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Two long H I tails in the outskirts of Abell 1367

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ABSTRACT

We present VLA D-array H I observations of the RSCG 42 and FGC 1287 galaxy groups, in the outskirts of the Abell 1367 cluster. These groups are projected ∼1.8 and 2.7 Mpc west from the cluster centre. The Arecibo Galaxy Environment Survey provided evidence for H I extending over as much as 200 kpc in both groups. Our new, higher resolution observations reveal that the complex H I features detected by Arecibo are in reality two extraordinary long H I tails extending for ∼160 and 250 kpc, respectively, i.e. among the longest H I structures ever observed in groups of galaxies. Although in the case of RSCG 42 the morphology and dynamics of the H I tail, as well as the optical properties of the group members, support a low-velocity tidal interaction scenario, less clear is the origin of the unique features associated with FGC 1287. This galaxy displays an exceptionally long 'dog leg' H I tail, and the large distance from the X-ray-emitting region of Abell 1367 makes a ram-pressure stripping scenario highly unlikely. At the same time, a low-velocity tidal interaction seems unable to explain the extraordinary length of the tail and the lack of any sign of disturbance in the optical properties of FGC 1287. An intriguing possibility could be that this galaxy might have recently experienced a high-speed interaction with another member of the Coma–Abell 1367 Great Wall. We searched for the interloper responsible for this feature and, although we find a possible candidate, we show that without additional observations it is impossible to settle this issue. While the mechanism responsible for this extraordinary H I tail remains to be determined, our discovery highlights how little we know about environmental effects in galaxy groups.

Key words: clusters galaxies: individual: Abell 1367 – galaxies: groups: individual: RSCG 42 – galaxies: ISM.

1 INTRODUCTION

H I tails and streams represent some of the clearest observational evidence of the effect of the environment on the gas content of galaxies. It is now well established that several environmental mechanisms can be responsible for such remarkable features. Late-type, gas-rich systems entering the central region of clusters (within a radius of ∼1 Mpc of the cluster centre) can have their gas stripped by ram pressure, $P_{\rm ram} = \rho_{\rm ICM} v_{\rm rel}^2$ (van Gorkom 2004; Roediger & Brüggen 2007). Several examples have been found in Virgo (Chung et al. 2007) as well as in Abell 1367 where Scott et al. (2010) report a 70-kpc tail emanating from CGCG 097−087. Moreover, Oosterloo & van Gorkom (2005) presented a 110-kpc H I structure emanating from NGC 4388, proposing that it is a result of ram-pressure stripping although not by the hot intracluster gas centred on M87, but rather by the hot halo gas of M86.

H I tails can also be generated, under suitable initial conditions, from tidal interactions. A pair of stellar tails are expected to result from a tidal interaction, and depending on the gas content of the progenitors, one or both of the tails may have a gaseous complement (Struck 1999). In galaxy groups, the lower relative velocities (<500 km s^{-1}) favour slow tidal interactions that can displace a large fraction of the H I from the parent galaxies and lead to lasting changes in their morphology. Bekki et al. (2005a) provide models in which they describe the formation of massive H I clouds with no optical counterparts as high-density regions of intragroup H I rings and arcs. In compact groups such as Stephan's Quintet, interactions can cause as much as 60 per cent of the group's H I to be found in tidal tails and bridges (Williams, McMahon & van Gorkom 1991). Even in clusters of galaxies, high-speed interactions can produce incredibly long H I tails.

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The best example is probably the case of NGC 4254 (Minchin et al. 2005, 2007; Haynes, Giovanelli & Kent 2007). Simulations (Bekki, Koribalski & Kilborn 2005b; Duc & Bournaud 2008) suggest that the H I stream in this system is tidal debris from an interaction.

As explained by Haynes et al. (2007), the location of NGC 4254 at ∼1 Mpc from M87 argues against ram pressure being the main cause of this tail. Instead, they claim that a more likely cause is a tidal interaction of the type expected under the harassment scenario proposed by Moore et al. (1996). This idea was taken further by Duc & Bournaud (2008). The latter authors presented a careful modelling of the tail originating from NGC 4254 leading them to propose a high-speed interaction with the more massive galaxy NGC 4192 (M98) as the source of the huge tail.

All these observational studies highlight the importance of H I tails for our understanding of environmental effects. Usually, the information provided by H I observations, such as velocity, mass and H I distribution, provides crucial constraints for theoretical predictions of different environmental mechanisms (Vollmer 2003; Duc & Bournaud 2008).

In order to unveil the main environmental mechanisms driving galaxy evolution in nearby clusters, we are conducting an H I, molecular gas, and star formation study of late-type galaxies in the spiral-rich cluster Abell 1367 (Scott et al. 2010; Scott et al., in preparation). Abell 1367 ($z = 0.022$) lies at about the same distance as Coma, but with only about half the Coma ICM mass, and consists of two approximately equal-mass subclusters (SE and NW) that are in the process of merging (Cortese et al. 2004). We are particularly interested to know if the young dynamical state of Abell 1367 and its lower ICM content have any bearing on the relative roles of ram pressure and tidal interactions in driving the evolution of its spirals. The Arecibo Galaxy Environment Survey (AGES; Cortese et al. 2008) revealed H I extending over up to 200 kpc in two groups, RSCG 42 and FGC 1287, located in projection beyond the cluster's 1°.1 virial radius (Rines et al. 2003). This Letter reports on follow-up VLA D-array H I mapping of the galaxies in these groups.

Based on a redshift to the cluster of 0.022 and assuming $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Spergel et al. 2007), the distance to the cluster is 92 Mpc with an angular scale of 1 arcmin ≈24.8 kpc. The virial radius then corresponds to ∼1.64 Mpc. We use J2000.0 coordinates throughout. Section 2 details the observations; observational results are given in Section 3 with discussion and concluding remarks in Section 4.

2 OBSERVATIONS

H I was observed in two fields (VLA-A and VLA-B) with the National Radio Astronomy Observatory (NRAO[1]) VLA in D-array configuration with ∼2.5 h integrations. The FWHM (32 arcmin) of the VLA primary beams for each of the observed fields (large white circles) and the intensity of the X-ray emission (*ROSAT*) from the cluster's ICM (cyan contours) are shown in the top panel of Fig. 1. In addition, we made two follow-up pointings with the Arecebo 305-m telescope.[2] The observational set-up for each of the VLA fields is listed in Table 1, including integration time, velocity resolution and velocity range.

The observations were made on 2007 April 16. The data were calibrated and imaged with the AIPS software package, but the standard calibration and reduction procedures had to be adapted to overcome a number of issues associated with the VLA-to-EVLA transition. For both fields, self-calibration (phase only) was carried out to mitigate the effects of side lobes from strong continuum sources. The continuum was fitted in line-free channels and subtracted from the cubes using the AIPS task UVLSF. Two of the observed galaxies have long, low surface brightness H I tails. In order to highlight the extent of these tails, we applied natural weighting resulting in a synthesized beam of ∼65 arcsec.

Field VLA-A encompasses the galaxy group RSCG 42 which has a velocity of 6296 km s^{-1} and lies ∼108 arcmin (2.7 Mpc) west (W) of the A 1367 cluster centre. In this data set, the H I mass detection threshold is $\sim1 \times 10^8\,\mathrm{M_\odot}$ (corresponding to 3σ over two consecutive 21 km s^{-1} channels). The equivalent column density sensitivity for emission filling the beam is then $\sim2 \times 10^{19}\,\mathrm{cm^{-2}}$. Field VLA-B contains the FGC 1287 triplet. The H I mass detection threshold is the same as for field A.

We used the ALFA feed array on the 305-m Arecibo Telescope to observe H I at two positions near LSBC D571−03 with 5- and 10-min on-source integrations on 2011 June 8. LSBC D571−03 is a candidate to have interacted with FGC 1287; the original H I detection of LSBC D571−03 in AGES was heavily contaminated by RFI.

3 RESULTS

The properties for each of the H I detections in both observed VLA fields and in one of the Arecibo follow-up pointings are set out in Table 2. The table shows the field, galaxy name, morphological type, optical velocity, H I mass, H I velocity, H I velocity width and H I mass.

Field VLA-A: RSCG 42

The positions of the H I detections in field VLA-A are shown in the bottom right-hand panel of Fig. 1. All detections, except AGC 210538, fall within the 32-arcmin FWHM of the primary beam. The Redshift Survey of Compact Groups (RSCG; Barton et al. 1996) catalogues RSCG 42 as a compact group with three members (CGCG 097−026, CGCG 097−027 and Mrk 0182). The most striking H I feature is the ∼160 kpc tail extending NE from CGCG 097−026 toward SDSS J113709.84+200131.0, with an indication of a smaller tail extending W of CGCG 097−026 which are consistent with a tidal interaction between these two group members. The orientation of the tails is approximately perpendicular to the major axis of CGCG 097−026. Both galaxies are significantly bluer (SDSS $g - i = 0.2$ and 0.21, respectively) than the other galaxies detected in H I in this VLA field.

Based on the method from Kewley et al. (2002) the SFR(FIR) for CGCG 097−026 is $\sim5.7\,\mathrm{M_\odot\,yr^{-1}}$. The optical, NIR and H$\alpha$ discs of both CGCG 097−026 and CGCG 097−027 ($\Delta V \sim 400\,\mathrm{km\,s^{-1}}$) are highly perturbed, and the H I velocity field (not shown) reveals H I at intermediate velocities between the two galaxies, providing confirmation that CGCG 097−027 is involved in the interaction as well. The complementary H I deficiencies (−0.84 and 0.48, respectively) suggest that H I from CGCG 097−027 (an Sc spiral) has been displaced in the interaction. We estimate the H I mass of the tail to be $9.3 \pm 1 \times 10^9\,\mathrm{M_\odot}$. Overall, the distribution and kinematics

[1] NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[2] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

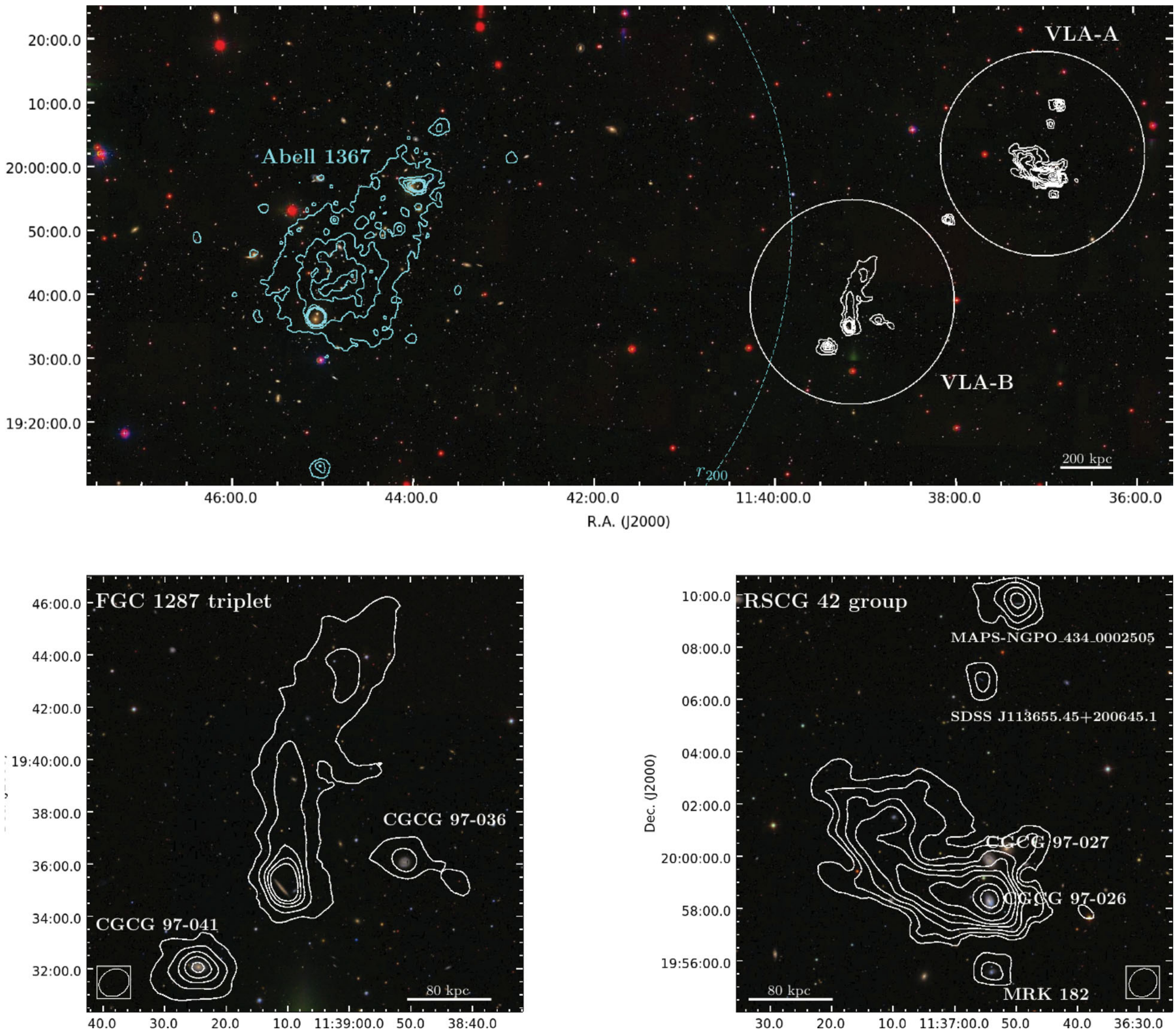

Figure 1. Upper panel: relative location of the RSCG 42 (VLA-A) and FGC 1287 (VLA-B) groups with respect to the Abell 1367 cluster centre. The FWHM of the primary beam (32 arcmin) for each of the VLA D-array fields is indicated with a white circle. X-ray emission (*ROSAT*) from the cluster ICM is indicated with cyan contours. The cluster's virial radius (1.64 Mpc ∼1°.1) is indicated with a dashed cyan chord. Lower left-hand panel FGC 1287 triplet: white contours trace the natural weight H I surface density, with the outer contour indicating a column density of $N_{\rm H\,I} = 2.0 \times 10^{19}$ cm^{-2}, with higher levels at (5, 10, 15, 20 and 40) $\times\ 10^{19}$ cm^{-2}. Lower right-hand panel RSCG 42 compact group: the contours trace the natural weight H I surface density, with the outer contour indicating a column density of $N_{\rm H\,I} = 1.7 \times 10^{19}$ cm^{-2}, with higher levels at 3, 6, 10, 15, 25, 35, 50 and 70 $\times\ 10^{19}$ cm^{-2}. In all the three panels, the first H I contour corresponds to a 3σ detection in two channels. The contours are overlaid on SDSS *u*-, *g*- and *r*-band composite images. In the lower panels, the size of the D-array synthesized beam is indicated with the white boxed ellipse.

Table 1. VLA observational parameters.

Field[a]	α_{2000} ($^{\rm h\,m\,s}$)	δ_{2000} ($^{\circ\,\prime\,\prime\prime}$)	Array config	Integration time (h)	Beam[b] size (arcsec)	Channel[c] separation (km s^{-1})	Velocity range (km s^{-1})	rms (mJy beam^{-1})	rms (K)
A	11 37 01.0	20 02 08.8	D	2.7	69 × 60	21	5763–6859	0.33	0.05
B	11 39 08.3	19 39 02.2	D	2.3	72 × 60	21	6261–7362	0.36	0.05

[a]Fields VLA-A and VLA-B (D-array) correspond to VLA Project ID: AC857.
[b]Beam size for the natural weight cubes.
[c]Post-Hanning smoothing, the velocity resolution is two times channel separation.

Table 2. Properties of H I detections.

Field	Galaxy ID identifier	RA (2000)[a] (h m s)	Dec (2000)[a] (0′ ″)	Type[b]	$V_{\rm opt}$ [c] (km s^{-1})	$V_{\rm H\,I}$ (km s^{-1})	W_{20} (km s^{-1})	$M_{\rm H\,I}$ (10^9 M$_{\odot}$)
VLA-A	MAPS–NGP O 434 2505	11 36 49.61	20 09 40.5	S	6296	6285 ± 5	150 ± 10	1.2
VLA-A	Mrk 0182	11 36 54.00	19 55 34.81	Compact	6328	6245 ± 6	70 ± 2	0.4
VLA-A	CGCG 097−027	11 36 54.23	19 59 50.04	Sc	6630	6630 ± 48	240 ± 96	1.2
VLA-A	CGCG 097−026 (disc + tails)	11 36 54.40	19 58 15.00	SBa pec	6191	6195 ± 2	390 ± 4	17.8
VLA-A	SDSS J113655.45+200645.1	11 36 55.45	20 06 45.1	–	–	6120 ± 9	60 ± 18	0.2
VLA-A	SDSS J113709.84+200131.0	11 37 09.84	20 01 31.0	–	6056	6140 ± 11	240 ± 22	2.3
VLA-A	AGC 210538	11 38 03.82	19 51 41.9	–	6196	6195 ± 13	210 ± 26	1.9
VLA-B	CGCG 097−036	11 38 50.98	19 36 05.24	S0/a	6787	6810 ± 6	100 ± 12	0.8
VLA-B	FGC 1287 (disc + tail)	11 39 10.90	19 35 06.0	Sdm	6825	6780 ± 2	220 ± 4	9.4
VLA-B	CGCG 097−041	11 39 24.40	19 32 7.2	Sb	6778	6778 ± 5	259 ± 10	2.8
Arecibo	LBSC D571−03	11 38 28.15	19 58 50.0	Sm	6989	6983 ± 1	124 ± 2	1.8

[a]Optical position from NED.
[b]Hubble type from GOLDMine (Gavazzi et al. 2003b) or if unavailable NED.
[c]Optical velocity from NED or if unavailable from SDSS redshift.

of H I are consistent with a tidal interaction amongst the group members.

Field VLA-B: FGC 1287

H I was detected in FGC 1287 (Sdm, $g - i = 1.21$) and two neighbouring galaxies (CGCG 097−041 and CGCG 097−036) with a remarkably small spread in H I velocities (32 km s^{-1}). Their positions are shown in the lower left-hand panel of Fig. 1. All three detections in H I including the FGC 1287 tail lie within the FWHM of the field's primary beam. H I velocities along the optical major axis of FGC 1287 are consistent with a rotating H I disc with velocities in the range ∼6600–6800 km s^{-1}. An additional velocity component along the major axis (∼6900 km s^{-1}) is located near the NE edge of the optical disc and contains ∼25 per cent of the H I mass in the disc. We estimate the H I mass of the tail to be $5.7 \pm 1 \times 10^9$ M$_{\odot}$.

A faint H I bridge, seen just below the 3σ level, seems to be joining the FGC 1287 H I tail to CGCG 097−036, suggesting an interaction. However, no sign of a perturbed optical/Hα morphology is observed in either CGCG 097−036 or FGC 1287. For FGC 1287, $\log(F(\mathrm{H}\alpha)) = -13.42 \pm 0.06$ erg cm^{-2} s^{-1}, EW(Hα) = 25.1 ± 3.5 Å (Gavazzi, private communication). It is important to remember that FGC 1287 is almost perfectly edge-on, making it difficult to clearly determine its optical morphology.

4 DISCUSSION AND CONCLUDING REMARKS

As the lower panels of Fig. 1 clearly show, RSCG 42 and FGC 1287 both contain spectacular H I tails with projected lengths of ∼160 and 250 kpc, respectively. The large H I masses in these groups imply they are on their initial infall to the cluster. Had the groups previously transited the cluster core, almost all the H I would be expected to have been removed (Abadi, Moore & Bower 1999; Bravo-Alfaro et al. 2000). Moreover, the cluster crossing time of $\sim 2.5 \times 10^9$ yr being much larger than the H I tail survival time-scale, together with the tail orientations, rules out a cluster core transit as the origin of the tails. In both cases, the H I mass in the tails is approximately equal to the H I in the two galaxies from which the tails appear to emanate (CGCG 097−026 and FGC 1287). Overall, the available evidence seems to favour a tidal interaction amongst the RSCG 42 group members as the cause of the CGCG 097−026 H I tail.

For FGC 1287, the cause of the tail is less clear. Whereas the morphology of the tail could at a first sight resemble similar features observed in ram-pressure-stripped cluster galaxies, the ICM densities extrapolated from the cluster X-ray emission at the distance of this group would require unrealistically high relative velocities and is inconsistent in direction with infall to the cluster. Although we cannot exclude that the group harbours a hot intragroup medium component, a hydrodynamical mechanism would not be able to explain why only FGC 1287 was subject to gas stripping, and cannot easily reproduce the change in direction along the tail.

Tidal interactions amongst the low-velocity dispersion triplet could account for the large H I mass which appears to have been removed from the disc of FGC 1287, but is inconsistent with the lack of disturbed features in the other group members. More importantly, the extraordinary length of the H I tail suggests that the interaction forces operated principally in the plane of the sky. Moreover, the interaction which produced the H I tail appears to have caused remarkably little damage to the stellar and Hα disc of FGC 1287. This lack of stellar disc perturbation is more characteristic of a high-speed velocity tidal interaction than a low-velocity gravitational encounter amongst the group members. Observations of other groups, such as Stephan's Quintet show that high-density groups with a high-speed intruder can have a large fraction of their H I outside the discs of the group members and lead to long tails with changes in direction along the tails (Williams, Yun & Verdes-Montenegro 2002; Renaud, Appleton & Xu 2010), although in that case with damage to the optical discs and associated stellar tails. The only other H I tail over 200 kpc long known to date is the one associated with NGC 4254, and, in that case, a high-speed interaction has emerged as the most likely scenario. In order to look for possible candidate intruders, we used NED to search all galaxies within a velocity range of ±500 km s^{-1} and radius of 750 kpc to find any additional bound group members and non-bound, high-velocity interaction partners.

Our search revealed a single low surface brightness galaxy, LSBC D571−03 ($11^{\rm h}\,38^{\rm m}\,28\overset{\rm s}{.}1$, $+19^{\circ}\,58'\,50''$), $V_{\rm opt} = 6989$ km s^{-1} projected 25.1 arcmin (640 kpc) from FGC 1287. Intriguingly, this galaxy lies exactly on the continuation of the H I tail of FGC 1287. The projected separation from FGC 1287 is consistent with an interaction with a motion in the plane of the sky of 1000 km s^{-1} that happened $\sim 6 \times 10^8$ yr ago; such a high-speed encounter would be compatible with the lack of optical disturbance in FGC 1287. In addition, the velocities at the end of the H I tail (6820 km s^{-1}) are intermediate between those in the rotating disc of FGC 1287 (6600–6750 km s^{-1}) and the H I detection of LSBC D571−03 (Fig. 2). Finally, the velocity of the anomalous H I component in the disc of FGC 1287 (6850–7000 km s^{-1}) is similar to that of LSBC D571−03

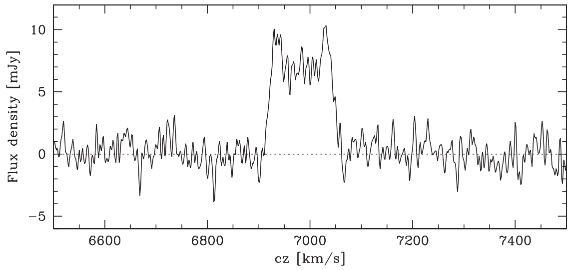

Figure 2. LSBC D571–03 Arecibo H I spectrum at the position of the optical galaxy. The velocity resolution is $4\,\mathrm{km\,s^{-1}}$ and the rms noise is 1.22 mJy.

($V_{\mathrm{H\,I}} = 6983\,\mathrm{km\,s^{-1}}$). However, the optical morphology and the Arecibo H I single dish spectrum (Fig. 2) do not show any obvious sign of disturbance. Moreover, the fact that LSBC D571−03 at $m_g = 16.4$ appears to be significantly fainter than FGC 1287 ($m_B = 14.31$) raises the question why only the brightest system is showing clear signs of interaction. Thus, for the moment, we can only speculate that this tail may have been produced by a high-speed encounter with another galaxy, and only additional data will allow us to gain additional insights into this unique system.

Whatever the true mechanism(s) at work here, our new discoveries highlight how little we know about environmental effects in groups infalling to clusters and emphasize the importance of group interactions in the evolution of cluster spirals beyond the central cluster region.

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