VERITAS Observations of the Coma Cluster of Galaxies

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Abstract. Clusters of galaxies are one of the few prominent classes of objects predicted to emit gamma rays not yet detected by satellites like EGRET or ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs). The detection of Very High Energy (VHE, E > 100 GeV) gamma rays from galaxy clusters would provide insight into the morphology of non-thermal particles and fields in clusters. VERITAS, an array of four 12-meter diameter IACTs, is ideally situated to observe the massive Coma cluster, one of the best cluster candidates in the Northern Hemisphere. This contribution details the results of VERITAS observations of the Coma cluster of galaxies during the 2007-2008 observing season.

Keywords: Coma Cluster, Galaxy Clusters, TeV γ-Ray Observations

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INTRODUCTION

Galaxy clusters are the largest gravitationally bound objects in the universe. A significant fraction of observable matter is embedded in galaxy clusters which can have masses up to $10^{15} M_\odot$. Due to their size and breadth of astrophysical phenomenon they have been studied in almost every waveband. Some of the radio and X-ray observations provide direct evidence for non-thermal particles and magnetic fields within the Intra Cluster Medium (ICM), pointing to the possibility of Very High Energy (VHE, E > 100 GeV) emission [1,2].

NON-THERMAL EMISSION FROM CLUSTERS OF GALAXIES

Observational evidence in the X-ray, radio and extreme ultraviolet indicates the presence of a population of non-thermal particles within clusters. Synchrotron emission in the form of radio halos directly point to highly energetic electrons. These electrons are probably accelerated to relativistic energies by shocks and mergers. In fact, most clusters exhibit evidence for recent merger events. Individual cluster members such as Active Galactic Nuclei and supernovae could also accelerate electrons to these energies [3]. If these same processes are efficient at accelerating other particles, there might also be a population of highly energetic protons. Protons produced in this fashion will diffuse and remain within the cluster for longer than a Hubble time due to their low energy loss rate and the sheer size of the cluster. Electrons however will cool much faster and thus provide an instantaneous snapshot of the acceleration processes going on within a cluster [4]. Both protons and electrons can produce VHE emission. Electrons via Inverse Compton off the Cosmic Microwave Background (CMB) and protons through hadronic cascades. Starting with these acceleration mechanisms there are multiple paths that generate non-thermal radio, X-ray and gamma-ray emission, but protons only produce gamma rays through hadronic cascades [5]. Thus the observation of gamma-ray emission produced via hadronic cascades can elucidate the astrophysical processes present in galaxy clusters which is critical in understanding cosmological structure formation. Furthermore, the detection of VHE gamma rays from a galaxy cluster, combined with multi-wavelength observations, would provide a detailed understanding of the morphology of non-thermal particles and fields in the cluster.

There have been several predictions for gamma-ray emission from clusters [3,4,6,7]. Each of these predictions are strongly dependent on the efficiency of the emission processes. However, galaxy clusters are one of the few objects predicted to emit gamma-ray radiation that have yet to be detected by satellites like EGRET or ground-based IACTs [8,9,10]. Only a small fraction of the energy deposited into the ICM in a merger event need be converted to non-thermal energy for there to be a detectable VHE signal. However, some authors have also stated that the probable emission from galaxy clusters is well below the sensitivity of the modern Imaging Atmospheric Cherenkov Telescopes (IACTs) [11,12]. Either the assumptions on the efficiency of non-thermal energy conversion are overly optimistic or there is something unknown about the non-thermal processes taking place inside clusters of galaxies.
THE COMA CLUSTER

The Coma cluster is a nearby cluster of galaxies which is well-studied at all wavelengths [1, 2, 13]. It is at a distance of $\sim 100\text{Mpc}$ ($z \sim 0.023$) and has a mass of $2 \times 10^{15}M_\odot$. The thermal X-ray plasma has a temperature of 8.25 keV. In many ways, the Coma cluster is the best candidate for VHE gamma-ray emission. The radio halo, Coma C, is located within the cluster, indicating the presence of non-thermal electrons. In the X-ray, there is excess hard emission seen by BeppoSAX [14], RXTE [15] and INTEGRAL [16] above the standard thermal component, although the BeppoSAX detection is disputed. This emission could be interpreted as inverse Compton scattering of CMB photons by electrons. Secondary electrons might also contribute to a UV excess in the 130-180 eV range [17, 18]. There is evidence [1] of a recent merger event between the central galaxies (NGC 4889 and NGC 4874) which might be responsible for the radio emission. Under this assumption, Berrington and Dermir [3] argue that Coma should be detectable by modern IACTs if protons are accelerated with the same efficiency as electrons. Previous VHE gamma-ray observations of Coma by H.E.S.S. resulted in upper limits of 3.7% of the Crab for point-like emission (above 1 TeV). They also reported an upper limit of 65.6% of the Crab flux (above 2 TeV) for extended emission centered on the core. [10].

OVERVIEW OF VERITAS

VERITAS is an array of four 12 m diameter IACTs located in Southern Arizona ($31^\circ\ 40'\ 30''\ N,\ 110^\circ\ 57'\ 08''\ W$) at an elevation of 1268 m. Fully operational since the Spring of 2007, VERITAS is sensitive in the energy range from 100 GeV to greater than 30 TeV and has a 3.5 degree field of view. VERITAS has an energy resolution of 15% – 20% and a 0.1° angular resolution (per event, 68% containment). Under normal operating conditions VERITAS can detect a source at 5% of the Crab Nebula’s flux in 2.5 hours and 1% in 50 hours (depending on the spectrum). A detailed description of the VERITAS instrument and technique is available in [19], [20] and [21].

DATA SET

Observations of the Coma cluster were made with the full telescope array from March through May, 2008. After quality selection, the total exposure is 18.6 hours live time. FIR measurements indicate that the weather was ideal over the entire observing period. All observations were performed in a small range of zenith angles (9 – 20°). Data were taken on moonless nights in “wobble” mode, where the telescopes are offset from the source by 0.5°, to allow for simultaneous background estimation using events in the same field of view.

RESULTS AND OUTLOOK

The data are processed using the standard cleaning and analysis methods. For details on these, see [22]. Event selection is performed using weak source cuts optimized
for a 0.3% Crab flux source. Upper limits (99% confidence level) on the integral flux above 300 GeV are calculated using the method of Helene [23]. For a point-like core region ($r < 0.115^\circ$), there were 204 ON and 2340 OFF events resulting in an excess of -8.7. The upper limit on the gamma-ray flux from the core region is $8.82 \times 10^{-9}$ ph m$^{-2}$ s$^{-1}$ (0.7% of the Crab flux). The preliminary upper limit on a mildly extended region ($r < 0.300^\circ$) is $2 \times 10^{-8}$ ph m$^{-2}$ s$^{-1}$ ($\sim$ 3% of the Crab flux). There are 1419 ON and 2865 OFF events resulting in an excess of 13.5 for this extended region.

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Upper limits on selected cluster members (NGC 4889, NGC 4874 and NGC 4921) are summarized in Table 1. In addition to these results for specific locations, a search in the field of NGC 4921 is also performed (see Figure 1). No significant sources of gamma-rays are seen and the distribution of significances is well fit by a Gaussian centered on 0.0 with a width of 1.0 (see Figure 2).

In summary, VERITAS observed the Coma galaxy cluster for approximately 19 hours in Spring 2008. No evidence for point-source emission was observed within the field of view and a preliminary upper limit of $\sim$ 3% of the Crab flux is given for a moderately extended region centered on the core. Even though the search for TeV emission from clusters of galaxies has not resulted in any detections, the outlook for detecting gamma-ray emission from clusters is promising in light of the recent launch of the Fermi satellite.

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