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Search for Dark Matter Annihilation in Draco with STACEE

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Abstract: For some time, the Draco dwarf spheroidal galaxy has garnered interest as a possible source for the indirect detection of dark matter. Its large mass-to-light ratio and relative proximity to the Earth provide favorable conditions for the production of detectable gamma rays from dark matter self-annihilation in its core. The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is an air-shower Cherenkov telescope located in Albuquerque, NM capable of detecting gamma rays at energies above 100 GeV. We present the results of the STACEE observations of Draco during the 2005-2006 observing season totaling 10 hours of livetime after cuts.

Introduction

Dark matter is thought to be an important component of the Universe and research into its nature is actively pursued using a variety of techniques. Dark matter may be weakly interacting massive particles (WIMPs) which would tend to accumulate at the bottom of gravitational potential wells, such as galaxies, where they could undergo self-annihilation processes. Depending on WIMP mass and branching ratios, a measurable flux of high energy gamma rays could result.

The Draco dwarf spheroidal galaxy has long garnered interest as a potential source of concentrated dark matter [1]. Draco has one of the highest known mass-to-light ratios (M/L), perhaps as high as $500M_\odot/L_\odot$ [2]. Current observations are consistent with a cuspy density profile [3], which would enhance the gamma-ray production rate. Furthermore, since Draco is a satellite of the Milky Way, its relative proximity to the Earth ($d \sim 75\ kpc$)[4] might allow for the detection of such gamma rays.

STACEE Observations of Draco

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is a gamma-ray telescope operating at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM. STACEE is a wavefront-sampling Cherenkov telescope which uses 64 of the mirrors in the NSTTF heliostat array for a total of $\sim 2400\ m^2$ of collecting surface. Cherenkov light from gamma-induced air showers is reflected off the heliostats onto secondary mirrors on a tower on the south side of the field. These secondaries focus the light onto photomul-

	ON events	OFF events	Excess	Significance
After Time Cuts	177498	177273	225	$+0.39\sigma$
+ grid ratio Cut	3094	3120	-26	-0.33σ

Table 1: Data summary of STACEE observations of Draco during the 2005-2006 observing season, representing approximately 3.67×10^4 s of livetime.

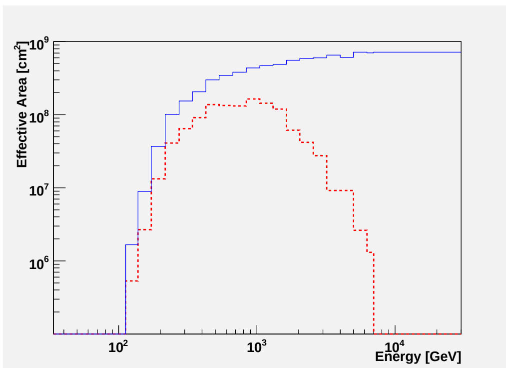

Figure 1: Effective area curves for STACEE observations of Draco. The blue (solid) line represents the STACEE effective area without cuts, the red (dashed) line represents the STACEE effective area including the grid-ratio cut.

tiplier tubes (PMTs) in such a way that each PMT sees the light from a single heliostat. Pulses from the PMTs are split, with one copy discriminated and used in the formation of a trigger and the other digitized using a 1 GS/s FADC. The trigger selects showers that deposit light evenly over the heliostat field, which favors those showers initiated by gamma rays over those resulting from charged cosmic rays, the most important background for the STACEE experiment. For a more complete description of the STACEE experiment, see [5].

The basic unit of observation for STACEE is the "ON-OFF" pair; 28 minutes on-source and 28 minutes off-source. Both observations view the same path across the sky in local coordinates (altitude and azimuth), but separated by 30 minutes in celestial coordinates (right ascension). The off-source observation allows for a measurement of the local background conditions. We measure the significance of a measurement as

$$\sigma = \frac{ON - OFF}{\sqrt{ON + OFF}} \approx \frac{S}{\sqrt{2B}} \qquad (1)$$

where S is the signal and B is the background.

STACEE observations of Draco total 35 "ON-OFF" pairs, of which approximately 10 hours of livetime remain after excluding periods with bad weather and known technical difficulties. Our data set is summarized in Table 1.

Data Analysis

Our raw background trigger rate from cosmic rays is approximately 5 Hz. In order to reduce this, we perform a grid-ratio cut which preferentially removes hadron-induced showers. This technique has been used successfully by the CELESTE experiment [6] and our implementation is described in more detail in [7]. A simplistic description of the technique is that the "smoothness" of a shower is measured by the height-to-width ratio (H/W) of the sum of pulses from all 64 channels in the detector. This quantity depends on the relative timing of each FADC trace, which depends on the assumed impact point of the shower core (i.e., the extrapolated shower axis). The grid-ratio cut is based on how sharply peaked the H/W distribution as a function of assumed core position is. Gamma-ray showers, smooth and symmetric, are expected to produce narrower H/W distributions than hadronic showers, which result in broader, clumpier deposits of Cherenkov light. Applied to our 2002-2004 Crab data, the grid-ratio cut improves the detection significance from 4.8σ to 8.1σ.[8].

As seen in Table 1, we do not detect an excess gamma-ray signal from Draco in our data set. We derive an upper limit for the flux from Draco given a measure of our detector response to a candidate source spectrum. We discuss two possible source spectra, an $E^{-2.2}$ power law (suggested by the gamma-ray flux from the galactic center[9]) and a candidate dark matter spectrum taken from Tyler[1], with an energy-dependent shape given by

$$\phi(x < 1) = \frac{e^{-8x}}{x(x^{1.5} + 0.00014)}, \qquad (2)$$

where $x = E/m_\chi c^2$. This gives a sharp cutoff at the energy corresponding to the candidate WIMP mass.

Power Law Spectrum: Figure 1 shows effective area curves for STACEE observations of Draco. Gamma-ray showers were simulated using the Monte Carlo chain of the CORSIKA air shower simulation together with our own optical ray-tracing model for the heliostats, secondaries, and PMTs, and a simulation of the electronics [8, 10]. The effective area is given by the product of the probability that a shower triggers our detector and the area over which the simulated showers were generated.

STACEE has an energy-dependent response which means the sensitivity to a given source depends on its energy spectrum. Figure 2 shows the result of convolving the effective area curves with candidate spectra. As is customary, we define the energy thresholds of our measurements as the peak of these curves.

The flux limit is defined by

$$N_{UL} = T \int_0^\infty A(E)\Phi(E)dE \qquad (3)$$

where N_{UL} is given by the 95% upper limit of the excess $N_{ON} - N_{OFF}$, T is the livetime, and $A(E)$ is the effective area. The differential flux, $\Phi(E) = C\phi(E)$, contains a normalization constant with units of $[cm^{-2}\ s^{-1}\ GeV^{-1}]$.

For the data given in Table 1, including the grid-ratio cut, $N_{UL} = 138$ and the resulting upper limit is $\Phi(E) < 4 \times 10^{-8}\ \left(\frac{E}{GeV}\right)^{-2.2}$ $\gamma\ s^{-1}\ cm^{-2}\ GeV^{-1}$ at a characteristic energy of 220 GeV. Figure 3 shows a comparison of this limit with the published upper limit of the Whipple collaboration[11] and our own Crab spectrum.

Tyler Spectrum: Tyler provides a prescription for converting a flux limit into a cross-section limit ($< \sigma v >_{\chi\bar{\chi}}$) assuming a spherical isothermal halo

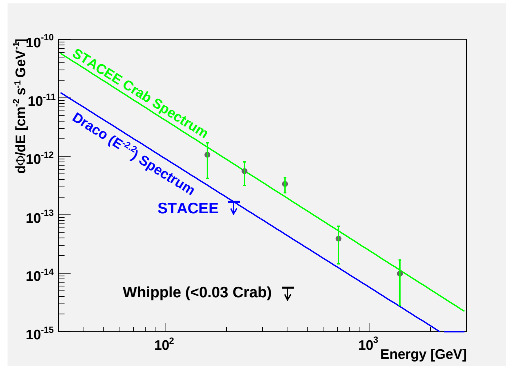

Figure 3: STACEE Flux limits for a $E^{-2.2}$ spectrum as applied to Draco (blue). For comparison, also shown is the energy spectrum of the Crab Nebula (green) as measured by STACEE during 2003-2005 which is well fit by the form: $\frac{dN}{dE} = 1.2 \times 10^{-7}\ E^{-2.23}$

model where the mass density is given by $\rho_{halo} = Ar^{-2}$. We avoid a divergence at the center by including a constant-density core physically motivated by an equilibrium between infalling particles and annihilation:

$$R_{min} = R_{ext} < \sigma v >^{1/2}_{\chi\bar{\chi}} \left[\frac{\rho_{halo}}{4\pi G m_\chi^2}\right]^{1/4} \qquad (4)$$

where R_{ext} is the outer radius of Draco and $< \sigma v >_{\chi\bar{\chi}}$ is the expectation value of the self-annihilation rate, given by the product of the cross-section and the velocity of the WIMPs in the halo. We then substitute this into our flux equation

$$\Phi_\gamma(E) = \frac{4A^2}{3d^2 R_{min}} < \sigma v >_{\chi\bar{\chi}} \phi_\gamma(E) \qquad (5)$$

and solve for the self-annihilation rate. The resulting limits are shown in Figure 4.

Conclusions

STACEE does not detect a significant signal from Draco, and sets upper limits on cross-sections for WIMP with rest-mass energy greater than about 150 GeV.

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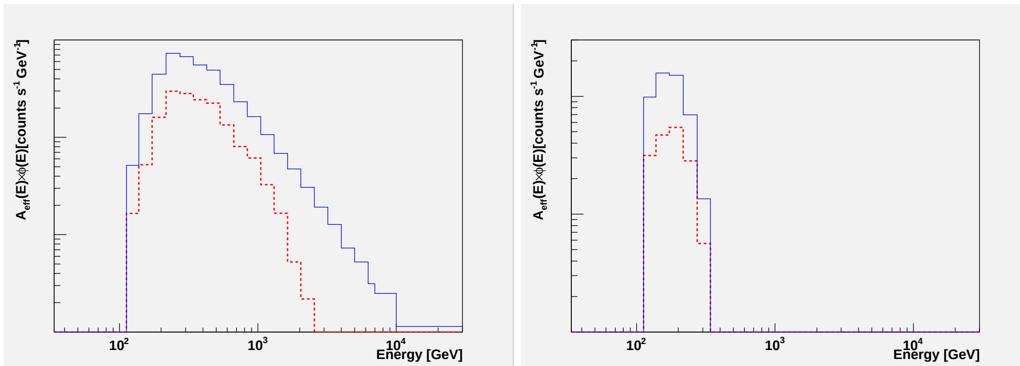

Figure 2: Response Functions for STACEE observations of Draco given two candidate spectra. The left figure corresponds to an $E^{-2.2}$ spectrum, and the right figure corresponds to a Tyler spectrum (Eq. 2) for an example $300\ GeV/c^2$ WIMP. The blue (solid) curves represent the STACEE sensitivity without cuts, the red (dashed) curves include the grid-ratio cut.

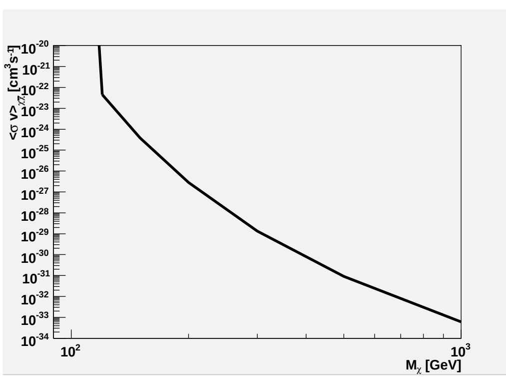

Figure 4: Upper limits on the WIMP self-annihilation rate (cross-section multiplied by halo WIMP velocity) for the Tyler spectrum as a function of m_χ as applied to the STACEE Draco observations.

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