^{-12}$ ph. cm^{-2} s^{-1}. Finally potential emission connected to the accretion shock at the outskirts of the cluster has been searched. Therefore a very extended region with a radius of 0.91° (3.5 Mpc) has been explored. For this case the data set is reduced to 8.6 live hours due to the lack of suitable off-source data for the background estimation and there the flux upper limit was determined to

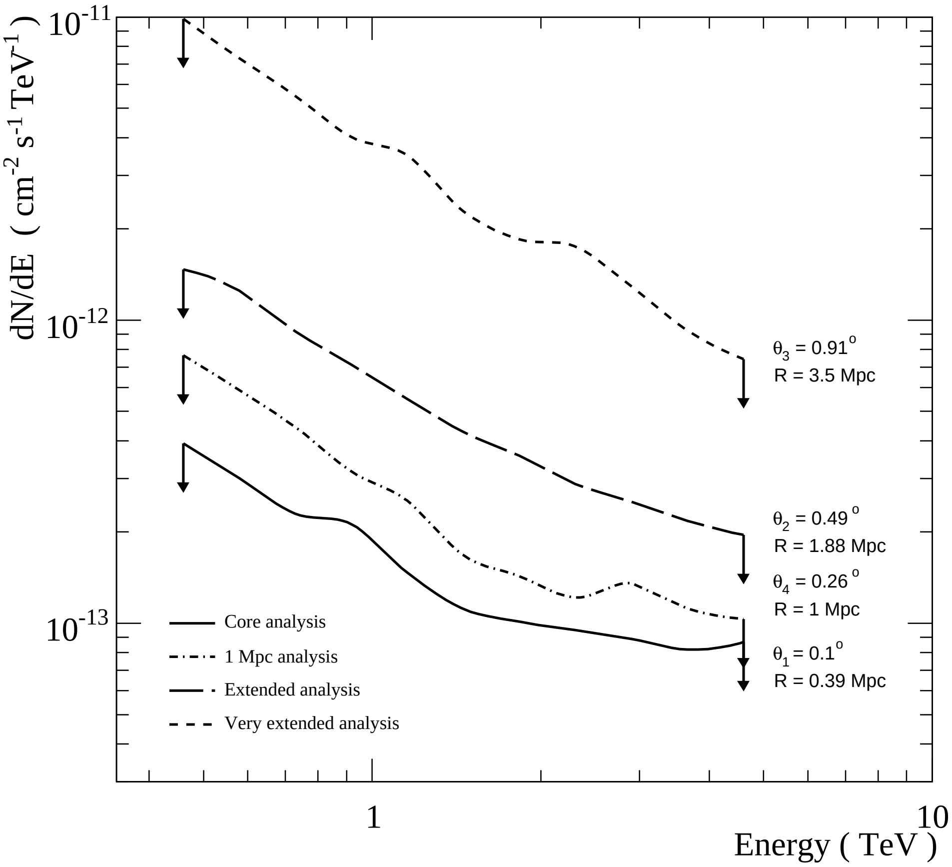

Fig. 2. Upper limits on gamma-ray emission from Abell 85 for various integration regions as a function of energy. For a description of the different geometrical size cuts see main text.

F (>460 GeV) $< 9.9 \times 10^{-12}$ ph. cm^{-2} s^{-1}. The upper limits on gamma-ray emission from Abell 85 for various integration regions as a function of energy can be see in Fig 2.

V. Discussion

From the upper limits of the gamma-ray luminosity of the cluster Abell 85 it is possible to estimate upper limits on the total energy in hadronic cosmic rays in this cluster. For this purpose a spectral index of the cosmic rays of -2.1 is adopted and these limits are calculated for three different assumptions on the spatial distribution of cosmic rays. A hard spectral index seem to be realistic since no losses of hadronic cosmic rays at relevant energies occur in clusters and therefore the source spectrum of cosmic rays should be seen [3], [4]. Firstly for the spatial distribution of the energy density in cosmic rays a scenario is adopted where it is constant throughout the cluster volume. Secondly it is assumed that the distribution of cosmic rays follows the large scale distribution of the gas density excluding the central cooling core. And thirdly it is presumed that the cosmic rays are very centrally concentrated in clusters and their distribution follow gas density profile including the central cooling core. Within a radius of 1 Mpc for the three different models of cosmic ray concentration it is found that the total energy in cosmic rays is less than 15% (constant distribution,) 8% (cosmic rays follow gas density without cooling core) and 6% (cosmic rays follow gas density including cooling core) of the thermal energy of the intra-cluster medium [20]. It has to be noted that magneto-hydrodynamic instabilities disfavor very centrally peaked distributions of cosmic rays [25], [26] and an upper limit on the energy of cosmic rays of 8% seems to be realistic. This value is at the lower bounds of model predictions. Similar results have very recently also been inferred from deep radio observations for the galaxy cluster Abell 521 [27]. Therefore it seems quite likely that the next generation of gamma-ray observatories like CTA will be necessary to detect galaxy clusters in the VHE gamma-ray regime.

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