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UPPER LIMIT FOR γ-RAY EMISSION ABOVE 140 GeV FROM THE DWARF SPHEROIDAL GALAXY DRACO

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ABSTRACT

The nearby dwarf spheroidal galaxy Draco, with its high mass to light ratio, is one of the most auspicious targets for indirect dark matter (DM) searches. Annihilation of hypothetical DM particles can result in high-energy γ-rays, e.g., from neutralino annihilation in the supersymmetric framework. A search for a possible DM signal originating from Draco was performed with the MAGIC telescope during 2007. Analysis of the data results in a flux upper limit (2 σ) of 1.1×10^{-11} photons cm^{-2} s^{-1} for photon energies above 140 GeV, assuming a pointlike source. A comparison with predictions from supersymmetric models is also given. While our results do not constrain the mSUGRA phase parameter space, a very high flux enhancement can be ruled out.

Subject headings: dark matter — galaxies: dwarf — galaxies: individual (Draco) — gamma rays: observations

Online material: color figure

1. INTRODUCTION

Astronomical observations provide strong evidence for the existence of a new type of nonluminous, nonbaryonic matter, contributing to the total energy density of the universe about six times more than baryonic matter (Spergel et al. 2007). This so-called dark matter (DM) makes its presence known through gravitational effects, and could be made of as yet undetected relic particles from the big bang. Weakly interacting massive particles (WIMPs) are candidates for DM, with the lightest supersymmetric particle (neutralino) being one of the most favored candidates in the list of possible WIMPs. Stable neutralinos are predicted in many supersymmetric (SUSY) extensions of the standard model of particle physics (Jungman & Kamionkowski 1995). Since neutralinos are Majorana particles, pairs of neutralinos can annihilate and produce standard model particles. Direct annihilations into $\gamma\gamma$ or $Z\gamma$ produce a sharp line spectrum with a photon energy depending on the neutralino mass. Unfortunately, these processes are loop-suppressed and therefore very rare. Neutralinos can also annihilate

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TABLE 1

Parameters Considered for Cusp and Core DM Density Profiles (Sanchez-Conde et al. 2007)

Profile	ϵ	C	r_b (kpc)
Cusp	1	$3.1 \times 10^7\ M_\odot\ \mathrm{kpc}^{-2}$	1.189
Core	0	$3.6 \times 10^8\ M_\odot\ \mathrm{kpc}^{-3}$	0.238

to pairs of τ or quarks, leading in subsequent processes to π^0-decays, resulting in a continuous photon spectrum.

Draco is a dwarf spheroidal galaxy accompanying the Milky Way at a galactocentric distance of about 82 kpc. It is characterized by a high mass to light ratio $M/L > 200$, implying a high DM concentration (Mayer et al. 2007; Bergström & Hooper 2006), complying with the trend generally deduced for low-luminosity galaxies (e.g., Persic et al. 1996).

2. EXPECTED γ-RAY FLUX FROM NEUTRALINO SELF-ANNIHILATION

The expected γ-ray flux depends on details of the supersymmetric (SUSY) model as well as on the density distribution of the DM in the observed source. In general, the DM is assumed to be distributed in an extended halo around spheroidal galaxies. The radial profile of the DM distribution in the halo is modeled by a power law, $\rho_{\mathrm{DM}}(r) = Cr^{-\epsilon}$, where the parameter $\epsilon \geq 0$ describes the shape of the DM distribution in the crucial innermost region. A value of $\epsilon = 0$ results in the so-called core model, with a central flat region, whereas profiles with $0.7 < \epsilon < 1.2$ denote the so-called cusp profiles. In addition, we chose an exponential cutoff as proposed by Kazantzidis et al. (2004):

$$\rho_{\mathrm{DM}} = Cr^{-\epsilon} \exp(-r/r_b),$$

with the values for r_b, C, and ϵ given in Table 1 for a cusp and a core profile for Draco. With the present angular resolution of the MAGIC telescope (0.1°), the two models are indistinguishable, since the limited angular resolution smears the determination of the profile (see Fig. 1). From this figure we can see that the two profiles can be discriminated at an angular distance of 0.4°, where the intrinsic flux is already decreased by a factor 20. Depending on SUSY model parameters, the annihilation cross section, the average number of photons produced per annihilation, and the shape of the γ spectrum can drastically change. Any change in the shape of the DM density distribution along the line of sight can also significantly change the γ-ray flux. Equation (1) describes the expected γ-ray flux above an energy E_0 from neutralino self-annihilation within Draco,

$$\Phi_\gamma(E > E_0) = \frac{1}{4\pi} f_{\mathrm{SUSY}} \langle J(\Psi) \rangle_{\Delta\Omega}, \qquad (1)$$

where $f_{\mathrm{SUSY}} = \left[N_\gamma(E > E_0)\langle\sigma v\rangle\right]/(2m_\chi^2)$, $\rho(r)$ is the DM density profile derived from Draco, N_γ is the photon yield per annihilation with $E > E_0$, m_χ is the neutralino mass, $\langle\sigma v\rangle$ is the thermally averaged annihilation cross section, $B(\Omega)$ is the point-spread function (PSF) of the telescope, Ψ is the pointing angle ($\Psi = 0$ for the center of Draco), Ω is the solid angle of the telescope's resolution, and LOS is the line of sight.

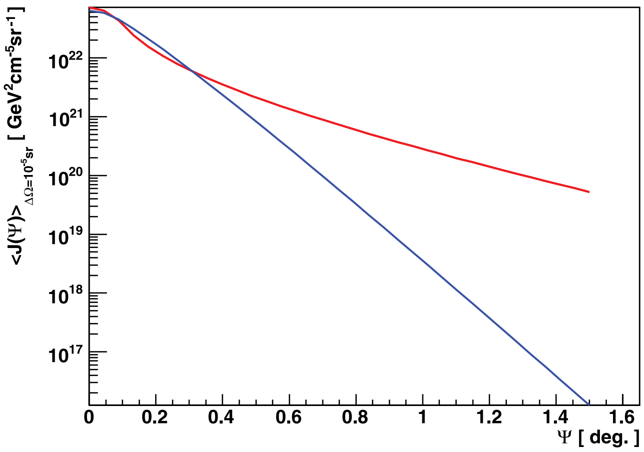

Fig. 1.—The factor $\langle J(\Psi)\rangle_{\Delta\Omega}$ for the cusp (*red*) and core (*blue*) profiles; $\Psi = 0$ corresponds to the center of Draco. At an angular distance of 0.4° of the center of Draco, $\langle J(\Psi)\rangle_{\Delta\Omega}$ is reduced by a factor of around 20 for both models.

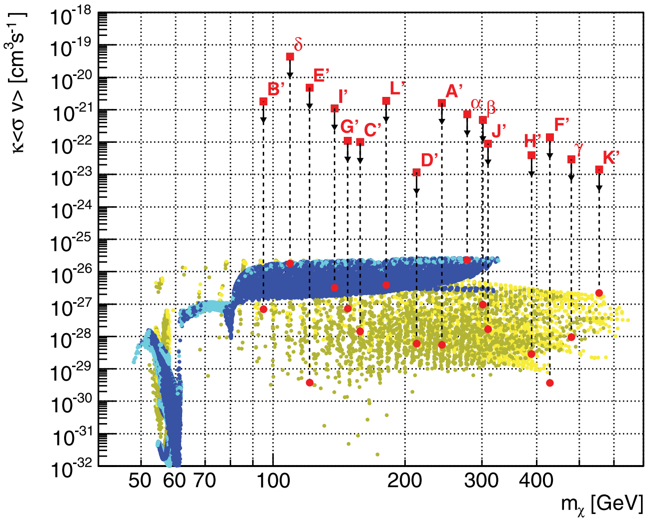

Fig. 2.—Thermally averaged neutralino annihilation cross section as a function of the neutralino mass for mSUGRA models after renormalization to the relic density, as described in the text. The red dots marked with roman letters indicate benchmark models by Battaglia et al. (2004). Dots marked with greek letters are models chosen by the authors. The red boxes indicate the flux upper limit, displayed in units of $\langle\sigma v\rangle$, assuming a smooth DM halo as given in Table 1. See text for details.

The factor $\langle J(\Psi)\rangle_\Omega$ is shown for the cusp and the core model in Figure 1. Even though this factor converges for both models for small pointing angles Ψ to the same value $\langle J(\Psi)\rangle_\Omega$, there is an uncertainty in the distribution of the DM, whether clumpy or from a hypothetical central black hole (Strigari et al. 2007; Colafrancesco et al. 2007), which could lead to a significant flux enhancement.

Due to the high predictive power of the mSUGRA framework, where the SUSY breaking effects are transmitted from the high-energy scale to the electroweak scale by gravitons (Chamseddine et al. 1982; Inoue et al. 1982a, 1982b, 1984), we simulated several million models using the parameters $m_0 \leq 6$ TeV, $m_{1/2} \leq 4$ TeV, $-4\ \mathrm{TeV} \leq A_0 \leq 4$ TeV, $\tan\beta \leq 50$, and $\mu > 0$ (Stark et al. 2005; Gondolo et al. 2000). Figure 2 summarizes the resulting thermally averaged neutralino annihilation cross sections for all models not violating any observational constraints and resulting in a total DM relic density $\Omega_{\mathrm{DM}}h^2$ in agreement with the 2 σ upper limit (u.l.) of 0.113 as derived from combined data from SPSS and *WMAP* (Tegmark et al. 2006). The yellow points correspond to models with $m_0 \leq 2$ TeV (as favored by particle physics), and the blue points represent $m_0 > 2$ TeV. Models resulting in a relic density below the lower *WMAP* limit of 0.097 are

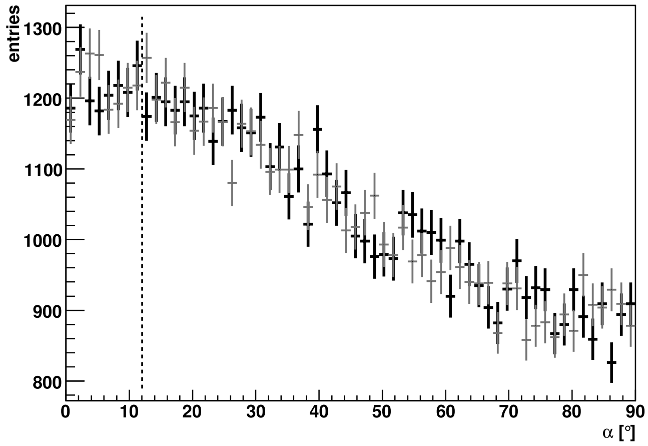

FIG. 3.—Distribution of the α parameter for γ-ray candidates coming from the center of Draco (*black marker*) and background (*gray markers*) for data taken between 2007 May 9 and May 20. The energy threshold is 140 GeV. For the signal region ($\alpha < 12°$), the number of ON events is 10883, and the number of OFF events is 10996. With the method of Rolke et al. (2005), the 2 σ upper limit on excess events is 231. [*See the electronic edition of the Journal for a color version of this figure.*]

included, since neutralinos could contribute only a fraction to the total DM in the universe. For these models (shown as dark blue and dark yellow points in Fig. 2), a scale factor of $\kappa = \left[(\Omega_\chi h^2)/(\Omega_{\rm WMAP} h^2)\right]^2$ is applied to adjust for the DM relic density.

3. OBSERVATIONS OF DRACO AND ANALYSIS

Among all imaging air Cerenkov telescopes in operation, MAGIC is the largest single-dish facility (see e.g., Baixeras et al. 2004 and Cortina et al. 2005 for a detailed description) and has the lowest energy threshold. MAGIC is located on the Canary Island La Palma (28.8°N, 17.8°W, 2200 m a.s.l.). The field of view (FOV) of the 576 pixel photomultiplier camera is 3.5°. The angular resolution is $\sim$0.1°, and the energy resolution above 150 GeV is about 25%. MAGIC has a trigger threshold of $\sim$60 GeV for small zenith angles (ZAs), which increases for larger ZAs.

Data were taken in the false-source tracking (wobble) mode (Fomin et al. 1994) with two pointing directions at 24′ distance and opposite sides of the source direction in May 2007, for a total observation time of 7.8 hr. Even though the source is expected to be extended, the wobble mode is justified, as at a distance of 24′ from the center of Draco the expected flux from this direction is less than 5% of the flux coming from the center of Draco for both the cusp and the core model (see Fig. 1). The ZA ranges between 29° and 42°.

First, calibration of the data (Gaug 2005) was performed. The arrival times of the photons in core pixels (>6 photoelectrons [phe]) are required to be within a time window of 4.5 ns, and for boundary pixels (>3 phe) within a time window of 1.5 ns of a neighboring core pixel. The next step includes the Hillas parameterization of the shower images (Hillas 1985). Two additional parameters were computed, the time gradient along the main shower axis and the time spread of the shower pixels (Tescaro et al. 2007). Hadronic background suppression was achieved using the random forest (RF) method (Breiman 2001; Albert et al. 2007), where for each event the "HADRONNESS" is computed, based on Hillas and the time parameters. The γ/hadron separation is realized by a cut in HADRONNESS, derived from a γ Monte Carlo test sample (Heck et al. 1998; Majumdar et al. 2005), requiring a γ-cut efficiency of 70%. The RF method was also used for energy estimation.

4. RESULTS

We searched for a steady γ-ray emission from the direction of the dwarf spheroidal galaxy Draco. The analysis energy threshold, defined as the peak of the energy distribution of Monte Carlo–generated γ events after cuts, is 140 GeV. Images of air showers initiated by γ-rays coming from the center of Draco are characterized by a small α image parameter, which is the angle between the main axis of the shower image and the connecting line between the center of gravity of the shower and the source position in the camera. The distribution of α is shown in Figure 3 for all events after cuts. No significant excess was found. The 2 σ u.l. on the number of excess events was calculated using the method of Rolke et al. (2005), applying a systematic error of 30%.

TABLE 2

MODEL PARAMETERS

Parameter	A′	B′	C′	D′	E′	F′	G′	H′
m_0 (GeV)	107	57	80	101	1532	3440	113	244
A_0 (GeV)	0	0	0	0	0	0	0	0
$m_{1/2}$ (GeV)	600	250	400	525	300	1000	375	935
$\tan\beta$	5	10	10	10	10	10	20	20
m_χ (GeV)	243	95	158	212	121	428	148	389
$\kappa\langle\sigma v\rangle$ (cm^3 s^{-1})	$5.55 \cdot \times 10^{-29}$	6.83×10^{-28}	1.42×10^{-28}	6.05×10^{-29}	3.74×10^{-30}	3.65×10^{-30}	7.18×10^{-28}	2.87×10^{-29}
$F_{2\sigma}$ (cm^3 s^{-1})	1.63×10^{-21}	1.79×10^{-21}	1.00×10^{-22}	1.15×10^{-23}	4.82×10^{-21}	1.42×10^{-22}	1.11×10^{-22}	3.92×10^{-23}
u.l. on flux enhancement	2.9×10^7	2.6×10^6	7.0×10^5	1.9×10^5	1.3×10^9	3.9×10^7	1.5×10^5	1.4×10^6
Parameter	I′	J′	K′	L′	α	β	γ	δ
m_0 (GeV)	181	299	1001	303	5980	180	1140	4540
A_0 (GeV)	0	0	0	0	−300	−2800	−1800	300
$m_{1/2}$ (GeV)	350	750	1300	450	680	720	1120	300
$\tan\beta$	35	35	46	47	50	5	50	35
m_χ (GeV)	138	309	554	181	277	301	479	109
$\kappa\langle\sigma v\rangle$ (cm^3 s^{-1})	3.17×10^{-27}	1.67×10^{-28}	2.22×10^{-27}	3.85×10^{-27}	2.27×10^{-26}	9.75×10^{-28}	9.43×10^{-29}	1.79×10^{-26}
$F_{2\sigma}$ (cm^3 s^{-1})	1.08×10^{-21}	9.02×10^{-23}	1.44×10^{-23}	1.91×10^{-21}	7.22×10^{-22}	4.78×10^{-22}	2.97×10^{-23}	4.39×10^{-20}
u.l. on flux enhancement	3.4×10^5	5.4×10^5	6.5×10^3	4.9×10^5	3.2×10^4	4.9×10^5	3.1×10^5	2.4×10^6

NOTES.—Thermally averaged neutralino annihilation cross section $\langle\sigma v\rangle$, the u.l. on the flux $F_{2\sigma}$, displayed in units of $\langle\sigma v\rangle$, and the 2 σ u.l. on the flux enhancement. Models A′–L′ correspond to the benchmark models given by Battaglia et al. (2004). Models α–δ are typical models chosen by the authors with $A_0 \neq 0$.

The number of excess events was converted into an integral flux u.l., depending on the assumed underlying spectrum. For a power law with spectral index -1.5, typical for a DM annihilation spectrum, and assuming a pointlike source, the 2 σ u.l. is

$$\Phi_{2\sigma}(E > 140 \text{ GeV}) = 1.1 \times 10^{-11} \text{ photons cm}^{-2} \text{ s}^{-1}.$$

We computed the γ-ray spectra expected from neutralino annihilations for different mSUGRA model parameters, using the benchmark points defined in Battaglia et al. (2004), and for other models. Assuming these underlying spectra, the u.l. on the integrated flux above 140 GeV is computed. Using equation (1) and assuming a DM distribution following the profiles according to Table 1, the flux u.l. is displayed in units of a thermally averaged cross section in Table 2 and Figure 2:

$$F_{2\sigma} = \frac{\Phi_{2\sigma}(E > E_0)}{\Phi_\gamma(E > E_0)} \langle \sigma v \rangle.$$

As can be seen, the measured flux u.l. is several orders of magnitude larger than predicted for the smooth DM distribution. However, a highly clumpy structure of the DM distribution or a central black hole could provide a significant flux enhancement (Strigari et al. 2007; Colafrancesco et al. 2007), which would decrease $F_{2\sigma}$. The analysis presented here can set a limit on the flux enhancement depending on the mSUGRA input parameters. For the benchmark models, the values for $\kappa\langle \sigma v \rangle$ and $F_{2\sigma}$ are displayed in Table 2 and Figure 2. For these models, the u.l. on the flux enhancement is around $O(10^3\text{--}10^9)$.

5. CONCLUSIONS

We present the first search for γ-rays from the direction of Draco using an imaging air Cerenkov telescope (IACT). No signal was detected. The 2 σ u.l. on a steady γ-ray emission above 140 GeV originating from Draco does not exceed 1.1×10^{-11} photons cm^{-2} s^{-1} if the underlying spectrum follows a power law with spectral index -1.5.

For the mSUGRA benchmark models defined in Battaglia et al. (2004) and assuming a smooth DM density distribution for Draco, as given in Sanchez-Conde et al. (2007), our flux upper limits are $O(10^3\text{--}10^9)$ above the predicted values. It is therefore not possible to constrain the mSUGRA phase space by these results, but a very high flux enhancement can be excluded.

Even though an indirect DM detection by measuring γ-rays from neutralino annihilation within the halo of Draco seems out of reach for present IACTs, future satellite telescopes such as *GLAST*, with lower energy thresholds, might be sensitive enough to reach the mSUGRA parameter space.

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