MAGIC observation of the unassociated Fermi-LAT object 2FGL J1410.4+7411

J.A. BARRIO[1], M. DORO[2], I. LOZANO[1], N. MIRABAL[1], S. PAIANO[2], K. SATALECKA[1] FOR THE MAGIC COLLABORATION.

[2] *Universidad Complutense de Madrid, Spain*
[3] *Università and INFN of Padova, Italy*

lozano@gae.ucm.es

Abstract: We report on the observation using the MAGIC Telescopes of the unassociated Fermi object 2FGL J1410.4+7411. This source was selected through a systematic search among the population of the 2-year Point Source Catalog unassociated Fermi objects, to be one of the most promising dark matter subhalo candidates. The obtained results are presented. We conclude that the synergy between Fermi and Cherenkov telescopes, along with multiwavelength observations, could play a key role in indirect searches for dark matter.

Keywords: dark matter theory, dark matter experiments, gamma-ray detectors, gamma-ray experiments

1 Introduction

The concordance cosmological model, thoroughly validated by measurements, requires 83% of the total mass density in the Universe to be non-baryonic [1, 2]. Thus, the identification of this so-called Dark Matter (DM) is currently one of the most relevant issues in Physics. Assuming that DM is constituted of weakly interacting massive particles (WIMPs), which could self annihilate or decay into Standard Model particles, its nature can be unraveled by the detection of these products, photons amongst them [3]. This is the principle of indirect detection searches carried out in the gamma-ray energy band. This energy band is currently best explored in its high energy regime (HE, typically from 100 MeV to 50 GeV) by the Large Area Telescope on board the *Fermi* Gamma-ray Space Telescope (*Fermi*-LAT) [4], and in its very high energy band (VHE, typically from 100 GeV to tens of TeV) by the current generation of ground-based Imaging Atmospheric Cherenkov telescopes (IACTs), namely H.E.S.S. [5], MAGIC [6] and VERITAS [7].

A gamma-ray signal from WIMP annihilation would have a very distinctive spectral shape: features such as annihilation lines, internal bremsstrahlung, as well as a characteristic cut-off at the WIMP mass, are expected [8]. The spectrum of WIMP annihilation or decay must be universal, so even if one can detect all the previously mentioned features in a single measured spectrum, an ultimate confirmation of the DM origin of the signal would be the detection of the same spectral shape in different gamma-ray sources [9, 10, 11, 12]. The expected gamma-ray flux due to DM annihilation can be factorized into two terms: the so-called astrophysical and particle physics factors. The latter factor is universal, and only depends on the DM particle model. On the contrary, the astrophysical factor is proportional to the DM density squared integrated along the line of sight, and it is thus source dependent. Consequently, regions where high DM density is foreseen are the best candidates for detection in the gamma-ray light of DM annihilation.

No clear DM signal has been detected so far in any of the most promising targets, including dwarf spheroidal galaxies [13, 14, 15, 16], the Galactic Center [17, 18], or galaxy clusters [19, 20, 21, 22]. Yet, other regions of high DM density potentially exist in the Galaxy: N-body cosmological simulations have uncovered how the cold DM distribution evolves from almost homogeneous initial conditions into a hierarchical and highly clustered state at present [23, 24]. High resolution simulations of Milky Way-like DM halos indicate that the halos should not be smooth but must exhibit a wealth of substructure down to even the smallest scales resolved in the simulations [25, 26, 27]. These subhalos could be too small to have accumulated enough baryonic matter to start star formation and would therefore be essentially invisible to astronomical observations [28, 29]. Some of these subhalos could be massive enough and close enough that they could be observed as bright gamma-ray emitters due to the annihilation of WIMPs [30]. These subhalos would most probably only be visible in the GeV–TeV gamma-ray regime and they may not been cataloged yet in gamma-ray sky surveys. Since gamma-ray emission from WIMP annihilation or decay is expected to be steady from any given subhalo, such hypothetical sources would be found in deep sky surveys [31], and most likely would be among the the *Fermi*-Large Area Telescope (LAT) detected sources as unassociated sources with no conventional counterpart at any other wavelength, the so-called Unassociated *Fermi* Objects (UFOs).

As already mentioned, one of the smoking guns for DM existance could be a detection of a very distinct spectral cut-off close to the WIMP mass. Most probably, such a cut-off lies at too high an energy (see, e.g., the lower limits on the neutralino mass of 46 GeV [32]) to be measurable by *Fermi*-LAT within reasonable time (if at all possible). Consequently, the complementarity between *Fermi*-LAT and IACTs appears naturally, where the all sky coverage of the former would be complemented by the high sensitivity at very high gamma-ray energies of the latters. UFOs can provide a population of objects in which to search for the spectral universality that would be required by any DM detection claim.

The search for DM subhalos in the gamma-ray band is an ongoing effort with multiple approaches based on the exploitation of *Fermi*-LAT data [33, 34, 35, 36, 37, 38, 39]. MAGIC observations of UFOs selected from the 1st *Fermi*-LAT Catalog are reported in [40]. Similar efforts by VERITAS are presented in [41]. Additionally, the feasibility of

DM subhalo searches with wide-field IACTs has been studied [42].

2 Candidate search

Fermi-LAT is the most suitable instrument to search for DM subhalo candidates in the HE gamma-ray band, due to its full sky coverage and sensitivity. The 2FGL catalog consists of 1873 sources significantly detected in the range from 100 MeV to 100 GeV, the vast majority of them being point-like. Out of the total number of sources in the catalog, 605 are sources not associated to any known object. The selection of DM subhalo candidates out of the 2FGL catalog is based on spectral characteristics, time variability, and potential associations. Our selection criteria demand the selected sources to meet the following requirements:

- *To be unassociated*:

  As previously mentioned, DM subhalos could be too small to accrete sufficient baryonic matter in order to significantly emit through conventional processes in a different energy range than gamma-rays. Therefore, DM subhalos would be part of the population of objects not associated with conventional emitters. The 2FGL catalog contains 605 objects in accordance with this selection criterion.

- *To lay outside the Galactic Plane*:

  A noteworthy fraction of galactic baryonic objects are found in the Galactic Plane, unlike the galactic DM substructures whose galactic latitude distribution is homogeneous [25, 26]. Furthermore, the denser concentration of baryonic objects in the Galactic Plane makes the tidal disruption of DM subhalos more likely in that region. Additionally, due to the fact that source association algorithms have difficulties in very crowded environments, unassociations due to an excess of candidacies are more common for those sources located at low galactic latitudes. These two facts imply that most UFOs are located in the Galactic Plane. Additionally, the galactic diffuse gamma-ray background is much stronger at low galactic latitudes which makes the detection of some faint UFOs, nearby or within the Galactic Plane, dependent on the assumed galactic gamma-ray background model. Consequently, in order to obtain a robust sample of DM subhalo candidates, UFOs with small galactic latitudes, $|b| < 10°$, are discarded. 272 UFOs remain after this restriction.

- *To be an unambiguous detection*:

  The 2FGL catalog yields a *Flag* parameter for each source. If its value is greater than zero, it indicates that there are potential problems concerning the detection or characterization of the source. Therefore we require this number to be zero. 201 UFOs are left after applying this cut.

- *To be non-variable:*

  As already mentioned, the photon flux from WIMP annihilation is expected to be constant, and thus variable sources must be rejected. The 2FGL provides a *variability index* based on a month-by-month absolute flux statistical comparison. A value greater than 41.64 indicates $< 1\%$ likelihood of being a steady source. Therefore sources whose *variability index* surpasses that limit are discarded. Only 188 sources survive this cut.

- *To be a hard source detected at GeV energies*:

  Several studies, based on the computation of the expected photon yield from WIMP annihilations as a function of energy [43, 8], conclude that the corresponding spectra, which essentially follow the shape of the annihilation photon yield, are hard spectra until the WIMP mass cut-off. Consequently, we require that sources described by a power-law have spectral index < 2.5 and a significantly detected integral photon flux in the most energetic 2FGL catalog energy bin, from 10 to 100 GeV. Only 23 UFOs are left after this final cut.

2.1 Fermi-LAT analysis of high energy photons

The total number of HE photons with energies above 10 GeV is a determinant quantity since it provides evidence of the robustness of the *Fermi*-LAT measurement in the 10 GeV–100 GeV energy band and supports the extrapolation of *Fermi*-LAT fluxes beyond the IACTs' lower energy thresholds.

We analyzed *Fermi*-LAT data for each of the 23 selected sources using *Fermi* `ScienceTools` version *v9r23p1* [45]. The best suited event selection quality cuts for off-plane point source analysis were applied by means of the `gtselect` tool, namely, event class 2 and higher were considered for photons above 10 GeV. Additionally, a maximum zenith angle cut of 100° was applied and the latest Instrument Response Functions *Pass7_v6* were considered. The tool `gtmktime` was used to select good time intervals. Additionally, photons arriving when the satellite was crossing the South Atlantic Anomaly were discarded as well as those recorded at a rocking angle greater than 45°. We extracted all selected photons with energies above 10 GeV coming from a circular region around the source nominal position, corresponding to the *Fermi*-LAT Point Spread Function radius at 10 GeV for 68% containment (which corresponds to 0.25°) [44]. Given the fact that all sources exhibit a clear detection between 10 GeV and 100 GeV one can assume that the majority of the extracted photons can be linked to the putative source gamma-ray emission. After performing the extraction of the HE photons all the sources provided four or more photons over 10 GeV.

2.2 Search for potential counterparts

For each of the 23 DM subhalo candidates, an extensive and independent search for potential counterparts was performed. We explored the main astronomical catalogs and mission archives around the 2FGL nominal position of the sources, conservatively considering a 20 arcmin search radius in order to additionally inspect the vicinity of the sources, and not only the 2FGL catalog 95% error region. The purpose of this search is neither to associate nor to identify counterparts for 2FGL sources, but it is rather to disfavor IACT observations on objects whose *Fermi*-LAT gamma-ray flux could be eventually attributed to an already known conventional source.

The search was performed with the on-line tools provided by the NASA's High Energy Astrophysical Archive [46], and the ASI Science Data Center (ASDC, [47]). We scrutinized the observation archives from current and past gamma-ray missions like AGILE, INTEGRAL, CGRO, HETE-2, COS-B; X-ray missions like ROSAT, Chandra, XMM-Newton, Swift, Suzaku, RXTE; and radio catalogs from the NRAO VLA Sky Survey, SUM Sky Survey, Green Bank Survey, FIRST Survey, and Planck mission. When no gamma-ray, X-ray or radio source was present in the region of interest we also queried the extreme ultraviolet, ultraviolet, optical, and infrared HEASARC collection of tables. Additionally, we performed dedicated analyses of public Swift-XRT data (triggered by a proposal focused on high Galactic latitude UFOs described in [48]) by means of the Swift-XRT data products generator [49]. Sources with no potential X-ray or strong radio counterparts[1] inside their 95% *Fermi*-LAT error region form the most favored subset of DM subhalo candidates.

2.3 Prospects for DM subhalo candidates detection with MAGIC

Out of the list of DM subhalo candidates, not all of them are good targets for MAGIC due to two main reasons: either they require a too long observation time to be detected or they are not properly visible from the telescope site.

IACTs are able to detect strong sources, like Crab Nebula or bright Active Galactic Nuclei in high or flaring states within a few minutes. However, for fainter sources, the required observation time is much longer, from few to hundreds of hours. Since the total observing time for an IACT is limited ($\sim$ 1000 hours per year), the feasibility of detection of a certain source in a reasonable time is crucial when proposing candidate targets for this kind of telescopes. For sources previously unexplored in the VHE regime, the spectral information, which is needed to compute the detection time, is obviously missing. In the case of well known sources with detailed information on spectral energy distribution, one can perform a model dependent extrapolation of the spectral behavior at very high energies and then estimate the detection time. This is not the case for the UFOs that form our list of DM subhalo candidates, where only *Fermi*-LAT spectral information is available. Therefore the detection prospects of MAGIC for this collection of sources strongly rely on the *Fermi*-LAT data.

The detection time for a certain source depends only on its spectrum and the detector capability. The latter is codified in the instrument's effective area, background rate and energy threshold. In order to estimate the detection time, the expected signal rate and background rate are required. While the latter is obtained from Monte Carlo (MC) simulations, the signal rate is estimated as the convolution of the spectrum of the source and the effective area of the instrument above the energy threshold of the same.

Under the hypothesis that our candidates are located at Galactic distances and, as such, do not suffer from extinction due to extragalactic background light, we performed a direct extrapolation of the spectrum measured by *Fermi*-LAT (as provided by the 2FGL catalog) to the VHE range. The spectral information we considered was that provided in the 2FGL catalog. In a first step a *nominal scenario* (NS) was defined, where the nominal values of the normalization factors and spectral indices from the 2FGL catalog were used for the extrapolations. In a second step, which we called the *conservative scenario* (CS), we took into account the uncertainties in the spectrum parameters provided in the 2FGL. In this *conservative scenario* the detection time was computed for a normalization factor one standard deviation below and a spectral index one standard deviation above the 2FGL nominal values. Additionally, in order to approximate the shape of gamma-ray spectrum from the annihilation of WIMPS of different masses, we truncated the NS and CS spectra with sharp cut-off at 250 GeV, 500 GeV and 1 TeV.

Eventually, the actual calculation of the minimum observing time needed for the detection of each candidate is performed by inserting the corresponding signal and background rates into equation 17 from [52], and imposing a detection significance of 5σ (standard deviations). It is worth noting that the MAGIC detection prospects have been computed based on MC simulations for low zenith angle observations. These results can, however, be extended up to zenith angles as large as 45° without a sizable impact on the detection times.

3 2FGL J1410+7411

As already discussed, sources with no counterparts at other wavelengths are preferred for initial MAGIC observations. Only one source visible from the MAGIC latitude fulfill this prescription, namely 2FGL J1410.4+7411. This source is therefore favored with respect to the rest of candidates. It is only observable under an approximate minimum zenith angle of 45° from the MAGIC latitude. This candidate does not have a particularly hard spectrum (the spectral index is 1.9) but has 13 *Fermi*-LAT photons above 10 GeV and shows an integral flux of 0.9% C.U. The time required for a significant detection of this source with MAGIC, assuming the *nominal scenario* and no cut-off, is around 35 h.

4 MAGIC observations

MAGIC consists of a system of two telescopes operating in stereoscopic mode since fall 2009 at the Canary Island of La Palma (28.8 N, 17.8 W, 2200 m a.s.l.) [53].. Out of the 23 selected DM clump candidates, 12 can be observed from the MAGIC latitude. So far, the best candidate, namely, 2FGL J1410+7411, has been observed under dark night conditions and lowest zenith angle range possible. Both conditions are needed when the sensitivity at low energies is pursued. The source was surveyed in false tracking mode [54]. Data was analyzed in the MARS analysis framework by means of the standard stereoscopic analysis routines [55]. Contemporaneous Crab Nebula data were used to verify the proper performance of the telescopes and analysis routines.

Fig. 1: The 2FGLJ1410+7411 *Fermi*-LAT spectrum extrapolated assuming the *nominal scenario* (NS, blue solid line) and the*conservative scenario* (CS, blue dashed line). The red arrows depict the MAGIC differential flux ULs calculated using the Rolke method and assuming a power law spectrum with a spectral index of 1.9. The black lines show the flux level of 100%, 10% and 1% Crab Nebula flux.

The observations of 2FGL J1410+7411 were performed from January till March 2013. The zenith angle window ranged from 45° to 47°. The total exposure time was 13

1. We define strong radio sources as those radio emitters showing fluxes above 50 mJy in the NVSS [50] or SUMSS [51], in accordance with the definitions adopted in those catalogs.

h. After data quality selection the exposure time reduced down to 7 h. No signal was found over the background. Using the Rolke method [56] we calculated differential flux upper limits in equidistant energy bins from 200 GeV to 10 TeV. Figure 1 shows the extrapolated 2FGL J1410.4+7411 *Fermi*-LAT spectrum and the MAGIC differential flux upper limits. The direct extrapolation of the *Fermi*-LAT spectrum is compatible with the derived upper limits.

5 Discussion & Conclusions

A dedicated search designed to select possible DM clump candidates out of the 2FGL Catalog has been presented, concluding with 23 candidates out of the 650 UFOs. After studying the prospects of detection for each of these sources, the best candidate was observed by the MAGIC Telescopes. No signal was detected from 2FGL J1410+7411, therefore we cannot neither rule out nor confirm the possibility that the emission in the *Fermi*-LAT energy range is due to DM. Further multiwavelenght observations are needed in order to shed light on the real nature of these objects.

Acknowledgments: 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. N.M. gratefully acknowledges support from the Spanish MICINN through a Ramón y Cajal fellowship. I.L. gratefully acknowledges support from the Spanish MICINN through a FPU fellowship.

References

[1] Komatsu E. et al. ApJS 192 (2011) 18
[2] Ade P.A.R., submitted to A&A (2013)
[3] Bertone G. ed., Cambridge University Press 2010 isbn:978-0-521-76368-4
[4] NASA 2013, `http://fermi.gsfc.nasa.gov`
[5] H.E.S.S. coll. 2013, `http://www.mpi-hd.mpg.de/hfm/HESS/`
[6] MAGIC coll. 2013, `http://wwwmagic.mppmu.mpg.de/`
[7] VERITAS coll. 2013 `http://veritas.sao.arizona.edu/`
[8] Cirelli M. et al., JCAP 3 (2011) 51
[9] Pieri L. et al., Phys.Rev.D 83 (2011) 023518
[10] Lee S.K et al., JCAP 0907 (2009) 007
[11] Ando S. et al., Phys.Rev.D 78 (2008) 101301
[12] Baltz, E. A.et al., Phys.Rev.D 61 (1999) 023514
[13] Aleksić J. et al., JCAP 6 (2011) 35
[14] Aliu E. et al., Phys.Rev.D 85 (2012) 062001
[15] Abramowski A. et al., Astroparticle Physics 34 (2011) 608-616
[16] Ackermann M. et al., Phys.Rev.Lett. 107 (2011) 241302
[17] Aharonian F. et al., Phys.Rev.Lett. 97 (2006) 221102
[18] Abramowski et al., Phys.Rev.Lett. 106 (2011) 16130
[19] Ackermann M. et al., JCAP 5 (2010) 25
[20] Aleksić, J. et al., ApJ 710 (2010) 634-647
[21] Abramowski et al., ApJ 750 (2012) 123
[22] Abramowski A. et al., Astrophys. Journal 735 (2011) 12
[23] Angulo R. E. et al., MNRAS 426 (2012) 2046-2062
[24] Prada F. et al., MNRAS 423 (2012) 3018-3030
[25] Diemand, J. et al., Nature 454 (2008) 735-738
[26] Springel, V. et al., Nature 456 (2008) 73-80
[27] Stadel, J. et al., MNRAS 398 (2009) L21
[28] Diemand J. et al., Nature 433 (2005) 389
[29] Sawala T. et al., MNRAS 431 (2013) 1366
[30] Pieri, L. et al., MNRAS 384 (2008) 1627
[31] Kamionkowski, M. et al., Phys.Rev.D 81 (2010) 043532
[32] Beringer J. et al., Phys.Rev.D 86 (2012) 010001
[33] Nieto, D. et al., 3rd Fermi Symposium, Rome (2011)
[34] Mirabal N., MNRAS 429 (2013)
[35] Mirabal N. et al., MNRAS 424 (2013) L64
[36] Ackermann M. et al., ApJ 747 (2012) 121
[37] Belikov A. V. et al., Phys.Rev.D 86 (2012) 043504
[38] Zechlin, H.S. et al., JCAP 11 (2012) 50
[39] Zechlin, H.S. et al., A&A 538 (2012) A93
[40] Nieto, D. et al., 32nd International Cosmic Ray Conference, Beijing (2011)
[41] Geringer-Sameth A. et al., 4th Fermi Symposium, Monterrey, CA (2012)
[42] Brun P. et al., Phys.Rev.D 83 (2011) 015003
[43] Cembranos, J. A. R. et al., Phys.Rev.D 83 (2011) 083507
[44] Ackermann M. et al., ApJs 203 (2012) 4
[45] NASA 2013 `http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/`
[46] NASA 2013 `http://heasarc.gsfc.nasa.gov/`
[47] ASI 2013 `http://www.asdc.asi.it/`
[48] Donato D. et al., Bulletin of the American Astronomical Society (2010) 671
[49] SWIFT 2013 `http://www.swift.ac.uk/user_objects/`
[50] Condon J. J. et al., ApJ 115 (1998) 1693-1716
[51] Mauch T. et al., MNRAS 342 (2003) 1117
[52] Li, T.P. et al., ApJ 272 (1983) 317
[53] Aleksić J. et al., Astropart. Phys. 35 (2012) 435
[54] V. P. Fomin et al., Astropart.Phys. 2 (1994) 137
[55] MAGIC Collaboration, R. Zanin et. al., 33rd ICRC, Rio de Janeiro, Brasil
[56] Rolke, W. et al., NIM A551(2005) 493-503