ARE THE H\textsubscript{I} DEFICIENT GALAXIES ON THE OUTSKIRTS OF VIRGO RECENT ARRIVALS?

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ABSTRACT

The presence on the Virgo cluster outskirts of spiral galaxies with gas deficiencies as strong as those of the inner galaxies stripped by the intracluster medium has led us to explore the possibility that some of these peripheral objects are not newcomers. A dynamical model for the collapse and rebound of spherical shells under the point mass and radial flow approximations has been developed to account for the amplitude of the motions in the Virgo I cluster (VIC) region. According to our analysis, it is not unfeasible that galaxies far from the cluster, including those in a gas-deficient group well to its background, went through its core a few Gyr ago. The implications would be: (1) that the majority of the H\textsubscript{I}-deficient spirals in the VIC region might have been deprived of their neutral hydrogen by interactions with the hot intracluster medium; and (2) that objects spending a long time outside the cluster cores might keep the gas deficient status without altering their morphology.

Subject headings: galaxies: clusters: individual (Virgo) — galaxies: evolution — galaxies: ISM — galaxies: spiral

1. AN INTRIGUING POSSIBILITY WORTH EXPLORING

A recent characterization of the large-scale 3D distribution of the neutral gas (H\textsubscript{I}) deficiency around the Virgo I Cluster (VIC) region by Solanes et al. (2002, hereafter Paper I) has shown that there are a significant number of galaxies with a dearth of atomic hydrogen at large Virgocentric distances. These peripheral gas-deficient objects, which can be observed both in the cluster front and in a probable background group well behind the cluster core, show gaseous deficiencies comparable in strength to 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). There is now compelling evidence for the decisive participation of this process in the gaseous deficiencies of spirals located in the centers of rich clusters, either directly from observations (Giovanelli & Haynes 1985; Gavazzi & Jaffe 1987; Dickey & Gavazzi 1991) —including the discovery of shrunken gaseous disks (Cayatte et al. 1994; Bravo-Alfaro et al. 2000) and the finding that H\textsubscript{I} deficient spirals are on very eccentric orbits (Solanes et al. 2001) — or from theoretical studies that have checked the efficiency of this mechanism (Stevens, Acreman, & Ponman 1999; Quilis, Moore, & Bower 2000; Vollmer et al. 2001, to name only a few).

In the outer cluster regions the low density of the intergalactic medium calls, in principle, for alternative gas removal mechanisms, such as gravitational tidal interactions. Indeed, observational evidence suggests that processes of this kind might have played an important role on the evolution of the galactic population in distant clusters (e.g., van Dokkum et al. 1999) due to favorable conditions for frequent low-relative velocity encounters among the galaxies in early epochs. Although in the VIC region low-relative-velocity galaxy-galaxy interactions may also be responsible for the gaseous deficiencies observed in some of the peripheral galaxies, it should not be forgotten that the dynamics of the Virgo region is dominated by large-scale non-Hubble radial streaming motions. In this context, it is plausible that some galaxies at large Virgocentric distances are on very eccentric orbits that carry them right through the cluster center with high relative velocities and are therefore liable to have suffered a strong interaction with the ICM.

One of the most influential studies of the Local Supercluster based on dynamical model calculations is the analysis by Tully & Shaya (1984) of the infall of galaxies in the Virgo Southern Extension (or Virgo II cloud) toward the VIC. The clumpy distribution of galaxies in space led these authors to predict a very irregular infall rate which would be responsible for the secular evolution of the mix of morphological types in the cluster. It was suggested that the formation of the cluster took place at an early epoch — when the universe was about one fourth of its present age (R. B. Tully 2002, private communication) — by a first generation of, probably, early-type galaxies. Afterwards, infall was reduced until very recently when the large spiral-rich Virgo II cloud has begun to fall into the cluster diluting the fraction of early-type systems. The fact that Tully & Shaya saw very few outwardly moving galaxies outside the 6° VIC circle supported their argument that most, or perhaps all, spirals and irregulars in Virgo, mostly supplied by the Virgo II cloud, were recent arrivals.

All the findings of Tully & Shaya (1984) were based on a data set that contained a limited number of galaxies with relatively uncertain distance estimates. Now, with a much larger sample and more accurate distances, we provide evidence that a substantial number of galaxies, with a wide range of clustercentric
distances, are expanding away from Virgo. This suggests that these galaxies are probably reemerging after infall. If our
aggregation of galaxies segregated in the four-dimensional position-radial velocity phase space. Up to 15 of the galaxies listed in the data set in Paper I can be identified as probable members of this group, since they all share similar positions on the sky (12°15′ < R.A. < 12°30′ and +6° < Decl. < +10°). In addition, 12 of these objects have LOS distances between 27 and 30 Mpc, and 8 of them (11 out of the initial 15) have systemic velocities between ~600–1300 km s⁻¹. Certainly, the lack of good resolution in the radial direction prevents us for claiming that we have identified a true group on a sufficiently safe basis. Yet, the fact that one third of its potential members have gas deficiencies that deviate more than 2σ from normalcy and that two of them have H I masses less than 10% of the expectation values for their morphology—characteristics that are both typical of rich cluster interiors—reinforces the impression that it is not a fortuitous feature.

3. INFALL MODEL WITH REBOUND

To model the virgocentric velocity field, we have implemented a simple point mass model for the spherical collapse of a zero-pressure fluid (see, e.g., Ekhholm & Teerikorpi 1994, and references therein). However, the solution of the problem is not limited to the classical deduction of the velocity field of objects until a singularity first develops. The calculations are extended beyond that time until galaxies recollapse again by allowing that the spherical shells of matter reaching the singularity pass through themselves and reemerge.

In the present paper, we take the, admittedly crude, point of view of treating galaxies as test particles moving in a constant point-mass potential well, which allows us to ignore the effects of shell crossing on their first orbit. Shell crossing is most important inside the previously relaxed cluster body, but galaxies on first infall spend little time in this region because of their radial trajectories and high pericentric velocities. Hence, the gravitational acceleration they undergo during their first crossing of the cluster core is not expected to differ substantially from that exerted if all the mass were concentrated at the center.

Under the point mass approximation, the velocity relative to the center of Virgo, v, for mass-less shells of radius r in a universe with null cosmological constant (a non-null cosmological constant has a negligible contribution in the local universe) is given by the pair of parametric equations

\[ \frac{\eta - \sin \eta}{(1 - \cos \eta)^{3/2}} = \frac{\sqrt{GM_{\text{VIC}}}}{r^{3/2}} \], \quad v = \frac{r \sin \eta (\eta - \sin \eta)}{l_0 (1 - \cos \eta^2)} \]  \[ (1) \]

for the bound shell case, and by

\[ \frac{\sinh \eta - \eta}{(\cosh \eta - 1)^{3/2}} = \frac{\sqrt{GM_{\text{VIC}}}}{r^{3/2}} \], \quad v = \frac{r \sinh \eta (\sinh \eta - \eta)}{l_0 (\cosh \eta - 1)^2} \]  \[ (2) \]

for the unbound case. In these expressions, \( M_{\text{VIC}} \) is the effective total mass of the VIC region (strictly speaking, the point mass representative of the region under consideration around the VIC center), \( l_0 \) is the current age of the universe, and \( G \) is the gravitational constant. In our double-infall model bound shells reach maximum expansion for development angles \( \eta = \pi \) and \( 3\pi \), whereas full collapse is achieved when \( \eta = 2\pi \) and \( 4\pi \).

The predicted radial velocity, \( V_r \), of a galaxy at a distance \( R \) from the Local Group (LG) and observed at an angular distance \( \theta \) from the Virgo center can be evaluated from
\[
V(R) = V_{\text{VIC}} \pm v_V \sqrt{1 - \frac{R_{\text{VIC}}^2 \sin^2 \theta}{r^2}},
\]

where \(R_{\text{VIC}}\) and \(V_{\text{VIC}}\) are, respectively, the barycentric distance and velocity of the VIC in the LG reference frame. The linear and angular distances of the galaxy are related through the cosine law

\[
d^2 = 1 + D^2 - 2D \cos \theta,
\]

where \(d = r/R_{\text{VIC}}\) and \(D = R/R_{\text{VIC}}\) are the linear distances expressed in Virgo’s distance units. The \((-)\)-sign applies for galaxies with \(D < \cos \theta\), while the \((+)\)-sign is for \(D \geq \cos \theta\).

4. Model Predictions vs. Observations

As shown in the previous section, our simple dynamical model describing the velocity field in the VIC region involves parameterization in terms of \(t_0, M_{\text{VIC}}, R_{\text{VIC}},\) and \(V_{\text{VIC}}\)—the systemic velocity can be replaced by the cosmological velocity of Virgo for a given infall velocity of the LG. In spite of the fact that only three of these parameters are independent, it is advisable to work with no more than two free parameters, as the current velocity-distance data on the VIC are still insufficient to constrain models with so much freedom. For this reason, we allow the Virgo mass and distance to vary freely while keeping \(V_{\text{VIC}}\) fixed to 980 km s\(^{-1}\). We have, nonetheless, checked that the range of values of \(V_{\text{VIC}}\) allowed by the observations does not lead to significantly different results. The viability of the solutions will be cross-checked by comparing the value of \(t_0\) predicted by the best fits to the observations with the cosmological age of 13 ± 1 Gyr derived for the \(\Omega_m = 0.3, \Omega_\Lambda = 0.7\) CDM model in the \(H_0\)-Key Project by Freedman et al. (2001) and the more precise \(t_0 = 13.6 \pm 0.2\) Gyr recently inferred by Sievers et al. (2002) from CMB observations.

The systemic velocity-distance diagram for the VIC region plotted in Figure 2a shows the basic expected features: an initial steeply rising velocity-distance relation at the cluster front, a central broad region with the maximum observed velocity amplitudes, and a final ascending part of the relation, expected to approach the local Hubble law asymptotically. Ultimately, all the available good-quality observations should be considered to define the constraints of dynamical models like ours. Unfortunately, as illustrated in Figure 2b, even after we have extended the predictions to the first orbit following rebound, the theoretical pattern cannot explain the motions of various systems within the post-rebound expansion regime. This fact and the difficulties inherent to the modeling of the motions in the innermost cluster region—where multiple rebounds are expected to occur—prompted us to restrict the acceptable range of models by putting all the weight of the fits on the envelope to the streaming velocities within the asymptotic regime (cf. Fig. 2b). This is indeed the fitting procedure adopted by first-infall models and has the advantages of: (1) relying on the subset of observations that offer the highest constraining power; (2) being unaffected by shell crossing; and (3) being barely sensitive to the angular distance from the VIC center.

The three solid curves in Figure 2a demonstrate the locus of the optimum model for lines-of-sight corresponding to angular separations of 4°, 6°, and 8°. We find it compelling that, in spite of the fact that the minimization relies on a fraction of the data, our best solution explains a large number of the galaxy motions around the VIC region. The good accordance between the observations and the prediction of the double-infall model is reinforced by the remarkable symmetry of the motions with respect to the local Hubble flow defined by the imaginary straight line passing through the position of the LG and that of the predicted VIC barycenter (cf. Fig. 2b). Moreover, the error contours in the \((M_{\text{VIC}}, R_{\text{VIC}})\) plane drawn in Figure 3 show that our predictions are in reasonable agreement with previous estimates of the values of these parameters. Thus, while mass calculations of the central cluster region based on the X-ray emission or the virial theorem amount to about several times \(10^{14}\) M\(_\odot\), our best estimate \(M_{\text{VIC}} = 2.8 \times 10^{15}\) M\(_\odot\) approaches the values \(\lesssim 2 \times 10^{15}\) M\(_\odot\) inferred from modelings of the velocity field of the Local Supercluster (Tully & Shaya 1984; Fouqué et al. 2001). The acceptable barycentric distances are also well within the very poorly constrained range \((\sim 16–24\) Mpc) of VIC distances reported in the literature, although our most likely value \(R_{\text{VIC}} = 21.0\) Mpc advocates a large-distance scale which, for a cosmological VIC velocity of 1200 km s\(^{-1}\), brings the local value of the Hubble constant to about 60 km/s/Mpc. Furthermore, our best solution leads to \(t_0 = 13.5\) Gyr, in excellent agreement with previous estimates based on CMB observations.
agreement with the expansion ages advocated in Freedman et al. (2001) and Sievers et al. (2002). Finally, note from eq. (3) that the constraint provided by the motion of the LG with respect to the VIC (i.e., a null systemic velocity at our position) is automatically satisfied by the models.

5. IMPLICATIONS ON THE ORIGIN OF THE GAS DEFICIENCY

One of the most striking predictions of our model, illustrated in Figure 2b, is that various H1-deficient galaxies in the frontside and backside of Virgo can be accommodated in the same way on an orbit following rebound and on a first infall trajectory. We conclude that these galaxies might not be recent arrivals but have already plunged into the VIC center in the past. Especially interesting is the case of the H1-deficient background group observed at \( R \sim 28 \) Mpc and \( V \sim 1000 \) km s\(^{-1}\), whose near turnaround position in the Hubble diagram and the assumed standard harmonic oscillation movement of the galaxies around the cluster center, together with a cosmic age presumably close to 13.5 Gyr, indicate that it might have passed through the Virgo core about 4.5 Gyr ago. The fit to the observed velocity field also indicates that a significant number of galaxies in the VIC region might be currently falling towards the cluster from the frontside —perhaps not for the first time either—, so it does not substantiate former claims of a paucity of objects of this sort (Fouqué et al. 2001).

We do not claim, however, that this is the only possible solution satisfying the observations. For instance, an alternative model based on the assumption that the gas-deficient group in the background is also on first infall gives similarly reasonable best values of the assumed parameters: \( M_{\text{vir}} = 1.8 \times 10^{15} \) M\(_{\odot}\) and \( R_{\text{vir}} = 20.2 \) Mpc, leading to \( t_0 = 14.0 \) Gyr. Nor are we endorsing the argument that all H1-deficient galaxies in the VIC region have passed through the cluster core. It is clear from Figures 2a,b that the positions of some gas-poor galaxies, especially in the front cluster side, are best explained according to our model if they are on first infall. In any event, our dynamical modeling of the VIC region has shown that characteristics such as a large Virgocentric distance or a near turnaround position are not by themselves conclusive indications of a recent arrival. The substantial H1 deficiency of the background subclump found in Paper I may well have originated in an earlier passage of this entity through the Virgo core.

Even if our suggestion that the H1-deficient group on the backside of the VIC might not be a recent arrival is finally proven well-founded, it is still necessary to find an explanation for the apparently long time (\( \sim 4.5 \) Gyr) that these galaxies have maintained a substantial dearth of gas without noticeable consequences on their morphologies: 9 of its 15 probable members are late-type spirals, whereas the 5 with the largest gaseous deficiencies have types Sb or later. (Nor do the magnitudes of these latter galaxies show any evidence of a substantial dimming.) Yet, the details and chronology of the evolution of galactic properties triggered by the sweeping of the atomic hydrogen, as well as its repercussions on the star formation rate, are still poorly understood. For instance, estimates for gas consumption time scales in the absence of gas replenishment from a sample of 36 spiral galaxies of various morphologies by Larson, Tinsley, & Caldwell (1980) produced values ranging from 0.9 to 15 Gyr, with a median of 3.9 Gyr. These authors also discussed the color evolution of disk galaxies whose star formation has been truncated at various past times and concluded that substantial reddening in the latest spiral types requires that most of their star formation ceased about 5 Gyr ago. On the other hand, recent observational studies of the galaxy populations in clusters at different redshifts (e.g., Fasano et al. 2000) indicate that while the quenching of star formation induced by the removal of the gas appears to be rapid (\( \sim 1 \) Gyr), the morphological evolution of disk galaxies takes several billion years. Perhaps evolution is still slower for objects, such as the members of the gas-deficient cloud detected in the background of Virgo, that spent most of their time out of the aggressive cluster environment.

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FIG. 3.—1, 2, and 3σ confidence limits on \( M_{\text{vir}} \) and \( R_{\text{vir}} \) obtained from our dynamical model of the VIC region. The cross indicates the best estimates of these parameters.