A search for a dark matter annihilation signal towards the Canis Major overdensity with H.E.S.S.

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***Abstract*. A search for a dark matter (DM) annihilation signal into gamma-rays towards the direction of the Canis Major (CMa) overdensity has been performed with the HESS telescope. The nature of CMa is still controversial and one scenario represents it as a dwarf galaxy, making it an interesting candidate for DM annihilation searches. A total of 9.6 hours of high quality data were collected with the H.E.S.S. array of Imaging Atmospheric Cherenkov Telescopes (IACTs) and no evidence for a very high energy γ-ray signal was found. Constraints on the velocity-weighted annihilation cross section $\langle\sigma v\rangle$ are calculated for specific WIMP scenarios, using a NFW model for the DM halo profile and taking advantage of numerical simulations of hierarchical structure formation. 95 % C.L. exclusion limits of the order of 5 $\times$ 10^{-24} cm^3 s^{-1} are reached in the 500 GeV - 10 TeV WIMP mass range.**

***Keywords*: TeV gamma rays - dark matter - dwarf galaxies**

I. Introduction

Many astrophysical objects, ranging from DM clumps to galaxy clusters are expected to lead to DM particle annihilation signals that are detectable with Imaging Atmospheric Cherenkov Telescopes (IACT). Regions of high concentration of DM are good candidates to search for such annihilations and the Galactic Centre (GC) was first considered. H.E.S.S. observations of the GC region [Aharonian et al. 2004] revealed a source of VHE γ-ray emission (HESS J1745-290) but ruled out the bulk of the signal as of DM origin [Aharonian et al. 2006c]. There are also other candidates with high DM density in relative proximity that might lead to detectable DM annihilation signals. Satellite dwarf galaxies of the Milky Way (MW) such as Sagittarius, Draco or Canis Major are popular targets, owing to their relatively low astrophysical background [Evans, Ferrer and Sarkar 2004]. A null result concerning the search for DM towards the Sagittarius dwarf spheroidal galaxy (Sgr dSph) direction was published by the H.E.S.S. collaboration [Aharonian et al. 2008]. The present paper, based on [Aharonian et al, 2009], reports the search for a DM annihilation signal towards the direction of the CMa overdensity with the H.E.S.S. array of Cherenkov telescopes. The paper is organized as follows: in Sec 2 the controversial nature of the CMa overdensity is briefly discussed; in Sec 3 the analysis of the data is presented, while in Sec 4 the predictions for DM annihilation into γ-rays in the CMa overdensity are discussed. Constraints on the WIMP velocity-weighted annihilation rate are given.

II. A Galactic warp or the relic of a dwarf galaxy?

Since its discovery [Martin et al. 2004], the nature of the Canis Major (CMa) overdensity is the subject of many discussions over whether it is a dwarf galaxy or simply a part of the warped Galactic disk. According to [Momany et al. 2006], the CMa overdensity simply reflects the warp and flare of the outer disk of the MW. The second scenario, which is of interest for the aim of this paper, considers this elliptical overdensity as the remnant of a disrupted dwarf galaxy that could have created the Monoceros "ring" structure [Martin et al. 2004]. Indeed, numerical simulations show that such a structure can be explained by an in-plane accretion event, in which the remnant of the dwarf galaxy would have an orbital plane close to the Galactic plane. The mass, luminosity and characteristic dimensions of CMa appear quite similar to those of the Sgr dwarf galaxy. As for many dSph, the CMa overdensity would thus be an interesting candidate for DM detection. In the remainder of the paper, the Canis Major object is assumed to be a dwarf galaxy.

The CMa overdensity is located towards the Galactic anti-centre direction at roughly 8 kpc from the sun [Bellazinni et al. 2004] and is the closest observed dwarf galaxy. It is a very extended object (Δl = 12°, Δb = 10°) with a roundish core approximately centered at l = 240° and b = -8° according to various star surveys in this region [Martin et al. 2004], [Martinez et al. 2004]. In contrast to other dwarf galaxies, neither dispersion velocity measurements, nor luminosity profiles are available so that an accurate modelling of the CMa DM halo profile is not possible. However, there are enough constraints to estimate the expected γ-ray flux from DM particle annihilations in this object. The annihilation cross-section is given by the particle physics model (see section IV). As concerns the mass content of CMa, the narrow dispersion between the average mass values found for different dSph galaxies in the local group [Mateo 1998], [Walker et al. 2007] is an indication that dSph's may possibly have a universal host halo mass [Dekel and Silk 1986]. The mass of the CMa dwarf galaxy can then be inferred to be in the same range as the Sgr dwarf galaxy and many other dSph's so that the CMa total mass would range between 10^8 and 10^9 $M_\odot$ [Martin et al. 2004]. For instance, reference

[Evans, Ferrer and Sarkar 2004] gives a model where the CMa mass is taken as 3×10^8 $M_\odot$. The H.E.S.S. large FoV covers a large part of the CMa core, optimizing the chances to see a potential DM annihilation signal.

III. H.E.S.S. OBSERVATIONS AND ANALYSIS

A. The H.E.S.S. array of Imaging Atmospheric Cherenkov Telescopes

H.E.S.S. is an array of four Imaging Atmospheric Cherenkov Telecopes (IACT's) [Hofmann et al. 2003] located in the Khomas Highland of Namibia at an altitude of 1800 m above sea level. The instrument uses the atmosphere as a calorimeter and images electromagnetic showers induced by TeV γ-rays. Each telescope collects the Cherenkov light radiated by particle cascades in the air showers using a large mirror area of 107 m^2 and a camera of 960 photomultiplier tubes (PMT's). The four telescopes are placed in a square formation with a side length of 120 m. This configuration allows for a accurate reconstruction of the direction and energy of the γ-rays using the stereoscopic technique. The cameras cover a total field of view of 5° in diameter. The energy threshold of the H.E.S.S. instrument is approximately 100 GeV at zenith and its sensitivity allows to detect fluxes larger than 2×10^{-13} cm^{-2} s^{-1} above 1 TeV in 25 hours. More details on the H.E.S.S. experiment can be found in [Aharonian et al. 2006b].

B. Data processing

Observations of the CMa dwarf galaxy with H.E.S.S. were carried out in November 2006 with pointing angles close to the zenith and extending up to 20°. The nominal pointing direction was l = 240.15° and b = -8.07° in Galactic coordinates. The data were taken in "wobble mode" with the telescope pointing typically shifted by ±0.7° from the nominal target position. The dataset used for image analysis was selected using the standard quality criteria, excluding runs taken under bad or variable weather conditions. The CMa dataset amounts to 9.6 hours of live time after quality selection.

The data processing uses a combination of 2 techniques. The first technique computes the "Hillas geometrical moments" of the shower images to reconstruct shower geometry and energy, and to discriminate between γ-ray and hadronic events [Aharonian et al. 2005]. The second technique uses a semi-analytical model of air showers which predicts the expected intensity in each camera pixel [de Naurois et al. 2003]. The combination of these two techniques, referred hereafter as "Combined Hillas/Model analysis", uses a combined estimator (the so-called "Combined cut") and provides an improved background rejection. The background is estimated following the template background method [Rowell 2003]. Table I shows the different cut values used to select the γ-ray events. Events that pass the analysis cuts are labelled as "γ candidates" and are stored in the so-called γ candidate map $n_\gamma^{\rm candidate}(l, b)$. Events that do not pass the analysis cuts are defined as "background events" and are stored in the so-called background map $n_{\rm bck}(l, b)$.

Cut name	γ-event cut value
Combined cut	≤ 0.7
Image charge min.	≥ 60 photo-electrons
Reconstructed shower depth min.(rad. length)	-1
Reconstructed shower depth max. (rad. length)	4
Reconstructed nominal distance	$\leq 2.5°$
Reconstructed event telescope multiplicity	≥ 2

TABLE I
LIST OF CUTS USED IN THE ANALYSIS

The 2.5°×2.5° excess sky map is obtained by the following equation:

$$n_\gamma^{\rm excess}(l, b) = n_\gamma^{\rm candidate}(l, b) - \alpha(l, b) \times n_{\rm bck}(l, b), \quad (1)$$

where $\alpha(l, b)$ refers to the template normalisation factor as described in [Rowell 2003]. To search for a gamma-ray signal, the raw fine-binned maps are integrated with a 0.1° radius around each point to match the H.E.S.S. angular resolution, resulting in new oversampled maps of gamma-ray candidates and background events, and a corresponding gamma-ray excess map. Using the prescription of Li and Ma [Li and Ma 1983] to derive the significance for each point of the oversampled map on the basis of the gamma-ray candidate and background counts and the template normalization factor, no significant excess is found at the target position or at other points in the field of view. As the excess map does not show any signal, an upper limit on the number of gamma-ray events for each point in the map can be derived using the method of Feldman and Cousins [Feldman and Cousins 1998]. The uncorrelated γ candidate and normalized background maps, plotted on a 0.2°×0.2° grid to have bins not smaller than the H.E.S.S. angular resolution, are used for the upper limits calculations.

IV. PREDICTIONS FOR DARK MATTER ANNIHILATIONS IN THE CANIS MAJOR OVERDENSITY

The DM particles are expected to annihilate into a continuum of γ-rays through various processes such as the hadronization of quark final states, hadronic decay of τ leptons and subsequent decay of mesons. Two DM candidates are commonly discussed in literature: the so-called neutralino arising in supersymmetric extensions of the standard model (SUSY) [Jungman, Kamionkowski and Griest 1996], and the first excitation of the hypercharge gauge boson in Universal Extra Dimension theories (UED) called the $B^{(1)}$ particle [Servant and Tait 2003]. Typical masses for these DM candidates range from 50 GeV to several TeV. The expected flux ϕ_γ of γ-rays from WIMP annihilations occuring in a spherical dark halo is commonly written as a product of a particle physics term

($\mathrm{d}\Phi^{\mathrm{PP}}/\mathrm{d}E_\gamma$) and an astrophysics term (f^{AP}):

$$\phi_\gamma = \frac{\mathrm{d}\Phi^{\mathrm{PP}}}{\mathrm{d}E_\gamma} \times f^{\mathrm{AP}} \quad (2)$$

The velocity-weighted cross-section for WIMP annihilation $\langle\sigma v\rangle$ and the WIMP mass are fixed to compute the particle physics term in Eq.2:

$$\frac{\mathrm{d}\Phi^{\mathrm{PP}}}{\mathrm{d}E_\gamma} = \frac{\langle\sigma v\rangle}{4\pi m_{\mathrm{DM}}^2}\left(\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\right)_{\mathrm{DM}}, \quad (3)$$

where $(\mathrm{d}N/\mathrm{d}E_\gamma)_{\mathrm{DM}}$ is the γ-ray spectrum originating for DM particle annihilation. The shape of the continuum γ-ray spectrum predicted in the framework of the phenomenological Minimal Supersymmetric extension of the Standard Model (pMSSM) depends on the model in a complicated way. A simplified parametrization of this shape, for higgsino-like neutralinos mainly annihilating via pairs of W and Z gauge bosons, was taken from [Bergström, Ullio and Buckley 1998]. In the case of KK $\mathrm{B}^{(1)}$ particle annihilations, the branching ratios to final states are independent of the WIMP mass. The differential photon continuum has been simulated with the PYTHIA package [Sjöstrand T. et al. 2003] using branching ratios from [Servant and Tait 2003].
The astrophysics term f^{AP} is given by

$$f^{\mathrm{AP}} = \int_{\Delta\Omega}\int_{\mathrm{los}} \rho^2(l)\mathrm{d}l\mathrm{d}\Omega, \quad (4)$$

where $\rho(l)$ is the mass density profile of the CMa dwarf galaxy and $\Delta\Omega$ the detection solid angle ($\Delta\Omega = 10^{-5}$ sr, corresponding to the integration radius of 0.1°).

A. Model of the Canis Major Dark Matter halo within the ΛCDM cosmology

The estimate of the astrophysical term f^{AP} relies on the modelling of the CMa DM mass distribution. Observationally, the DM mass content of dSph galaxies can be derived using velocity dispersion measurements of their stellar population as well as their luminosity profile. The comparison between models and observations can constrain the parameters of their assumed density profiles. In the case of the CMa dSph, the lack of available observational data prevents the modelling of its density profile in the same way as in the literature [Evans, Ferrer and Sarkar 2004], [Colafrancesco, Profumo and Ullio 2007], [Aharonian et al. 2008].
In the absence of observational data, a standard cusped NFW halo [Navarro, Frenk and White 1997] was assumed to model the CMa dwarf mass distribution:

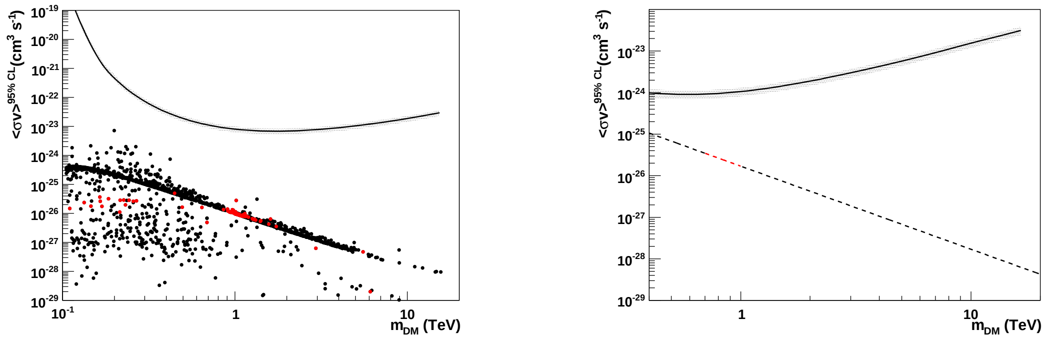
$$\rho_{\mathrm{cusped}}(r) = \frac{\rho_0}{\frac{r}{r_{\mathrm{s}}}(1+\frac{r}{r_{\mathrm{s}}})^2}, \quad (5)$$

where ρ_0 is the overall normalisation and r_{s} the scale radius. The parameters ρ_0 and r_{s} determining the shape of the profile as well as the halo virial mass M_{vir} are found by solving a system of 3 equations relating the virial mass, radius and concentration parameter. The concentration parameter is obtained from the halo concentration fit of [Dolag et al. 2004]. An iterative procedure was used to take the tidal stripping of CMa by the gravitational field of the MW into account. An important question is now whether or not tidal forces significantly remodel the internal structure of tidally affected dSph. Discrepant results have been reported in the literature regarding this question [Reed et al. 2005], [Stoehr et al. 2002]. Here, it is assumed that tidal forces do not affect the inner part of the density profile so that the initial halo structural parameters are kept constant during the stripping procedure. The remaining mass is typically found to be an order of magnitude lower than the virial mass.
The astrophysical term f^{AP} can then be computed as a function of the halo mass by performing the line-of-sight integration of the CMa dSph squared mass density, according to Eq. 4. The values of f^{AP} obtained range from f^{AP} ~2.3 10^{23} GeV^2 cm^{-5} for a halo mass of 10^6 $\mathrm{M}_\odot$ to f^{AP} ~1.2 10^{25} GeV^2 cm^{-5} for a halo mass of 10^{10} $\mathrm{M}_\odot$.

B. Sensitivity to the annihilation cross-section of WIMP candidates

In this part, the CMa total mass is fixed to be 3×10^8 $\mathrm{M}_\odot$, which is the mass quoted by[Evans, Ferrer and Sarkar 2004]. The value of the astrophysical factor is f^{AP} =2.2 10^{24} GeV^2 cm^{-5}. Limits on the velocity-weighted annihilation cross-section $\langle\sigma v\rangle^{95\%\mathrm{C.L}}$ can then be derived as a function of the DM particle mass in the framework of SUSY and KK models. The SUSY parameters were computed with the micrOMEGAs v1.37 software package [Belanger et al. 2004]. Fig. 1a shows the H.E.S.S. exclusion limits on the velocity weighted cross-section. The black points illustrate the computed pMSSM scenarios and the red points represent those satisfying the WMAP+SDSS constraints on the CDM relic density $\Omega_{\mathrm{CDM}}h^2$ [Tegmark et al. 2006]. $\Omega_{\mathrm{CDM}}h^2$ is allowed to range between 0.09 and 0.11. The H.E.S.S. observations of the CMa dSph allows to exclude velocity weighted cross-sections of the order of 5×10^{-24} cm^3 s^{-1}, comparable with those derived for the Sgr dSph modelled with a cusped NFW profile. The limits obtained are an order of magnitude larger than the velocity-weighted annihilation cross sections of higgsino-like neutralinos.

In the case of KK scenarios, predictions for the velocity-weighted cross-section are computed with the formula given in [Baltz and Hooper 2005]. The expression of $\langle\sigma v\rangle$ is inversely proportional to the squared mass of the lightest Kaluza-Klein (LKP) particle, namely the $\mathrm{B}^{(1)}$ particle. Considered KK models that reproduce the CDM relic measured by WMAP and SDSS require a LKP mass ranging from 0.7 TeV to 1 TeV. Fig. 1b shows the H.E.S.S. limits obtained within these models. The H.E.S.S. observations do not constrain the KK velocity weighted cross-section.



(a) pMSSM models

(b) KK models

Fig. 1. Upper limits at 95% CL on the velocity weighted cross-section as a function the DM particle mass in the case of pMSSM (left panel) and KK (right panel) scenarios, for an assumed CMa total mass of 3×10^8 $M_\odot$. The shaded area represents the 1σ error bars on $\langle \sigma v \rangle^{95\% C.L}$ (see text for details). (left) The pMSSM models are represented by black points, and those giving a CDM relic density in agreement with the measured WMAP+SDSS value are illustrated by red points. (right) The KK models are represented by the black dashed line, and those verifying the WMAP+SDSS constraint on $\Omega_{\rm CDM}h^2$ are labelled in red.

V. Conclusions

The CMa overdensity is the subject of many debates over whether it is a dwarf galaxy or the warp and flare of the Galactic outer disk. Considering the first scenario, its relative proximity makes it potentially the best region for searches of a DM annihilation signal. However, the lack of observational data prevents the precise modelling of its density profile. Assuming a NFW profile and a mass content of 3×10^8 $M_\odot$ within its tidal radius, typical of dwarf galaxies, H.E.S.S. is close to exclude a few pMMSM scenarios with higgsino-like neutralinos, but does not reach the necessary sensitivity to test models compatible with the WMPA+SDSS constraint on the CDM relic density. In the case of DM made of $B^{(1)}$ particle from KK models with extra dimensions, no constraints are obtained.

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