Deep survey of the Segue 1 dwarf spheroidal galaxy with the MAGIC Telescopes

JELENA ALEKSIĆ[1], SAVERIO LOMBARDI[2], JAVIER RICO[1], MANEL MARTINEZ[1] FOR THE MAGIC COLLABORATION.

[1] *Institut de Física d'Altes Energíes, Ed. Cn. Campus UAB, E-08193 Bellaterra, Spain*
[2] *Instituto Nazionale di Astrofisica, I-00136 Rome, Italy*

jelena@ifae.es

Abstract: Discovering the nature of dark matter is one of the most exciting tasks of modern science. Among the targets suitable for dark matter searches, dwarf spheroidal galaxies are considered to be excellent candidates and, among them, Segue 1 stands out with mass-to-light ratio estimated to be of the order of 1000. We present the results of the stereoscopic observations of Segue 1 with the MAGIC Telescopes, carried out between 2011 and 2013. With more than 100 hours of good quality data, this is the deepest observational campaign on any dwarf galaxy carried so far by any Imaging Air Cherenkov Telescope. The analysis of the data is performed using a dedicated likelihood approach, optimized for signals with characteristic spectral features. We search for dark matter particles with mass in the 100 GeV - 10 TeV range, considering theoretical scenarios with different final state Standard Model particles, annihilation with internal bremsstrahlung and monochromatic line signals.

Keywords: dark matter searches, Segue 1, MAGIC Telescopes

1 Introduction

The notion of dark matter has been present for almost a century, but the question about its nature is still unanswered. Observational evidence on all scales and cosmological predictions indicate that dark matter represents almost 85% of the matter content of our Universe, an almost 25% of its total energy budget [1]. Discovering its essence is one of the most important tasks of modern science.

Nevertheless, despite strong efforts over the years, no experiment so far has been able to detect dark matter, directly of indirectly. The current searches are mainly focused on dark matter composed of weakly interacting massive particles (WIMPs), that are of non-baryonic nature, produced thermally in the early Universe, and are stable on cosmological scales. WIMPs are expected to annihilate or decay into Standard Model (SM) particles, such as photons, that could be detected by the existing experiments. With the mass range predicted for WIMPs, those photons might be visible in the gamma-ray domain, currently best explored from space by the Large Area Telescope on board the Fermi satellite (Fermi-LAT [2]) and from ground by the Imaging Air Cherenkov Telescopes (IACTs): H.E.S.S [3], MAGIC [4] and VERITAS [5].

The gamma-ray flux from dark matter annihilation or decay that is to be measured on Earth is determined by two independent factors: one, coming from the particle physics and other, related to the astrophysics. The particle physics term is fixed for a given dark matter model and does not depend on the observed source. It describes the shape of the expected spectrum and gives the number of photons produced above a given energy threshold for the dark matter scenario in question. On the other hand, the astrophysical factor is determined by the dark matter density profile of a specific source and its distance.

The typical annihilation (decay) gamma-ray spectrum is predicted to be continuous and featureless, with photons mainly produced from the pion decay and the final state radiation of charged particles. Nevertheless, some distinctive spectral features could be present, like monochromatic line from direct dark matter annihilation (decay) into photons, or pronounced peak towards the kinematic limit from emission of virtual internal bremsstrahlung (VIB) photons [21].

The IACTs are observatories that deal with great variety of scientific objectives. The preference, however, is usually given to the astrophysical sources of conventional origin, whose spectral distributions are, in majority of cases, rather featureless and unknown in advance. Consequently, standard analysis tools and methods of IACTs are adapted for such signals, at the expense of sources whose emissions are predicted to contain some distinctive spectral features. Therefore, in this work, an alternative analysis approach is used instead: the *full likelihood* method is optimized for recognition of characteristic signatures dark matter interactions may leave in the spectrum [6]. Full likelihood takes maximal advantage of the spectral information, and almost solely through the inclusion of the a priori knowledge on the expected gamma-ray spectrum in the likelihood, it achieves significantly better sensitivity than the method currently used as standard in analysis chains of the IACTs.

Here are presented the details on the latest dark matter searches with MAGIC. First, the objectives of the project are presented, together with the motivation behind the choice of Segue 1 as a suitable dark matter target. This is followed by the details of the observations with MAGIC and subsequent analysis. Lastly, results are interpreted in the light of various dark matter annihilation and decay scenarios.

2 Indirect Dark Matter Searches with MAGIC

MAGIC efforts in dark matter searches have so far been directed towards the Galactic Center [7], the Perseus galaxy cluster [8], the dwarf spheroidal galaxies (dSphs) Draco, Willman 1 and Segue 1 [9], and unidentified Fermi objects as possible dark matter substructures [10, 11]. While the last one is a still ongoing project, the rest of the results were obtained with the MAGIC-I only, from usually up to few tens of hours of observations. When system went stereo in 2009, it was opted to invest in a long-term observational campaign of the best dark matter candidate available to MAGIC, and accumulate many hours of good quality data. The resulting sample is to be used as a test area of the ever-evolving dark matter theories.

The source chosen as the most suitable candidate is the ultra-faint dSph galaxy Segue 1. Located at a distance of 23 kpc, this dSph is in the Northern hemisphere, outside of the Galactic plane and visible to MAGIC for ∼370 hours of dark time per year at low zenith angles. More importantly, this galaxy has the mass-to-light ratio estimated to ~ 3400 $M_\odot/L_\odot$, making it the most dark matter dominated object known so far [12]. In addition, its astrophysical factor J is the highest among the dSphs; its total baryonic content is negligible and almost no background of conventional origin is expected from this source at very high energies.

3 MAGIC Observations

MAGIC is a ground-based system of two, 17 m diameter IACTs, located at the Roque de los Muchachos Observatory, in the Canary island La Palma (28.8° N, 17.8° W, 2200 m a.s.l.). MAGIC-I has been operational since 2004, and in 2009 it was joined by MAGIC-II, Together, in stereoscopic mode, they allow for observations of significantly improved sensitivity, lower energy threshold and better energy and angular resolution [13].

Observations of Segue 1 were performed by MAGIC between January 2011 and February 2013, under dark night conditions, for zenith angle range between 13° and 37°, thus ensuring the low energy threshold of the analysis. During this period, the telescopes underwent a series of significant changes: at the end of 2011, the readout systems of both instruments were replaced by the more advanced, DRS4-based configurations; by the end of 2012, among other improvements, the camera of MAGIC-I was upgraded to the exact replica of that of MAGIC-II [14]. As a result, the performance of the system varied during the total period of Segue 1 observations; therefore, data from each of the different telescope states are analyzed separately, before being combined through the full likelihood analysis.

4 Results

The Segue 1 observations were analysed using the full likelihood approach, an optimized analysis method that takes complete advantage of the distinct features expected in the gamma-ray spectrum of dark matter origin, achieving better sensitivity with respect to the standard analysis of the IACTs [6].

The considered scenarios include: annihilation and decay into the final state SM particles, direct annihilation and decay into photon(s) and 3-body annihilation with virtual internal bremsstrahlung (VIB) contribution. To make the study as model-independent as possible, for all of the channels the branching ratio is assumed to be 100%. The dark matter particle mass takes values in the 100 GeV - 10 TeV range (200 GeV - 20 TeV for the decay scenarios). Furthermore, no additional boosts to the signal, either from presence of substructures or from quantum effects were taken into the account.

In particular, constraints are calculated for the following final state channels: $b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$ and W^+W^-. Search for monochromatic line is done assuming direct annihilation into two photons, and one photon and Z boson. Lastly, the contribution of VIB photons to the gamma-ray spectrum and their impact on detection prospects is considered. Assuming a fermionic dark matter particle, that couples to muons or tau leptons via Yukawa interactions with the scalar η, helicity suppression in the s-wave contribution to the $\langle\sigma_{\rm ann}v\rangle$ can be lifted by emission of a VIB photon. Depending on the mass-splitting parameter μ, that is defined as the squared ratio of the masses of the scalar and dark matter particle, $\mu = (m_\eta/m_\chi)^2$, the VIB contribution to the spectrum is more or less pronounced [21]. We calculate the upper limits on $\langle\sigma_{\rm ann}v\rangle$ for $\mu^+\mu^-(\gamma)$ and $\tau^+\tau^-(\gamma)$ channels, for the most degenerate states ($1 \leq \mu \leq 2$) for which the VIB contribution is the most pronounced. For both considered channels, estimated bounds are up to two - three orders of magnitude stronger than for the annihilation into the same final states, but without the VIB photons.

5 Conclusions

We report on indirect dark matter searches in dSph galaxy Segue 1 with MAGIC, from the observations carried out in stereo mode between January 2011 and February 2013.

The gathered data have been analyzed by means of the full likelihood method. Given that no significant gamma-ray signal was found, the limits are derived for annihilation and decay rates assuming various dark matter models.

The acquired results represent an improvement, with respect to the previously most sensitive MAGIC dark matter searches, of an order of magnitude. This campaign is expected to continue in the following years, and to leave an important landmark in the field in the pre-Cherenkov Telescope Array [22] era.

Acknowledgment: We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN, the Swiss National Fund SNF, and the Spanish MICINN is gratefully acknowledged. This work was also supported by the Marie Curie program, by the CPAN CSD2007-00042 and MultiDark CSD2009-00064 projects of the Spanish Consolider Ingenio 2010 programme, by grant DO02-353 of the Bulgarian NSF, by grant 127740 of the Academy of Finland, by the YIP of the Helmholtz Gemeinschaft, by the DFG Cluster of Excellence Origin and Structure of the Universe, and by the Polish MNiSzW grant 745/N-HESS-MAGIC/2010/0.

References

[1] Planck Collaboration, (2013) arXiv:1303.507.
[2] NASA Goddard Space Flight Center, `http://fermi.gsfc.nasa.gov` (May 2013).
[3] H.E.S.S. Collaboration, `http://www.mpi-hd.mpg.de/hfm/HESS` (May, 2013).
[4] MAGIC Collaboration, `http://magic.mppmu.mpg.de` (May, 2013).
[5] VERITAS Collaboration, `http://veritas.sao.arizona.edu` (May 2013).
[6] J. Aleksić, J. Rico and M. Martinez, Journal of Cosmology and Astroparticle Physics 10 (2012) 032 doi:10.1088/1475-7516/2012/10/032.
[7] J. Albert et al., The Astrophysical Journal Letters 638 (2006) L101-L104 doi:10.1086/501164.
[8] J. Aleksić et al., The Astrophysical Journal 710 (2010) 634-647 doi:10.1088/0004-637X/710/1/634.
[9] J. Aleksić et al., Proceedings of the 32nd ICRC, 2011.
[10] D. Nieto et al., Proceedings of the 32nd ICRC, 2011.
[11] J. Aleksić et al., Proceedings of the 33rd ICRC, Id. 1044, 2013.

[12] J. Simon et al., The Astrophysical Journal 733 (2011) 46 doi:10.1088/0004-637X/733/1/46.
[13] J. Aleksić et al., Astroparticle Physics 35 (2012) 435-448 doi:10.1016/j.astropartphys.2011.11.007.
[14] D. Mazin et al., Proceedings of the 33rd ICRC, Id.0074, 2013.
[15] M. Ackermann et al., Physical Review Letters 107 (2011) 241302 doi:10.1103/PhysRevLett.107.241302.
[16] J. Aleksić et al., Journal of Cosmology and Astroparticle Physics 06 (2011) 035 doi:10.1088/1475-7516/2011/06/035.
[17] M. Cirelli et al., Physical Review D 86 (2012) 083506 doi:10.1103/PhysRevD.86.083506.
[18] A. Abramowski et al., Physical Review Letters 110 (2013) 041301 doi:10.1103/PhysRevLett.110.041301.
[19] M. Ackermann et al., Physical Review D 86 (2012) 022002 doi:10.1103/PhysRevD.86.022002.
[20] A.Geringer-Sameth and S.M. Koushiappas, Physical Review D 86 (2012) 021302 doi:10.1103/PhysRevD.86.021302
[21] T. Bringmann et al., Journal of Cosmology and Astroparticle Physics 07 (2012) 054 doi:10.1088/1475-7516/2012/07/054
[22] The CTA Consortium, `https://www.cta-observatory.org` (May 2013).