Search for dark matter annihilation in Draco with the Solar Tower Atmospheric Cherenkov Effect Experiment

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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 a detectable flux of gamma rays from dark matter self-annihilation in its core. The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is an atmospheric 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 10.2 hours of live time after cuts. We do not detect a significant gamma-ray signal from Draco, and place an upper limit on a power-law spectrum of $\frac{dN}{dE}|_{\mathrm{Draco}} < 1.6 \times 10^{-13}(\frac{E}{220\ \mathrm{GeV}})^{-2.2}\gamma\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{GeV}^{-1}$ Assuming a smooth Navarro-Frenk-White profile for the dark-matter halo and an annihilation spectrum, we also derive upper limits for the cross-section-velocity product ($\langle\sigma v\rangle$) for weakly interacting massive particles self-annihilation.

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I. INTRODUCTION

In the flat universe described by the ΛCDM cosmological model, dark matter is believed to comprise 23% of the total energy density of the universe [1]. Very little about dark matter is known other than by its gravitational influence. Both observational constraints and particle physics models independently suggest that dark matter may take the form of weakly interacting massive particles (WIMPs), a general class of particles with low matter-interaction cross-sections ($\sigma \ll 10^{-40}$ cm^2) and high masses (10–1000 GeV) [2]. Since there is no standard model particle with these properties, a likely candidate is the lightest particle of supersymmetric extensions to the standard model.

Given the inherent difficulties with both the accelerator production and the direct detection of such a particle, an indirect search method can complement other search methods. In models where WIMPs can self-annihilate, the annihilation cross-section is typically many orders of magnitude higher that the matter-interaction cross-section [2,3]. A strong gamma-ray source can then occur in a region where the WIMPs have a particularly high density. Depending on the distance to the source, the dark-matter distribution, the WIMP mass, and the branching ratios of the reaction products, a measurable flux of high-energy gamma rays could result [4].

The strongest predicted source is the center of our galaxy, but disentangling a dark-matter-induced gamma-ray signal from other astrophysical backgrounds is difficult [3]. Dwarf galaxies present an attractive alternative since

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they are less active and tend to be dark-matter dominated. In particular, the Draco dwarf spheroidal galaxy has gained notice as a potential gamma-ray source [5] because of its high mass-to-light ratio, the possibility of a a cuspy central profile [6], and its relative proximity to the Earth ($\mathcal{D} \sim$ 75 kpc) [7]. Despite some debate on the form of the halo, recent studies rank it as one of the most promising candidates for the indirect detection of dark matter via gamma rays [8].

II. 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 atmospheric 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-ray-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 from each heliostat onto a single photomultiplier tube (PMT). 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 digitizer. The trigger selects showers that deposit light evenly over the heliostat field. Such a trigger favors those showers initiated by gamma rays over those resulting from charged cosmic rays, the most important background for STACEE. For a more complete description of the STACEE detector, see [9].

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 in [10].

STACEE observations of Draco total 35 "ON-OFF" pairs, of which 10.2 hours of live time remain after excluding periods with bad weather and known technical difficulties. Our data set is summarized in Table I.

TABLE I. Data summary for STACEE observations of Draco during the 2005–2006 observing season, representing 3.67×10^4 s of live time including the grid-ratio cut as described in the text.

	ON events	OFF events	Excess	Significance
After time cuts	177498	177273	225	$+0.39\sigma$
+ grid-ratio cut	3094	3120	-26	-0.33σ

III. DATA ANALYSIS

A. Data selection criteria

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 successfully used elsewhere [11] and our implementation is described in more detail in [12]. A basic 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 is as a function of assumed core position. Gamma-ray showers, which are smoother and more symmetric, are expected to produce narrower H/W distributions than hadronic showers, which result in broader, clumpier deposits of Cherenkov light. Applied to data taken on the Crab Nebula, the grid-ratio cut improves the detection significance from 4.8 standard deviations (σ) to 8.1 standard deviations [13].

As seen in Table I, 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, a power law (suggested by the gamma-ray flux from the galactic center [14]) and a candidate dark-matter spectrum, which will necessarily have a sharp cutoff at the energy corresponding to the candidate WIMP mass.

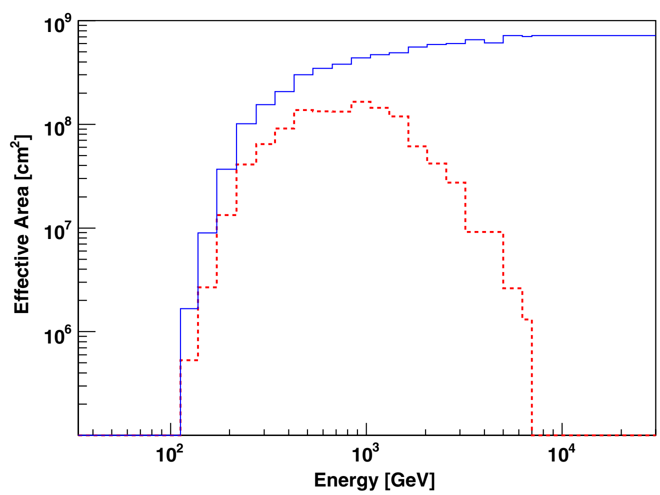

FIG. 1 (color online). Effective area curves for STACEE observations of Draco. The blue (solid) line represents the STACEE effective area without cuts, the red (dashed) line represents the STACEE effective area after cuts, including a grid-ratio cut.

B. Detector sensitivity

The intensity distribution of Cherenkov light striking the ground is strongly dependent on the energy of the incoming gamma ray. Our sensitivity is also dependent on the location of the center of the shower relative to the heliostat field. We use simulated showers in order to derive a measure of the detector response called the effective area, given by the product of the probability that a shower triggers our detector with the area over which the simulated showers were generated. Our simulations were created with the CORSIKA air shower simulation package [15] together with our own optical ray-tracing model for the heliostats, secondaries, and PMTs, and a simulation of the electronics [13,16]. Figure 1 shows effective area curves for STACEE observations of Draco.

C. Determining the gamma-ray flux limit

A flux limit can be found for a given source by integrating the detector response over all energies and comparing it with the upper limit of our observed counts, where $N_{\rm UL}$ is given by the 95% upper limit of the excess $N_{\rm ON} - N_{\rm OFF}$:

$$N_{\rm UL} = T \int_0^\infty A_{\rm eff}(E)\left(\frac{dN}{dE}\right)dE, \tag{1}$$

where T is the live time and $A_{\rm eff}(E)$ is the effective area. The differential flux, $dN/dE = C\phi(E)$, is composed of a spectral shape function scaled by a normalization constant.

For the data given in Table I including the grid-ratio cut, $N_{\rm UL} = 138$, and the resulting upper limit for an $E^{-2.2}$ power law is:

$$\left.\frac{dN}{dE}\right|_{\rm Draco} < 1.6 \times 10^{-13}\left(\frac{E}{220\ \rm GeV}\right)^{-2.2} \quad [\gamma\ {\rm s}^{-1}\,{\rm cm}^{-2}\,{\rm GeV}^{-1}] \tag{2}$$

at an energy threshold of 220 GeV. Since STACEE has an energy-dependent response, our sensitivity to a given source depends on its energy spectrum. Our energy threshold is defined as the peak of the response curve, as is customary in gamma-ray astronomy. Figure 2 shows a comparison of this limit with the published upper limit of the Whipple collaboration [17].

We also include a measured spectrum of the Crab Nebula using the same observation techniques as above:

$$\left.\frac{dN}{dE}\right|_{\rm Crab} = (7 \pm 2) \times 10^{-13}\left(\frac{E}{220\ \rm GeV}\right)^{-(2.2\pm 0.3)} \quad [\gamma\ {\rm s}^{-1}\,{\rm cm}^{-2}\,{\rm GeV}^{-1}], \tag{3}$$

where the errors listed represent the systematic uncertainty in a power-law fit to the data. The Crab is a standard-candle source for gamma-ray astronomy and this differential energy spectrum, also shown in Fig. 2, agrees with other published spectra [18,19].

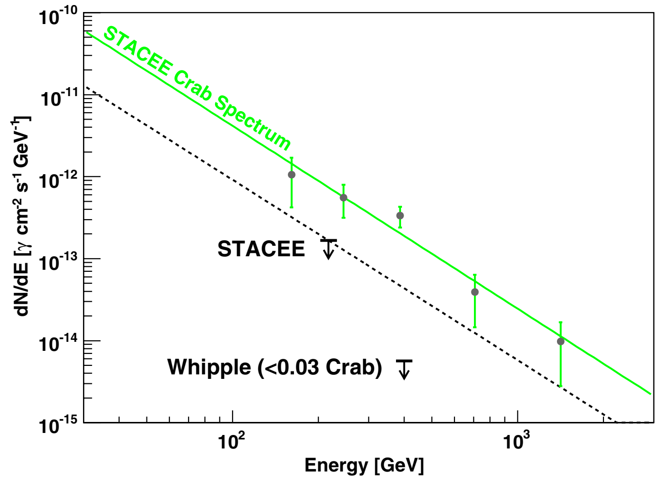

FIG. 2 (color online). STACEE Flux limits for a $\frac{dN}{dE} \propto E^{-2.2}$ energy spectrum as applied to Draco. Also shown is the energy spectrum of the Crab Nebula as measured by STACEE, which is well fit by Eq. (3)

D. Estimating the WIMP self-annihilation rate

In order to determine the gamma-ray flux from a dark-matter halo, we follow [8]:

$$\left.\frac{dN}{dE}\right|_i = \phi_i(E)\frac{\langle\sigma v\rangle_i}{M_\chi^2}\mathcal{L}(\rho_s, r_s, \mathcal{D}), \tag{4}$$

where $\mathcal{L}$ is a structure component in terms of a scale density (ρ_s), a scale radius (r_s), and the distance to the galaxy center ($\mathcal{D}$). The subscript i represents the intermediate state in the decay channel from self-annihilation to gamma rays. The spectrum has the form:

$$\phi_i(E) = \alpha_1 \frac{E}{M_\chi}\left(\frac{E}{M_\chi}\right)^{-1/2}\exp\left[-\alpha_2\frac{E}{M_\chi}\right], \tag{5}$$

where the constants α_1 and α_2 depend on the decay channel of the self-annihilation. Our upper limit is calculated based on several decay channels discussed in [8] (WW, Z^0Z^0, $b\bar{b}$, $t\bar{t}$, and $u\bar{u}$). In this case, the limit will be dominated by the channel with the hardest spectrum, $u\bar{u}$ ($\alpha_1 = 0.95$ and $\alpha_2 = 6.5$), since our energy threshold is similar to the WIMP mass.

Starting with a general matter-density profile:

$$\rho(r) = \frac{\rho_s}{\tilde{r}^\gamma(1+\tilde{r})^{\delta-\gamma}}, \tag{6}$$

where $\tilde{r} \equiv r/r_s$ has been normalized to the scale radius and $\gamma = 1$ and $\delta = 3$ for the commonly-used Navarro-Frenk-White profile [20]. The self-annihilation rate goes as ρ^2, so we integrate this over volume and divide by $4\pi\mathcal{D}^2$ to get the flux at the Earth, which gives us

$$\mathcal{L} = \frac{\rho_s^2 r_s^3}{3\mathcal{D}^2}. \tag{7}$$

It is argued in [8] is that the term $\rho_s^2 r_s^3$ is tightly constrained

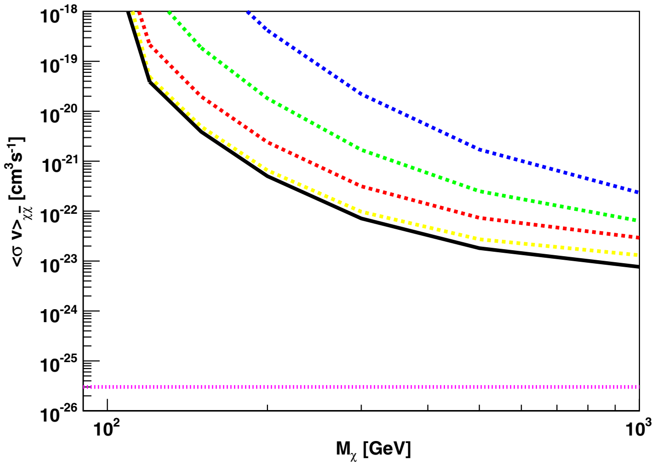

FIG. 3 (color online). Upper limits on the WIMP self-annihilation rate (cross-section multiplied by WIMP velocity) for the dark-matter spectrum in Eq. (5) as a function of m_χ as applied to the STACEE Draco observations. The dashed lines represent the contributions of different decay channels. We exclude the area above the solid line, which is the sum of the individual decay channels. The limit is dominated by the hardest part of the spectrum, the $u\bar{u}$ channel. Also shown is a dotted line at a characteristic value of $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ cm^3 s^{-1}, corresponding to a relic density from freeze-out given current cosmological constraints [3].

by velocity dispersion measurements and is also relatively insensitive to the inner slope (γ) of the profile. We conservatively use the lower bound of $\rho_s^2 r_s^3 \sim 10^{14.8}$ $M_\odot^2$kpc^{-3} given there for Draco.

Finally, we substitute Eq. (4) into Eq. (1) and solve for $\langle\sigma v\rangle$ as a function of M_χ to determine an upper limit, as shown in Fig. 3.

IV. CONCLUSIONS

STACEE is a low-threshold, ground-based atmospheric Cherenkov telescope that carried out observations of Draco during the 2005-06 observing season. Draco's location and its inferred dark-matter halo make it a possible source of detectable gamma rays due to WIMP self-annihilation at its core. We do not detect a significant gamma-ray signal from Draco; we set an upper limit of approximately 23% of the Crab flux assuming a differential spectral index of $\alpha = -2.2$ at energies above 220 GeV. Assuming a density profile for the halo and an annihilation spectrum, we also set upper limits on cross-sections for WIMPs whose rest-mass energy is greater than about 150 GeV. The limits we derive do not include any "boost" factor due to substructure (clumping) in the dark-matter halo which may increase the flux by as much as a factor of 100 [8].

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