Carnegie Observatories Astrophysics Series, Vol. 3:
Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004
ed. J. S. Mulchaey, A. Dressler, and A. Oemler (Cambridge: Cambridge Univ. Press)

Interaction of Galaxies with the Intracluster Medium

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Abstract

Although speculations of an interaction between galaxies and the intracluster medium date back more than 30 years, the impact and importance of a possible interaction have long remained elusive. In recent years the situation has completely changed. A wealth of data and detailed hydrodynamical simulations have appeared that show the effects of interactions. Single-dish observations show that cluster galaxies are deficient in their neutral hydrogen content out to two Abell radii. The deficient galaxies tend to be on radial orbits. Detailed imaging of the neutral hydrogen distribution in individual galaxies in two nearby clusters show a remarkable trend of H I extent with location in the cluster. These trends can be reproduced in simulations of ram pressure stripping by the intracluster medium using SPH and full three-dimensional hydrodynamic codes. Detailed imaging studies of individual galaxies have found a number of galaxies with undisturbed stellar disks, truncated gas disks that are much smaller than the stellar disks, asymmetric extraplanar gas in the center, and enhanced central star formation. These phenomena have all been predicted by hydrodynamical simulations. For the first time detailed observations of gas morphology and kinematics are used to constrain simulations. Simple models of ram pressure stripping are consistent with the data for some galaxies, while for other galaxies more than one mechanism must be at work. Optical imaging and spectroscopic surveys show that small H I disks go together with truncated star-forming disks, that hydrogen deficiency correlates with suppressed star formation rates, and that the spatial extent of H I deficiency in clusters is matched, or even surpassed, by the extent of reduced star formation rates.

Recent volume-limited imaging surveys of clusters in the local Universe show that most gas-rich galaxies are located in smaller groups and subclumps, which have yet to fall into the clusters. These groups form an ideal environment for interactions and mergers to occur, and we see much evidence for interactions between gas-rich galaxies.

1.1 Introduction

It has long been known that in the local Universe the mix of morphological types differs in different galactic environments, with ellipticals and S0s dominating in the densest clusters and spirals dominating the field population (Hubble & Humason 1931). This so-called density-morphology relation has been quantified by Oemler (1974) and Dressler (1980), and is found to extend over 5 orders of magnitude in space density (Postman & Geller 1984). Whether this relation arises at formation (nature) or is caused by densitydriven evolutionary effects (nurture) remains a matter of debate. More recent studies of clusters of galaxies at intermediate redshifts show that both the morphological mix and the star formation rate strongly evolve with redshift (Dressler et al. 1997; Poggianti et al. 1999; Fasano et al. 2000). In particular the fraction of S0s goes down and the spiral fraction and star formation rate go up with increasing redshift. There are many physical mechanisms at work in clusters or during the growth of clusters that could affect the star formation rate and possibly transform spiral galaxies into S0s. In this review I will limit myself to the role that the hot intracluster medium (ICM) may play.

The first suggestion that an interaction between the ICM and disk galaxies may affect the evolution of these galaxies was made immediately after the first detection of an ICM in clusters (Gursky et al. 1971). In a seminal paper on "the infall of matter into clusters," Gunn & Gott (1972) discuss what might happen if there is any intergalactic gas left after the clusters have collapsed. The interstellar material in a galaxy would feel the ram pressure of the ICM as it moves through the cluster. A simple estimate of the effect assumes that the outer disk gas gets stripped off when the local restoring force in the disk is smaller than the ram pressure. Thus, disks gets stripped up to the so-called stripping radius, where the forces balance. They estimate that for a galaxy moving at the typical velocity of 1700 km s^{-1} through the Coma cluster the interstellar medium (ISM) would be stripped in one pass. This would explain why so few normal spirals are seen in nearby clusters. In particular it would explain the existence of so many gas-poor, non-star-forming disk galaxies, first noticed by Spitzer & Baade (1951) and later dubbed "anemics" by van den Bergh (1976).

Ram pressure stripping is but one way in which the ICM may affect the ISM. The effects of viscosity, thermal conduction, and turbulence on the flow of hot gas past a galaxy were considered by Nulsen (1982), who concluded that turbulent viscous stripping will be an important mechanism for gas loss from cluster galaxies. While the above-mentioned mechanisms would work to remove gas from galaxies and thus slow down their evolution, an alternative possibility is that an interaction with the ICM compresses the ISM and leads to ram pressure-induced star formation (Dressler & Gunn 1983; Gavazzi et al. 1995).

On the observational side there has long been evidence that spiral galaxies in clusters have less neutral atomic hydrogen than galaxies of the same morphological type in the field (for a review, see Haynes, Giovanelli, & Chincarini 1984). The CO content, however, does not seem to depend on environment (Stark et al. 1986; Kenney & Young 1989). Both single-dish observations and synthesis-imaging results of the Virgo cluster show that the H I disks of galaxies in projection close to the cluster center are much smaller than the H I disks of galaxies in the outer parts (Giovanelli & Haynes 1983; Warmels 1988a,b,c; Cayatte et al. 1990, 1994). All of these phenomena could easily be interpreted in terms of ram pressure stripping. Dressler (1986) made this even more plausible by pointing out that the gas-deficient galaxies seem statistically to be mostly on radial orbits, which would carry them into the dense environment of the cluster core. However, nature turned out to be more complicated than that. In a comprehensive analysis of H I data on six nearby clusters, Magri et al. (1988) conclude that the data cannot be used to distinguish between inbred and evolutionary gas-deficiency mechanisms, or among different environmental effects. Although H I deficiency varies with projected radius from the cluster center, with the most H I-poor objects close to the cluster centers, no correlation is found between deficiency and relative radial velocity, as would be expected from ram pressure stripping.

In more recent years a number of developments have taken place. First, there was a flurry of activity on the theoretical front, and for the first time detailed numerical simulations on the effects of ram pressure stripping appeared. Since then, both improved statistics on H I deficiency and detailed multiwavelength observations of cluster galaxies undergoing trauma appeared. More recently, detailed comparisons have been made between individual systems and numerical simulations. Finally, synthesis imaging of neutral hydrogen no longer needs to be limited to a few selected systems in nearby clusters, and results of volume-limited surveys of entire clusters at redshifts between $z = 0$ and $z = 0.2$ have started to appear in the literature. In this review I will first discuss what we have learned about the statistical properties of the H I content of cluster galaxies. Then I will review some of the recent numerical work that has been done and compare these with observational results. After that I will discuss what we have learned from imaging surveys, and in conclusion I will discuss the importance of ICM interaction for galaxy evolution.

1.2 The Statistics of H I Deficiency

The most comprehensive survey on H I content in cluster galaxies to date is the work by Solanes et al. (2001). These authors compiled H I data on 1900 spiral galaxies in 18 nearby clusters. The data are mostly obtained with the Arecibo telescope, a single pixel telescope, and give information about the total amount of neutral hydrogen within the Arecibo beam ($3'$) centered on optically selected galaxies. Galaxies are earmarked as belonging to a cluster when they fall within a projected distance of 5 Abell radii (R_A), i.e. within $7.5\,h^{-1}$ Mpc, from the cluster center and have a radial velocity that is less than 3 times the average velocity dispersion from the cluster mean. Only clusters are included for which there are good H I data for at least 10 galaxies within 1 R_A of the cluster center. H I deficiency is calculated according to the recipe of Haynes & Giovanelli (1984): $\log_{10}(M_{\rm H\,I}$ observed/$M_{\rm H\,I}$ expected), where the expected H I mass is derived from a sample of isolated spirals of the same morphological type and optical diameter. To get significant statistics the cluster sample is then divided into two groups, a deficient cluster sample and a non-deficient cluster sample. The deficient sample contains all clusters for which the H I deficiency distribution over galaxies is significantly different within 1 R_A from that of the galaxies outside 1 R_A. One of the most remarkable results of the analysis of that database is shown in Figure 1.1. It shows the H I-deficiency fraction, i.e. the fraction of galaxies with a deficiency greater than 0.3, in bins of projected radius from the cluster center for the superposition of all the H I-deficient clusters. Galaxies with a deficiency greater than 0.3 are galaxies that are deficient in neutral hydrogen by a factor of 2 or more as compared to isolated galaxies of the same morphological type and size in the field. The percentage of H I-deficient spirals increases monotonically going inward. What is surprising is that this monotonic rise starts as far out as 2 R_A. This suggests that the effect of the cluster environment can be felt out to 2 Abell radii, far beyond the reaches of the dense ICM.

No correlation is found for the fraction of H I-deficient spirals (i.e. the number of spirals with an H I deficiency DEF ≥ 0.30 within 1 R_A of the cluster center compared to all galaxies of that type found in that region) with global cluster properties, such as X-ray luminosity, X-ray temperature, and radial velocity dispersion. As pointed out in their paper, this could be a selection bias. If stripped spirals would lose all their gas they may be transformed into S0s and they would be left out from the statistics. It is somewhat plausible that this is indeed the case since the fraction of spirals is clearly anti-correlated with X-ray luminosity. The most important result of the paper, apart from the extent of the occurrence of deficient

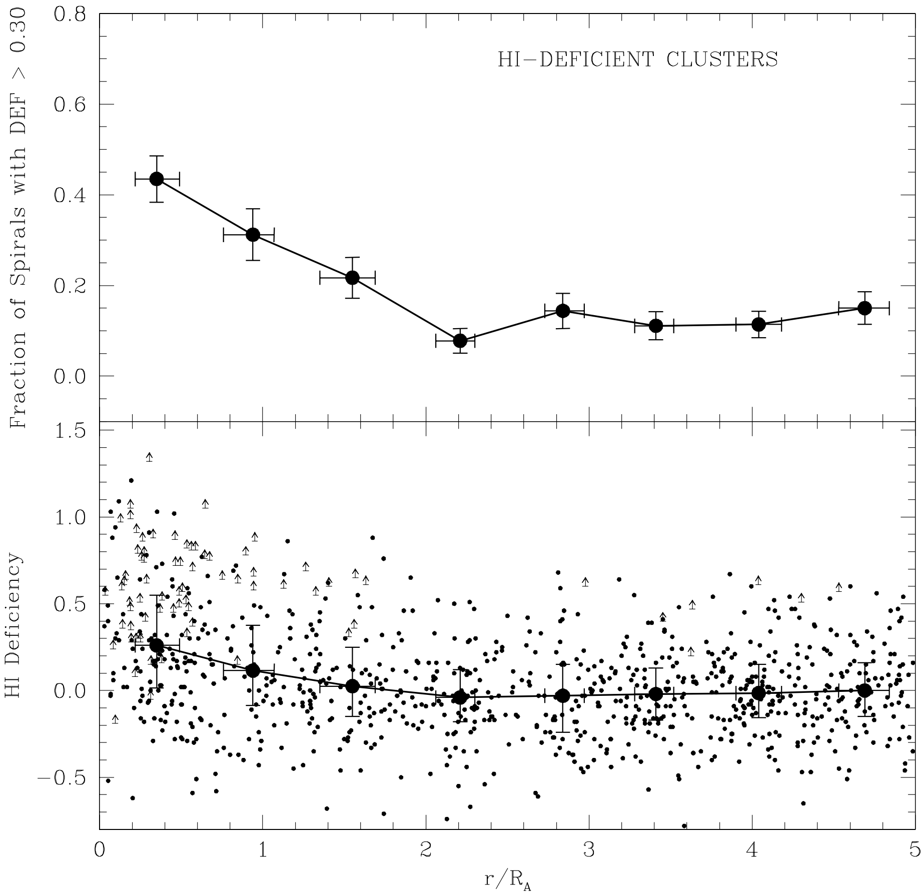

Fig. 1.1. *Top*: H I-deficiency fraction, in bins of projected radius from the cluster center, for the superposition of all the H I-deficient clusters. *Bottom*: H I deficiency versus projected radius from the cluster center. Small dots show the radial variation of H I deficiency for individual galaxies, while the arrows identify non-detections plotted at their estimated lower limit. Large dots are the medians of the binned number distribution. (Taken from Solanes et al. 2001.)

galaxies, is the correlation between deficiency and orbital parameters. This is shown in Figure 1.2. It shows, for the composite deficient cluster, the radial run of the line-of-sight velocity dispersion for the most deficient spirals, the non-deficient spirals, for all spirals, and for ellipticals and lenticulars. If galaxies are on radial orbits the measured velocity dispersion should decrease at large distances from the cluster center. Although all spirals show a decrease in velocity dispersion at large distances, this effect is by far the most pronounced in the H I-deficient spirals. The ellipticals and S0s have a constant velocity dispersion with radius. This confirms the result by Dressler (1986). These results suggest that deficiency is

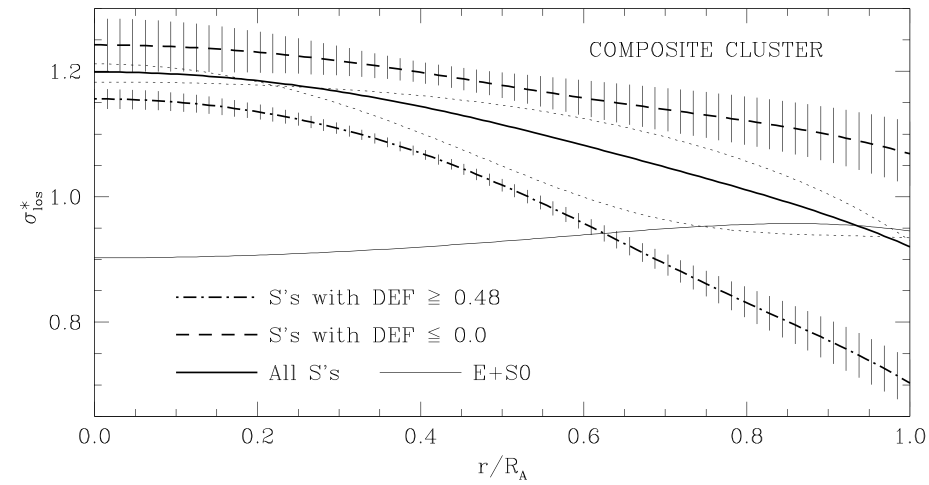

Fig. 1.2. Radial run of normalized line-of-sight velocity dispersion for the composite H I-deficient cluster. (Taken from Solanes et al. 2001.)

most pronounced when galaxies go through the dense cluster center at high velocities and, as such, support the idea that ram pressure stripping causes the deficiency.

1.3 Simulations

In the early 70s, several papers appeared considering the effect of the ICM on galaxies in clusters, including ram pressure stripping (Gunn & Gott 1972), evaporation (Cowie & Songaila 1977), and turbulent viscosity and evaporation (Nulsen 1982). Not much work was done, however, to connect theory with observations. The first paper that specifically looks at observational characteristics is that by Stevens, Acreman, & Ponman (1999). This paper focuses on the impact of the ICM on an elliptical galaxy with a hot ISM and calculates the observational signatures of this in the hot ICM, predicting bow shocks, wakes, and tails. Some, but still precious few, examples of structures that could be interpreted like this exist in the X-ray literature (Stevens et al. 1999). Observationally, there is much more evidence for the impact of the ICM on the cool ISM of disk galaxies. From a view point of galaxy evolution this is also the more important question. In clusters star formation rates are known to evolve rapidly between intermediate redshifts and the local Universe (Balogh et al. 1999; Poggianti et al. 1999). A mechanism is required to bring star formation almost completely to a halt, and a major issue is whether ram pressure stripping could do this to disk galaxies. The original analytical estimates of Gunn & Gott (1972) predict that gas gets stripped from a galaxy up to a stripping radius, within which the restoring force from the disk exceeds the ram pressure. The first numerical simulations (Abadi, Moore, & Bower 1999), using a 3-dimensional SPH/*N*-body simulation to study ram pressure stripping of gas from spiral galaxies orbiting in clusters, confirm that gas in disk galaxies gets stripped up to the stripping radius estimated by Gunn & Gott (1972). At small radii the potential provided by the bulge component contributes considerably. They estimate that a galaxy passing through the center of Coma would have its gaseous disk truncated to $\sim$4 kpc, losing about 80% of its gas. However, the process is in general not efficient enough to account for the rapid and widespread truncation of star formation observed in cluster galaxies. Quilis, Moore, & Bower (2000) use a finite-difference code to achieve higher resolution in order to be able to include complex turbulent and viscous stripping at the interface of cold and hot gaseous components, as well as the formation of bow shocks in the ICM ahead of the galaxy. From only a few selected runs on galaxies with holes in the central gas distribution, they reverse the conclusion of Abadi et al. (1999) and state that ICM-ISM interaction could explain the morphology of S0 galaxies and the rapid truncation of star formation implied by spectroscopic observations. The main difference with the Abadi et al. result is the use of a complex multi-phase structure of the ISM. They show that the presence of holes and bubbles in the diffuse H I can greatly enhance the stripping efficiency. As the ICM streams through the holes in the ISM it ablates the edges and prevents stripped gas from falling back. Schulz & Struck (2001), in a comprehensive study using SPH, an adaptive mesh HYDRA code, and including radiative cooling, confirm that low-column density gas is promptly removed from the disk. They also find that the onset of the ICM wind has a profound effect on the gas in the disk that does not get stripped. The remnant disk is compressed and slightly displaced relative to the halo center. This can trigger gravitational instability, angular momentum gets transported outward, and the disk compresses further, forming a ring. This makes the inner disk resistant to further stripping, but presumably susceptible to global starbursts. These various simulations appear to more or less agree on the effects of the ISM. All of the above work modeled the ICM as a constant wind. Vollmer et al. (2001) took a different approach. Using an *N*-body/sticky-particle code, they simulate galaxies in radial orbits through the gravitational potential of the Virgo cluster. The galaxies thus experience a time-variable ram pressure, and maximal damage to their gaseous disks only becomes apparent well after closest approach to the Virgo cluster center. Thus, if we see galaxies with truncated H I disks or distorted velocity fields, they are likely to be on their way out from the center. They also find that a considerable part of the stripped total gas mass remains bound to the galaxy and falls back onto the galactic disk after the stripping event, possibly causing a central starburst. The results of Schulz & Struck (2001) and Vollmer et al. (2001) are the first to produce simultaneously stripping in the outer parts and a mechanism to enhance star formation in the inner parts. This may help use up any remaining gas in the central regions, and it could possibly do some secular bulge building. There is observational evidence for stripped H I disks with enhanced central H I surface densities (Cayatte et al. 1994), and there are several lines of evidence that the most recent episode of star formation in cluster galaxies occurred in the central parts (e.g., Rose et al. 2001).

1.4 Comparison of Simulations with H I Imaging

The wealth of single-dish data on the H I content of selected spirals in the cluster environment has shown beyond doubt that H I deficiency occurs among cluster spirals. These data are less suitable to study the mechanisms that remove the gas. Projection effects along the line of sight and uncertainties about the orbital history of individual galaxies complicate matters. H I imaging has so far provided far less statistics, but in the imaging data individual galaxies can be selected that appear to have distortions in their H I morphology or kinematics that are unique to the cluster environment. A prime example is the occurrence of tiny H I

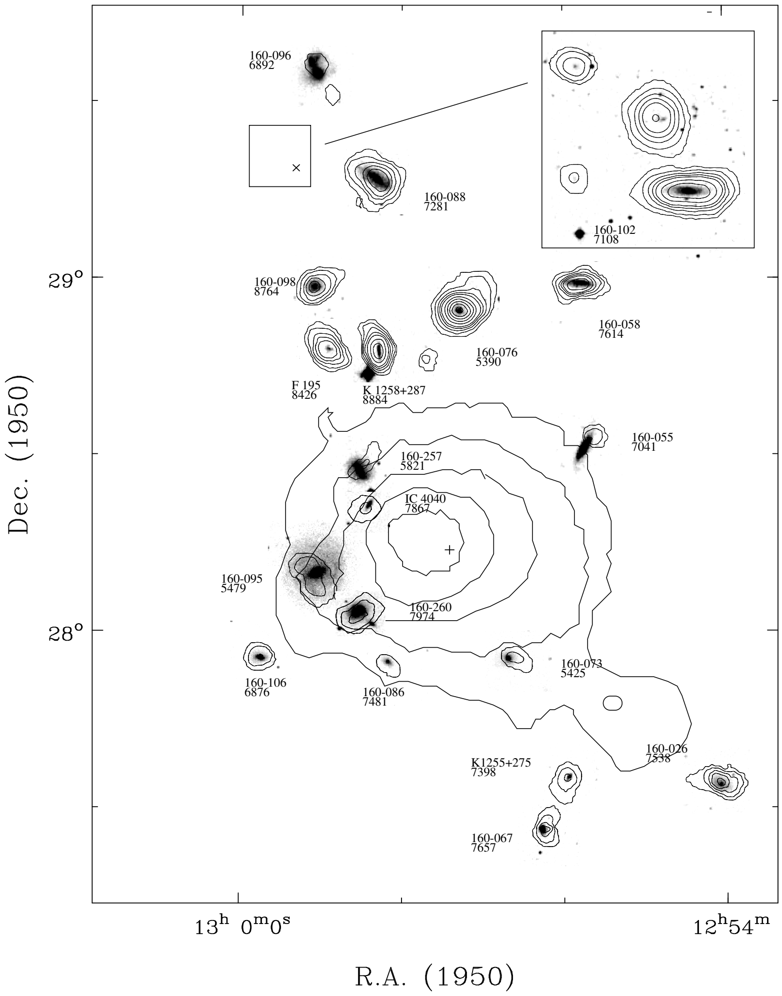

Fig. 1.3. Composite of individual H I images of Coma spirals observed with the VLA. Galaxies are shown at their proper position and they are magnified by a factor of 7. The H I images (contours) are overlaid on DSS optical images (greyscale). The large-scale contours sketch the X-ray emission as observed by Vikhlinin, Forman, & Jones (1997). (Taken from Bravo-Alfaro et al. 2000.)

disks in Virgo (Warmels 1988a,b; Cayatte et al. 1990). The size of the gaseous disks is considerably smaller than the optical disk. The effect is most pronounced close to the cluster center and gently decreases at increasing distance from the center. In addition to Virgo, this has now also been seen in the Coma cluster (Bravo-Alfaro et al. 2000, 2001). Figure 1.3 shows an overlay of the total H I emission (contours) on an Digital Sky Survey (DSS) optical image in greyscale. Each galaxy is located at its proper position in Coma, but the images are blown up by a factor of 7. The thick contours are the X-ray emission as observed with *ROSAT*. The first thing to note is that the H I disks seen in projection on the X-ray emission are in general smaller compared to the optical image than for galaxies far from the center

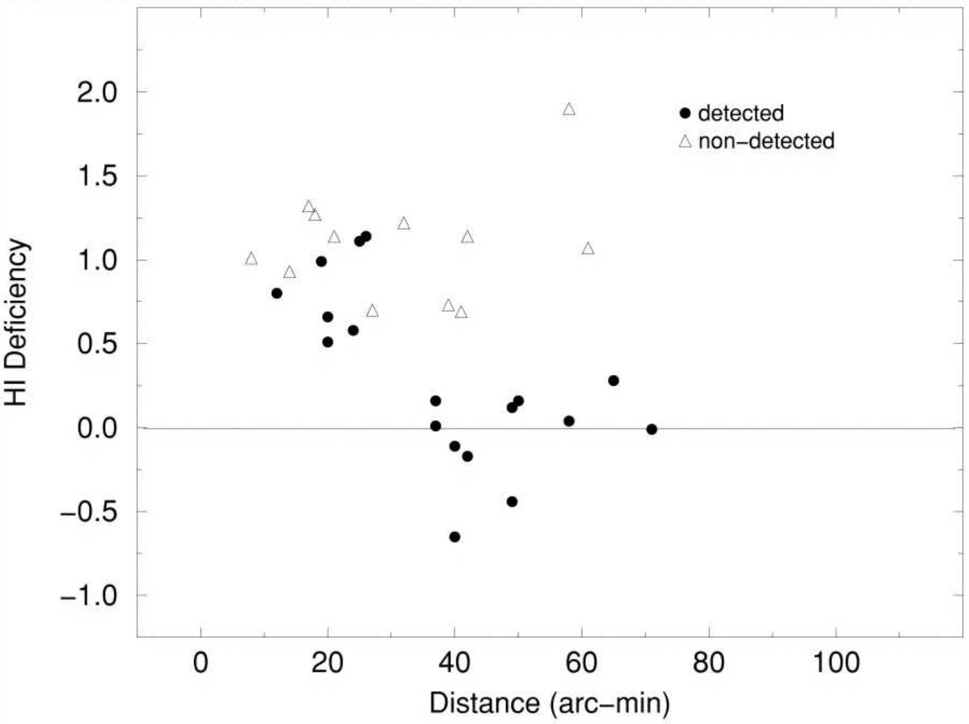

Fig. 1.4. Distribution of H I-deficiency parameter as a function of the projected distance from the center of Coma. Filled circles correspond to H I-detected galaxies and triangles to the lower limits of the deficiency parameter for the galaxies that are not detected in H I. (Taken from Bravo-Alfaro et al. 2000.)

of Coma. An example in case is the galaxy CGCG 160-095 (NGC 4921) east of the center, where H I is only seen in one half of the disk. This must be caused by a mechanism that only affects the gas, and ram pressure stripping is a good candidate. Figure 1.4 shows the H I deficiency versus projected distance from the center. Its interpretation is already more complicated. Though none of the galaxies projected on to the X-ray emission has a normal H I content (deficiency 0.0), there are several non-detections out to large projected radii. Possibly these galaxies have already gone through the center.

Imaging of Virgo and Coma indicates that H I disks that are smaller than the optical ones may be generic to cluster galaxies. Numerical simulations show that this is what one expects from ram pressure stripping. Abadi et al. (1999) show the results of a simulation with a constant ram pressure typical of the Virgo cluster ICM and galaxies moving with relative velocities of 1000 km s^{-1}, for galaxies of different size. The dependence of stripping radius on disk scale length (plotted in their Fig. 3) is consistent with the result found by Cayatte et al. (1994). Even more impressive is the result of Vollmer et al. (2001) shown in Figure 1.5. The simulation specifically models galaxies on radial orbits through the Virgo potential. The figure plots H I deficiency versus H I to optical diameter. Both the model data (stars) and observed values (Cayatte et al. 1994) are shown. The solid line corresponds to a model

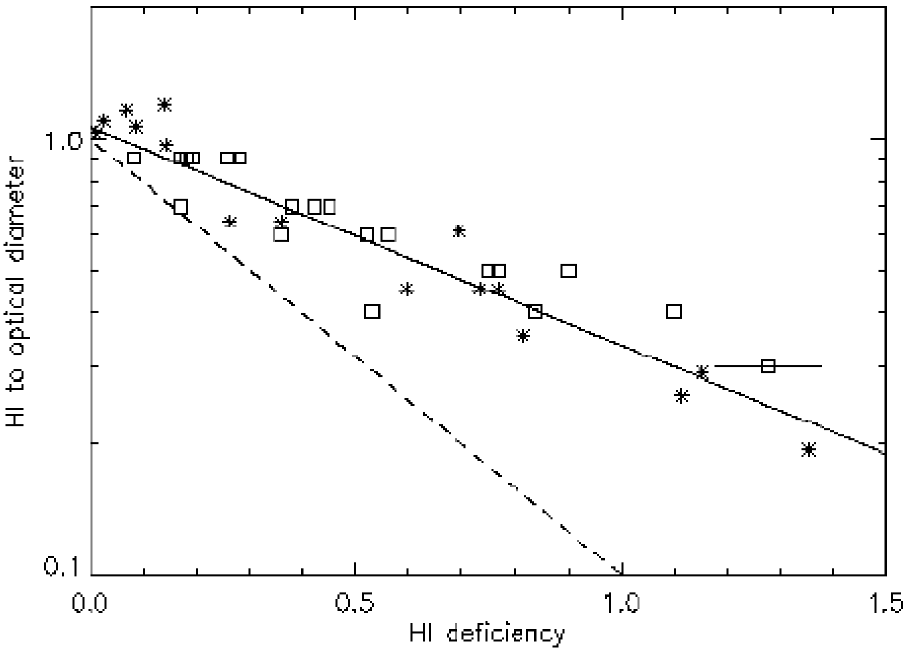

Fig. 1.5. Normalized H I to optical diameter as a function of the H I deficiency for the Virgo cluster. *Squares*: observed values (Cayatte et al. 1994); *stars*: model values. The solid line assumes that the H I surface density has the same value before and after the stripping event. (Taken from Vollmer et al. 2001.)

where only the outer parts of the disk get stripped, and the constant central H I radial surface density remains unchanged in the stripping process.

Vollmer, in a series of papers (Vollmer et al. 1999, 2000, 2001; Vollmer 2003), tries to reproduce observed gas distribution and kinematics of selected Virgo spirals with his *N*-body/sticky particle simulations. The galaxies are selected based on their H I morphology, and all show truncated H I disks. This is the first time ever that both gas distribution and kinematics are put to test in comparison with models. In several cases, the simulations can reproduce the observed signatures in the gas, and all of these galaxies are found to be on their way out of the cluster, having passed through the dense center. In one case (NGC 4654), Vollmer (2003) shows that both ram pressure stripping and a gravitational interaction must be at play.

One of the most interesting things that has been found recently is a number of galaxies with truncated H I disks, normal or enhanced star formation in the central regions, and some extraplanar gas on one side of the galaxy, while the stellar disks are completely undisturbed. These may be the best candidates for galaxies that are currently undergoing an ICM-ISM interaction. A prime example is NGC 4522, studied by Kenney and collaborators in great detail. Kenney & Koopmann (1999) first pointed out that NGC 4522 is one of the best candidates for ICM-ISM stripping in action. Figures 1.6–1.8 summarize the main characteristics

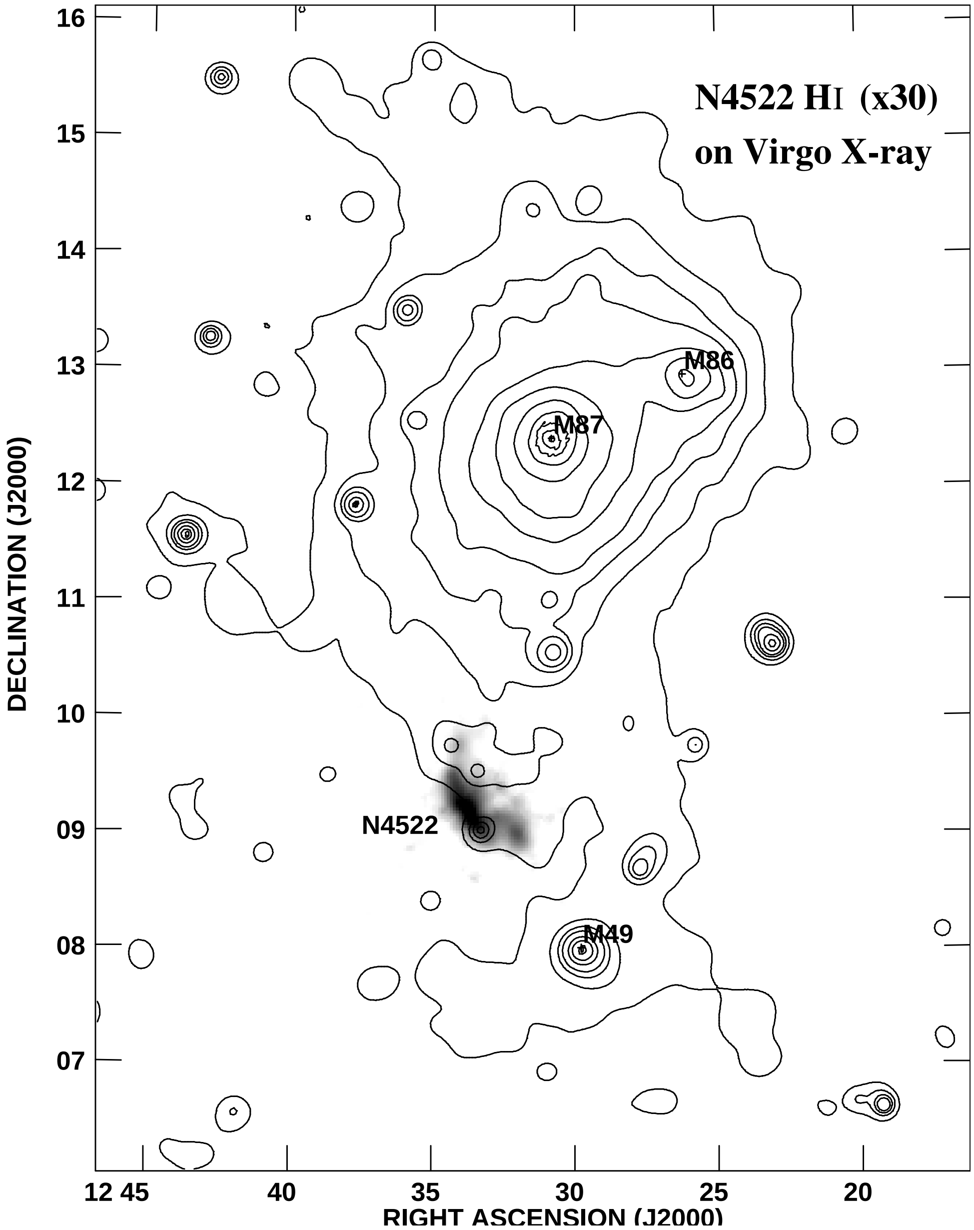

Fig. 1.6. H I greyscale image of NGC 4522, scaled up in size by a factor of 30, superposed on a *ROSAT* X-ray image of the Virgo cluster from Böhringer et al. (1994). The image indicates the locations of the giant ellipticals M87, M86 and M49, which are associated with sub-clusters. (Taken from Kenney et al. 2004.)

of this galaxy. NGC 4522 is located within a subclump of the Virgo cluster centered on M49. A *ROSAT* map (Fig. 1.6) shows weak extended X-ray emission at the projected location of NGC 4522. All the known peculiarities of NGC 4522 are associated with gas, dust, and H II

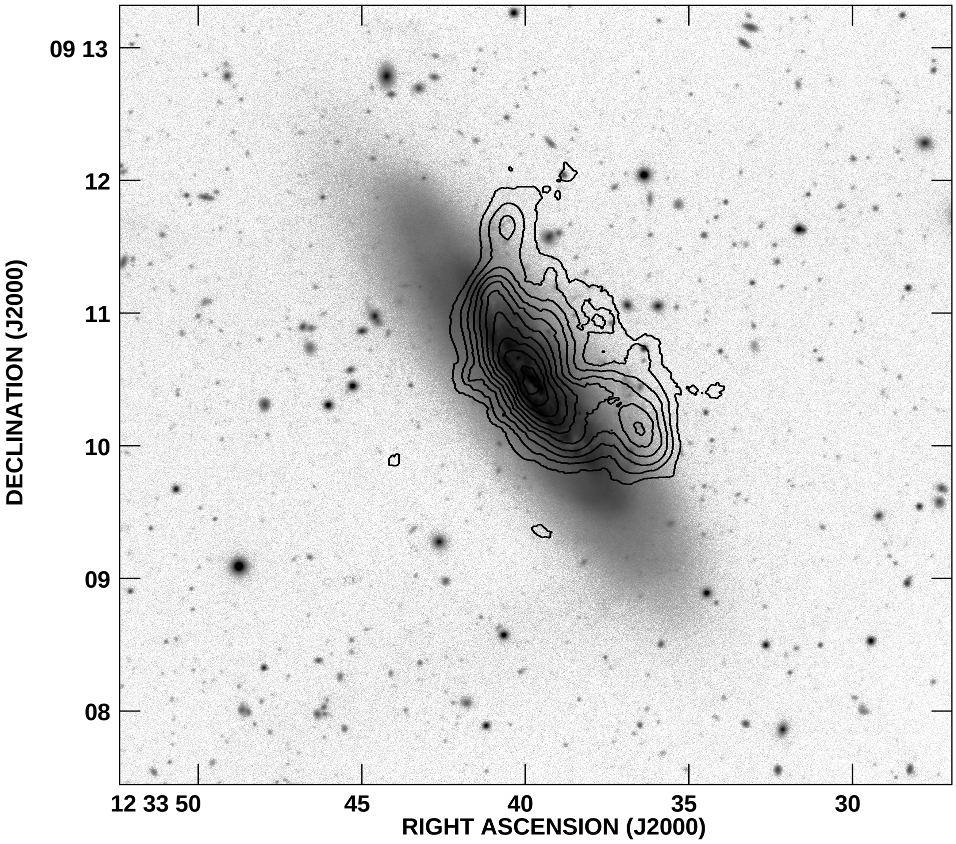

Fig. 1.7. H I contours overlaid on an *R*-band greyscale image from the WIYN telescope (Kenney & Koopmann 1999). Note the undisturbed outer stellar disk. (Taken from Kenney et al. 2004.)

regions, not with the older stars. The H I (Fig. 1.7) is spatially coincident with the undisturbed stellar disk in the central 3 kpc (0.4 R_{25}) of the galaxy. At 0.4 R_{25} the H I truncates abruptly and is only seen above the plane to the SW. About half of the total H I appears to be extraplanar, extending to $\sim$3 kpc above the plane (Kenney, van Gorkom, & Vollmer 2004). There is striking similarity between the spatial distribution of the Hα emission and the H I emission (Fig. 1.8). The Hα emission from the disk is confined to the inner 3 kpc as well, and extraplanar Hα filaments (10% of the Hα emission) emerge from the outer edge of the Hα disk (Kenney & Koopmann 1999). Note that there are H II regions associated with each of the two major extraplanar H I peaks, and that those in the SW are much more luminous.

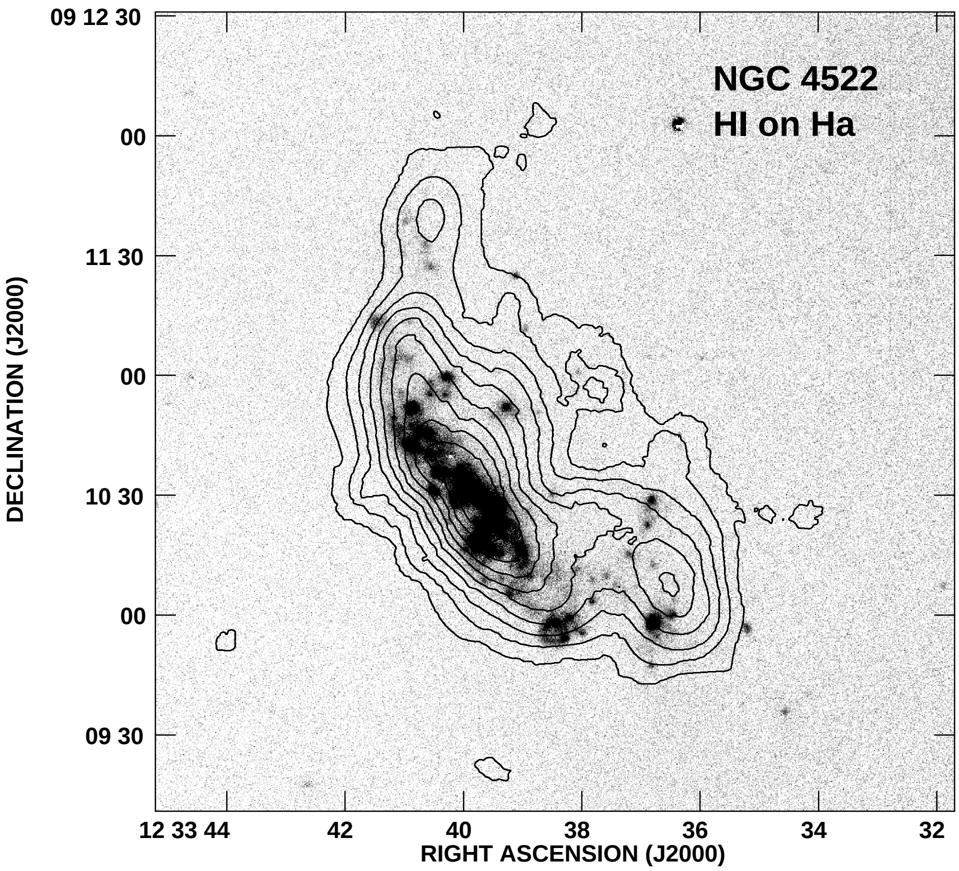

Fig. 1.8. H I contours overlaid on an Hα greyscale image from Kenney & Koopmann (1999). Note that there are H II regions associated with each of the two major extraplanar H I peaks. (Taken from Kenney et al. 2004.)

These data strongly suggest an ICM-ISM interaction. The undisturbed stellar disk rules out a gravitational interaction. The truncated H I disk suggests ram pressure stripping is at work. The extraplanar gas has almost certainly been swept out of the disk. A detailed simulation by Vollmer et al. (2000) suggests that the gas is falling back after a stripping event, but this is inconsistent with the observed kinematics (Kenney et al. 2004). More likely, the gas is still on its way out due to ram pressure stripping (Kenney & Koopmann 1999). The combined characteristics such as a stripped H I disk, only central Hα emission in the disk, and extraplanar gas on only one side of the galaxy make this such a convincing candidate for an ICM-ISM interaction. Evidence for enhanced central star formation in some other examples makes this even more interesting. A central starburst would help use up any remaining gas, and a morphological transformation would be in place.

1.5 Surveys and the Importance of Interactions with the ICM

So far I have only presented evidence, based on selected cases, that interaction with the ICM occurs. The small gaseous disks in the optically selected samples of Virgo and Coma are almost certainly due to ram pressure stripping. A growing number of spiral galaxies are found with an unusual morphology in H I, Hα, and radio continuum, such as the long-known examples in A1367 (Gavazzi et al. 1995), in Virgo galaxies such as NGC 4522, NGC 4388 (Veilleux et al. 1999), NGC 4569, and NGC 4438 (B. Vollmer, in preparation), and in Coma (Bravo-Alfaro et al. 2001; Beijersbergen 2003; Gregg, Holden, & West 2004). These are prime candidates for ongoing ram pressure stripping.

How important are these ICM-ISM interactions for the evolution of galaxies in clusters? An important first step to address this question is the imaging study by Koopmann & Kenney (1998, 2004) of 55 Virgo cluster spirals in Hα and *R* band. They find that the total massive star formation rates in Virgo cluster spirals have been reduced by factors up to 2.5 in the median compared to isolated spirals. The reduction in total star formation is caused primarily by truncation of the star-forming disks (seen in 52% of the spirals). Some of these have undisturbed stellar disks and are likely the product of ICM-ISM stripping, but others have disturbed stellar disks, and are likely the product of tidal interactions or minor mergers, possibly in addition to ICM-ISM stripping. Some evidence is found for enhanced star formation rates due to low-velocity tidal interactions and possibly accretion of H I gas. A strong correlation is found between H I deficiency and normalized Hα flux. The authors conclude that the survey provides strong evidence that ICM-ISM interactions play a significant role in the evolution of most Virgo spirals by stripping gas from their outer disks.

So far I have only discussed H I results obtained on individual galaxies that were selected because they were interesting or, at best, because they were in some optical flux-limited sample. To see how the gas content and morphology depends on cluster environment, optically unbiased studies need to be done. Ideally one should probe the entire volume of clusters, including the low-density outskirts, to get some idea of the gas content and star formation properties as function of local or global density.

The first volume-limited H I survey of a cluster was done of the Hydra cluster (McMahon 1993; van Gorkom 1996). Dickey (1997) surveyed two clusters in the rich group of clusters in the Hercules cluster. These surveys already show that there is a great variety in the neutral hydrogen properties of clusters. Hydra shows barely any evidence for hydrogen deficiency, despite the fact that it is very similar in its global properties to the Virgo cluster. The most likely explanation of these results is that Hydra is in fact a superposition of at least three groups along the line of sight, seen in projection close to each other. The most striking result of the Hercules survey (Dickey 1997) is the spatial variation of H I properties within the clusters. Galaxies in A2147 and the southwest of A2151 show strong H I deficiency, while galaxies in the northeast of A2151 are gas rich. It is perhaps one of the most convincing demonstrations of environmental impact on galaxy properties. The X-ray luminous clusters have strong H I deficiency, whereas the parts of the clusters that have no detectable ICM have an abundance of gas-rich galaxies.

A more systematic survey of five nearby clusters (Abell 85, 754, 496, 2192, 2670) is currently being done at the VLA (Poggianti & van Gorkom 2001; van Gorkom et al. 2003).

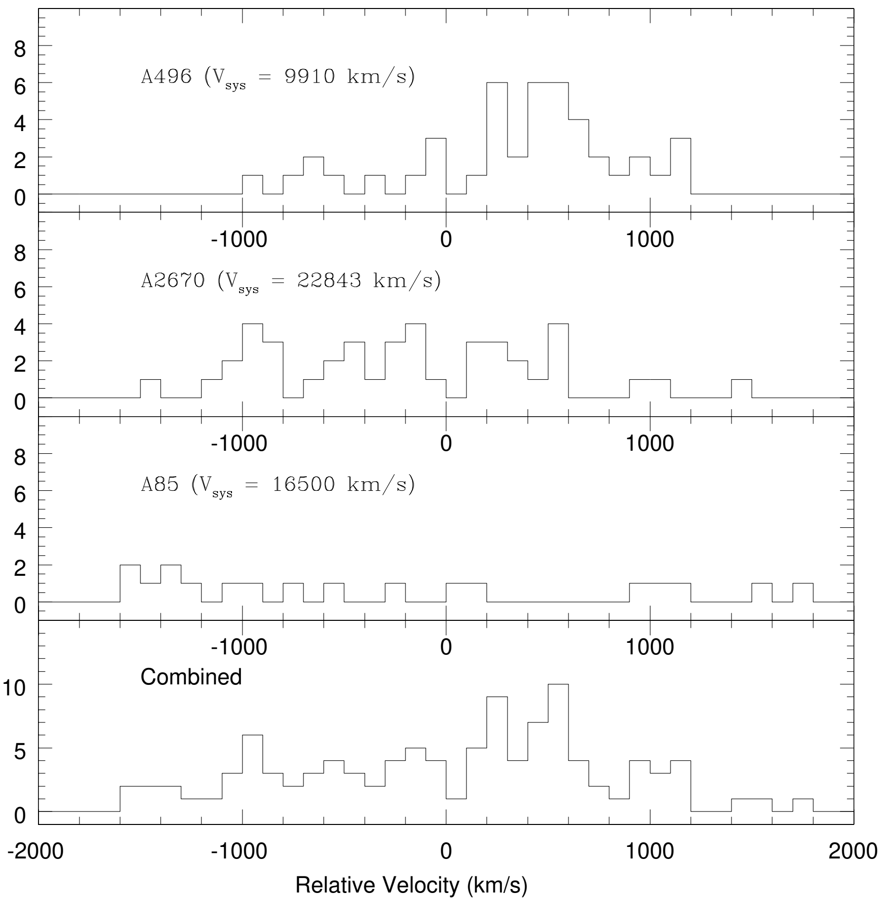

Fig. 1.9. The velocity distribution of the H I-detected galaxies in Abell 496, 2670 and 85 with respect to the mean velocity of the cluster. At the bottom is shown the combined distribution for the three clusters. Note the very non-Gaussian distribution of the velocities. In Figure 1.11 an example is shown of spatial and velocity clustering of H I-detected galaxies.

Each cluster is completely covered out to 2 R_A, thus covering the dense inner parts and the low-density outer parts, and the entire optical velocity range is probed. The most striking result is that in all clusters the H I detections are highly clustered both spatially and in velocity. Figure 1.9 shows the velocity distribution of the H I detections in three of the clusters. Although the velocity distribution of the optically cataloged galaxies in each of the clusters is Gaussian, the velocity distribution of the gas-rich galaxies is far from Gaussian. Figure 1.10 shows the total H I image of Abell 2670. Contours represent the integrated H I emission for individual galaxies. At first glance the image looks like the images of the Virgo and Coma cluster, with small H I disks close to the center and large H I disks further out. But this image now shows the H I emission from all galaxies in the cluster with H I masses $\geq$

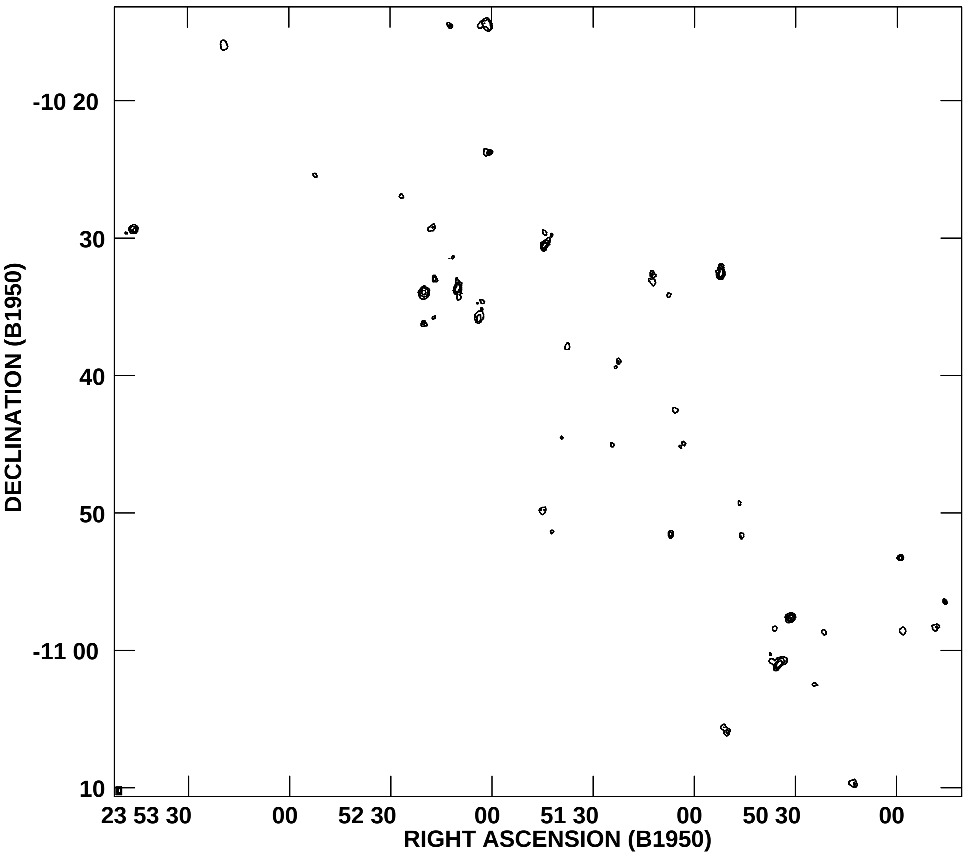

Fig. 1.10. H I emission of the cluster Abell 2670 at a redshift of $z = 0.08$. The image is centered on the center of the cluster, and the H I detections are spread over a region of $5 \times 2h^{-1}$ Mpc. All galaxies with an H I mass $\geq 2 \times 10^8 M_\odot$ in the velocity range of the cluster are shown.

$2 \times 10^8 M_\odot$. Figure 1.11 shows an overlay of a group of galaxies to the NW on the DSS. The internal velocity dispersion of this group is only a few$\times$100 km s^{-1}. These galaxies are very gas-rich, and obviously conditions for interactions and merging are ideal. Several galaxies do, in fact, show evidence for distorted H I. These results indicate that gas-rich disk galaxies that make it into the center of a cluster are likely to be seriously affected by interaction with the ICM. It is likely that a significant fraction of disk galaxies falling into clusters are located in low-velocity dispersion, loose groups. The interactions in these groups, before the actual infall, may be more damaging to the morphology than any ICM interaction thereafter. The most dramatic example (Fig. 1.12) of that is the H I image of a number of S0 galaxies in the outskirts of the Ursa Major cluster by Verheijen & Zwaan (2001). Optically one would

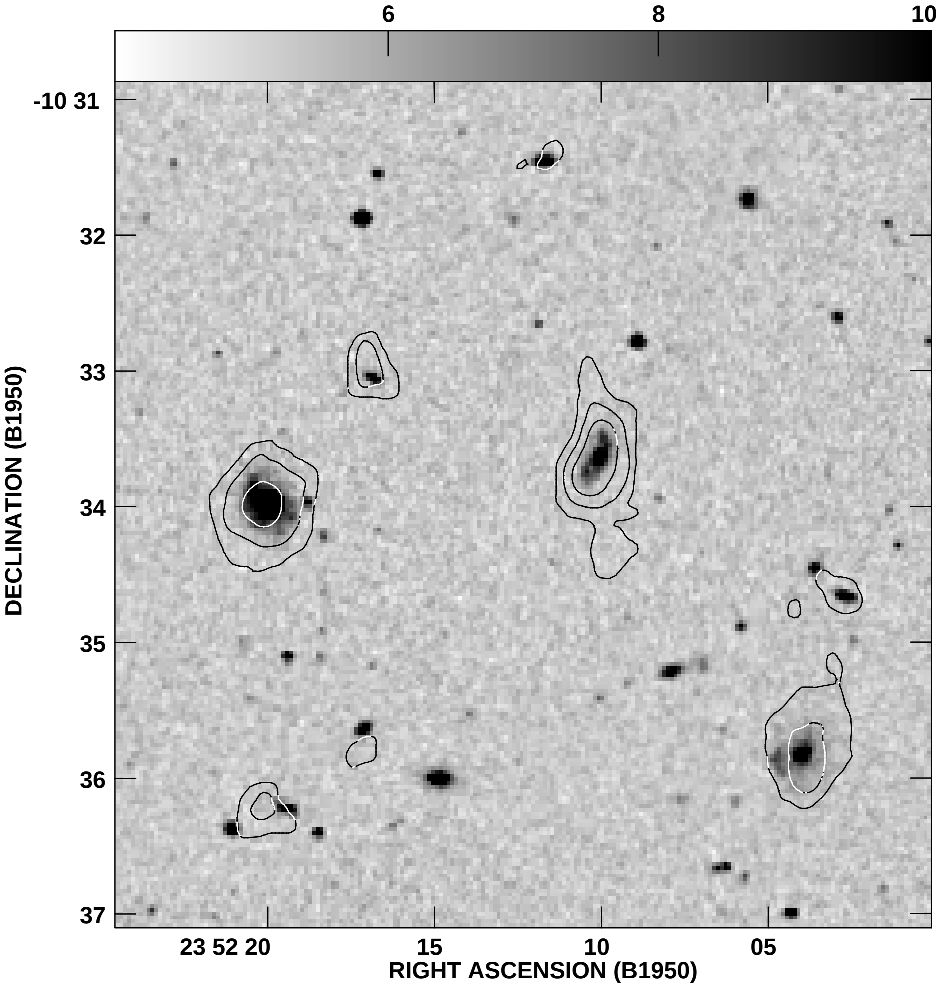

Fig. 1.11. An overlay of the total H I emission (contours) on a DSS optical image (greyscale) of a group of galaxies in the NE part of the A2670 cluster. The internal velocity dispersion of this group is only a few$\times$100 km s^{-1}. These are very gas-rich galaxies. Note the distorted H I contours indicative of interactions.

not have guessed that anything dramatic is about to happen to these galaxies. The H I shows that strong interactions are already taking place.

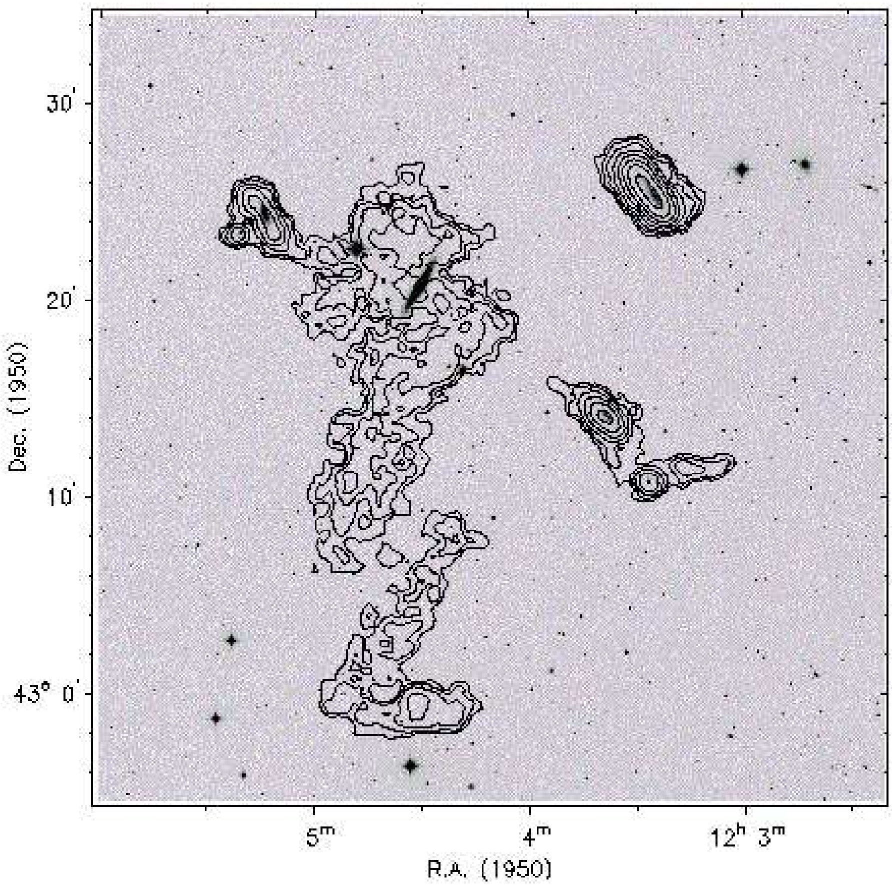

Fig. 1.12. Recently discovered H I filaments near the S0 galaxy NGC 4111 in the Ursa Major cluster. The S0 galaxy is located in a small group, and the H I morphology indicates that tidal interaction between the galaxies is taking place. (Taken from Verheijen & Zwaan 2001.)

1.6 Concluding Remarks

We can now begin to answer the question posed in the introduction: are interactions with the ICM important for the evolution of disk galaxies. The answer is a definite yes for disk galaxies in cluster environments. We see individual galaxies that show all the signs of an ongoing interaction, signs that are predicted by detailed hydrodynamical simulations. We see trends in galaxy properties, such as the truncated gaseous disks in the center of Virgo and Coma, and truncated star formation disks in Virgo (Koopmann & Kenney 2004), which can be reproduced in simulations of ICM interactions with the cold ISM in disk galaxies. These interactions should produce a population of early-type, non-star-forming disk galaxies with a range of bulge-to-disk ratios, as was predicted by Dressler & Gunn (1983) and as has been found in Virgo (Koopmann & Kenney 2004). However, other effects also play a role in clusters. Galaxies are found that experience both stripping and gravitational interactions (Vollmer 2003; Koopmann & Kenney 2004), and examples of gravitationally induced star formation have also been found (Rose et al. 2001; Sakai et al. 2002; Koopmann & Kenney 2004). However, the dominant environmental effect on cluster disk galaxies is a reduction of the star formation rate, which goes hand-in-hand with hydrogen deficiency, and for most galaxies this is due to ram pressure stripping (Koopmann & Kenney 2004).

On larger scales, Solanes et al. (2001) found evidence that the H I deficiency goes out as far as 2 R_A. Although this is surprisingly far, the fact that the deficient galaxies at large distances from the cluster tend to be on radial orbits makes it plausible that the cause of the deficiency is ram pressure stripping as well. The extent of the H I deficiency fits in nicely with the results of Balogh et al. (1998), who find that the star formation rate, as measured by the [O II] equivalent width, is depressed in clusters out to 2 R_{200} ($\sim$2 R_A), and more recently the analyses of the 2dF and the SDSS survey results (Lewis et al. 2002; Gómez et al. 2003; Nichol 2004), which indicate that star formation rates begin to drop between 1 and 2 virial radii. These results are somewhat at odds with the H I imaging results, where evidence is found that the groups in the outskirts of clusters are very gas rich. Many examples of ongoing interactions are found in these locations. In a simple scenario the interactions would bring gas to large distances from the galaxies, which could then easily be stripped as the galaxies fall into the denser ICM.

It is an intriguing possibility that the impact and reach of the ICM is closely related to the dynamical state of the cluster. Cluster-(sub)cluster merging can give rise to bulk motions, shocks, and temperature structure within the ICM. In merging clusters, observational evidence has been found for large velocities in the ICM (Dupke & Bregman 2001), enhanced star formation (Miller & Owen 2003; Miller 2004), and distortion of radio sources by the ICM motions (Bliton et al. 1998). If stripping would mostly depend on the motions of the ICM and the dynamical state of the cluster, it would more easily explain why the effects are seen far out into the infall region. The radial orbits measured for the more distant H I-deficient galaxies would then reflect the infall direction of the most recent accretion event in the cluster.

Acknowledgements. I am grateful to the organizers of this conference for inviting me to give this review. I thank Jose Solanes, Marc Verheijen, Hector Bravo-Alfaro, Dwarakanath, Jeff Kenney, Bianca Poggianti, Raja Guhathakurta, Ann Zabludoff, David Schiminovich, Monica Valluri, Eric Wilcots, and Bernd Vollmer for help with figures and many discussions on these topics. I thank the Kapteyn Institute, where part of this work was done, for their hospitality. This research was supported by an NSF grant to Columbia University and a NWO bezoekers beurs to Groningen.

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