Searches for Dark Matter signatures in the Segue 1 dwarf spheroidal galaxy with the MAGIC-I telescope

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Despite the interest in Dark Matter (DM) searches is currently more focused on underground experiments, a signature of DM annihilation/decay in gamma-rays from the space would constitute a smoking gun for its identification. Here, we present the results of the survey of Segue 1 by the MAGIC-I telescope performed in 2008 and 2009. This source is considered by many as the most DM dominated Milky Way satellite galaxy known so far. The nearly 43 hours of data taken constitute the deepest observation ever made on a single dwarf galaxy by Cherenkov telescopes. No significant gamma-ray emission was found above an energy threshold of 100 GeV. Integral upper limits on the gamma-ray flux were calculated assuming various power-law spectra for the possible emission spectrum and for different energy thresholds. We also discuss a novel analysis that fully takes into account the spectral features of the gamma-ray spectrum of specific DM models in a SuperSymmetric scenario.

I. INTRODUCTION

In the ΛCDM cosmological scenario about 80% of the matter of the Universe is believed to be composed of non-baryonic matter, called Dark Matter (DM). The most popular DM candidates are the WIMPs (weakly interacting massive particles) supposed to be cold, electrically neutral, stable, and massive [1]. Among the huge plethora of WIMP candidates, the best motivated ones are related to the SuperSymmetrical (SUSY) and Extra Dimensional extensions of the Standard Model of particle physics [2].

In the Minimal SuperSymmetric extension of the Standard Model (MSSM), the neutralino $\chi$ represents an excellent cold DM candidate with a relic density compatible with the WMAP bounds. Since the neutralino is a Majorana particle, pairs of $\chi$ can annihilate into Standard Model particles, e.g., quarks, leptons, and W bosons. The subsequent hadronization of those particles results in a continuum emission of gamma-rays characterized by a cut-off at the neutralino mass and by possible spectral features like bumps or a hardening of the spectral slope.

The expected gamma-ray flux from DM-annihilating astrophysical objects, as function of the energy threshold $E_0$ and the integration region $\Delta \Omega$, within which the signal is integrated, can be factorized in two terms:

$$\Phi(> E_0, \Delta \Omega) = \Phi^{PP}(> E_0) J(\Delta \Omega)$$

The so-called particle physics factor $\Phi^{PP}$ depends on the features of the DM particle, and can be written as:

$$\Phi^{PP}(> E_0) = \frac{1}{4\pi} \frac{<\sigma_{\text{ann}}v>}{2m_\chi} \int_{E_0}^{m_\chi} \sum_{i=1}^{n} B^i \frac{dN^i}{dE} dE,$$

where $<\sigma_{\text{ann}}v>$ is the velocity averaged annihilation cross-section, and $B^i$ is the particular branching ratio for the $i$-th annihilation channel.

The term $J(\Delta \Omega)$ (the so-called astrophysical factor) is given by the line–of–sight integral over the DM density squared within a solid angle $\Delta \Omega$, and depends on the density profile of the DM halo of the source:

$$J(\Delta \Omega) = \int_{\Delta \Omega} \int_{v_{\text{los}}} \rho^2(r(s, \Omega)) ds d\Omega.$$

Since the gamma-ray flux of DM annihilation is proportional to the square of the DM density, only sources...
with high expected DM densities are good targets for DM indirect searches. Among these, the dwarf spheroidal satellite galaxies (dSphs) of the Milky Way (MW) are interesting objects thanks to their relative proximity to the Earth, to their high mass-to-light ratio (with values within tens and thousands of $M_\odot/L_\odot$) and to the expected absence of conventional gamma-ray sources within the system [2,3]. So far, around two dozen dSphs have been identified. Segue 1, discovered in 2006 by the SDSS [5], is located at 28 kpc from the Galactic Center, at (RA,DEC)=(10.12$^h$, 16.08$^\circ$). Kinematics studies applied to 66 member stars allowed to estimate its mass-to-light ratio to be in the range 1320-3400 $M_\odot/L_\odot$ [3], highlighting Segue 1 as the most DM dominated dSph known so far.

The MAGIC-I telescope is a 17 m dish Imaging Atmospheric Cherenkov Telescope (IACT), located at the Roque de los Muchachos Observatory, in the Canary Island of La Palma (2200 m a.s.l.). Thanks to its low energy threshold ($\sim$60 GeV at Zenith), high flux sensitivity (1.8% of the Crab Nebula flux in 50 hour of observations above $\sim$250 GeV), and good angular and energy resolution (0.1$^\circ$ and 30% respectively, at 100 GeV) [6], MAGIC-I is a suited instrument for the indirect search for DM candidates with energy of the neutralino mass or the Kaluza-Klein state.

II. MAGIC-I OBSERVATION AND ANALYSIS RESULTS

A search for a possible DM gamma-ray signal coming from Segue 1 was performed by the MAGIC-I telescope between November 2008 and March 2009, for a total of 29.4 hours of observation time (after data selection). The data analysis was performed using the standard MAGIC-I analysis and reconstruction software [8]. The number of gamma-ray candidates events from the direction of the source was estimated using the distribution of $|\alpha|$ angles, which are related to the orientation of the showers. The overall analysis cuts were optimized and cross-checked for point-like sources with the aid of contemporaneous Crab Nebula data. In Figure 1 the $|\alpha|$-plot above 100 GeV is shown. The number of excess events was computed in a fixed fiducial signal region with $|\alpha| < 14^\circ$ and resulted to be $N_{\text{exc}} (> 100 \text{ GeV}) = -279 \pm 329$, corresponding to a significance of $-0.85\sigma$, computed using eq.(17) of Li&Ma [9]. Since results were consistent with no signal over the background, we derived Upper Limits (ULs) on the flux, calculated using the Rolke method [11] at 95% confidence level, and assuming a 30% systematic uncertainty. Figure 2 shows the integral flux ULs from Segue 1 considering different energy thresholds $E_0$ and different power-law spectra with spectral index $\Gamma = -1, -1.5, -1.8, -2, -2.2, -2.4$. It is worth noting that, using the Rolke method, the ULs on the number of the excess events, and consequently the integral flux ULs, are affected by statistical fluctuations quantified by the significance of the observation $\sigma_{\text{Li, Ma}}$. This is an intrinsic feature of the statistical method exploited in the analysis and it should be taken into account when comparing ULs from different analyses. To show this effect, in Figure 2 we plot also the ULs (dashed lines) computed assuming a value for $\sigma_{\text{Li, Ma}}$ equal to zero (with number of ON events equal to the number of OFF events in the signal region of $|\alpha|$-plot) for different values of spectral index and energy threshold.
III. CONSTRAINTS ON DARK MATTER MODELS

Assuming a particular form for Segue 1 DM halo, and a given particle model for the DM candidates, we can translate the integral ULs derived from the Segue 1 observation into constraints on the DM annihilation rate.

Motivated by results from cosmological simulation, the DM halo around Segue 1 was modeled by using the Einasto radial profile [12] with \( \sigma_s = 1.1 \times 10^8 \) M\( \odot \) kpc\(^{-3}\), \( r_s = 0.15 \) kpc, and \( n = 3.3 \). With those parameters, the total astrophysical factor of Segue 1 results to be \( J(\Delta \Omega) = 1.78 \times 10^{19} \) GeV\(^2\) cm\(^{-5}\) sr. Since the analysis was performed assuming point-like source cuts (corresponding to an angular integration of 0.14° above 100 GeV), we estimated the effective astrophysical factor within the analysis cuts to be used in the following analysis, being its value \( J(\Delta \Omega) = 1.14 \times 10^{19} \) GeV\(^2\) cm\(^{-5}\) sr (corresponding to the 64% of the total astrophysical factor).

Concerning the particle physics, we restricted ourselves to the case of a SUSY model in which the presence of a discrete symmetry (R–parity) guarantees that the Lightest SuperSymmetric Particle (LSP) is stable over cosmological timescales and, therefore, a good DM candidate. We considered a 5-dimensional subspace of the MSSM called mSUGRA [13], for which the basic parameters are the universal masses of the gauginos (\( m_{1/2} \)) and scalars (\( m_0 \)), the trilinear coupling (\( A_0 \)), the ratio of the vacuum expectation values of the two Higgs fields (\( \tan \beta \)) and the sign of the Higgsino mass term (\( \text{sign}(\mu) \)). In order to study the phenomenology of mSUGRA we performed a grid scan over the parameter space, for a total of \( 5 \times 10^6 \) points (for the details see [10]).

The full circles of Figure 3 represent all the models of the scan \( i) \) where the lightest SUSY particle is a neutralino, \( ii) \) that survive the Standard Model constraints and \( iii) \) with a relic density compatible with the value derived by WMAP data within three times its experimental error \( \sigma_{W M A P} \) [14]. For each DM model of the scan, we computed the integral flux UL (above an energy threshold \( E_0 \)), using the Segue 1 data and the specific gamma-ray spectrum derived from the individual DM model. Since the spectra for each DM model have different shapes and cut-offs, the value of the optimal energy threshold \( E_0 \) was computed individually for each DM mass. We then converted the flux ULs into ULs on the velocity averaged cross-section to have a direct comparison of experimental data with the theoretical predictions. The results are plotted in Figure 3 as function of the neutralino mass: each DM model of the scan (full circle) is compared to its own UL (square). For each point we defined an enhancement factor (ENF) as the ratio between the UL on the velocity averaged cross-section and the value predicted by mSUGRA. This quantity quantifies how far away we are from excluding some portions of the mSUGRA parameters space. From Figure 3 it can be seen that ENFs for model compatible with the WMAP bounds are typically above \( 10^3 \), while typical values are of the order of \( 10^{4-5} \).

IV. IMPACT ON PAMELA PREFERRED REGION

We tested our ULs on some of the models proposed in the literature that can explain the PAMELA data [13] for the energy spectrum of the positron fraction \( e^+/(e^+ + e^-) \) as due to DM annihilation into leptons. The regions in the \( \langle m_{\chi} < \sigma_{ann} v \rangle \) plane that provide a good fit to the PAMELA measurements [10, 17] for three different channels of DM annihilation are shown in Figure 4. The annihilation channels \( \chi \chi \rightarrow \mu^+ \mu^- \), \( \chi \chi \rightarrow \tau^+ \tau^- \) have been taken from SuperSymmetry, while for \( \chi \chi \rightarrow \phi^+ \phi^- \rightarrow 2e^+e^- \) the existence of a new dark force, mediated by the carrier \( \phi \) that decays into leptons [18], has been assumed. In Figure 4 we plot the ULs obtained from the Segue 1 data, using again the specific DM annihilation spectra. We can see that, in this case, the ENFs needed to meet the PAMELA-favoured region...
are much smaller than those found for mSUGRA, and in the case of annihilation into $\tau^+\tau^-$ our ULs are probing the relevant regions. However, it is worth mentioning that, since the uncertainty in the Segue 1 astrophysical factor is quite large [12], an improvement in the astrophysical factor value could be able to put more stringent constrains and to confirm the exclusion of the PAMELA region for DM particle annihilating in $\tau^+\tau^-$. 

V. CONCLUSIONS

A search for a possible DM gamma-ray signal coming from Segue 1 was performed by the MAGIC-I telescope. No hints of signal were found above the background for energies larger than 100 GeV. Integral ULs on the gamma-ray emission were computed assuming different power-law energy spectra. Within the mSUGRA scenario, a large scan of neutralino models was performed over the parameter space. Subsequently for each simulated DM model, the ULs on the velocity averaged annihilation cross-section ($m_\chi$, $<\sigma_{ann} v>$) were derived separately for each point in the scan in order to account for the dependence on the specific spectra. Results indicate that a general exclusion plot cannot be drawn to constrain the parameter space, so we provide the results in terms of enhancement factors. A minimum boost on the flux is found of the order of $10^4$ (for models compatible with WMAP) while the typical values are at $10^{4-5}$. MAGIC-I data of Segue 1 can be useful to put constrains on those DM models that are provided in the literature to explain the PAMELA data. Our ULs are probing the PAMELA region for the DM models annihilating into $\tau^+\tau^-$ but the robustness of this result could be improved, decreasing the uncertainty in the astrophysical factor. Although the MAGIC-I observation did not result in a detection, and the ULs require still high flux enhancement factors to actually match the experiment sensitivity, an analysis like the one presented here is able to point out details and features that can be important for future deep exposures of this or similar objects, with next-generation Cherenkov experiments.

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