Indirect Dark Matter Searches with VERITAS

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***Abstract*. A leading candidate for astrophysical dark matter (DM) is a massive particle with a mass in the range from 50 GeV to greater than 10 TeV and an interaction cross section on the weak scale. The self-annihilation of such particles in astrophysical regions of high DM density can generate stable secondary particles including very high energy gamma rays with energies up to the DM particle mass. Dwarf spheroidal galaxies of the Local Group are attractive targets to search for the annihilation signature of DM due to their proximity and large DM content. We report on gamma-ray observations taken with the Very Energetic Radiation Imaging Telescope Array System (VERITAS) of several dwarf galaxy targets as well as the globular cluster M5 and the local group galaxies M32 and M33. We discuss the implications of these measurements for the parameter space of DM particle models**

***Keywords*: VERITAS Gamma-ray Dark Matter**

I. Introduction

The existence of astrophysical non-baryonic dark matter (DM) has been established by its gravitational effect on galaxy rotation [1] and the velocity dispersions of objects from dwarf galaxies [2] through large galaxy clusters [3]. Additional evidence of DM existence comes from cosmic microwave background measurements [4] and gravitational lensing of galaxies by foreground galaxy clusters, for example, the evident separation of dark and baryonic matter in 1E0657-558, the "bullet cluster" [5].

At present though, the existence of dark matter is solely inferred from its gravitational influence. The particle nature of dark matter is yet to be revealed through direct detection in terrestrial dark matter searches, its production in particle accelerators, or indirect dark matter searches looking for evidence of a flux of known particles produced by annihilation of dark matter particle pairs. Here we report on an indirect dark matter search carried out using VERITAS located at the Fred Lawrence Whipple Observatory in southern Arizona, USA, at an elevation of 1268m [6]. Gamma rays can be produced either directly from the pair annhilation of weakly interacting massive particles (WIMPs) or as secondary decay products from the primary particles produced in WIMP annihilation. The former would produce a monoenergetic source of gamma rays equal to the WIMP mass and would constitute definitive evidence for particle dark matter. The latter mechanism would produce a spectrum of gamma-ray energies with a cutoff at the WIMP mass.

TABLE I
SUMMARY OF OBSERVATION PERIOD AND OBSERVED TIME FOR INDIRECT DM SEARCH

Source	Period	Hours Observed
Draco	2007 Apr-May	22.3
Ursa Minor	2007 Feb-May	26.0
Willman 1	2007 Dec-2008 Feb	13.7
M5	2009 Feb-Mar	15.6
M33	2007 Nov-2008 Feb	15.8
M32	2008 Oct-2009 Jan	13.2

For astrophysical targets, the WIMP annihilation rate and associated gamma-ray flux are highly uncertain due to theoretical uncertainties and limited observational constraints on the DM halo profile. Therefore, VERITAS has surveyed a variety of possible sources in its dark matter search. We present here results from observations of three dwarf spheroidal galaxies (dSph): Draco, Ursa Minor, and Willman 1; the globular cluster M5; and the local group galaxies M32 and M33. The emphasis of the program has been to target dSphs due to their relative proximity and low expected background from known astrophysical gamma-ray sources.

VERITAS can detect and measure gamma rays in the ∼100 GeV - 30 TeV energy range with an energy resolution of 15-20%, and angular resolution of $\sim 0.1^\circ$ per event. Further technical description of VERITAS can be found in [7].

II. Dwarf Galaxy Results

Dwarf spheroidal galaxies typically have stellar velocity dispersions implying a high mass-to-light (M/L) ratio indicative of their dynamics being dominated by dark matter. Observations of the Draco, Ursa Minor, and Willman 1 dSph galaxies were performed in 2007 and 2008 in three and four telescope array configurations. Details of the observations are summarized in Table I. Gamma-ray candidates are selected from stereo reconstructed events on the basis of the summed digital pulse height from the camera phototubes, the image distance from the center of field of view, and mean scaled width and length cuts optimized for a signal that is 3% that of the Crab Nebula. As the data were acquired in "wobble" mode in which the telescope array was pointed at an offset of 0.5° from the targeted source, the net signal is calculated using the "reflected region" background model [8]. Using the Li and Ma eqn. 17 method [9] to calculate the significance, no excess above background

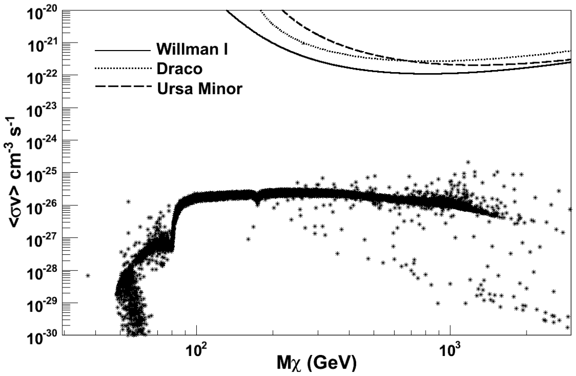

Fig. 1. Upper limits on $\langle\sigma v\rangle$ as a function of neutralino mass, m_χ using a composite neutralino spectrum (see [11] and the values of J from Table III. Black triangles represent points from MSSM models that fall within ± 3 standard deviations of the relic density measured in the 3 year WMAP data set [4].

was detected from any of the three dSphs. Gamma-ray flux upper limits were calculated at the 95% confidence level using the bounded profile likelihood ratio statistic developed by Rolke [10]. Table II summarizes the results for each of the three dwarf galaxies. Following the formalism of [11] we set limits in the WIMP parameter space $(m_\chi, \langle\sigma v\rangle)$:

$$\frac{\langle\sigma v\rangle}{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}} < R_\gamma(95\%\text{ C.L.})\left(\frac{m_\chi}{100\text{ GeV}}\right)^2 \times\left(\frac{1.45\times 10^4\text{GeV}}{J}\right) \times\left\{\phi_{1\%}\int_{200\text{ GeV}}^{\infty} A(E)\left[\frac{dN(E,m_\chi)/dE}{10^{-2}\text{GeV}^{-1}}\right]dE\right\}^{-1}$$

where $\phi_{1\%} = 6.64\times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is 1% of the integral Crab Nebula flux above 100 GeV [12], $A(E)$ is the energy-dependent effective collecting area, and J is a dimensionless astrophysical factor normalized to the product of the square of the critical density, $\rho_c = 9.74\times 10^{-30}\text{g cm}^{-3}$ and the Hubble radius, $R_H = 4.16$ Gpc. We provide limits on the WIMP parameter space based on the assumption of a smooth NFW profile [13] with J values given in Table III. This provides conservative estimates of the expected flux. Significant "boosts" of the flux with respect to this smooth halo assumption are possible from halo substructure that can produce enhancements as large as a factor of 100 [14].

Figure 1 shows $\langle\sigma v\rangle$ limits as a function of neutralino mass using the expression given above. Also plotted are values from Minimal Supersymmetric Standard Models (MSSM) generated with DarkSUSY [15] that are consistent with the WMAP bounds on the relic DM density [4]. The limits indicate that a boost factor of ~ 1000 would be necessary to produce a signal within our present sensitivity.

III. Globular Cluster and Local Group Galaxy Results

As part of the VERITAS indirect dark matter search program, we also targeted the globular cluster, M5 and the Local Group large galaxies, M32 and M33. Details of the exposure are given in table I. Analysis of these data were carried out in a similar manner to that described in section II. The mean scaled length and width, and the summed pulse height selections applied to M5 are stricter than those for the dSphs, M32, and M33. The details of the M5 analysis are given in [16]. Globular clusters and large galaxies may have significant sources of background from standard very high energy gamma-ray producing phenomena such as supernova remnants and compact binary objects. Thus, while they are worthwhile targets for an indirect DM search, interpretation of any signal would be more complicated. However, we found no gamma-ray excess above background of any significance for these three targets. The results are summarized in table IV

IV. Conclusions

We have carried out a search for very high energy gamma rays from three dwarf spheroidal galaxies: Draco, Ursa Minor, and Willman I; the globular cluster, M5; and the local galaxies M32 and M33 as part of an indirect dark matter search program on the VERITAS IACT array. No significant excess above background was observed from any target. We set upper limits on the flux and, for the dwarf spheroidal galaxies limits on the cross section times velocity, $\langle\sigma v\rangle$, for neutralino pair annihilation as a function of neutralino mass. The $\langle\sigma v\rangle$ limits indicate that a substantial boost factor above smooth dark halo expectations would be required of MSSM-type models.

We will continue our program in the future with an emphasis on further dSph observations. Next generation IACT arrays now being planned such as the Advanced Gamma-ray Imaging System (AGIS) and the Cherenkov Telescope Array (CTA) will provide an order of magnitude increase in sensitivity over current arrays such as VERITAS, MAGIC II, and HESS and can be expected to constrain some models of both supersymmetric dark matter or Kaluza-Klein dark matter associated with models of universal extra dimensions even in the conservative smooth DM halo paradigm. Along with observations by the Fermi Gamma-ray Space Telescope and new particle searches at the Large Hadron Collider, prospects for understanding the nature of dark matter over the next decade look to be promising.

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TABLE II
SUMMARY RESULTS OF DWARF GALAXY OBSERVATIONS

Quantity	Draco	Ursa Minor	Willman I
Exposure (hr)	18.38	18.91	13.68
Signal Region (events)	305	250	326
Total Background (events)	3667	3084	3602
Number Backgrd. Regions	11	11	11
Significance[a]	-1.51	-1.77	-0.08
95% c.l. (counts)[b]	18.8	15.6	36.7
Effective Area (m^2)	12518	16917	33413
Energy Threshold (GeV)	200	200	200
Flux Limit 95% c.l. ($cm^{-2}s^{-1}$)	2.82×10^{-12}	1.35×10^{-12}	2.23×10^{-12}

[a] Li and Ma eqn. 17 method [9]
[b] Rolke method [10]

TABLE III
PARAMETERS USED FOR THE ASTROPHYSICAL FACTOR, J CALCULATION.

Quantity	Draco	Ursa Minor	Willman I
R_{dSph} (kpc)[a]	80	66	38
r_t (kpc)[b]	7	7	7
$\rho_s (M_\odot/kpc^3)$[c]	4.5×10^7	4.5×10^7	4×10^8
r_s (kpc)[d]	0.79	0.79	0.18
J[e]	4	7	22

[a] Earth-dwarf galaxy distance
[b] The value of J is negligibly changed for tidal radius, r_t, as low as 0.9 kpc.
[c] scale density
[d] scale radius
[e] J is expressed as a dimensionless value normalized to the critical density squared times the Hubble radius, $3.832 \times 10^{17} GeV^2 cm^{-5}$.

TABLE IV
SUMMARY RESULTS OF GLOBULAR CLUSTER AND LARGE GALAXY OBSERVATIONS

Quantity	M5	M32	M33
Exposure (hr)	15.0	11.29	11.83
Signal Region (events)	25	262	147
Total Background (events)	251	2156	992
Number Backgrd. Regions	11	7	7
Significance[a]	-0.3	0.59	0.41
95% c.l. (counts)[b]	13.6	12.9	31.8
Flux 95% c.l. (photons s^{-1})	2.5×10^{-4}	3.2×10^{-4}	7.4×10^{-4}

[a] Li and Ma eqn. 17 method [9]
[b] Rolke method [10]

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