2008

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*The Galaxy Disk in Cosmological Context*
*Proceedings IAU Symposium No. 254, 2008*
*J. Andersen, J. Bland-Hawthorn & B. Nordström, eds.*

DOI: 00.0000/X000000000000000X



# The Evolution of Galaxy Disks in Dense Environments – Lessons from Compact Galaxy Groups

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**Abstract.** Disk galaxies in compact galaxy groups exhibit a remarkable shortfall of neutral hydrogen compared to both isolated spirals and spirals in more loose groups, but the origin of this HI deficiency remains unclear. Based on a sample of highly HI deficient compact galaxy groups, here updated to also include HCG 58 and 93, we summarise the first results of a multi-wavelength campaign aimed at understanding the processes responsible for modifying the HI content of galaxy disks in these environments. While tidal stripping, ram pressure stripping by hot intragroup gas, and star-formation induced strangulation could individually be affecting the ISM in some of the group members, these processes each face specific difficulties in explaining the inferred deficiency of HI for the sample as a whole. A complete picture of the mechanisms driving the ISM evolution in the disk galaxies of these groups has thus yet to emerge, but promising avenues for further progress in this field are briefly discussed on the basis of the present sample.

**Keywords.** galaxies: evolution; galaxies: interactions; galaxies: ISM; X-rays: galaxies: clusters

## 1. Introduction

A substantial fraction of all galaxies in the nearby Universe reside in a group or cluster environment. Disk galaxies are not only less common within such environments than in the field, but they also tend to be deficient in neutral hydrogen. For a group or cluster as a whole, this HI deficiency $\Delta_{\rm HI}$ can be quantified as

$$\Delta_{\rm HI} = \log M_{\rm HI,pred} - \log M_{\rm HI,obs}, \tag{1.1}$$

where $M_{\rm HI,obs}$ is the total observed HI mass of the group or cluster, and $M_{\rm HI,pred}$ is that predicted for a corresponding ensemble of isolated galaxies of similar optical morphology and luminosity. At the scale of small groups, comprehensive radio studies have shown such HI deficiencies to be particularly pronounced in Hickson (1982) compact groups (HCGs) (Verdes-Montenegro et al. 2001). Tidal interactions can be expected to play a prominent role in affecting the evolution of galaxy disks in these systems, given the compactness and low velocity dispersions ($\sigma \sim$ a few hundred km s$^{-1}$) of the environment. However, there is also an indication from *ROSAT* data that significant HI deficiency in these groups correlates with the presence of a detectable X-ray emitting intragroup medium (IGM), suggesting that galaxy–IGM interactions such as ram pressure stripping of HI may also be important.

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**Table 1.** Summary of group sample and X-ray observations. Distances assume $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$. Velocity dispersions are taken mainly from Ponman et al. (1996).

| Group | Dist. (Mpc) | $\Delta_{\rm HI}$ | $\sigma$ (km s$^{-1}$) | X-ray obs. | Expo. time (ks) |
|---|---|---|---|---|---|
| HCG 7 | 54 | 0.60 | 95 | *XMM* | 29 |
| HCG 15 | 92 | 0.46 | 404 | *XMM* | 26 |
| HCG 30 | 63 | 1.37 | 72 | *Chandra* | 29 |
| HCG 37 | 97 | 0.33 | 446 | *Chandra* | 18 |
| HCG 40 | 98 | 0.60 | 157 | *Chandra* | 46 |
| HCG 44 | 23 | 0.69 | 145 | *Chandra* | 20 |
| HCG 58 | 89 | 0.51 | 178 | *ROSAT* | 11 |
| HCG 93 | 64 | 0.99 | 234 | *ROSAT*/*Swift* | 14/4 |
| HCG 97 | 86 | 0.35 | 383 | *Chandra* | 36 |
| HCG 100 | 69 | 0.27 | 100 | *Chandra* | 42 |

Since a non-negligible fraction of all groups in the Universe (including so-called 'fossil' groups) may at some point experience a phase resembling that of HCGs, an improved understanding of the impact of the HCG environment on the group members may well have ramifications extending beyond these somewhat atypical groups. In order to explore the origin of the shortfall of HI in HCGs, and more generally to shed light on disk galaxy evolution in these environments, we have therefore embarked on a multi-wavelength campaign aimed at establishing the detailed properties of the gas and galaxies in the most HI deficient HCGs. The initial focus has been on the properties of any X-ray emitting IGM, in an attempt to constrain the importance of galaxy–IGM interactions in these groups.

## 2. Sample and Observations

Our full sample comprises the ten most HI deficient systems from the study of Verdes-Montenegro et al. (2001). These all have HI masses well below that expected for their galaxy contents, and so should represent groups in which the processes destroying HI should be in active, or very recent, operation. *Chandra* and *XMM-Newton* X-ray data are now available for eight of these, and this subset is described in Rasmussen et al. (2008), along with details of the associated X-ray analysis. On the radio front, the existing Very Large Array data of the sample have been complemented by single-dish Green Bank Telescope (GBT) observations, partly to aid in the search for extended, smoothly distributed HI emission within the central group regions (Borthakur et al., in preparation). The resulting HI deficiencies range from $\Delta_{\rm HI} = 0.27$–$1.37$, with a characteristic uncertainty of 0.2, which is dominated by the standard error on the predicted HI mass. Table 1 summarises the sample and its current X-ray coverage.

The two groups without *Chandra* or *XMM* data, HCG 58 and 93, have been targeted in *ROSAT* pointings. As a by-product of our effort to also obtain UV data for the sample, we have recently acquired a short *Swift* X-ray exposure of HCG 93, with similar data underway for HCG 58. No obvious diffuse X-ray emission is detected in the *Swift* data of HCG 93, consistent with the earlier *ROSAT* result of Ponman et al. (1996), but the sensitivity of the *Swift* data is insufficient to provide strong constraints on the density of any IGM. The IGM in HCG 58 also remained undetected in the *ROSAT* analysis of Osmond & Ponman (2004).

## 3. Results So Far

The X-ray analysis of the *Chandra*/*XMM* subsample (Rasmussen et al. 2008) has revealed a remarkable diversity in hot IGM properties across the sample, with diffuse

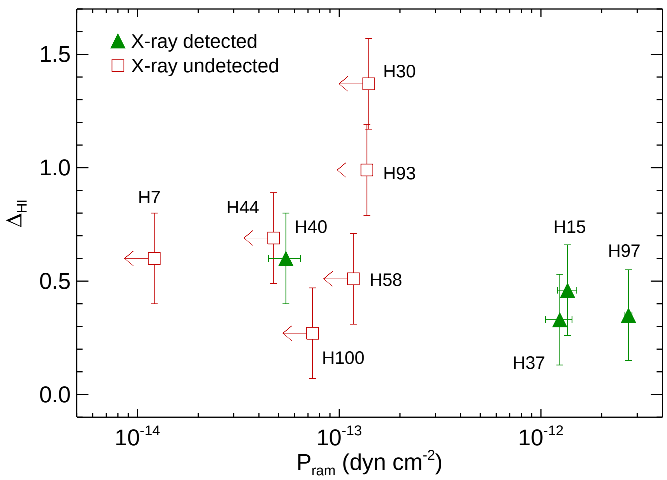


**Figure 1.** HI deficiencies and characteristic mean ram pressure for the various groups. Empty squares represent groups with no detectable hot gas.

X-ray emission in the groups ranging from undetected (e.g., in the highly HI deficient HCG 30) to similar to that in massive X-ray bright groups (e.g., in HCG 97). For HCG 58 and 93, not included in this earlier analysis, the existing *ROSAT* data can be used to place constraints on their hot IGM masses. If assuming IGM temperatures of $kT = 0.5 \pm 0.1$ and $0.6 \pm 0.1$ keV as estimated from their galaxy velocity dispersions (Osmond & Ponman 2004), the *ROSAT* results of Osmond & Ponman (2004) and Ponman et al. (1996) for HCG 58 and 93, respectively, translate into $3\sigma$ upper limits to their 0.3–2 keV X-ray luminosity and hot gas mass inside the region of our GBT coverage ($r \approx 4.5'$) of $L_X < 1 \times 10^{41}$ erg s$^{-1}$ and $M_{IGM} < 6 \times 10^{10}$ M$_\odot$ (HCG 58), and $L_X < 2 \times 10^{40}$ erg s$^{-1}$ and $M_{IGM} < 1.5 \times 10^{10}$ M$_\odot$ (HCG 93). These limits are fairly typical of the X-ray undetected groups in our sample.

The diversity in hot gas content across the full group sample immediately suggests that galaxy–IGM interactions may not be dominant in removing HI from the disks of the group members. This interpretation is supported by Figure 1, which reveals no clear correlation between measured $\Delta_{HI}$ and characteristic 'mean' ram pressure $\langle P \rangle = \langle n_{IGM} \rangle \sigma^2$ in each group, where $\langle n_{IGM} \rangle$ is the inferred mean hot IGM density within the region covered by the GBT data, and $\sigma$ is the galaxy velocity dispersion.

However, the efficiency of ram pressure stripping depends not only on the IGM properties but also on the gravitational restoring force of the individual group members. In order to quantitatively investigate the importance of stripping in each X-ray detected group, we constructed a detailed disk–bulge–halo galaxy model, constrained by the average stellar mass, disk rotational velocity, Hubble type, and predicted initial HI content of our late-type group members (see Rasmussen et al. 2008 for details). The model was evolved in a radial orbit within each group gravitational potential as determined from the X-ray analysis, enabling the IGM ram pressure and HI mass loss due to stripping to be evaluated at each point in the orbit. Some contribution to HI removal could also come from viscous stripping (Nulsen 1982), which was also included in the model. Figure 2 compares observed values of $\Delta_{HI}$ to the resulting model predictions. Uncertainties in model values result from assuming different initial conditions for the adopted radial orbits. Observed values of $\Delta_{HI}$ generally exceed modelled ones, except in HCG 97 and

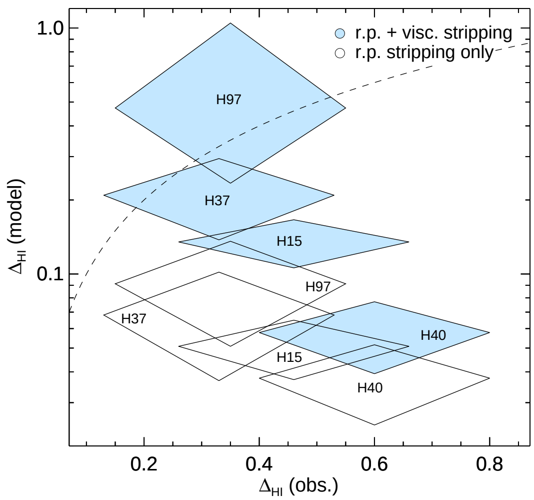


**Figure 2.** Observed HI deficiencies compared to our stripping calculations for the X-ray detected groups. Results are shown for ram pressure stripping alone (empty diamonds), and when viscous stripping is included (shaded). Dashed line represents equality between observed and predicted $\Delta_{\rm HI}$.

potentially HCG 37, suggesting that galaxy–IGM interactions alone cannot in general explain the observed HI deficiencies, even in the X-ray detected groups.

Such interactions may nevertheless still indirectly affect the HI in spiral disks by facilitating *strangulation*. Many disk galaxy formation models predict that low-redshift spirals, at least above some threshold mass, are surrounded by hot gaseous halos from which gas may cool out to provide fuel for ongoing star formation in the disk (e.g., Toft et al. 2002). The removal of this coronal gas by external forces could contribute to HI deficiency, if the limited supply of HI in the disk is consumed by star formation without being replenished from the gaseous halo. Detailed hydro–simulations indicate that this process could be efficient even in low-mass groups (Kawata & Mulchaey 2008). Our own stripping calculations suggest that ram pressure could potentially remove a sizable fraction of any hot halo gas around the group members in the X-ray detected groups, from ~30% in HCG 40 to ~70% in HCG 97. This process could therefore be important in shutting off the gas supply that may otherwise ultimately fuel star formation in the disks of the group members.

## 4. Implications and Discussion

The *Chandra* and *XMM* data, in most cases representing an improvement in sensitivity by 1–2 orders of magnitude over the previous *ROSAT* data, manifestly show that the presence of a substantial hot IGM is not a prerequisite for high HI deficiency in these groups, despite earlier indications of a connection (Verdes-Montenegro et al. 2001). Although galaxy–IGM interactions can clearly have affected the HI disks of galaxies within X-ray bright groups such as HCG 97, such processes cannot generally be dominant in removing HI from the group members in our sample.

Other mechanisms could help account for the observed shortfall of HI within these groups. HI consumption by star formation, aided by the removal of a continuous supply of HI to the disk, could be playing a prominent role. One problem faced by this scenario, however, is that the time-scale required to exhaust the HI supply to observed levels (assuming $\Delta_{\rm HI} = 0$ initially), is, on average, at least five Gyr at the current star formation rates (SFRs) in the groups. Strangulation may therefore not have been important in establishing current HI levels within our sample.

Another possible explanation for the lack of HI are recent tidal interactions, clearly taking place in some of the groups as evidenced by Figure 3. However, analysis of SDSS data has established that such interactions are commonly accompanied by a clear SFR enhancement (e.g., Li et al. 2008), and yet the SFRs in Hickson groups as determined from *IRAS* fluxes are not elevated relative to values for field spirals (Verdes-Montenegro et al. 1998). Our X-ray analysis also shows no clear evidence of enhanced nuclear activity within galaxies in the X-ray brighter or more HI deficient groups, suggesting that strong nuclear starbursts or AGN activity triggered by tidally induced gas inflows are not more common or prominent within the more 'evolved' groups. Typical indirect signatures expected of tidal interactions are thus generally very modest in these groups, and such interactions may furthermore not themselves destroy HI.

In summary, obvious mechanisms that could be invoked to explain the pronounced deficiency of HI observed for the sample clearly each face some difficulties. The X-ray results indicate that galaxy–IGM interactions may have played a role in destroying HI in the X-ray bright groups, but it remains unclear whether, for example, tidal interactions on their own can explain the reduced HI content in the remaining systems.

## 5. Prospects for Future Work

There are several directions in which we hope to take further studies of these systems in order to shed additional light on the fate of their missing HI. For example, constraints on the typical column densities of HI removed from individual galaxies may allow estimates of the time-scale for this material to be either photo-ionized by the intergalactic UV background, or thermally evaporated in the X-ray bright groups. In the latter case, a detailed comparison of the X-ray and HI morphology of the groups will also establish to what extent hot and cold intergalactic gas can, in fact, co-exist in these systems. This should help in building a more complete picture of the mechanisms affecting any HI that is not being destroyed *in situ* within the group members, e.g. by star formation.

Another interesting possibility to explore is related to the evidence that SFRs in Hickson groups are not globally enhanced relative to the field. This result could potentially be misleading, perhaps masking an evolutionary trend in which galaxies joining these groups initially experience an episode of enhanced star formation which is then followed by an environment–driven suppression. This possibility could be reflected in a larger intrinsic variation in specific SFRs compared to similar field spirals. Since the existing SFR estimates of our group members are almost exclusively based on *IRAS* fluxes, for which only upper limits are available for many of the galaxies, deeper complementary data are required to obtain more robust constraints on SFRs for all group members. For this purpose, we are currently in the process of obtaining UV data for all groups in the sample (including HCG 58 and 93), using the high-throughput UVOT telescope on *Swift*. We note that some of our groups have SDSS spectroscopic coverage, but the SDSS fibres only sample the central region of these very nearby galaxies, whereas the *Swift* data should enable mean SFR estimates across the full galactic disks.

These UV data may also have other useful applications, such as allowing a search for evidence of recent interactions that have primarily affected the young stellar component in the disks. As an example, Figure 3 shows a comparison between the UV and near-infrared light (dominated by young and old stars, respectively) for two of our group members which both appear tidally disturbed in optical DSS images. While the near-infrared light

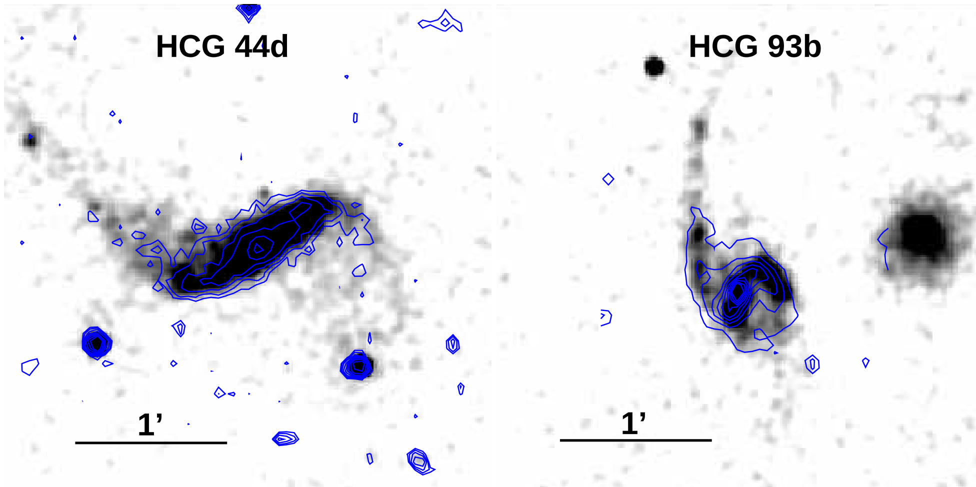


**Figure 3.** *Swift* UV images of HCG 44d and HCG 93b with 2MASS *JHK* contours overlayed. The highly disturbed UV morphologies suggest recent tidal interactions in both cases.

shows a clear warp in both cases, the UV light appears particularly distorted, suggesting strong recent interactions in both cases. A comparative lopsidedness analysis of the UV and NIR light could verify this quantitatively, and should be possible for most of the bright group spirals given the reasonably narrow point spread function of UVOT (with FWHM $\approx 2''$ at UV wavelengths). Such an approach may aid in quantifying the stage and time-scale of ongoing tidal interactions, for comparison to the observed H I deficiencies.

We note in closing that considerable effort has been devoted in the literature to elucidating the nature and properties of Hickson compact groups. It is our hope that continued work on the sample discussed here will ultimately contribute to an improved understanding not only of HCGs in particular, but of galaxy groups in general, and of the cosmological evolution of galactic disks in such environments.

*Acknowledgements*

Support for this work was provided by the National Aeronautics and Space Administration through Chandra Postdoctoral Fellowship Award Number PF7-80050.

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