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Search for dark matter in compact hydrogen clouds

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ABSTRACT
The recently published GALFA-HI Compact Cloud Catalogue lists 20 neutral hydrogen clouds that might pinpoint previously undiscovered high-latitude dwarf galaxies. Detection of an associated gamma-ray dark matter signal could provide a route to distinguish unambiguously between truly dark matter dominated systems that have accumulated neutral hydrogen but have not successfully ignited star formation and pure gaseous structures devoid of dark matter. We use 4.3 years of *Fermi* observations to derive gamma-ray flux upper limits in the 1–300 GeV energy range for the sample. Limits on gamma rays from pair annihilation of dark matter are also presented depending on the yet unknown astrophysical factors.

Key words: (cosmology:) dark matter – gamma-rays: observations – Galaxy: halo – Galaxy: structure

1 INTRODUCTION

The number of dark matter subhalos surrounding the Milky Way has puzzled dark matter aficionados for over more than a decade. While cosmic large-scale structures are well described by the Lambda Cold Dark Matter (ΛCDM) cosmological model, a number of discrepancies exist between the standard theory of galaxy formation and observations of substructures at smaller scales (Frenk & White 2012). In particular, numerical ΛCDM simulations consistently predict that galaxies must be surrounded by a huge population of subhalos (Klypin et al. 1999; Moore et al. 1999). Intuitively, subhalos would encompass anything from the largest satellites (*e.g.* dwarf galaxies) to substructures with masses around $10^{-4} M_{\odot}$ (Loeb & Zaldarriaga 2005). Unfortunately, completing a survey of the smallest gravitationally bound systems is not straightforward (Ando et al. 2008). At faint flux levels, it becomes ever more difficult to recognise sparsely populated stellar systems. Important progress has been made recently resulting from newly discovered ultra-faint dwarf galaxies, which have nearly doubled the number of known dwarfs (Willman et al. 2005; Belokurov et al. 2007). Yet the dwarf counts in the Milky Way remains far to small compared to the number of subhalos predicted by simulations.

Interestingly, the discovery of compact hydrogen clouds potentially located in the Galactic halo has revived the possibility of a larger population of galaxy candidates that could be traced by neutral hydrogen (Lockman 2002; Ryan-Weber et al. 2008). This point was made even earlier by Klypin et al. (1999) who recognised that the much broader and physically distinct set of enigmatic HI structures commonly referred to as high-velocity clouds (HVCs) could represent the missing dark matter subhalo population (Oort 1970; Bregman 1980; Braun & Burton 1999; Blitz et al. 1999). Although intriguing, to date, a firm HI cloud-subhalo link has not been established (Quilis & Moore 2008).

Prompted by the recent release of the GALFA HI Compact Cloud Catalogue (Saul et al. 2012), we revisit the possibility that some compact hydrogen clouds can be used as a proxy for missing dark matter subhalos. There are inherent problems when trying to test this possibility, especially the lack of distance and mass information for such systems. Another major hurdle is the absence of associated stellar populations in most compact hydrogen clouds. In fact, it is even possible that many of these systems never formed stars (Ricotti 2009). Lewis et al. (2000) proposed exploiting "pixel gravitational lensing" as a way to map the dark matter content in hydrogen clouds. However, the shortage of properly aligned nearby background galaxies prevents a generalised application to a large sample.

For this reason, we explore a different approach to determine their dark matter content. If compact hydrogen clouds are dark matter dominated systems, nearby dense objects could potentially produce a detectable dark matter annihilation signal in gamma rays (Bergström et al. 1999; Baltz et al. 2000). In that vein, Flix et al. (2005) looked for spatial coincidences between unidentified EGRET sources and HVCs. With the vast improvements in gamma-ray sensitivity and angular resolution afforded by *Fermi*

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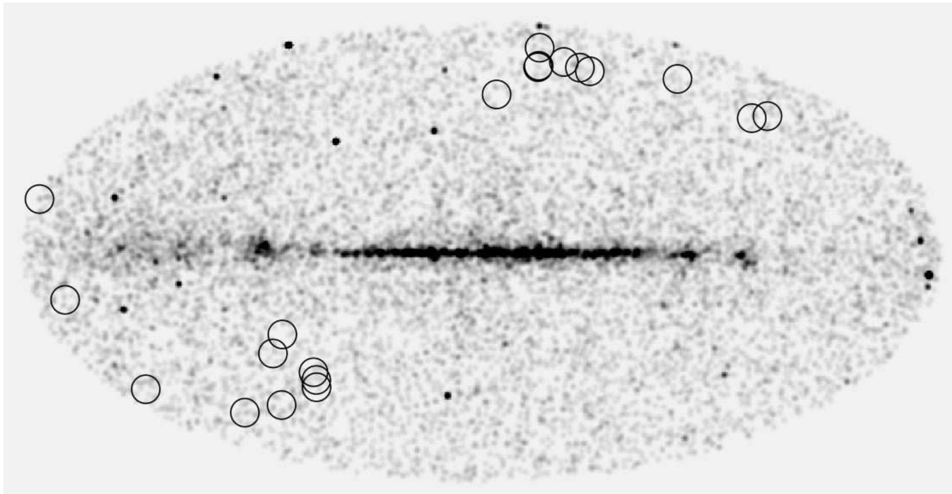

Figure 1. Aitoff projection of the *Fermi* all-sky LAT map, showing the locations of the 20 galaxy candidates in our study. Galactic coordinates.

(Atwood et al. 2009), we can search for annihilating dark matter in GALFA-HI compact hydrogen clouds directly. This study should serve not only to investigate a possible tracer of gas-bearing dark matter seeds that never formed stars, but also to set a general upper bound on the annihilation cross section $\langle \sigma v \rangle_\chi$ of a hypothesised weakly interacting massive particle (WIMP). Searches for dark matter signals using *Fermi* have been conducted unsuccessfully in a wide variety of astrophysical systems (Buckley & Hooper 2010; Ackermann et al. 2011; Ando & Nagai 2012; Mirabal et al. 2012). This work simply extends the hunt to a new sample.

The paper is structured as follows. In Section 2 we explain the selection of high-latitude galaxy candidates from the GALFA-HI Compact Cloud Catalogue, as well as the *Fermi* LAT analysis. In Section 3 we derive gamma-ray flux upper limits for Segue 1 and set dark matter annihilation constraints for the galaxy candidates. Finally, we briefly summarise our interpretation and possible future directions in Section 4.

2 GALAXY CANDIDATES AND *FERMI* LAT ANALYSIS

The GALFA-HI Compact Cloud Catalogue (Saul et al. 2012) is generated from the Galactic Arecibo *L*-Band Feed Array HI (GALFA-HI) Survey Data Release One (Peek et al. 2011). At completion, GALFA-HI will cover 13,000 deg^2 of the sky in the 1420 MHz hyperfine transition of hydrogen between $V_{LSR} = \pm 650$ km s^{-1}. Using a novel cloud detection algorithm, Saul et al. (2012) identified a total of 1964 compact ($< 20'$) hydrogen clouds in the initial 7520 deg^2 Data Release One. The catalogue breaks down the clouds into a scheme that includes high-velocity clouds (HVCs), galaxy candidates, cold low-velocity clouds (CLVC), warm low-velocity clouds, and warm positive low-velocity clouds in the third Galactic quadrant. For our purposes, we are only concerned with the 27 possible galaxy candidates that might form the core sample of potentially undiscovered dark matter subhalos. In order to guard against possible gaseous disk interlopers that may have been pushed into the halo by stellar feedback (Ford et al. 2008), we also prune galaxy candidates at $|b| \leqslant 10°$. Finally, we are left with a subset of 20 high-latitude galaxy candidates. In Fig. 1, we show the distribution of these systems on the sky.

Table 1. Gamma-ray flux upper limits at 95% confidence level.

Galaxy Candidate	l (°)	b (°)	$F_{\rm lim}$ (1–300 GeV) (ph cm^{-2} s^{-1})
003.7+10.8+236	108.53	-51.02	6.4×10^{-11}
019.8+11.1+617	133.84	-51.16	5.5×10^{-11}
044.7+13.6+528	164.15	-38.83	1.1×10^{-10}
063.7+33.3+447	164.58	-12.64	2.8×10^{-10}
100.0+36.7+417	178.44	13.67	1.1×10^{-10}
143.7+12.9+223	220.08	41.96	6.6×10^{-11}
147.0+07.1+525	228.97	42.22	4.1×10^{-11}
162.1+12.5+434	233.73	57.73	6.3×10^{-11}
183.0+04.4–112	278.82	65.41	8.0×10^{-11}
184.8+05.7–092	281.76	67.21	1.1×10^{-10}
187.5+08.0+473	287.03	70.18	4.5×10^{-11}
188.9+14.5+387	285.67	76.84	6.0×10^{-11}
195.9+06.9–100	311.64	69.59	4.0×10^{-11}
196.6+06.5–105	313.31	69.06	4.1×10^{-11}
215.9+04.6+205	351.18	58.53	7.3×10^{-11}
331.8+21.0+303	79.13	-27.58	5.9×10^{-11}
339.0+09.0–237	76.00	-41.18	9.1×10^{-11}
341.7+07.7–234	77.58	-43.95	3.9×10^{-11}
342.1+20.6+208	87.76	-33.78	7.3×10^{-11}
345.0+07.0–245	80.58	-46.48	4.1×10^{-11}

In order to explore the gamma-ray emission, we use the publicly available dataset acquired by the Large Area Telescope (LAT) instrument on board the *Fermi* Gamma-ray Space Telescope (Atwood et al. 2009). The LAT is a pair-conversion gamma-ray detector sensitive to photon energies from 20 MeV to 300 GeV. We retrieve all photons of 'source' class (`evclass=2`) within a 10° circular region centred at the position of each galaxy candidate. The data analysed here were collected between 2008 August 4 and 2012 November 20 (approximately 4.3 years of data). Good time intervals were processed using the available `v9r27p1` *Fermi* Science Tools with the standard `P7SOURCE_V6` instru-

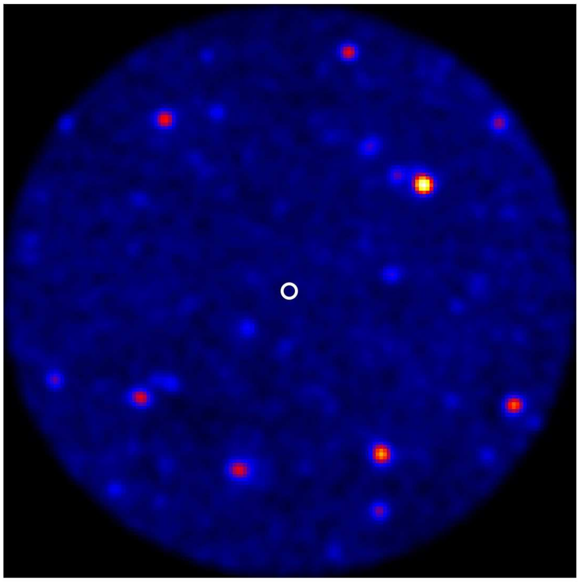

Figure 2. Smoothed *Fermi*-LAT (1–300 GeV) count map of galaxy candidate 143.7+12.9+223. The small white circle marks the centre of the Region of Interest (ROI). The map corresponds to a 20° circular region.

ment response function. Throughout, we apply a maximum zenith angle cut of 100°. We further filter the data using the `gtmktime` filter expression recommended by the LAT team, namely "(DATA_QUAL==1) && (LAT_CONFIG==1) && ABS(ROCK_ANGLE)<52" The final analysis for each region includes all the point sources listed in the 2FGL catalogue (Nolan et al. 2012), the current Galactic diffuse emission model `gal_2yearp7v6_v0.fits`, and the extragalactic isotropic model `iso_p7v6source.txt`.

The resulting dataset is analysed with a binned likelihood method using the `gtlike` tool in the standard *Fermi* Science Tools[1]. For each position, we create a count map made up of 30 logarithmically uniform energy bins using `gtbin`. We next construct a binned exposure map with `gtexpcube2`, and a model source and diffuse count map with `gtsrcMaps`. Fig. 2 shows a typical *Fermi* count map from the sample. In the absence of emission, flux upper limits are then derived using the implementation of `LATAnalysisScripts`[2]. This set of Python libraries unifies the `pyLikelihood` module included in the standard *Fermi* Science tools. Upper limits are computed with `calcUpper` assuming a power law spectrum of high-energy emission E^{-2} within a radius of 10°. We restrict our analysis to photons in the 1–300 GeV energy range. The *Fermi* LAT point spread function (PSF) is typically $0.8\,(E/1\mathrm{GeV})^{-0.8}$ deg, which in our selected energy range restricts the photons to less than 1° around each location (Geringer-Sameth & Koushiappas 2012). Table 1 summarises the 95% confidence level upper limits. Since the *Fermi* exposure is rather uniform over the sky the upper flux limits are fairly similar, except for a handful of locations with higher diffuse background emission or neighbouring bright gamma-ray sources.

1 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/binned_likelihood_tutorial.html
2 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/LATAnalysisScripts.html

3 DARK MATTER CONSTRAINTS

If compact hydrogen clouds are highly dark matter dominated objects their gamma-ray emission should be well characterised by a differential spectrum that can be written as

$$\frac{d\Phi}{dE}(E,\Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle_\chi}{2m_\chi^2}\frac{dN_\gamma}{dE} \times J(\Delta\Omega), \quad (1)$$

where $\langle\sigma v\rangle_\chi$ is the thermally averaged annihilation cross section, m_χ is the dark matter particle mass, and $\frac{dN_\gamma}{dE}$ is the photon spectrum of annihilation products (Abdo et al. 2010). The second term, or the so-called astrophysical factor $J(\Delta\Omega)$, corresponds to the integration of the dark matter density squared $\rho^2(l,\Omega)$ along the line of sight l of the compact cloud, over a solid angle $\Delta\Omega$, so that

$$J(\Delta\Omega) = \int_{\Delta\Omega}\int \rho^2(l,\Omega)\,dl\,d\Omega. \quad (2)$$

In principle, we expect compact clouds to be virtually free of gamma-ray emission from embedded diffuse and individual point sources. As a result, it is reasonable to expect that the differential spectrum from dark matter annihilation should dominate any gamma-ray signal in the direction of observation to these systems.

Formally, a robust computation of an upper limit on the annihilation cross section $\langle\sigma v\rangle_\chi$ requires some knowledge of the astrophysical factor $J(\Delta\Omega)$ of the system under consideration. Given a lack of direct observational constraints on the astrophysical factors of these galaxy candidates J_{gc}, we are only able to estimate $\langle\sigma v\rangle_\chi$ bounds from our sample by tying them to potentially similar systems in the Milky Way. Under the Ansatz that they are strongly dark matter dominated, the newly discovered ultra-faint dwarf galaxies would appear to be the closest relatives to compact hydrogen clouds (Strigari et al. 2008). As shown by Simon et al. (2011), Segue 1 represents the darkest of these systems with a very high mass-to-light ratio (~ 3400 $M_\odot/L_\odot$) and dark matter density $2.5^{+4.1}_{-1.9}$ $M_\odot$ pc^{-3}. It also boasts the largest astrophysical factor for known dwarfs $J_{Segue1} = 10^{19\pm0.6}$ GeV^2 cm^{-5} (Essig et al. 2010).

Hereafter, we derive upper limits on $\langle\sigma v\rangle_\chi$ relative to the bounds already imposed for Segue 1 using *Fermi* measurements (Abdo et al. 2010; Essig et al. 2010; Scott et al. 2010; Geringer-Sameth & Koushiappas 2012). Accordingly, we repeat the previous *Fermi* LAT analysis now centred on Segue 1 $(\ell,b) = (220.5°, 50.4°)$. The corresponding gamma-ray upper limit for Segue 1 is $F_{\mathrm{lim\ Segue1}}$ (1–300 GeV) = $3.5\ \times 10^{-11}$ ph cm^{-2} s^{-1}. In order to turn our flux upper limits into a bound on $\langle\sigma v\rangle_\chi$, we need to assume a specific annihilation channel. We adopt the strictest possible limit on dark matter annihilation into bottom quarks $b\bar{b}$ for Segue 1 based on 3 years of *Fermi* data, which translates into $\langle\sigma v\rangle_\chi \lesssim 3{\times}10^{-26}$ cm^3 s^{-1} for particle masses $m_\chi \lesssim 40$ GeV (Geringer-Sameth & Koushiappas 2012). Assuming the annihilation to be purely into $b\bar{b}$ and an average flux for the galaxy candidates $\langle F_{lim}(gc)\rangle = 7.7\times10^{-11}$ ph cm^{-2} s^{-1}, we can approximate $\langle\sigma v\rangle_\chi$ from these systems as

$$\langle\sigma v\rangle_\chi \lesssim 7\times10^{-26}\frac{J_{Segue1}}{J_{gc}} cm^3\ s^{-1}, \quad (3)$$

for $m_\chi \lesssim 40$ GeV WIMP masses annihilating to $b\bar{b}$, depending on the yet unknown J_{gc}.

4 DISCUSSION AND FUTURE PROSPECTS

We have reported gamma-ray flux upper limits for a subset of galaxy candidates from the GALFA-HI Compact Cloud Catalogue. It is difficult to imagine any of these systems beating the astrophysical factors of known dwarf galaxies that spans the gamut from 4×10^{17} GeV^2 cm^{-5} for Carina to 1.3×10^{19} GeV^2 cm^{-5} for the ultra-faint dwarf galaxy Segue 1 (Essig et al. 2010). Without mass and distance constraints, it will be difficult to place compact clouds in the context of other measurements. It is generally assumed that in order to be self gravitating, compact clouds could pack masses as low as a few M$_\odot$ to greater than $\sim 10^6$ M$_\odot$ for outer systems (Giovanelli et al. 2010; Saul et al. 2012). Our naive expectation is that $J_{Segue1}/J_{gc} \gg 1$ should hold in most cases.

As an illustration, the average compact cloud properties indicate a mass of $\sim 2\times10^4$ M$_\odot$ and a physical size of ~ 100 pc at distance of 100 kpc (Saul et al. 2012). Since the astrophysical factor is proportional to the density squared, we can roughly approximate $J_{Segue1}/J_{gc} \approx 10^3$ for $M_{Segue1} \sim 6\times10^5$ M$_\odot$ (Simon et al. 2011). To be sure, arguments consistent with an interpretation that Segue 1 is a tidally disrupting star cluster contaminated by the Sagittarius stream should be definitively ruled out (Niederste-Ostholt et al. 2009). For the entire family of ultra-faint galaxies, it is also critical to derive more reliable estimates of the J-factor (Walker et al. 2011).

This null result joins the ranks of past dark matter annihilation searches, which have failed to detect a gamma-ray signal in systems suspected of high dark matter content (Bringmann & Weniger 2012). Unfortunately, as with the rest of dark matter pursuits, this is an everything or nothing undertaking. Here, we are further hampered by the fact that we are seeking a detection with nearly no information about distances and masses of the objects involved. Nonetheless, *Fermi* will continue to collect data and stricter gamma-ray limits for these systems can be reached. Above $E \gtrsim 100$ GeV, the Cherenkov Telescope Array (CTA) will be crucial to escalate the dark matter search to unprecedented bounds (CTA Consortium 2011; Doro et al. 2013). There is also sufficient motivation to explore signatures for other reasonable dark matter candidates at other wavelengths (Feng 2010).

From our measurements, it is still unclear where GALFA-HI galaxy candidates fit in the larger dark matter subhalo picture. Searches for stellar counterparts associated with these gas-bearing systems are underway and should intensify (Saul et al. 2012). If this goal is accomplished, member stars could be used to produce a dark matter density profile. In an optimistic scenario, compact clouds could validate a sort of "hiding in plain sight" model whereby dark matter subhalos at small scales would be traced directly through neutral hydrogen.

Alternatively, dedicated observational studies could finally establish that all compact clouds are purely baryonic and hence devoid of dark matter (Plöckinger & Hensler 2012). The disagreement between observations and ΛCDM simulations might then have to be invoke more inventive solutions (Boylan-Kolchin, Bullock & Kaplinghat 2012). Regardless, the potential dark matter fingerprint discussed here stands a possible diagnostic of suspected nearby dark matter dominated galactic candidates. With the advent of Skymapper (Keller et al. 2007) and the Large Synoptic Survey Telescope (Ivezić et al. 2008), it might be possible to trace the subhalo population directly using faint stars. A cross-match between stellar concentrations and compact hydrogen cloud positions should be conducted as soon as said surveys are completed.

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