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H.E.S.S. observations of the globular clusters NGC 6388 and M 15 and search for a Dark Matter signal

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Abstract: The globular clusters NGC 6388 and M 15 have been observed by the H.E.S.S. array of Cherenkov telescopes for a live time of 27.2 and 15.2 hr, respectively. No γ-ray signal is found at their nominal target position. In the primordial formation scenario, GCs are formed in a dark matter halo and dark matter could still be present in the baryon-dominated environment of globular clusters. The dark matter content of NGC 6388 and M 15 is modeled taking into account the astrophysical processes that can be expected to influence the dark matter distribution during the evolution of the globular cluster: the adiabatic contraction of dark matter by baryons, the adiabatic growth of a black hole in the dark matter halo, and the kinetic heating of dark matter by stars. 95% confidence level exclusion limits on the dark matter particle velocity-weighted annihilation cross section are derived for these dark matter halos. In the TeV range, these limits reach at the $10^{25}\mathrm{cm}^3\mathrm{s}^{-1}$ level and a few $10^{24}\mathrm{cm}^3\mathrm{s}^{-1}$ for NGC 6388 and M 15, respectively.

Keywords: Gamma-ray observations, globular clusters, dark matter, black hole.

1 Introduction

Several Galactic globular clusters (GCs) have been observed with imaging atmospheric Cherenkov telescopes and upper limits on γ-ray emission from standard astrophysical processes have been reported on Omega Centauri, 47 Tucanæ, M 13, M 15, and M 5 [1, 2, 3, 4]. GCs are also potential targets for indirect dark matter (DM) searches [5]. They are dense stellar systems of $\sim$10 Gyr old, found in halos of galaxies, with typical masses between 10^4 and a few 10^6 $\mathrm{M}_\odot$. Observations of GCs do not suggest the presence of a signicant amount of DM, but rather that these objects are dominated by baryons [6]. In the primordial formation scenario of GCs [7], GCs were formed in dark matter (DM) minihalos before or during the reionization, before the formation of galaxies. However, the distribution of GC colors [8] suggests that only metal-poor clusters have a cosmological origin, while metal-rich clusters formed in star-forming events such as galaxy-galaxy mergers.

In the purpose of the paper, GCs are assumed to have formed in DM minihalos and thus were DM-dominated in their primordial stage. Note that M 15 is a metal-poor GC, $[\mathrm{Fe/H}]\simeq$-2.37 [9], while NGC 6388 is metal-rich, $[\mathrm{Fe/H}]\simeq$-0.55 [9], so the DM minihalo scenario is better motivated for M 15 than NGC 6388. However, NGC 6388 might host a $10^3\,\mathrm{M}_\odot$ black hole [10]. Such massive (10^3 $\mathrm{M}_\odot$) black holes are not easily formed in star-forming events [11] suggesting a primordial formation origin. During the evolution of the GC, the DM reacts to the infall of baryons and is pulled in towards the center. This process is usually referred to as the adiabatic contraction (AC) model [12, 13]. The effect of the contraction of DM in response to the baryon infall is particularly important for the calculation of the DM annihilation in baryonic environments such as the Galactic Center region [14, 15].

The distribution of baryons and DM is affected by the kinetic heating of DM by baryons [16] and by the presence of a black hole (BH) [17]. A growing body of observations on GCs shows that they may harbor intermediate mass black holes (IMBHs) with masses ranging from 10^3 to 10^5 $\mathrm{M}_\odot$, although the existence of these objects is not yet established. Among the GCs that may host IMBHs are NGC 6388 [10], ω Centauri [18] in the Milky Way or even G1 in M 31 [19, 20].

2 Observations

2.1 NGC 6388

NGC 6388 is one of the best known Galactic GC. It is located at $\sim 11.5\,\mathrm{kpc}$ from the Sun, at RA = $17^{\mathrm{h}}36^{\mathrm{m}}17.05^{\mathrm{s}}$ and Dec = $-44^\circ44'05.8''$ (J2000), and has a mass estimated to be $\sim 10^6$ $\mathrm{M}_\odot$. The stellar mass density in the core, with radius r_c = 0.4 pc (0.12 arcminutes), reaches $\sim 5\times10^5\,\mathrm{M}_\odot\mathrm{pc}^{-3}$. The tidal radius is r_t $\sim 25\,\mathrm{pc}$ [10]. Using the high-resolution HST and WFI observations at ESO, it is shown in [10] that the surface brightness density of stars significantly deviates from a flat core in the inner part, which is compatible with the existence of an IMBH with a mass of $\sim 5 \times 10^3\,\mathrm{M}_\odot$. A power law with a slope of -0.2 is detected in the surface brightness density profile, which suggests the presence of a central IMBH [21, 22]. The *Chandra* satellite has detected three X-ray sources, coincident in position with the centre of gravity of NGC 6388 located with an uncertainty of $0.3''$. One of these may be the X-ray counterpart of the putative IMBH [23].

The H.E.S.S. observations of NGC 6388 were taken between June 2008 and July 2009. The observation zenith angles range from 20° to 44° with a mean zenith angle of 22.9°, and the exposure time is 27.2 hours. The data analysis is described in [24]. No significant γ-ray excess is found above the background. The upper limit at 95% confidence level (C.L.) on the number of γ-rays is: $\mathrm{N}_\gamma^{95\%\mathrm{C.L.}} = 21.6$.

2.2 M 15

M 15 (NGC 7078) is a well-studied Galactic GC centered at the position RA = $21^\mathrm{h}28^\mathrm{m}58.3^\mathrm{s}$ and Dec = $12°10'00.6''$ (J2000). It is situated at $\sim 10\,$kpc from the Sun. Its estimated mass is $\sim 5\times10^5\,\mathrm{M}_\odot$. The stellar mass density in the core with radius $r_\mathrm{c} = 0.04$ pc is about $10^7\,\mathrm{M}_\odot\mathrm{pc}^{-3}$ [25], and the tidal radius is $r_\mathrm{t} \sim 30\,$pc. The surface brightness density of the GC M 15 suggests the presence of a stellar cusp in the inner part, at least down to distances of a few 10^{-2} pc [25]. M 15 may thus harbor an IMBH [26, 27] in its center. However, the study on milli-second pulsars in M 15 sets an upper limit of $10^3\,\mathrm{M}_\odot$ on the mass of a hypothetical central BH [28]. In what follows, no central back hole is assumed for the modelling of M 15.

The observations of M 15 by H.E.S.S. were carried out in 2006 and 2007 with an offset angle of 0.7° and zenith angles from 34° to 44° resulting in 15.2 hours of high quality data at a mean zenith angle of 37.0°. The data analysis reveals no significant γ-ray signal at the nominal position. The 95% C.L. upper limit on the number of γ-rays is $\mathrm{N}_\gamma^{95\%\mathrm{C.L.}} = 11.5$.

3 Dark matter constraints

The γ-ray flux expected from DM annihilations can be decomposed into an astrophysical term and a particle physics term as:

$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{1}{8\pi} \underbrace{\frac{\langle\sigma v\rangle}{m_\mathrm{DM}^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}}_{Particle\ Physics} \times \underbrace{\bar{J}(\Delta\Omega)\Delta\Omega}_{Astrophysics} . \tag{1}$$

The astrophysical factor ($\bar{J}$) is generally expressed as the integral over the line of sight (los) of the squared density averaged over the solid angle $\Delta\Omega$:

$$\bar{J} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{los} ds\, \rho^2(r(s)) \tag{2}$$

with $r(s) = \sqrt{s^2 + s_0^2 - 2ss_0\cos\theta}$, s_0 the distance of the source from the Sun and θ the opening angle of the integration cone centered on the target position.

3.1 Dark matter halo modeling

The primordial formation scenario of GCs [7] assumed here requires that they were formed in extended DM halos. The DM halo profile of a GC is thus modelled assuming an initial Navarro-Frenk-White (NFW) profile [29] described by:

$$\rho(r) = \rho_0 \left(\frac{r}{r_\mathrm{s}}\right)^{-1} \left(1 + \frac{r}{r_\mathrm{s}}\right)^{-2} . \tag{3}$$

This DM halo is parameterized by a virial mass M_vir and a concentration parameter c_vir. The normalization parameter ρ_0 and the scale radius r_s can be related to the virial mass and the concentration parameter using the following relations [29]

$$\rho_0 = \frac{M_\mathrm{vir}}{4\pi r_\mathrm{s}^3 f(c_\mathrm{vir})} \quad , \quad r_\mathrm{s} = \frac{R_\mathrm{vir}}{c_\mathrm{vir}} \ ; \tag{4}$$

where the function $f(x)$ is, neglecting constants, the volume integral of the NFW profile given by $f(x) \equiv \ln(1 + x) - x/(1 + x)$. In this paper, initial DM halos of GCs are modelled with $M_\mathrm{vir} = 10^7\,\mathrm{M}_\odot$. The value of c_vir used in the model of NGC 6388 is calculated using the relationship obtained in [30][1]. For M 15, the value of c_vir is taken from [5].

The presence of a central BH changes the DM and stellar densities in regions where the BH dominates the gravitational potential, *i.e.* for distances to the BH lower than the radius of gravitational influence r_h. The adiabatic growth of the BH leads to a spiked DM distribution with an index of 9/4 for an initial DM distribution with an index of 1, as for the NFW profile. The spike is smoothed by the kinetic heating of DM by stars over the timescale T_r, forming a density profile proportional to $r^{-3/2}$ called DM crest [31], which corresponds to the final profile.

The relaxation time has a much smaller value, $T_r \sim 10^7$ yr, in GCs than in galaxies, where it is typically of the order of 10^{13} yr [6]. Since GCs are among the oldest objects known, their present DM density depends on their history and evolution. During infall events such as core collapses [32], the DM is compressed towards the center following the AC scenario [13, 12]. This profile is referred to hereafter as the AC profile. But the kinetic heating of DM particles by stars [16] tends to wash out the adiabatic contraction effect over a timescale of the order of T_r. Both effects were taken into account in the modelling of M 15 and NGC 6388, following the approach of [31] and [33]. The dark halo models of M 15 and NGC 6388 are described in details in [24]. The DM halo of M 15 differs from the model published in [5], since the effect of DM heating by stars is considered in addition to the effect of adiabatic contraction. The inferred DM mass densities of NGC 6388 and M 15 are shown in figure 1.

To match the analysis cuts used in this work (see Section 2), $\Delta\Omega$ is set to 5×10^{-6} sr. The values of the astrophysical factor for the DM halo profiles are shown in table 4

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[1] In [30], $\mathrm{c_{vir}} = 9 \times (\mathrm{M_{vir}}/1.5 \times 10^{13}\mathrm{h}^{-1}\mathrm{M}_\odot)^{-0.13}$ where h is the present day normalized Hubble constant.

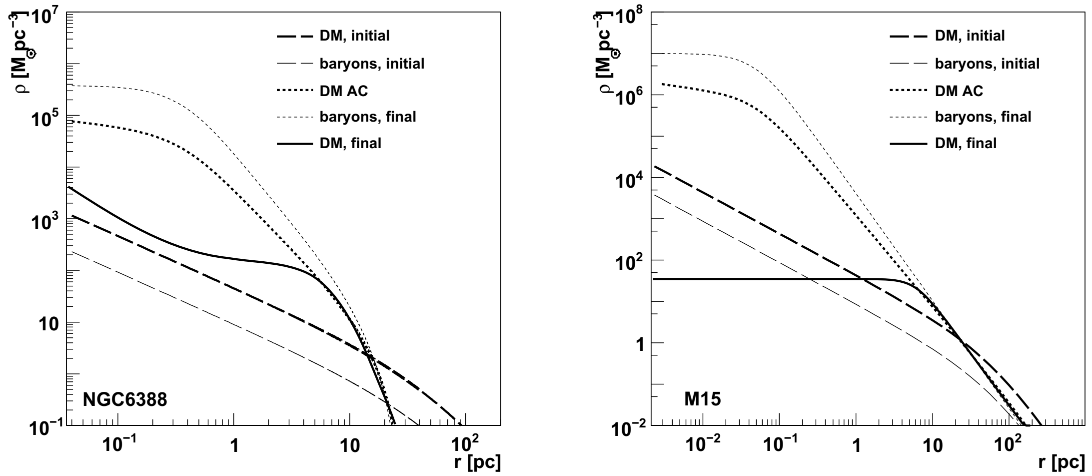

Figure 1: DM and baryonic mass density distributions in NGC 6388 (left) and M 15 (right). The DM density before (thick dashed line) and after (thick dotted line) the adiabatic contraction by baryons is shown. The initial DM distribution follows a NFW profile with $\mathrm{M_{vir}} = 10^7\,\mathrm{M_\odot}$. The initial (thin dashed line) and final (thin dotted line) baryonic densities are displayed. The final DM density distribution after the effects of the adiabatic growth of the IMBH at the center of NGC 6388 and the kinetic heating by stars is presented (thick solid line).

of [24]. In the case of the IMBH NFW and final DM profiles for NGC 6388, the calculation of the astrophysical factor requires a minimum cutoff for the integration radius. For the IMBH NFW and final profiles, the integral diverges as $r_{\rm min}^{-3/2}$ and $\log(r_{\rm min}^{-1})$ respectively, where $r_{\rm min}$ is the inner radius. $r_{\rm min}$ is usually taken as $\mathrm{Max}[r_S, r_A]$ where $r_S \equiv 2GM_{\rm BH}/c^2$ is the Schwarzschild radius of the black hole and $r_{\rm A}$ is the self-annihilation radius calculated for an annihilation time of 10 Gyr. Typical values of m_{DM} and $\langle\sigma v\rangle$ give $\mathrm{r_A} \simeq 10^{-5}$ pc so that $r_{\rm min} = r_{\rm A}$. The value of the astrophysical factor for the final profile is insensitive to the assumed value of $r_{\rm min}$. The evolution of M 15 leads to a depletion of DM, implying a decrease of $\bar{J}$. In the case of NGC 6388, the effect of the BH in the stellar environment boosts $\bar{J}$ to a value higher than that obtained for the initial NFW profile.

3.2 Exclusion limits

Figure 2 shows the 95% C.L. exclusion limits for NGC 6388 on $\langle\sigma v\rangle$ for the initial NFW (dashed line) and the final profile (solid line) derived from the 95% C.L. upper limit on the number of γ-rays. The generic parametrization from [34] as well as a parametrization including contributions from virtual internal Bremsstrahlung and final state radiation [35] are used for the differential γ-ray spectra. The parametrization from [34] is derived from a fit to the γ-ray spectrum from WIMP annihilations into W and Z pairs. The latter includes both γ-rays from virtual particles and from charged particle final states of the pair annihilation of winos [36]. The limits are 1 to 3 orders of magnitude above the natural value of the velocity-weighted annihilation cross section for thermally-produced DM [36]. Figure 2 shows the H.E.S.S. 95% C.L. exclusion limits for M 15 for the initial and final DM profiles, as well as those obtained with the Whipple Cherenkov telescope (blue area) in [5]. The thickness of the drawn lines represents the astrophysical uncertainty induced by the plausible mass range for the initial virial mass. The H.E.S.S. limit reaches $\langle\sigma v\rangle \sim 5\times10^{-23}\,\mathrm{cm^3s^{-1}}$ and $\langle\sigma v\rangle \sim 5\times10^{-24}\,\mathrm{cm^3s^{-1}}$ around $m_{\rm DM}$ = 2 TeV for the initial NFW profile and the final profile respectively. For comparison, the exclusion limit obtained for H.E.S.S. using the DM halo modelling of [5] are also shown (gray area).

4 Summary

The present paper gives for the first time exclusion limits on DM towards several GCs taking into account all relevant astrophysical effects affecting the hypothetical DM halo. H.E.S.S. observations reveal no significant γ-ray excess from point-like sources located at the position of NGC 6388 and M 15. The hypothetical DM halo has been modelled taking into account possible astrophysical processes leading to substantial changes in the initial DM profile: the adiabatic contraction of DM by baryons and the adiabatic growth of a BH at the center of the DM halo. The scattering of DM by stars in such a dense stellar environment has been taken into account to provide realistic final DM halos. This effect is of crucial importance to model DM halos in these baryon-dominated environments and leads to a depletion of DM during the evolution of the globular cluster. On the other hand, the presence of a central massive BH enhances the DM density in the center. The constraints on the velocity-weighted annihilation

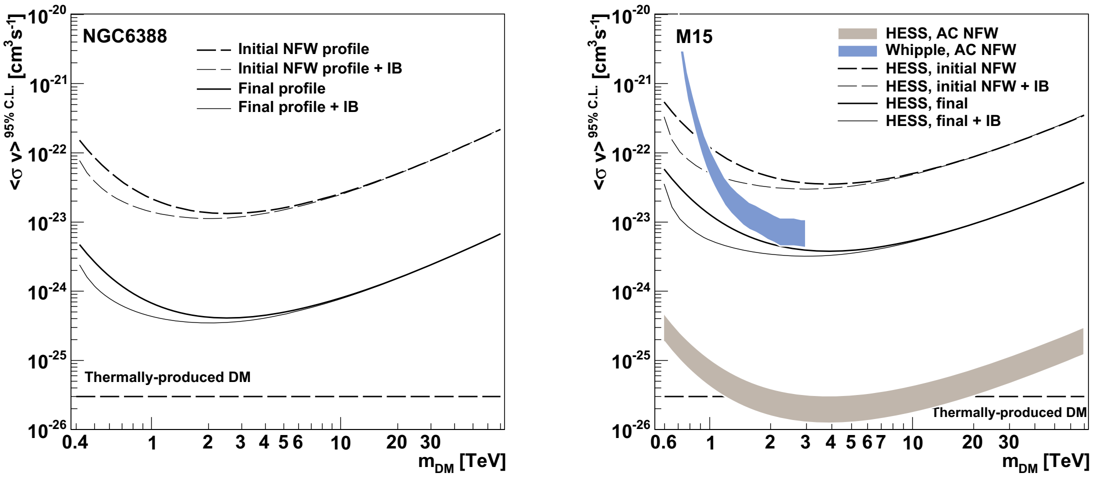

Figure 2: H.E.S.S. upper limits at 95% C.L. on the velocity-weighted annihilation cross section $\langle\sigma v\rangle$ versus the DM mass $m_{\rm DM}$ for NGC 6388 (left) and M 15 (right). DM halo profiles shown here correspond to the initial NFW profile (dashed thick line) and the realistic profile taking into account plausible astrophysical effects (solid thick line). The contribution from internal Bremsstrahlung and final state radiation to the annihilation spectrum is also shown (dashed/solid thin lines) for both profiles. The natural value of $\langle\sigma v\rangle$ for thermally-produced DM is also displayed (long-dashed line)

cross section of the DM particle lie at the level of a few 10^{-25} cm^{3}s^{-1} for NGC 6388 in the TeV energy range. Assuming the absence of a massive BH in the center of M 15, the constraints are of the order of a few 10^{-24} cm^{3}s^{-1}.

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