VERITAS Observations of Extragalactic Non-Blazars
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Abstract. During the 2007/2008 season, VERITAS was used for observations at E>200 GeV of several extragalactic non-blazar objects such as galaxy clusters, starburst and interacting galaxies, dwarf galaxies, and nearby galaxies. In these proceedings, we present preliminary results from our observations of dwarf galaxies and M87. Results from observation of other non-blazar sources are presented in separate papers in the proceedings.

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INTRODUCTION

VERITAS is an array of imaging atmospheric Cherenkov telescopes (IACTs) located at the Fred Lawrence Whipple Observatory on Mount Hopkins in Arizona. It consists of four 12m reflectors, each with a camera comprising 499 photomultiplier tubes arranged in a hexagonal lattice covering a field of view of 3.5°. The array is sensitive from 100 GeV to more than 30 TeV and can achieve 1% Crab detection in ~50 hours. For more details see Holder et al. [1].

For the 2007/2008 observing season, ~180 hours were allocated for extragalactic non-blazar sources. Of these, ~20 hours on the Coma Cluster [2] and ~13 hours on Active Galactic Nuclei (AGNs) near the Auger hotspots [3] are described in separate papers in these proceedings. In this paper, we will present the preliminary results from our observation of dwarf galaxies and the non-blazar AGN M87.

DWARF GALAXIES

A leading candidate for astrophysical dark matter (DM) is a weakly interacting massive particle (WIMP) with a mass in the range 50 GeV to more than 10 TeV. The self-annihilation of WIMPs in astrophysical regions of high DM density is predicted to generate stable secondary particles including VHE γ-rays with energies up to the WIMP mass. The detection of a γ-ray source with the unique spectral characteristics of self-annihilating DM would provide convincing evidence for the discovery of the particle physics counterpart to astrophysical DM.

DM distributions can be inferred directly from stellar kinematics. Once the DM distribution is known, constraints on the properties of the WIMP can be derived in the absence of a detection. VERITAS undertook observations of three dwarf galaxies during the period 2007-2008: Draco, Ursa Minor, Willman I. Draco and Ursa Minor are relatively high surface brightness objects for which large spectroscopic data sets exist. Willman I belongs to the group of faint stellar systems that were recently discovered in the Sloan Digital Sky Survey [4]. Although Willman I shares some similarities with tidally disrupted globular clusters, the extreme mass-to-light ratio inferred from its stellar velocity dispersion [5] suggests that it is a dwarf galaxy. Strigari et al. [6] have projected that this system may have significantly larger
DM annihilation signal than that calculated for previously known dwarf galaxies.

VERITAS took 20 hours of observation on both Draco and Ursa Minor from March 2007 to May 2007 and 15 hours of observation on Willman I from December 2007 to February 2008. No significant γ-ray emission were detected, and the 95% C.L. upper limits on the integral γ-ray flux from each source were set at the level of approximately 1 percent of the Crab Nebula flux. Using the DM distribution model presented in Strigari et al. [6], constraints on the thermally averaged product of velocity and cross section of WIMP ⟨σv⟩ as a function of its mass were derived from the γ-ray flux upper limits for Willman I (see Figure 1). For comparison with these constraints, models from the framework of the minimal supersymmetric extension to the standard model (MSSM) were generated with the DarkSUSY code [7]. The contribution of DM substructures can potentially boost the DM annihilation flux with respect to that expected for a smooth DM halo. The magnitude of this boost depends on the slope and cutoff of the substructure mass function. Strigari et al. [8] estimated the upper limit for the substructure enhancement to be ~100. The upper limits on ⟨σv⟩ in Figure 1 are shown for the cases of no enhancement and maximal enhancement from DM substructure.

**M87**

M87 is a nearby giant elliptical galaxy about 16 Mpc away near the center of the Virgo cluster and has been observed in energy range from radio to TeV γ-rays. Its core is an active galactic nucleus (AGN) powered by a supermassive black hole and its jet, resolved in radio, optical, and X-ray, is orientated within 19° of the observer’s line of sight, derived from superluminal motion observed in optical [9] and within 26° from radio observation [10]. Hence M87 is described as a misaligned BL Lac [11] [12].

TeV emission from M87 was first reported by the HEGRA collaboration from their 1998-1999 observations [13]. This was confirmed by the H.E.S.S. collaboration [14], which additionally reported year-scale flux variability and fast (2-day scale) variability during a high state of γ-ray activity in 2005. At the same period, Chandra recorded the compact knot HST-1, ~0.8” from the core, at ~50 times its observed intensity in 2000 [15]. While the rapid variability in TeV emission suggests a compact source region, most likely close to the black hole, it remains unclear whether the TeV emission comes from the core or the knot HST-1.

In 2007 VERITAS confirmed TeV emission above 250 GeV from M87 but at a lower flux than what was reported by H.E.S.S. in 2005, and no rapid variability was seen [19]. In the same paper, a year-scale correlation was suggested between γ-ray flux recorded over the past decade and X-ray flux in the 2-10 keV energy range recorded by ASM/RXTE. From this correlation and the non-detection from ASM of the 2005 flare in HST-1 knot observed by Chandra, the core was suggested to be most likely the TeV emission site. However, such γ-X-ray correlation was not seen with Chandra data in the 0.2-6 keV range. Since ASM/RXTE and Chandra have an overlap between 2-6 keV, to explain the observed correlation the spectrum would need to harden significantly within a very limited energy range (6-10 keV) which seems rather unphysical. A detailed examination of the TeV and ASM/RXTE X-ray correlation was presented in Cheung et al. [16], where the possibility of source contamination from a nearby galaxy and the annual modulation of M87 data from RXTE were investigated.

The day-scale variability was confirmed by the MAGIC collaboration [17] which reported a 13-day flare during the 2008 H.E.S.S./MAGIC/VERITAS joint monitoring campaign [18]. VERITAS received a trigger alert from the MAGIC collaboration during that time and we detected another flare and sent out a trigger alert. The preliminary results from VERITAS during this campaign are presented here.

M87 was observed with VERITAS for over 43 hours between December 2007 and May 2008 at a range of zenith angle from 19° to 36°. All the observations were performed with 4 telescopes in wobble mode. After eliminating bad weather observations and unstable trigger rate data, 41 hours of quality data (95% of the whole dataset) yielded a 7.08σ detection, with a time-averaged excess rate 0.14 ± 0.02 2mcrads−1, corresponding to 2.1% Crab rate observed at similar zenith angles.

The 2008 VERITAS data showed an indication of fast variability in February, comparable to what was reported by H.E.S.S. in 2005 [14] (details in forthcoming publication). Preliminary analysis shown that during the 3 nights with elevated excess rate, the averaged γ-ray rate corresponded to 9% Crab rate, while the rest of the dataset

**FIGURE 2.** M87 σ^2 distribution and significance map for 2008 observations.
averaged to 1% Crab rate. At the time of the flare, Chandra measured the core activity at a historical maximum, ~ 5 times its intensity in 2000, while the nearby compact knot HST-1 was in a quiet state, with a lower flux than the core (see figure [3]).

We have also regenerated the γ/X-ray correlation published in Acciari et al. [19] (figure [4]) with the updated ASM results from the ASM/RXTE website and this year’s data from VERITAS. The 2007 VERITAS flux point is recreated with simulations in correct azimuth pointings whereas the 2007 paper used simulations pointing to the North. The updated correlation plot exhibits the positive correlation between γ-ray and hard X-ray fluxes previously reported. However, the reason for such a correlation remains unclear.

**SUMMARY**

In 2007-2008, VERITAS performed observations on many extragalactic non-blazar objects such as galaxy cluster, dwarf galaxies, and non-blazar AGNs. Separate papers in these proceedings are presented to detail the observations and preliminary results of Coma cluster [2] and of Auger hotspots nearby AGNs [3].

VERITAS spent a total of 55 hours on dwarf galaxies Draco, Ursa Minor, and Willman I, and established flux upper limits on the order of 1% Crab. From Willman I’s upper limits, we have derived constraints on the thermally averaged product of velocity and cross section of WIMP.

M87 is detected at 7.08σ after 41 quality hours, with a marginal TeV flare that coincided with an X-ray flare in the core detected by Chandra, which again favors the core as the location of TeV emission. The results from the multiwavelength observation and the observed rapid variability disfavor γ-ray production models that involve the entire galaxy such as the dark matter annihilation model [20] or the extended kiloparsec jet [21], and strongly suggests the core as the most likely TeV emission site.
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