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H II REGIONS WITHIN A COMPACT HIGH VELOCITY CLOUD. A NEARLY STARLESS DWARF GALAXY?*

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ABSTRACT

Within the SECCO survey we identified a candidate stellar counterpart to the Ultra Compact High Velocity Cloud (UCHVC) HVC274.68+74.70-123 that was suggested by Adams et al. to be a possible mini halo within the Local Group of galaxies. The spectroscopic follow-up of the brightest sources within the candidate reveals the presence of two H II regions whose radial velocity is compatible with a physical association with the UVHVC. The available data do not allow us to give a definite answer on the nature of the newly identified system. A few alternative hypotheses are discussed. However, the most likely possibility is that we have found a new faint dwarf galaxy residing in the Virgo cluster of galaxies, which we name SECCO 1. Independently of its actual distance, SECCO 1 displays a ratio of neutral hydrogen mass to V luminosity of $M_{H\,I}/L_V \gtrsim 20$, by far the largest among local dwarfs. Hence, it appears to be a nearly starless galaxy and it may be an example of the missing links between normal dwarfs and the dark mini halos that are predicted to exist in large numbers according to the currently accepted cosmological model.

Key words: H II regions – galaxies: dwarf – galaxies: star formation

1. INTRODUCTION

Modern all-sky surveys have revealed that our census of dwarf galaxies is significantly incomplete even within the Local Volume (LV; see, e.g., Koposov et al. 2009). The Sloan Digital Sky Survey (SDSS), PAndAS, and Pan-STARRS surveys (see, e.g., Belokurov et al. 2006; McConnachie et al. 2009; Martin et al. 2013), among others, have significantly increased the number of known nearby dwarf galaxies, suggesting that many more remain to be discovered (Tollerud et al. 2008). Moreover, the newly discovered stellar systems show that actual dwarfs inhabit a much wider range of parameter space than previously believed (see Willman & Strader 2012; Belokurov 2013, for recent reviews). For instance, the faintest and most metal-poor star-forming galaxies were identified only in recent years: Leo T (Irwin et al. 2007), lying at $D \simeq 400$ Kpc with $M_V = -8.0$, and Leo P (Giovanelli et al. 2013), with $D \simeq 1.7$ Mpc and $M_V = -9.4$. Leo P, in particular, was discovered using a novel approach, i.e., by identifying a stellar counterpart of an Ultra Compact High Velocity Cloud (UCHVC) identified by the ALFALFA[11] H I survey (see also Tollerud et al. 2014 for the very recent identification of two dwarfs in the LV as counterparts to compact H I clouds). Along this line, Adams et al. (2013, A13 hereafter) selected from the ALFALFA database a sample of 59 UCHVCs that they proposed as good candidates to be faint (or even starless) dwarf galaxies associated with low-mass dark matter halos in the distance range $0.25\,\mathrm{Mpc} \leqslant D \leqslant 2.0\,\mathrm{Mpc}$. Triggered by the A13 analysis, we started the SECCO survey[12] (Bellazzini et al. 2014, B14 hereafter), aimed at searching for stellar counterparts in the 25 most promising candidate mini halos of the A13 sample.

Here we present the results of the spectroscopic follow-up of one candidate stellar counterpart, D1, identified in B14 by visual inspection of our deep images. Candidate D1 appears to be an irregular ensemble of partially resolved and relatively bright clumps of compact sources surrounded by some fuzzy light (see Figure 1) located just ∼30″ apart from the center of the A13 source HVC274.68+74.70-123 (whose angular size is 5′ × 4′; note that the density profile of the cloud is largely unresolved by the adopted beam). In B14 we concluded that the available data are consistent with a small dwarf Irregular at $D \gtrsim 3.0$ Mpc or with a distant group (or cluster) of galaxies (B14). To test these alternative hypotheses we obtained low resolution spectra of the two brightest, nearly point-like sources in the main clump of the candidate, labeled S2 and S3 in Figure 1. We anticipate that the spectrum and the velocity of S3 qualifies it as a stellar counterpart of the considered UCHVC, and the most likely hypothesis is that we have found a new very low surface brightness (SB), very star-poor dwarf galaxy in the Virgo cluster of galaxies.

* Based on data acquired using the Large Binocular Telescope (LBT). The LBT is an international collaboration among institutions in the United States, Italy, and Germany. LBT Corporation partners are The University of Arizona on behalf of the Arizona university system; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; The Ohio State University; and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota, and University of Virginia.

[11] http://egg.astro.cornell.edu/alfalfa/

[12] http://www.bo.astro.it/secco/SECCO/

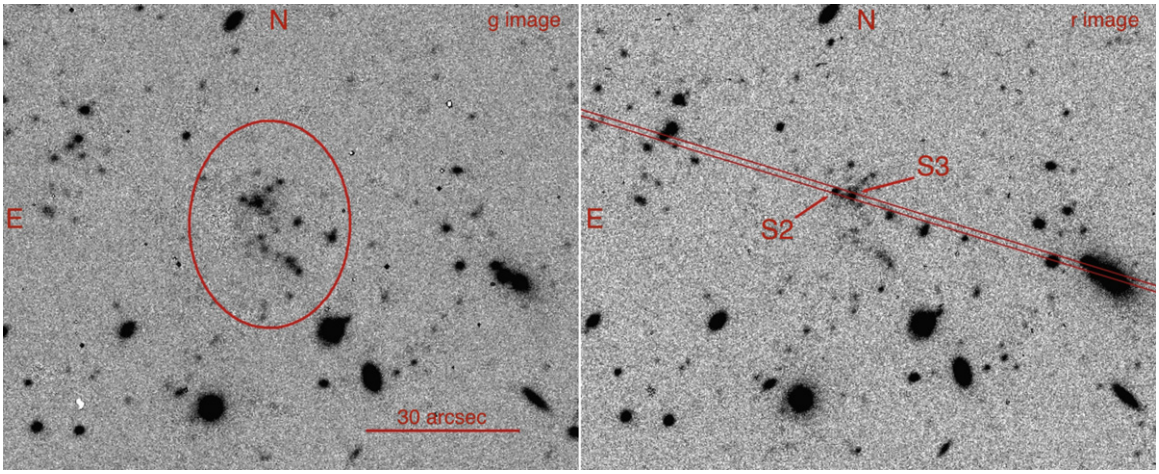

Figure 1. Deep g (left panel) and r (right panel) images zoomed on candidate D1. The ellipse on the left panel has a semimajor axis of 90 px = 20.″25 and axis ratio $b/a = 0.78$. The half-flux diameters of the associated UCHVC are $4' \times 5'$, much larger than the size of this image. In the right panel we have highlighted and labeled the two sources for which we obtained MODS1 spectra and the footprint of the adopted slit is also superimposed.

2. OBSERVATIONS, DATA REDUCTIONS, AND ANALYSIS

We obtained long-slit spectra with the Multi-object Double Spectrographs 1 (MODS1; Pogge et al. 2012) mounted on the Large Binocular Telescope (LBT; Mt Graham, AZ) during the nights of 2014 June 16, 17, and 19.[13] A total of seven $t_{\rm exp} = 1800$ s exposures were acquired with the MODS1 red arm equipped with the G670L grism and a slit 1.″2 wide. This setup provides a spectral coverage in the range of ≃5000–10000 Å with a spectral resolution of $R = \frac{\lambda}{\Delta\lambda} \sim 1100$. The spectra were corrected for bias and flat-field, sky-subtracted, wavelength calibrated, then extracted and combined into flux-calibrated summed spectra using the pipeline developed at the *Italian LBT Spectroscopic Reduction Center*.[14] The targeted sources are very faint ($r \sim 23.0$) and, consequently, the spectra have a low signal-to-noise ratio (typically S/N∼5–10 pixel^{-1}, depending on the wavelength); still, they are useful for our purposes.

In Figure 2(a) we show a portion of the final 2D spectra around the rest-frame H_α wavelength. The stellar continua of S2 and S3 are clearly visible. S3 shows obvious emission in H_α, and another H_α emission line, without any detectable stellar continuum, is identified ∼2″ above it (on the opposite side of S2 with respect to S3, along the direction of the slit). We rename the main component of S3 as S3A and the additional continuum-less component S3B (see the labels in Figure 2(a)). The H_α emission nearly at rest-frame clearly rules out the hypothesis that candidate D1 is a distant group/cluster of galaxies. The lack of stellar continuum in S3B is likely the main reason why this source cannot be identified in our deep images. However it is clear both from the images and from the spectra that (a) S3A is a complex source, partially resolved and with two additional point sources within 2.2″ from its center (B14), and (b) that the spectra of S3A and S3B contaminate each other, i.e., the two sources partially overlap. Inspection of the extracted spectra reveals that S2 does not present any spectral feature that can be used to classify or obtain an estimate of its radial velocity. In the following we will discuss in more detail the spectra of sources S3A and S3B.

In Figures 2(b) and (c), we show a portion of the 1D spectra of S3A and S3B, with the identified spectral lines in emission highlighted and labeled; from left to right $[O\,III]_{5007}$, H_α, $[N\,II]_{6584}$, $[S\,II]_{6717}$, and $[S\,II]_{6730}$. The line ratios of both S3A and S3B (see Table 1) are consistent with those of extragalactic H II regions (Kniazev et al. 2008), and not compatible with shocked gas (e.g., supernova remnants). While the $[S\,II/H_\alpha]$ and $[S\,II](6717/6731)$ ratios of S3B lie (formally) in the range typical of planetary nebulae, they are still compatible with H II regions if the errors are taken into account. On the other hand, S3A falls on the H II region loci in all the diagnostic diagrams. The close spatial and kinematic association strongly suggest that S3A and S3B are probably bright knots within an extended H II complex with different levels of excitation and displaying variations in the line ratios, like, e.g., the giant H II region NGC 595 in M33 (Relaño et al. 2010).

Given the low S/N and spectral resolution of our spectra, as well as the paucity of spectral features, we estimate the radial velocity in different ways, using original or smoothed (with a 5 px wide boxcar filter) spectra, including and excluding one or more lines from the analysis, and in all cases we obtain consistent results. Our final best estimate of the heliocentric radial velocity (V_h in the following) of S3A is obtained by cross-correlation of the smoothed spectrum with a synthetic flat spectrum with four gaussians of the proper width added at the rest-frame wavelength of the four lines identified in the right panel of Figure 2(b). In this way we get $V_h = -77 \pm 42$ km s^{-1}. The attached error bar takes into account both statistic and systematic uncertainties affecting our estimate, including significant uncertainties in the velocity zero point (VZP). Unfortunately, the low S/N of our spectra prevented the possibility to correct the VZP using telluric features. Since we placed the intensity peak of S3A (as identified in B14) at the center of the slit, the error on the VZP due to imperfect alignment should be limited to ±0.5 px, corresponding to ±40 km s^{-1}, by far the dominant source of uncertainty. On the other hand we had no previous knowledge of the position of S3B and its luminosity peak can be misaligned with respect to the slit center by as much as ≃4.9 px,

[13] Within an italian Director Discretionary Time program.
[14] http://lbt-spectro.iasf-milano.inaf.it

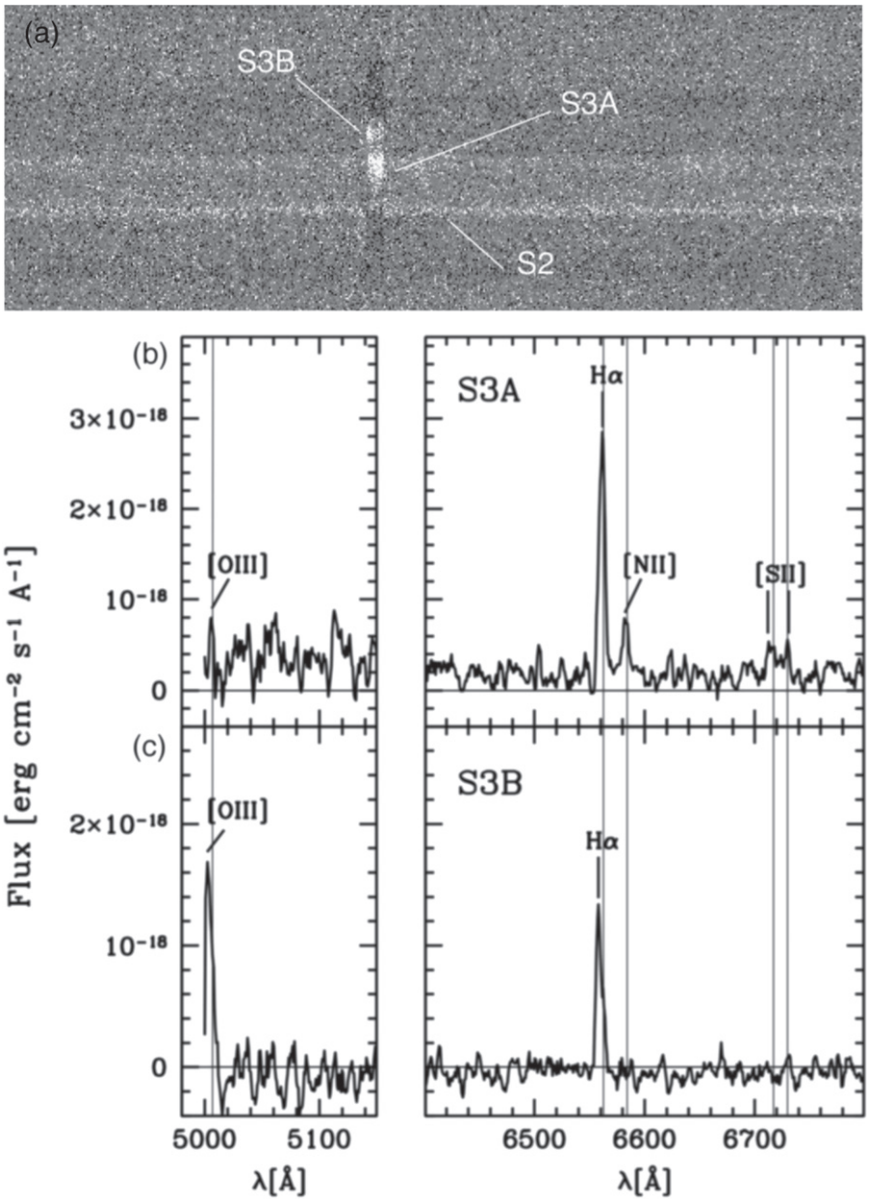

Figure 2. Panel (a): a portion of the combined 2D spectra around the wavelength of rest-frame H_α. The spectra are labeled after the associated sources. Note the lack of stellar continuum for S3B. Negative spectra footprints (dark features) are artifacts of the process of sky subtraction on stacked spectra. Panels (b) and (c): remarkable portions of 1D spectra of S3A (b) and S3B (c). The spectra have been smoothed with a boxcar filter of size 5 px. The emission lines that have been identified are labeled. Thin vertical lines mark the rest-frame wavelength of the lines, for reference.

corresponding to systematics in V_h up to ∼200 km s^{-1}; we adopt half of this value as a rough estimate of the 1σ error on the velocity of S3B. Using only H_α de-blended from the contamination by S3A, we find $V_h = -260 \pm 100$ km s^{-1} from the smoothed spectra of S3B.

Given their proximity in the sky (∼2″) and in velocity, it seems exceedingly unlikely that S3A and S3B are not physically associated. Hence the velocity of S3B is probably affected by a significant mis-centering bias and, consequently, we adopt the velocity of S3A as the systemic velocity of the two sources. This velocity is compatible with the velocity of the associated UCHVC ($V_h = -128 \pm 6$ km s^{-1}, from A13), implying that at the center of HVC274.68+74.70-123 there is indeed a stellar counterpart, with ongoing star formation. This conclusion is also supported by the fact that the stellar clump including S2 and S3, as well as another stellar blob associated with candidate D1 a few arcsec to the south of S3, is also detected in NUV images from the (*GALEX*) mission, and measured as a single source with $NUV_{mag} = 20.84 \pm 0.10$. Unfortunately, no FUV images of D1 are available.

With the information available in the spectra, we can attempt to estimate some physical and chemical properties of the two regions. From the ratio [S II]6717/[S II]6730 we obtain an electron density of ∼1100 cm^{-3} for S3A (assuming an electron temperature of 10,000 K). From the line ratio N2 = log ($[N\,II]_{6584}/H_\alpha$) = −0.52 ± 0.06, computed from the cumulative spectrum (S3A+S3B), we obtain a rough estimate of the average metallicity of the whole H II complex. Using the calibration for H II regions by Pettini & Pagel (2004), we find an oxygen abundance 12 + log(O/H) = 8.6 ± 0.5, larger than the typical values found in H II regions of local dwarfs (Lee et al. 2003).

Table 1
Spectroscopic Targets Observed with MODS1

	S2	S3A	S3B	Units
R.A.$_{J2000}$	12:21:54.4	12:21:54.2	⋯	hh:mm:ss
Decl.$_{J2000}$	+13:27:42.6	+13:27:41.6	⋯	dd:mm:ss
g_0	24.12 ± 0.07	23.63 ± 0.06[a]	⋯	mag
r_0	23.07 ± 0.04	23.07 ± 0.05[a]	⋯	mag
V_h	⋯	−77 ± 42	−260 ± 100[b]	km s^{-1}
[O III] flux	⋯	2.0 ± 1.0 × 10^{-18}	11.0 ± 1.0 × 10^{-18}	erg cm^{-2} s^{-1}
H$_\alpha$ flux	⋯	19.0 ± 1.0 × 10^{-18}	8.5 ± 1×10^{-18}	erg cm^{-2} s^{-1}
[N II] flux	⋯	6.0 ± 1 × 10^{-18}	⩽2.3 ± 1.4 × 10^{-18}[c]	erg cm^{-2} s^{-1}
[S II]$_{6717}$ flux	⋯	2.7 ± 1 × 10^{-18}	⩽0.3 ± 1.4 × 10^{-18}[c]	erg cm^{-2} s^{-1}
[S II]$_{6730}$ flux	⋯	2.9 ± 1 × 10^{-18}	⩽0.4 ± 1.4 × 10^{-18}[c]	erg cm^{-2} s^{-1}

Note. All data are from B14 except for the heliocentric radial velocity and the line fluxes.
[a] To account for the complex and extended nature of S3A we have also performed aperture photometry with an aperture radius of 10 px, finding $g = 22.57 \pm 0.06$ and $r = 22.37 \pm 0.05$, and, consequently, $(g - r)_0 = 0.20 \pm 0.08$.
[b] See the text for a discussion on velocity uncertainties.
[c] Upper limits derived by subtracting S3A fluxes from those obtained from the combined S3A+S3B spectrum.

3. A CLOUD IN THE GALACTIC HALO?

If S3A is a genuine H II region, the possibility that it belongs to our own Galaxy seems highly unlikely. Assuming that the most compact H II regions with the electron density of S3A (see below) have diameters ⩾1 pc (Hunt & Hirashita 2009), and adopting, very conservatively, the observed FWHM (≃1.″1 on the r images, where the stellar point-spread function has FWHM ≃0.″95) as the angular size of the region, it turns out that S3A must lie at least at $D \gtrsim 200$ kpc from us ($D \gtrsim 100$ kpc if we consider the separation between S3A and S3B as the typical size of the complex). Moreover, Galactic star-forming regions should lie in the Galactic disk, while the direction to HVC274.68+74.70-123 is nearly perpendicular to it and its velocity is completely incompatible with the disk. The hypothesis of an HVC located in the outer Galactic halo ($D \gtrsim 100$ kpc) and including a star-forming region appears similarly unlikely, since the cases of Galactic HVCs with an associated stellar component are exceedingly rare, if any (Ivezic & Christodoulou 1997; Stark et al. 2015).

There is another possibility that may be considered. HVCs are known to host ionized gas, in addition to H I (see, e.g., Putman et al. 2003 and references therein). It can be conceived that a relatively nearby HVC, partially ionized by radiation from massive stars in the Galactic disk, can be closely aligned along the line of sight, by chance, with background unrelated sources identified as candidate D1. In this case the emission lines we see in the spectra of S3A and B would not be associated with these sources but with the cloud, and would be superimposed on the featureless stellar continuum of the background sources. The main argument against this scenario is that emission lines are not seen superimposed on the continuum of S2, lying just ≃3.″5 apart from S3A, while H$_\alpha$ emission in HVCs is observed over scales comparable with the dimension of the clouds (see, e.g., Haffner et al. 2001). We note that no other rest-frame H$_\alpha$ emission is detected along the 5.′0 long MODS slit in our spectra, suggesting that the observed emission lines are indeed associated with the S3 stellar source. Moreover, HVCs display typical H$_\alpha$ fluxes of ≃0.1 Rayleigh and generally lower than ≃0.4 Rayleigh (Putman et al. 2003), while, assuming an area of 1 arcsec^2 for S3A and B, their H$_\alpha$ fluxes are ≃3.3 Rayleigh and ≃1.5 Rayleigh, i.e., a factor from ∼3 to ≳ 10 larger than this.

Table 2
Properties of SECCO 1

R.A.$_{J2000}$	12:21:54
Decl.$_{J2000}$	+13:27:36
l	274.68°
b	74.69°
g_{int}	20.1 ± 0.2
r_{int}	19.8 ± 0.2
$E(B - V)$	0.048
V_{int}	19.9 ± 0.2
r_h	∼11″
$\mu_{e,V}$	≃27.0 mag arcsec^{-2}
V_h	−128 ± 6 km s^{-1}

Note. Coordinates and $E(B - V)$ are from B14. V_h is from A13. $\mu_{e,V}$ is the mean V-band SB within the half-light radius.

The case for a Galactic HVC (associated with or simply aligned with S3A and B), as unlikely as it may appear, would provide a natural explanation (a) for the radial velocity of the system, which is clearly incompatible with the Hubble flow, and (b) for the derived N2 value, which is fully compatible with those observed in HVCs (Putman et al. 2003), while in the hypothesis of a dwarf galaxy (explored in the next section) it would imply an exceedingly high metallicity for the estimated optical luminosity.

4. A NEARLY STARLESS DWARF GALAXY?

Let us now consider the hypothesis that we have discovered a new faint dwarf galaxy, where a few clumps of star-forming regions are enclosed within a (comparatively) huge H I cloud. We preliminarily name it SECCO 1, after the name of the survey. Since there is no detectable smooth distribution of light around the clumps, to get an estimate of the integrated magnitude and of the half-light radius we recur to simple aperture photometry, taking the ellipse plotted in the left panel of Figure 1 as the tentative outer limit of the stellar system. The results are reported in Table 2. The integrated color, $(g - r)_0 = 0.27$, is typical of a star-forming galaxy (see Table 1). Unfortunately, we have only broad constraints on the distance. The fact that we do not resolve red giant branch (RGB) stars implies that $D \gtrsim 3$ Mpc (see B14) if an old population is there. In any case, the system is not participating

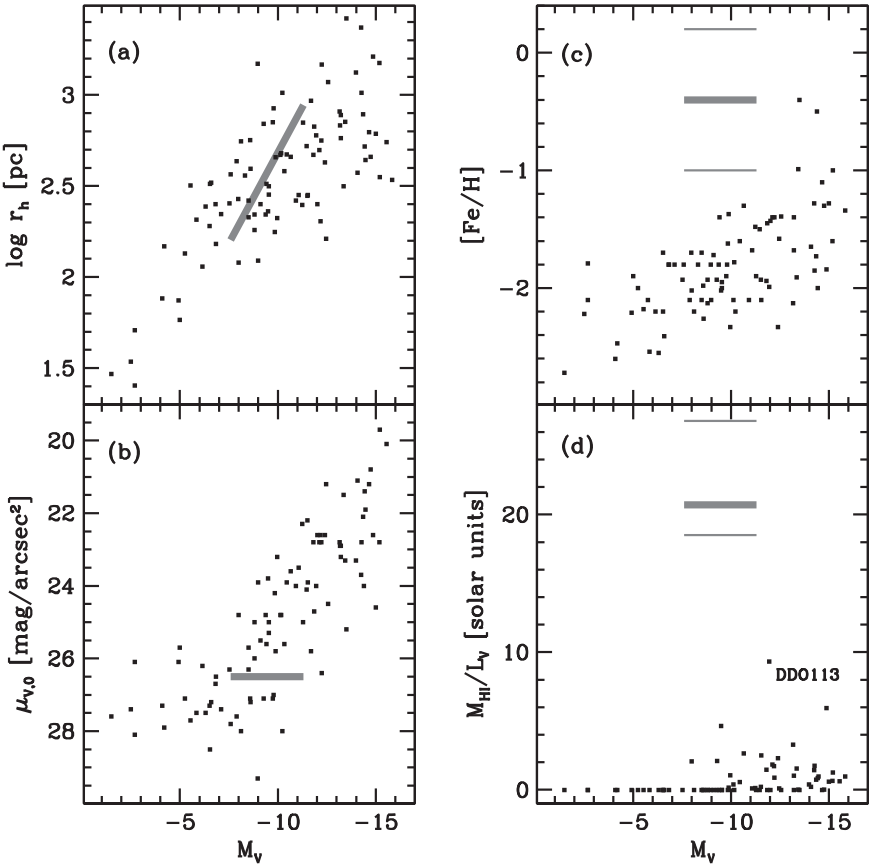

Figure 3. Range in various physical parameters spanned by SECCO 1, depending on the assumed distance (from $D = 3.0$ Mpc to $D = 16.5$ Mpc; gray bars), compared with the distribution of dwarf galaxies in the LV from the MC12 catalog (black dots). The gray lines in panels (c) and (d) enclose the $\pm 1\sigma$ error interval in [Fe/H] and $M_{\rm H\,I}/L_V$, respectively.

into the Hubble Flow, since for $D \gtrsim 3$ Mpc this implies $V_h \gtrsim +150$ km s^{-1}(McConnachie 2012, MC12 hereafter).

Adopting distances in the range 3.0 Mpc $\leqslant D \leqslant$ 16.5 Mpc (the latter value corresponding to the distance of the Virgo cluster; Mei et al. 2007), we can derive several physical characteristics of the stellar and gaseous body of SECCO 1.[15] In this distance interval, the system nicely fits into the observed $M_V - r_h$ and $M_V - \mu_V$ relations for local dwarf galaxies shown by MC12 (see Figures 3(a), (b)). The relevant quantities span the ranges $-7.6 \lesssim M_V \lesssim -11.3$, 160 pc $\lesssim r_h \lesssim$ 880 pc, $10^{6.3}\,M_\odot \lesssim M_{H\,I} \lesssim 10^{7.8}\,M_\odot$, and $10^{8.4}\,M_\odot \lesssim M_{dyn} \lesssim 10^{9.1}\,M_\odot$. For $D \leqslant 16.5$ Mpc the star formation rate, estimated from the H_α luminosity according to Kennicutt (1998), is $\leqslant 6.1 \times 10^{-6}\,M_\odot$ yr^{-1}, among the lowest rates recorded in local star-forming dwarfs (see, e.g., James et al. 2014).

Within this framework we see only two reasonable hypotheses for the location of SECCO 1.

1. SECCO 1 is a very low luminosity, low SB analog of the low-mass isolated star-forming galaxies studied by Cannon et al. (2011). These lie in the distance range 3.2 Mpc $\leqslant D \leqslant$ 18.7 Mpc and are associated with ALFALFA small clouds listed by Giovanelli et al. (2007) that have stellar counterparts that are visible in SDSS images. HVC274.68 +74.70-123 corresponds to AGC226067 in the Giovanelli et al. (2007) catalog, where it contains the note "No identifiable optical counterpart." Indeed SECCO 1 is barely visible even in our images, more than 4 mag deeper than SDSS. Hence it would represent an extremely dark member of this population. Still, all of the Cannon et al. (2011) galaxies are more or less compatible with being participants in the local Hubble Flow, while SECCO 1 is not.
2. SECCO 1 is a very low luminosity, low SB member of the Virgo cluster. Indeed, it lies at just 2.°44 from the center of the cluster and has a velocity well within the range spanned by cluster members (which reaches $V_h < -600$ km s^{-1}; Girardi et al. 1993). This hypothesis also implies the lowest (and most reasonable) total mass to light ratio for the system, $M_{\rm dyn}/L_V \simeq 470$, and the highest baryon fraction, $f_b = 0.046$.

Hypothesis 2 appears to be the more natural explanation of the available observational material. Still, according to the stellar mass–metallicity relation for galaxies by Ellison et al. (2008), the metallicity we obtain from N2 implies a stellar mass of about 10^8–10^9 $M_\odot$ for SECCO 1, which appears to be incompatible with the estimates from the integrated magnitude, independent of the assumed distance ($M_* \lesssim 10^{6.5}\,M_\odot$, adopting $M/L_V = 1.0$). However, the 1σ lower limit of our [Fe/H] estimate is marginally compatible with the M_V - [Fe/H] relation

[15] H I properties and dynamical mass are derived from Equations (7)–(9) of A13; note that the dynamical mass is estimated from the H I velocity width, hence it is very uncertain.

for LV dwarfs by MC12, if it is assumed that SECCO 1 lies in Virgo (see Figure 3(c)).[16]

The final word on the nature of SECCO 1 can be obtained only with *Hubble Space Telescope* observations, which would allow one to resolve RGB stars (if any) even at the distance of Virgo in such a low SB system (Jang & Lee 2014). High spatial resolution H I observations and H_α imaging may also provide very useful insight.

If SECCO 1 is indeed a dwarf galaxy, it would be an extremely gas-dominated and star-poor one, akin to the isolated "almost dark" dwarf galaxies discussed by Cannon et al. (2014). Independent of the assumed distance, its $M_{\rm H\,I}/L_V$ (and $M_{\rm H\,I}/L_r$) ratio, in solar units, is $\gtrsim$20, much larger than in the dwarfs listed by MC12 (Figure 3(d)) and by Cannon et al. (2011), which have $M_{H\,I}/L_V \lesssim 10$. Systems with $M_{H\,I}/L_V \gtrsim 20$ are quite rare (Cannon et al. 2014; Maddox et al. 2014) and may constitute the tip of the iceberg of a population of completely dark mini halos that is predicted to exist by the Λ-CDM cosmological model (Ricotti 2009; Sawala et al. 2013).

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Facilities: LBT, *GALEX*.

[16] The size, the integrated magnitude, the line ratios, and the metallicity of SECCO 1, if located in Virgo, are also compatible with those of "fireballs," star-forming knots of gas ram-pressure-stripped from dwarf galaxies within galaxy clusters (see Fumagalli et al. 2011; Yoshida et al. 2012). However, the lack of any obvious parent galaxy, the much lower star formation rate, and the large size of the associated UCHVC militates against the possibility of SECCO 1 being a leftover fireball.

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