Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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H I view of the Virgo cluster outskirts: implications on galaxy evolution

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Abstract. The H I deficiency pattern of the spiral population in the Virgo cluster region reveals a significant number of galaxies at very large clustercentric distances with gaseous deficiencies comparable to those measured in the cluster centers. We have used the output of cosmological N-body simulations to investigate whether the gas-deficient galaxies on the outskirts of the Virgo cluster may have previously passed through its core. We find that the maximum radius reached by infalling galaxies as they bounce out of a Virgo-like cluster must be less than 2.5 virial radii, which results in a predicted velocity-distance diagram noticeably different from the one drawn by the data. The latter is fairly well reproduced, however, after including in the simulations distance errors at the 20% relative rms level. Yet, for several objects apparently over 5 Mpc in front or behind the Virgo center the assumption that they are instead close enough to the cluster to have passed already through its core strains the bounds of plausibility. Hence, unless these outlying H I-deficient Virgo's spirals have grossly incorrect distances, they cannot have lost their gas by interactions with the intracluster medium. This suggests that the evolution of spirals might begin already on the suburbs of clusters.

1. Introduction

The characterization of the large-scale 3D distribution of the neutral gas (H I) deficiency around the Virgo I Cluster region by Solanes *et al.* (2002) shows a significant number of galaxies with a dearth of atomic hydrogen at large Virgocentric distances. Apart from a central enhancement of the H I deficiency, which is essentially coincident with the cluster core, important neutral gas deficiency is found associated with several nearby galaxies at line-of-sight (LOS) distances ∼10–15 Mpc, preferentially located to the north of M87 and moving away from the cluster with large relative velocities, and in a tentative background group of galaxies at LOS distances ∼25–30 Mpc, mostly with systemic velocities close to the cluster mean and lying in the region dominated by the southern edge of the classical M49 subcluster as well as by clouds W′ and W. These peripheral gas-deficient objects show gaseous deficiencies deviating more than $3\,\sigma$ from normalcy — equivalent to a factor of 5.25 decrease in $M_{\rm H\,I}$ (Solanes *et al.* 1996) —, which are as strong as those measured in the centers of Virgo and other rich galaxy clusters.

One of the mechanisms that can most naturally account for the observed reduction in the interstellar gas content of cluster galaxies is the ram pressure ablation caused by the rapid motion of galaxies through the dense intracluster medium (ICM). However, the majority of the outlying H I-deficient spirals in the Virgo region appear too far from the cluster (> 5 Mpc) to have already passed through its core. Here we use the structure of simulated dark matter (DM) halos in space phase to demostrate that the maximum

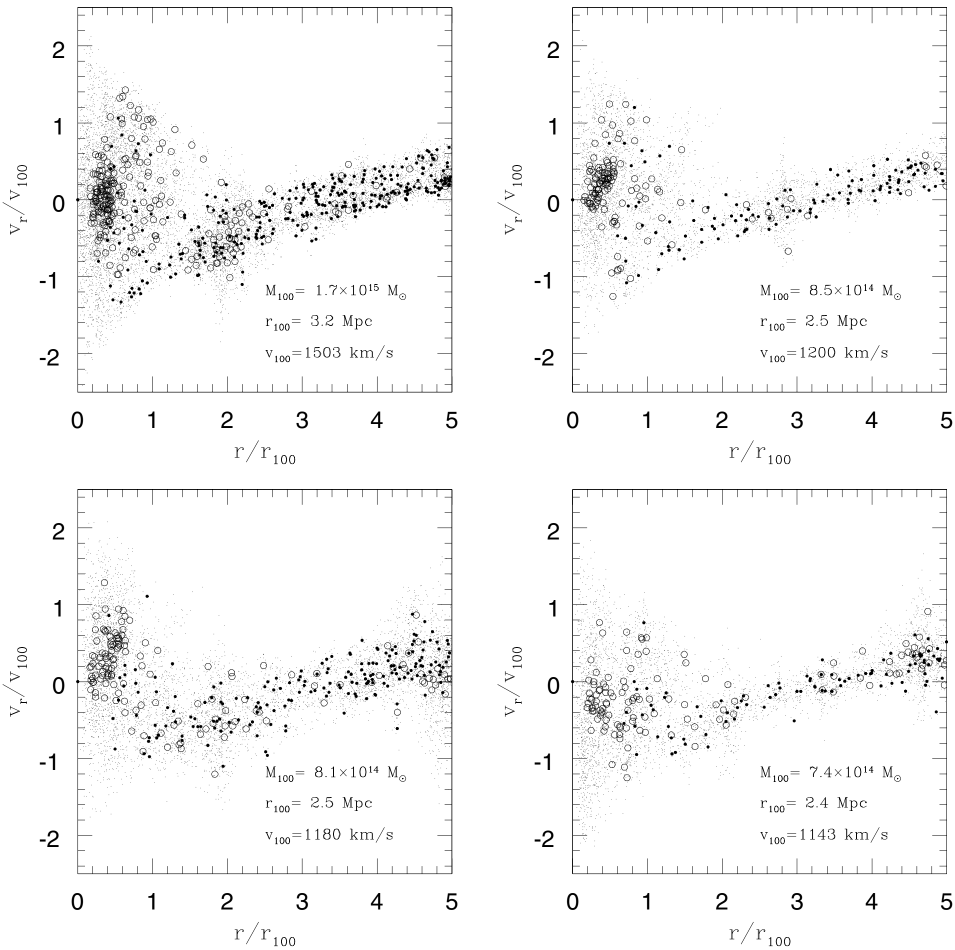

Figure 1. 3D radial phase space plots of DM particles in a ΛCDM cosmological N-body simulation for 4 massive halos at redshift $z = 0$. The *open circles* and *big dots* are the identified halos in the cosmological simulation respectively without and with galaxies within them.

rebound radius reached by galaxies falling into a cluster and bouncing out cannot explain the observed positions of these peripheral objects in velocity-distance plots. Among the alternative explanations for the presence of H I-deficient galaxies on the outskirts of the Virgo cluster that can be suggested, we pay special attention to the errors in the distance.

2. Maximum rebound radius for a Virgo-like cluster

For a better understanding of the kinematics of galaxies in the direction of the Virgo cluster, we have simulated an observation of the velocity-distance relation using the DM particles in the `GalICS` cosmological simulation (Hatton *et al.* 2003). This simulation is run for a flat ΛCDM universe with cosmological parameters $\Omega_0 = 1/3$, $h = 2/3$, and $\sigma_8 = 0.88$. DM halos are detected with a 'Friends-of-Friends' (FoF) algorithm with a variable linking length such that the minimum mass of the FoF groups is $1.65 \times 10^{11} M_\odot$

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(20 particles) at any time step. Over 2×10^4 halos are found at the final timestep, corresponding to the present-day ($z = 0$) universe.

Figure 1 shows the radial phase space diagrams, i.e. radial velocity vs. radial distance, both relative to the halo center, for four isolated massive halos. The halo centers are provided by the simulation output and correspond to the barycenter of the FoF groups of particles. Radial distances are normalized to the virial radius, r_{100}, corresponding to the radius where the mean density is 100 times the critical density of the universe. As illustrated in this figure, particles beyond the virialized core and outside the infalling/expanding zone of phase space cannot reach any further than $\sim 2.5\, r_{100}$, in consistency with the analysis of the orbital evolution of particles in the cosmological simulations of Fukushige & Makino (2001). Moreover, particles come in groups that appear to be tidally shredded in space phase. In fact, we have verified that particle condensations associated with galaxies avoid the fairly sparse regions of phase space where the outermost outgoing particles of the simulation are seen. In summary, given our estimate of the virial radius of the Virgo cluster (see next section), *galaxies that cross through the core of Virgo cannot bounce out beyond ∼4–5 Mpc from the cluster center.*

3. The velocity-distance relation of the Virgo cluster region

Among the 12 halos that `GalICS` produces at $z = 0$ with $M_{\rm FoF} > 10^{14}\, M_\odot$, we have chosen the one that resembles the Virgo cluster most, both in terms of mass and environment (see Sanchis *et al.* 2004 for details). Figure 2a shows the velocity-distance plot of the DM particles (*small points*) of this halo, conveniently rescaled to Virgo units, and from which particles statistically fainter than the typical magnitude limit of the observed catalogs (namely $B < 18$) have been removed. Any of the isolated massive halos in the `GalICS` simulation has a phase space diagram similar to that shown in Fig. 2a, once scaled to the Virgo cluster virial radius and circular velocity derived by Mamon *et al.* (2004) from X-ray observations: $r_{\rm Vir} = 1.65\, h_{2/3}^{-1}\,$Mpc and $v_{\rm Vir} = 780$ km s^{-1}.

Superposed to the DM particles in Figure 2a are all the spiral galaxies (*triangles*) from Sanchis *et al.* (2002) and the early-type galaxies (*circles*) from Sanchis *et al.* (2004) lying within a cone of half-opening 9° aligned with the axis connecting the observer to the center of the halo. This figure shows that the velocity field drawn by the galaxies is noticeably different from the one followed by the DM particles of the simulation. Nevertheless, both the distance to the halo and the rescaling factors appear to be well chosen, so the differences between the Virgo cluster and our Virgo-like halo should be attributable to other factors, such as the non-negligible errors affecting distance estimates. In contrast, because the errors in velocity are negligible, it appears unlikely that the galaxies that, for a given distance, lie within more than 1000 km s^{-1} from the locus of DM particles belong to the low- or high-velocity tails of large velocity dispersion groups near the cluster, since in our simulations there are no such high velocity dispersion groups outside the main mass concentration.

As expected, the observed velocity-distance diagram is fairly well reproduced when we incorporate to the simulation the mean relative distance error for the spiral galaxy sample calculated in the study by Solanes *et al.* (2002), who found a dispersion of the Tully-Fisher relation of roughly 0.4 mag, corresponding to an uncertainty of $\sim 20\%$ in relative distance (see Fig. 2b). Yet, it is possible to identify up to 13 highly H I-deficient galaxies with apparently reliable distance estimates that 1) appear to be located well in the foreground or background of the Virgo cluster (sometimes even outside the general locus of the DM particles) or 2) lie just outside the projected virial radius of the cluster,

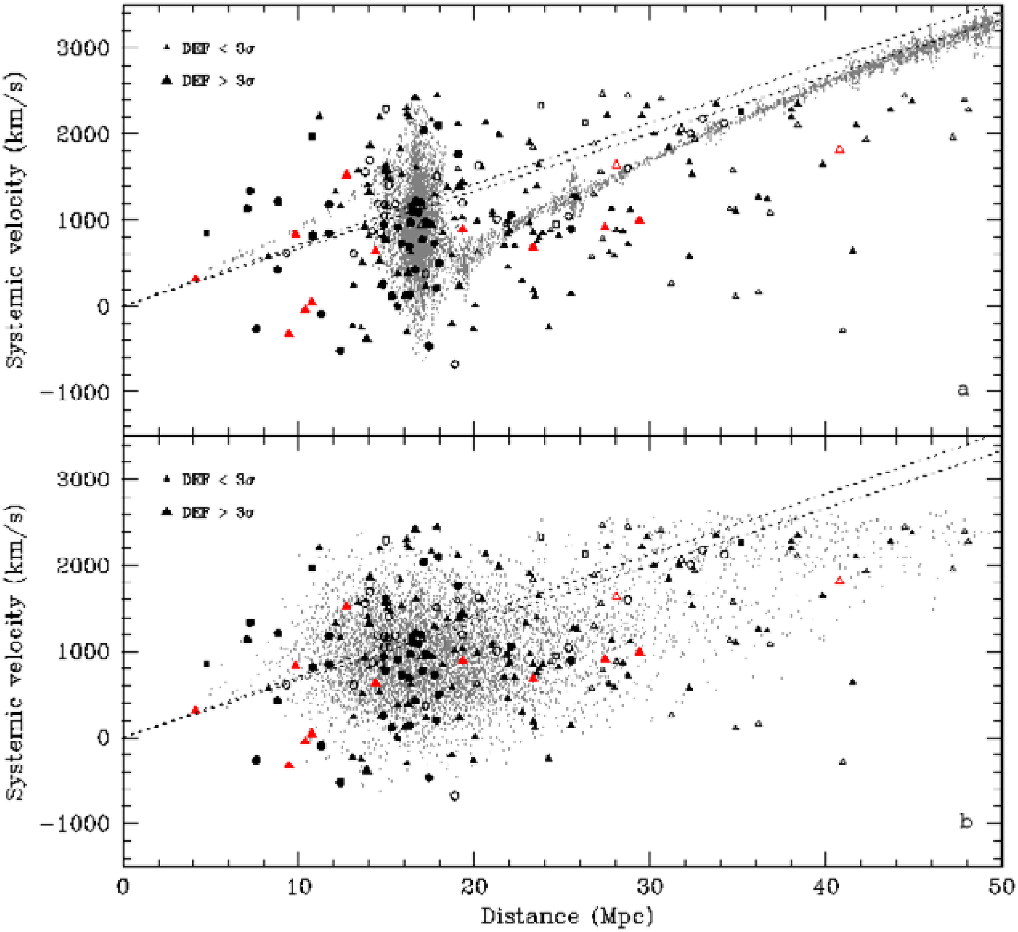

Figure 2. (a) Simulated and observed velocity-distance diagrams. *Dots* represent the velocity field traced by the DM particles. *Circles* and *triangles* represent early- and late-type galaxies, respectively. H I-deficient galaxies are shown as *filled triangles*, with the most probable cluster outliers (see Table 1) shown as *gray filled triangles*. *Squares* represent spirals with no H I deficiency data. *Open symbols* indicate galaxies with uncertain distances. *Dashed* lines show the unperturbed Hubble flow with $H_0 = 66.7$ and 70 km/s/Mpc, respectively (going upwards). (b) Same as (a) but incorporating Gaussian 20% relative distance errors for the DM particles.

for which their gas deficiency appears to be inconsistent with galaxy-ICM interactions (see the large gray filled triangles of Fig. 2b, as well as Table 1).

4. Implications of the outlying H I-deficient S's on galaxy evolution

Several alternatives for the origin of the H I deficiency of the 13 objects listed in Table 1 have been thoroughly assessed by Sanchis *et al.* (2004). Grossly incorrect distances, tidal interactions with close neighbors, and biases in the estimated H I-deficiency (e.g. S0/a's misclassified as Sa's) can provide valid explanations for almost every case of gas deficiency for these peripheral objects. Still the most plausible explanation for the gas-deficient galaxies lying behind the Virgo cluster at ∼25–30 Mpc from us is that they are in a background concentration of newcomers. The fact that 15 (60% of the total) of the

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Galaxy		RA	dec	T	B_T^c	D_{25}	θ	v	D
VCC	NGC	(J2000)						(km s^{-1})	(Mpc)
—	4064	$12^h04^m11\overset{s}{.}8$	$18°26'33''$	1	11.73	$4\overset{'}{.}0$	$8\overset{\circ}{.}8$	837	9.8
522	4305	$12^h22^m03\overset{s}{.}5$	$12°44'27''$	1	12.87	$2\overset{'}{.}0$	$2\overset{\circ}{.}2$	1814	40.7
524	4307	$12^h22^m06\overset{s}{.}3$	$09°02'27''$	3	11.84	$3\overset{'}{.}5$	$4\overset{\circ}{.}0$	913	27.4
559	4312	$12^h22^m32\overset{s}{.}0$	$15°32'20''$	2	11.76	$4\overset{'}{.}7$	$3\overset{\circ}{.}7$	47	10.8
713	4356	$12^h24^m15\overset{s}{.}9$	$08°32'10''$	6	13.02	$2\overset{'}{.}6$	$4\overset{\circ}{.}2$	998	29.4
979	4424	$12^h27^m13\overset{s}{.}3$	$09°25'13''$	1	11.99	$3\overset{'}{.}4$	$3\overset{\circ}{.}1$	314	4.1
1043	4438	$12^h27^m46\overset{s}{.}3$	$13°00'30''$	1	10.55	$8\overset{'}{.}7$	$1\overset{\circ}{.}0$	–45	10.4
1330	4492	$12^h30^m58\overset{s}{.}9$	$08°04'41''$	1	13.04	$1\overset{'}{.}9$	$4\overset{\circ}{.}3$	1638	28.1
1569	—	$12^h34^m31\overset{s}{.}4$	$13°30'23''$	5	14.62	$0\overset{'}{.}8$	$1\overset{\circ}{.}4$	687	23.3
1690	4569	$12^h36^m50\overset{s}{.}5$	$13°09'54''$	2	9.63	$10\overset{'}{.}4$	$1\overset{\circ}{.}7$	–328	9.4
1730	4580	$12^h37^m49\overset{s}{.}5$	$05°22'09''$	2	12.39	$2\overset{'}{.}0$	$7\overset{\circ}{.}2$	893	19.3
1760	4586	$12^h38^m28\overset{s}{.}1$	$04°19'09''$	1	12.06	$3\overset{'}{.}9$	$8\overset{\circ}{.}3$	639	14.4
1859	4606	$12^h40^m57\overset{s}{.}7$	$11°54'46''$	1	12.28	$2\overset{'}{.}9$	$2\overset{\circ}{.}5$	1528	12.7

Table 1. H I-deficient galaxies possibly outside the Virgo cluster.

galaxies listed in this range of projected distances by Solanes *et al.* (2002) share similar positions on the sky ($12^h15^m \leqslant$ RA $\leqslant 12^h30^m$ and $+6° \leqslant$ dec $\leqslant +10°$), while 12 of them have LOS distances between 27 and 30 Mpc, and 11 have systemic velocities between $\sim$600–1300 km s^{-1}, reinforces the impression that the presence of highly neutral gas deficient objects on Virgo's far side is real. Thus, in contrast to what it is commonly assumed, not all the H I-poor objects in the Virgo region reside in the neighborhood of the cluster core.

If our interpretation of the situation is correct, then we might have unveiled the first evidence of a group of severely H I-deficient galaxies on the suburbs of a cluster. Provided that severe cold-gas deficiency in S's deprived of their hot gas reservoirs inevitably triggers changes, first in the star formation rate and later on Hubble type, our finding suggests that the morphological evolution of disk galaxies is not restricted to the cluster environment but is also important in groups.

Certainly there is still room for an improved analysis. In particular, accurate distances obtained with Cepheids are necessary to do better on group membership assignments by reducing errors in the distance modulus below 0.2 mag (less than 10% fractional errors in distance). Similarly, VLA maps for both the highly H I-deficient galaxies lying on the outskirts of the Virgo cluster and their closest neighbors, would be most beneficial to identify the gas removal mechanism.

References

Fukushige, T. & Makino, J. 2001, *ApJ*, **557**, 533.
Hatton, S., Devriendt, J., Ninin, S., et al. 2003, *MNRAS*, **343**, 75.
Kitayama, T. & Suto, Y. 1996, *ApJ*, **469**, 480.
Mamon, G.A., Sanchis, T., Salvador-Solé, E., & Solanes, J.M. 2004, *A&A*, **414**, 445.
Sanchis, T., Solanes, J.M., Salvador-Solé, E., Fouqué, P., & Manrique, A. 2002, *ApJ*, **580**, 164.
Sanchis, T., Mamon, G.A., Salvador-Solé, E., & Solanes, J.M. 2004, *A&A*, in press.
Solanes, J.M., Giovanelli, R., & Haynes, M.P. 1996, *ApJ*, **461**, 609.
Solanes, J.M., Sanchis, T., Salvador-Solé, E., Giovanelli, R., & Haynes, M.P. 2002, *AJ*, **124**, 2440.