J. Astrophys. Astr. (2005) **26,** 71–87

The HI Content of the Eridanus Group of Galaxies

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Received 2004 August 23; accepted 2005 March 22

Abstract. The HI content of galaxies in the Eridanus group is studied using the GMRT observations and the HIPASS data. A significant HI deficiency up to a factor of 2–3 is observed in galaxies in the high galaxy density regions. The HI deficiency in galaxies is observed to be directly correlated to the local projected galaxy density, and inversely correlated to the line-of-sight radial velocity. Furthermore, galaxies with larger optical diameters are predominantly in the lower galaxy density regions. It is suggested that the HI deficiency in Eridanus is due to tidal interactions. In some galaxies, evidences of tidal interactions are seen. An important implication is that significant evolution of galaxies can take place in the group environment. In the hierarchical way of formation of clusters via mergers of groups, a fraction of the observed HI deficiency in clusters could have originated in groups. The co-existence of S0s and severely HI deficient galaxies in the Eridanus group suggests that tidal interaction is likely to be an effective mechanism for transforming spirals to S0s.

Key words. Galaxy: evolution—galaxies: groups, clusters—individual: Eridanus—radio lines: HI 21cm-line.

1. Introduction

Spiral galaxies in the cores of clusters are known to be HI deficient compared to their field counterparts (Davies & Lewis 1973; Giovanelli & Haynes 1985; Cayatte *et al.* 1990; Bravo-Alfaro *et al.* 2000; Solanes *et al.* 2001). Several gas-removal mechanisms have been proposed to explain the HI deficiency in cluster galaxies. There are convincing results from both the simulations and the observations that ram-pressure stripping (cf. Gunn & Gott 1972) is effective in galaxies which have crossed the high intra cluster medium (ICM) density region near the core of the cluster (Vollmer *et al.* 2001, van Gorkom 2003). "Galaxy harassment" can also affect outer regions of the disk as a result of repetitive fast encounters of galaxies in clusters (Moore *et al.* 1998). There can be other scenarios where galaxies can become gas deficient, e.g., thermal evaporation and viscous stripping (Cowie & Songaila 1977; Nulsen 1982; Sarazin 1988), and

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"galaxy starvation" where hot gas in the halos of galaxies is stripped. It is believed that halos contain a reservoir of hot gas, which sustains star formation in galaxies over their present ages (Larson *et al.* 1980).

Often one or more processes have been shown to be working in individual cases. There are no strong arguments for any of these processes to be globally effective in clusters. Cayatte *et al.* (1990) showed that the HI deficiency in Virgo galaxies can be understood by a combination of ram-pressure stripping and transport processes. However, there are several inconsistencies. Magri *et al.* (1988) showed that no single gas-removal process can be justified consistently in any cluster. Further uncertainties arise since some of the parameters driving these mechanisms are not known well, e.g., thermal conductivity of the ICM, amount of hot gas in halos, etc. It is also not clear that all severely HI deficient galaxies have crossed the core as required for ram-pressure to be effective. Contrary to what is expected from ram-pressure stripping, the low mass spirals and dwarfs are indistinguishable from the massive spirals in terms of HI deficiency (Hoffman *et al.* 1988). Valluri & Jog (1991) observed in Virgo and some other rich clusters that galaxies with medium to large optical sizes tend to be more severely HI deficient compared to smaller galaxies in terms of both the fractional number and the amount of gas lost. This behaviour is contrary to that expected from ram-pressure stripping or transport processes, however, consistent with that expected if tidal interactions were responsible for the gas deficiency. The exact mechanism responsible for HI deficiency in clusters is still uncertain. These difficulties have led one to speculate that cluster galaxies were perhaps HI deficient even before they fell into the cluster. Such a speculation is motivated by the hierarchical theory of structure formation where clusters build up via mergers of small groups. Groups of galaxies therefore provide an opportunity to trace early evolution of galaxies.

Several clusters have been imaged in HI. However, only limited HI data exist for large groups. Previous studies on groups were mainly aimed at Hickson Compact Groups (HCGs), which usually have less than 10 galaxies packed in a small volume. For instance, Verdes-Montenegro *et al.* (2001) imaged several HCGs in HI and found a significant HI deficiency in the galaxies. To our knowledge, the only large group studied in HI is Ursa-Major, which is rich in spirals, and has a few S0s and no ellipticals. Verheijen (2001) showed that there is no HI deficiency in the Ursa-Major galaxies. The environment in the Ursa-Major group is similar to that in the field. The HI data for groups in which the environment is intermediate between field and cluster is lacking. Here, we present an HI study of the Eridanus group which appears to be an intermediate system between a loose group like Ursa-major and a cluster like Fornax or Virgo. The properties of the Eridanus group are described in detail in Omar & Dwarakanath (2005a; hereafter paper-I). The Eridanus group has a significant population of S0s (paper-I). The origin of S0s has been the subject of much debate. Usually the population of S0s is enhanced in clusters where galaxy density is high. There are two hypotheses for the formation of S0s, one is "Nature" where it is believed that S0s were formed as such, and the other is "Nurture" (evolution) according to which these galaxies are transformed spirals. The presence of enhanced population of S0s in the Eridanus group indicates that significant evolution of galaxies has perhaps already occurred in the group. In the present study, HI content of galaxies in the Eridanus group is analysed. The aim is to identify the galaxy evolution processes in the group environment. Both the GMRT data and the HIPASS (HI Parkes All Sky Survey) data are used. The details of the GMRT observations, data reduction and analyses are presented in paper-I and Omar

(2004). Some new results based on follow-up VLA observations are also presented here.

2. The Eridanus group

The Eridanus group was identified as a moderate size cluster in a large scale filamentary structure near $cz \sim 1500$ km s^{-1} in the Southern Sky Redshift Survey (SSRS; da Costa *et al.* 1988). This filamentary structure, which is the most prominent in the southern sky, extends for more than 20 Mpc. The Fornax cluster and the Dorado group of galaxies are also part of this structure. Eridanus has ~ 200 galaxies distributed over ~ 10 Mpc region. The properties of the group are described in detail in paper-I. The distance to the group is estimated as $\sim 23 \pm 2$ Mpc. The group appears to be made of different sub-groups which have different morphological mix. One of the sub-groups, NGC 1407 (cf. Willmer *et al.* 1989), has a population mix of (E+S0s) and (Sp + Irrs) in the ratios of 70% and 30% respectively, which is quite similar to those found in clusters. The overall population mix in the Eridanus group is 30% (E + S0) and 70% (Sp + Irr). These sub-groups often have their brightest member as an elliptical or an S0. The brightest member in the entire group is a luminous ($L_B \sim 4 \times 10^{10}$ L$_\odot$) elliptical galaxy with diffuse X-ray emission ($L_{\times;\ 0.1-2.0\,\mathrm{keV}} \sim 2 \times 10^{41}$ erg s^{-1}) surrounding it. Diffuse X-ray emission ($L_{\times;\ 0.1-2.0\,\mathrm{keV}} \sim 7 \times 10^{40}$ erg s^{-1}) is also seen around another elliptical galaxy NGC 1395 which belongs to another sub-group. There is no appreciable difference in the velocities over which the early types and the late types are distributed. This is contrary to that seen in Virgo, Coma and several nearby Abell clusters where spirals have much flatter velocity distribution while E/S0s have nearly a Gaussian distribution in velocity (Binggeli *et al.* 1987; Colless & Dunn 1996; Biviano *et al.* 2002).

3. The HI content

A total of 57 galaxies in the Eridanus group were observed with the GMRT in the HI 21 cm-line. The details of the observations and the data analyses are described in paper-I. The HI detections were made for 31 galaxies. It was noticed that the HI flux densities of some large (dia. $> 6'$) galaxies were underestimated by the GMRT observations presumably due to inadequate sampling of the short (u, v) spacings. In the present study, the HI masses for such galaxies were replaced by those obtained from the HIPASS data (Meyer *et al.* 2004). In addition, HIPASS data were used for galaxies in the Eridanus region not observed by the GMRT. The final sample consisted of a total of 63 HI detected galaxies of different morphological types. The HI sample is described in Appendix A.

The HI masses of galaxies in the field environment are observed to be correlated with their Hubble types and optical diameters D_{opt} (e.g., Haynes & Giovanelli 1984, hereafter HG84). The HI deficiency (cf. HG84) for a galaxy of a given type can be estimated by comparing $\log(M_{\mathrm{HI}}/D_{\mathrm{opt}}^2)$ of the galaxy with that observed for field galaxies. In the present study, the ratio $\log(M_{\mathrm{HI}}/D_{\mathrm{opt}}^2)$ for each Eridanus galaxy is compared with the mean value of the ratio $\log(M_{\mathrm{HI}}/D_{\mathrm{opt}}^2)$ obtained by HG84 for isolated galaxies of similar types. A significant positive difference between the two ratios indicates an HI deficiency (def. $= \langle\log(M_{\mathrm{HI}}/D_{\mathrm{opt}}^2)\rangle_{\mathrm{field}} - \log(M_{\mathrm{HI}}/D_{\mathrm{opt}}^2)$). It should be noted that this deficiency parameter is distance independent. The optical

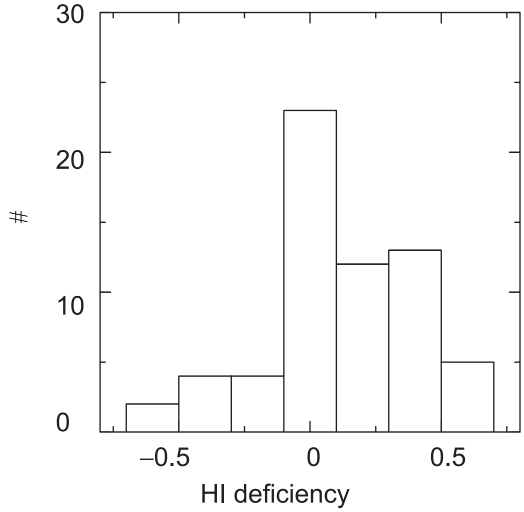

Figure 1. Histogram of the HI deficiency in the Eridanus galaxies.

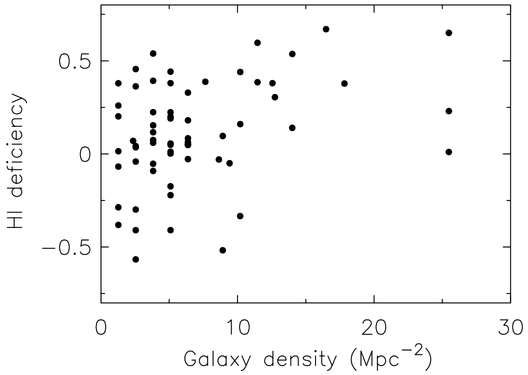

Figure 2. HI deficiency vs. the local projected galaxy density. The Spearman Rank-Order Correlation Coefficient test shows that the correlation is significant at $> 99\%$.

diameters of galaxies used in HG84 were from the Upsala General Catalog (UGC). The optical diameters of galaxies in the Eridanus group are from the Third Reference Catalog of Galaxies (RC3; de Vaucouleurs *et al.* 1991). The optical diameters in RC3 are at 25 mag arc sec^{-2} in the B-band. To convert the RC3 diameters or D_{25} to D_{opt} consistent with the UGC diameters, the conversion relation obtained by Paturel *et al.* (1991) was used. This relation predicts that the D_{opt} (UGC) is about 1.09 times the D_{25}.

A histogram of the HI deficiency for the Eridanus galaxies is plotted in Fig. 1. The HI deficiency is independent of the morphological type of the galaxies. It can be seen that although the distribution peaks at zero deficiency, there are more galaxies with positive differences. Some HI rich galaxies (def. < -0.5) are also seen in Fig. 1. These turn out to be interacting pairs, and hence the HI masses are likely to be overestimated.

Figure 2 shows the HI deficiency plotted against the local projected galaxy density. The projected galaxy density is estimated within a circular region of diameter 1.0 Mpc.

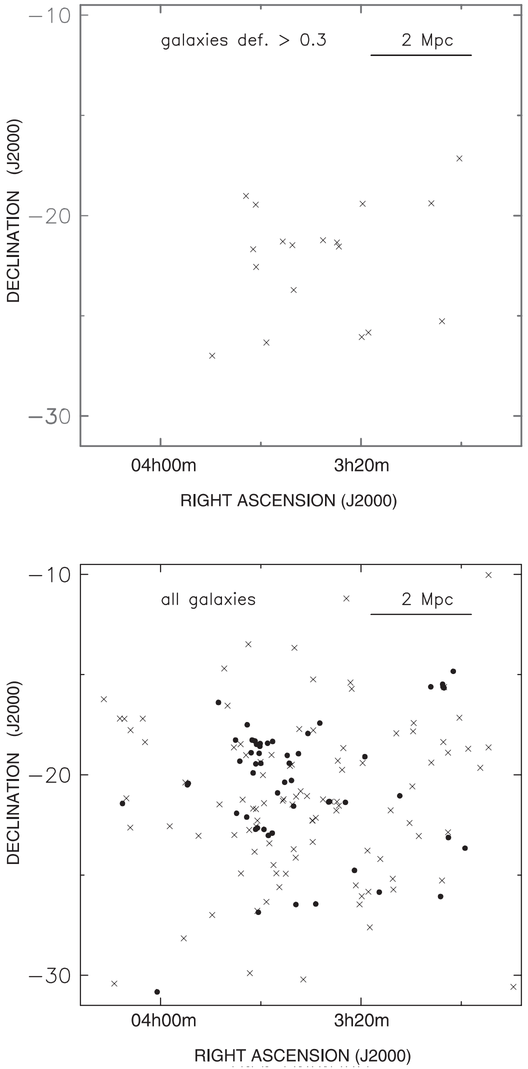

Figure 3. (Lower panel) All galaxies in the Eridanus group. The early type galaxies (E + S0) are marked as filled circles and late type galaxies (Sp + Irr) are marked as crosses. (Upper panel) Galaxies with Hɪ deficiency greater than 0.3. It can be seen that severely Hɪ deficient galaxies and early type galaxies are confined to the regions of higher galaxy densities.

It can be seen that in higher galaxy density (>10 Mpc^{-2}) regions, a majority of galaxies are Hɪ deficient while in the lower galaxy density regions both normal and deficient galaxies are present. Galaxies are Hɪ deficient up to a factor of 2–3 ($\sim$ 0.3–0.5 in log units) in these plots. The correlation between the projected galaxy density and Hɪ deficiency can also be seen in Fig. 3 where the locations of all identified group members (lower panel) and the locations of galaxies deficient by more than a factor of two are plotted (top panel). It is evident that severely Hɪ deficient galaxies and the early type galaxies are confined to the regions of higher galaxy densities. The Hɪ deficiency also shows a strong inverse correlation with the line-of-sight radial velocities (w.r.t. the

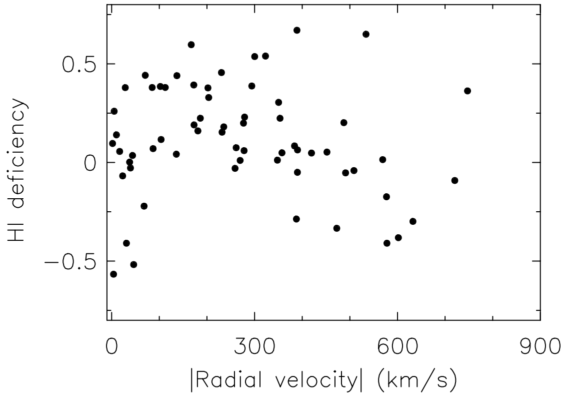

Figure 4. Hi deficiency is plotted against the line-of-sight radial velocities (w.r.t. the systemic velocity of the group) of galaxies in the group. The Spearman Rank-Order Correlation Coefficient test shows that the correlation is significant at $> 99.9\%$ for velocities > 100 km s^{-1}.

systemic velocity of the group) of galaxies in the group (Fig. 4). All of this information is used in the next section to identify the gas-removal mechanism active in the group.

4. The gas-removal processes

Several gas-removal mechanisms have been discussed in the literature to explain the Hi deficiency in cluster galaxies. These mechanisms are ram-pressure stripping, transport processes (thermal conduction, and viscous and turbulent stripping), galaxy harassment (tidal interactions), and galaxy strangulation, etc. All these mechanisms are expected to show some correlation of the Hi deficiency with the properties of the cluster-environment and of the galaxies. For instance, ram-pressure stripping will be more effective for galaxies with higher radial velocities in the group. The trend observed in Fig. 4 is opposite to that expected if ram-pressure stripping were globally effective in the Eridanus group. It can be shown that for galaxies in the Eridanus group the ram-pressure is one to two orders of magnitude lower than that in the cores of clusters (Omar 2004). This implies that ram-pressure stripping is of little importance in the Eridanus group.

The direct correlation of deficiency with the local projected galaxy density, and the inverse correlation with the line-of-sight radial velocity suggests that the Hi deficiency in Eridanus galaxies is due to tidal interactions. Galaxies in higher galaxy density regions will have a higher probability of tidal encounters. Therefore, a direct correlation of deficiency with the local projected galaxy density is expected. Further, the perturbation due to tidal interactions is expected to be maximum for slow encounters. In the Eridanus group where the velocity distribution of galaxies is peaked near the mean velocity of the group (paper-I) and falls off nearly as a Gaussian at higher relative velocities, galaxies having nearly zero radial velocities in the group will have a higher probability of interacting with a companion having a lower velocity difference. Therefore, the inverse correlation of Hi deficiency with the line-of-sight radial velocity is qualitatively understood. The presence of a wider distribution of deficiency near the zero radial velocity is likely to be due to projection effects. Galaxies with higher radial velocities but moving nearly perpendicular to the line-of-sight will have almost zero line-of-sight radial velocities. Therefore, some discordant points are expected near zero velocity in Fig. 4.

Tidal forces will affect both the gas and the stars in galaxies. In contrast, ram-pressure affects only the gas. If the Hɪ deficiency in the Eridanus group is indeed due to tidal interactions, some observational signatures of the same should be seen in both the stellar and the Hɪ disks. The tidal interactions often produce gaseous and stellar tidal tails extending to large distances in the IGM. Some of the gas and the stars will be lost from the galaxy to the IGM in this process. It will be difficult to detect this low column density tidal debris in the IGM except for those associated with recent events where the column densities could still be detectable. However, repeated tidal encounters in the high galaxy density regions will shrink the optical sizes of galaxies. Figure 5 indicates that the Eridanus galaxies with larger optical sizes are predominantly in the lower galaxy density regions. This trend is further indicative of the scenario of tidal interactions being effective in the Eridanus group.

It is worthwhile to discuss an important effect while estimating Hɪ deficiency using the $M_{\text{H}\textsc{i}} / D^2_{\text{opt}}$ parameter. Since both D_{opt} and $M_{\text{H}\textsc{i}}$ are reduced as a result of tidal encounters, the Hɪ gas loss inferred from this deficiency parameter will be a lower limit. In the absence of detailed simulations of repetitive tidal encounters in a group environment, such effects are hard to quantify.

5. The morphological peculiarities of the Eridanus galaxies

Some galaxies in the Eridanus group show tidal tails and other peculiarities like Hɪ extending out of the disk, Hɪ warps, asymmetric Hɪ disks, shrunken or fragmented Hɪ disks, kinematical or Hɪ lopsidedness, etc. Tidal interactions can produce long tails of gas and stars, and deformations in the disks of galaxies. Some representative examples of these peculiarities are shown in Figs. 6 and 7, and are discussed below.

5.1 *Shrunken H*ɪ *disks*

ESO 549-G 002 and NGC 1422 show shrunken Hɪ disks. Both of these galaxies are Hɪ deficient, and are in a region with a galaxy density ~ 20 Mpc^{-2}. The Hɪ deficiencies

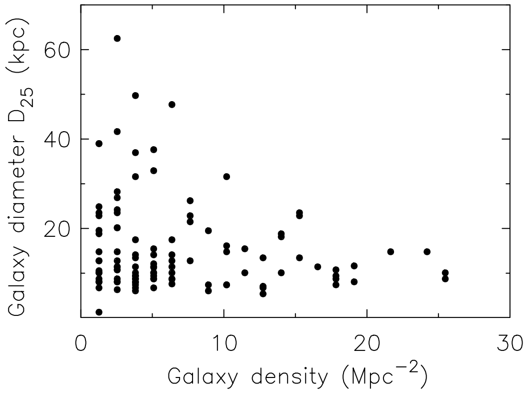

Figure 5. The optical disk diameters plotted against the local projected galaxy density.

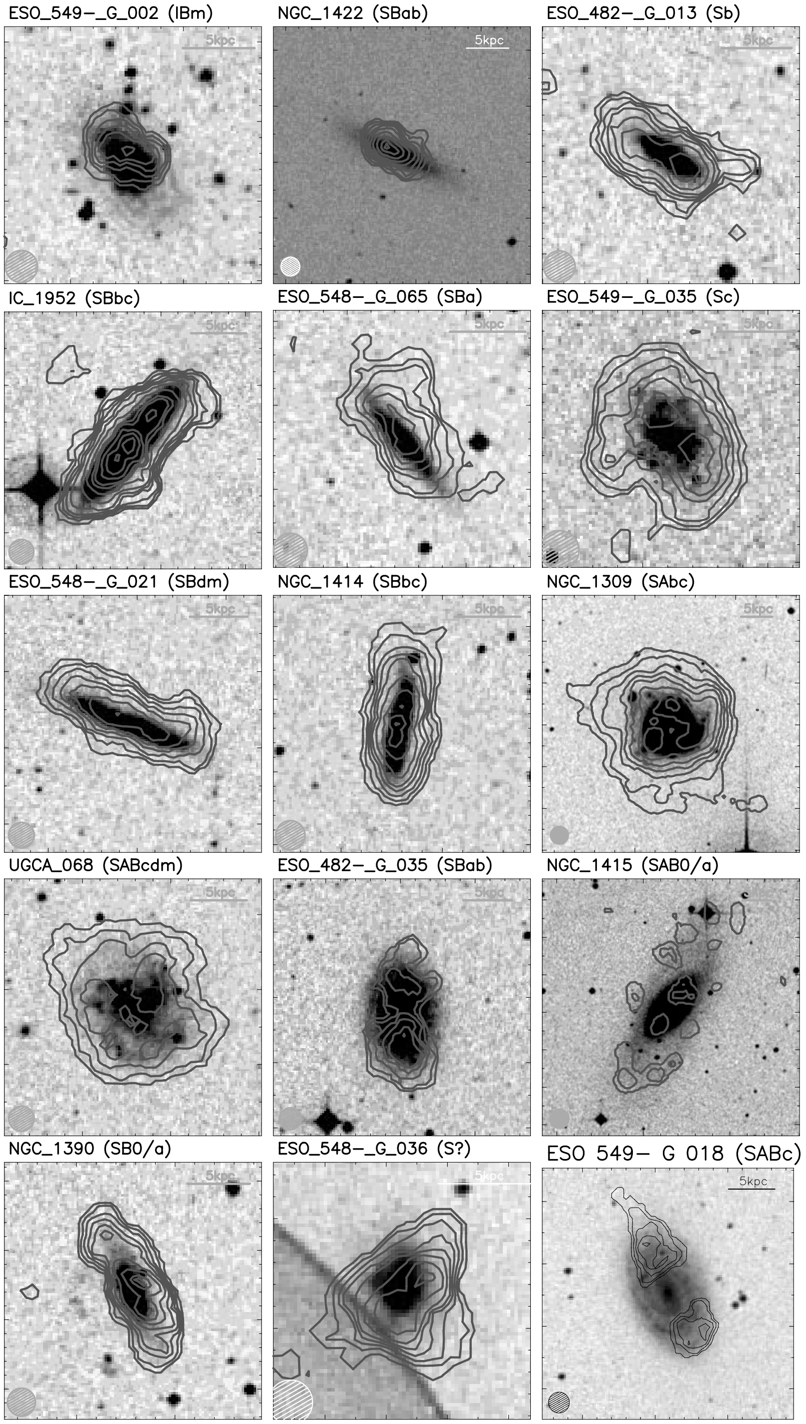

Figure 6. GMRT HI column density contours overlaid upon the optical DSS gray-scale images of Eridanus galaxies which show peculiar HI morphologies (see section 5 for details). The contour levels increase in units of $N_{\text{HI}} = 2 \times 10^{20}$ cm^{-2}. The first contour is at $N_{\text{HI}} = 10^{20}$ cm^{-2}.

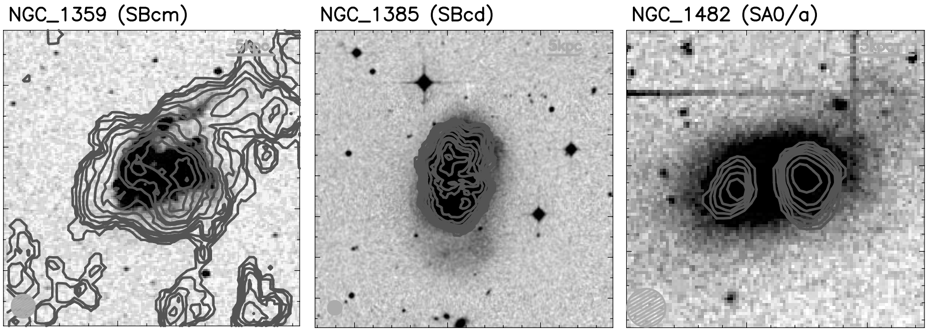

Figure 7. GMRT HI column density contours overlaid upon the optical DSS gray-scale images of Eridanus galaxies which have clearly visible tidal tails in optical.

for ESO 549-G 002 and NGC 1422 are 0.67 and 0.44 respectively. ESO 549-G 002 has a faint stellar envelop in the outer region and has an irregular optical morphology in the inner region. NGC 1422 is an edge-on galaxy with a prominent dust lane. It has an HI morphology similar to that seen in ram-pressure stripped galaxies in clusters where gas from the outer regions is preferentially removed. As it has been argued that the ram-pressure is not very effective in the Eridanus group, it indicates that the highly shrunken HI disk in NGC 1422 is due to some other reasons. Moreover, no tidal features are seen either in optical or in HI. The origin of the shrunken HI disk in NGC 1422 therefore remains elusive.

5.2 *Extra-planar gas and warps*

Some galaxies in the Eridanus group show HI extending out of the disk (see ESO 482-G 013, IC 1952, ESO 548-G 065, ESO 549-G 035 in Fig. 6). This extra-planar gas is seen in the form of wisps and small plumes of gas. It appears that this phenomena is often seen in the edge-on galaxies since the extra-planar gas will be easier to detect in these systems. It may be possible that other galaxies also have such features. The extra-planar gas might be quite common in galaxies. HI warps can be noticed in ESO 548-G 021 and NGC 1414.

5.3 *Asymmetric HI disks*

NGC 1309 and UGCA 068 have asymmetric HI disks. These two galaxies have normal HI content. One side of the galaxy appears more diffuse than the opposite side. These two galaxies also show kinematical asymmetries (paper-I). NGC 1309 has a warp in the outer region. UGCA 068 shows asymmetry in the rotation curve. We speculate that such features could be due to retrograde tidal encounters. The retrograde encounter described by Toomre & Toomre (1972) does not pull out stars (the gas will respond in the same way) but can cause both morphological and kinematical asymmetries.

5.4 *Peculiar HI disks*

The HI disks of ESO 482-G 035 and NGC 1415 are seen to be very peculiar. Both are early type disk galaxies, and it is not common to see fully developed HI disks in such galaxies. It is likely that the detected HI is in a ring rather than being in a fully developed disk. NGC 1415 is an S0/a galaxy with a faint optical ring in the outer regions where most of the HI is seen in isolated clouds. The inclination of the ring is mis-aligned with the inner disk by more than 20°.

The HI disk of NGC 1390 is bent in an arc shape. Some diffuse nebulosity is visible towards the west of this galaxy.

5.5 *Polar ring galaxy*

ESO 548-G 036 (S?) has the position angle of the HI disk inferred from HI kinematics almost normal to the position angle of the optical isophotes. The optical body resembles an S0 galaxy with a dust lane normal to the major axis of the main body. It is suggested that this is a polar ring galaxy. Polar rings are believed to be due to recent accretion of gas from tidal encounters. IC 1953, an HI rich galaxy at a projected separation of $\sim$ 50 kpc, is likely to be the companion.

5.6 *Tidal tails*

Either gaseous or stellar tidal features are seen in NGC 1359, NGC 1385, and NGC 1482 (Fig. 7). The HI tidal tail and some isolated HI features in the vicinity can be seen in NGC 1359. Both NGC 1385 and NGC 1482 are far-infrared luminous galaxies, and undergoing intense star forming activities. NGC 1385 has highly asymmetric diffuse stellar envelop, however no gaseous tidal tail is seen. NGC 1482 (S0/a) appears to have an HI ring coincident with the dust ring seen in the optical image. The apparent central HI hole in NGC 1482 is due to HI absorption against the radio emission. Stellar tidal features can be seen in NGC 1482. Follow-up VLA HI observations on these galaxies were carried out aimed at detecting any low column density tidal debris. The details are given in the next section.

6. Follow-up VLA observations

Although several peculiarities are seen in both the optical and the GMRT HI images of Eridanus galaxies, no tidal debris in HI were detected in the GMRT images. It is expected that tidal debris will have low column density gas which could have been missed in the GMRT images due to its limited sensitivity to the extended emission. Follow-up VLA observations were, therefore, carried out in its D-configuration which is most sensitive to the extended low column density emission. The observations were carried out on galaxies having one or more close neighbours or on galaxies which showed tidal features in optical. The details of the observations are given in Table 1. The observations were carried out in the D-north-C (DnC) hybrid configuration which gives a nearly symmetric synthesised beam for sources in the southern hemisphere. The data were analysed following the standard procedures using AIPS (Astronomical Image Processing System) developed by the National Radio Astronomy Observatory. The flux density scale is based on the standard VLA calibrator 0137+331. Observations were carried out in two polarizations. Fields 2 and 3 (cf. Table 1) were observed in the 4IF correlator mode at two different centre frequencies in the two IFs each of bandwidth 3.125 MHz with sufficient overlap so that the total usable bandwidth after stitching the two IFs was $\sim$ 5 MHz. Other fields were observed in the 2IF correlator

Table 1. VLA D-configuration observations.

#	Obs. date (dd-mm-yy)	Field centre ($\alpha^{h,m,s}$, J2000) ($\delta^{d,',''}$, J2000)			Galaxies	rms (mJy/bm)	$\theta_a \times \theta_b$, PA ($'' \times ''$, $^\circ$)
1	30-05-04	03	54	49.0	NGC 1482	1.4	74 × 57, 15.6
		−20	26	14.0	NGC 1481		
					ESO 549-G 035		
2	05-06-04	03	40	31.5	ESO 548-G 072	1.0	67 × 58, 04.5
		−19	25	00.0	ESO 548-G 065		
					ESO 548-G 064		
3	11-06-04	03	41	12.5	NGC 1415	1.0	76 × 56, 15.1
		−22	34	30.0	APM 482 + 009-132		
					ESO 482-G 031		
					NGC 1416		
4	12-06-04	03	33	34.8	ESO 548-G 036	1.2	75 × 56, 18.6
		−21	31	23.0	IC 1953		
5	13-06-04	03	37	28.3	NGC 1385	1.9	71 × 57, −8.6
		−24	30	05.0			
6	13-06-04	03	34	00.0	NGC 1359	1.9	84 × 55, 27.0
		−19	28	36.0	ESO 548-G 043		
					ESO 548-G 044		

Notes – (a) The bandwidth of each IF was 3.125 MHz. (b) Fields 1, 4, 5 and 6 were observed in 2 IFs with 128 channels in each IF. Fields 2 and 3 were observed in 4 IFs with 64 channels in each IF. The total integration time was ~ 3.2 h for the fields 1, 2, 3, and 4 and ~ 1.6 h for fields 5 and 6.

mode with 3.125 MHz of bandwidth. The velocity resolution was $\sim$ 10.4 km s^{-1} for fields 2 and 3, and $\sim$ 5.2 km s^{-1} for the other fields.

The HI emission was searched by eye in the channel images. The HI moment maps were constructed using the AIPS task MOMNT. Field 1 (NGC 1482; Fig. 8) and field 6 (NGC 1359; Fig. 9) show extended HI tails previously undetected in the GMRT images. The HI images of other galaxies are almost identical to those obtained from the GMRT. Both NGC 1482 and NGC 1359 are in the sub-groups of which they are the brightest members. Both galaxies show tidal features in their optical images. It appears that NGC 1482 has interacted with NGC 1481. NGC 1359 has two nearest neighbours, but HI streamers do not connect them. It appears that NGC 1359 has undergone multiple interactions as there are two different HI streamers or tails, one towards the north–east and the other towards the west winding towards the south. An understanding of the HI morphologies in these galaxies requires detailed N-body simulations. Nevertheless, these HI detections indicate that tidal interactions are effective in the Eridanus group.

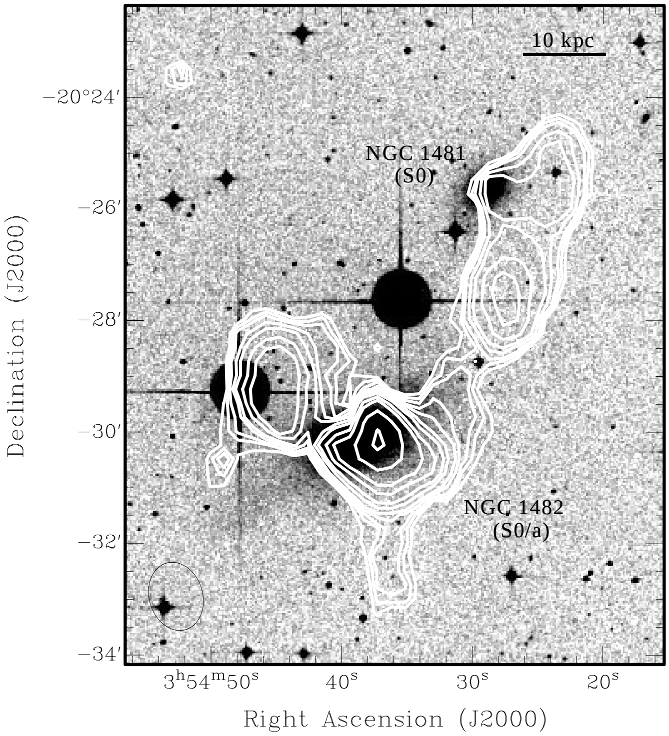

Figure 8. Contours of the VLA Hi image of NGC 1482 overlaid upon the optical image from DSS. The contours are at $N_{\rm HI}$ = 1, 1.5, 2, 3, 4, 6, 8, 12, 16, 24, 32 $\times 10^{19}$cm^{-2}. Faint stellar streamers can be seen around NGC 1482.

7. Discussion

Galaxies in the Eridanus group are Hi deficient up to a factor of 2–3 compared to their field counterparts. The direct correlation of the Hi deficiency with the local galaxy density, and the inverse correlation of the Hi deficiency with the line-of-sight radial velocities of galaxies suggest that the deficiency is due to tidal interactions. Since the Hi deficiency of the Eridanus galaxies is observed in all types of galaxies, the correlation of the Hi deficiency with the local galaxy density cannot be just a manifestation of the density-morphology relation. Although Eridanus appears as a loose group, it has significant sub-grouping. These sub-groups have regions of higher galaxy densities where Hi deficient galaxies are seen. A galaxy moving with a radial velocity of $\sim$ 240 km s^{-1} (velocity dispersion of the galaxies in the group) can cross a linear distance of $\sim$ 1 Mpc (typical extents of the sub-groups) in $\sim$5 Gyr (typical ages of the galaxies). The higher galaxy density and the relatively short crossing time in the sub-groups enhance the chances of encounters between the galaxies. Therefore, it appears that the sub-grouping is playing an important role in producing the Hi deficiency. Further, the inverse correlation of deficiency with the radial velocity indicates that it is necessary for a galaxy to interact with another galaxy with a smaller velocity difference to make the tidal encounters effective.

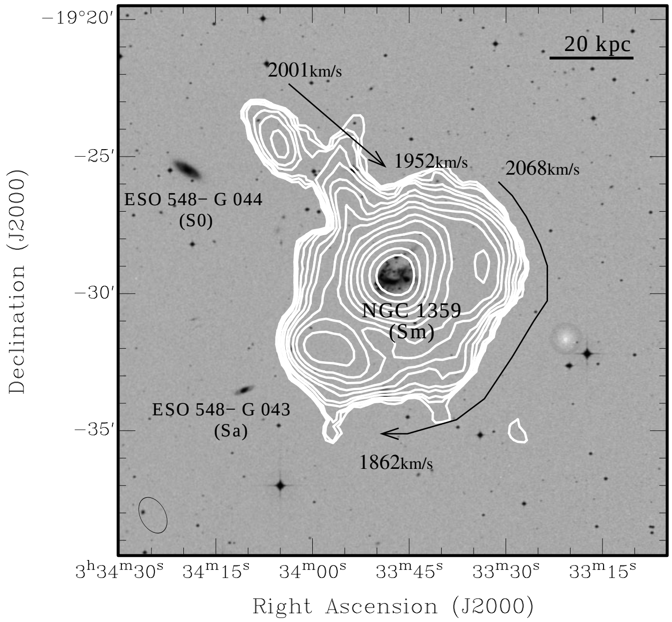

Figure 9. Contours of the VLA Hɪ image of NGC 1359 overlaid upon the optical image from DSS. The contours are at $N_{\text{H}\,\textsc{i}}$ = 1, 1.5, 2, 3, 4, 6, 8, 12, 16, 24, 32, 48, 64, 96, 128 $\times 10^{19}\text{cm}^{-2}$. Stellar tidal tail can be seen in NGC 1359. The approximate directions of the velocity gradients in the two tidal features are marked.

The observed Hɪ deficiency in a loose group like Eridanus has some interesting implications for the evolution of galaxies. Galaxies in clusters are known to be Hɪ deficient up to a factor of 10. However, the reasons for such large deficiencies are not completely understood. If clusters form as mergers of groups as expected in a hierarchical Universe, a fraction of the Hɪ deficiency seen in cluster galaxies might have originated in the group environment. In other words, clusters are built with galaxies, some of them are already Hɪ deficient. This implication is particularly important for simulations which try to match the observed Hɪ deficiency in cluster galaxies with what can be produced by ram-pressure stripping in the cluster environment (e.g., Vollmer *et al.* 2001). Tidal interactions will become less effective in removing matter from galaxies in a cluster environment as encounters will be relatively fast. However, increased frequency of encounters in clusters due to higher galaxy density may actually affect the outer regions of galaxies as envisaged by the process of "galaxy harassment". Therefore, it is possible that tidal interactions play an important role in the evolution of galaxies in both the group and the cluster environments.

The origin of S0s in high galaxy density regions is not understood. Whether S0s are due to some evolutionary processes driven by the environment ("Nurture") or due to the result of natural processes of galaxy formation ("Nature") is being debated. Several co-workers (Dressler *et al.* 1997; Poggianti *et al.* 1999; Fasano *et al.* 2000) found that in observations of clusters at intermediate redshifts ($z \sim 0.1 - 0.3$), the fraction of S0s tends to grow at the expense of the spiral population as the redshift decreases. These observations support the "Nurture" scenario. Several mechanisms have been proposed for the transformation of spirals into S0s, e.g., ram-pressure stripping, galaxy harassment, strangulation. The present observations in the Eridanus group indicate that both the severely H I deficient galaxies and the S0s are found in the higher galaxy density regions in the Eridanus group. It may be an indication that both the H I deficient and the S0 galaxies originated through similar processes. Since the ram-pressure is not playing any major role in the Eridanus group, the S0s in Eridanus are produced by some other process. Tidal interactions appear to be a favourable mechanism for transformation of spirals into S0s in the wake of the current understanding of the Eridanus group from this study.

The H I deficiency observed in the Eridanus galaxies is consistent with the H I deficiency seen in other low velocity dispersion groups and clusters, viz., the Hickson Compact groups (Verdes-Montenegro *et al.* 2001) and the Fornax cluster (Schroder *et al.* 2001). Mulchaey (2000) observed that groups of galaxies are filled with the metal-enriched intra-group medium with average metallicity ~ 0.3. While other mechanisms can also enrich the intra-group medium with metals, gas lost from the galaxies via tidal interactions will have some contribution to the metal content of the intra-group medium.

The environment in the Eridanus group is intermediate between that in a loose group like the Ursa-Major and a cluster like the Fornax or the Virgo (paper-I). The Ursa-Major has a few S0s and the H I contents of spirals are similar to the field spirals. However, the Eridanus group which has a relatively large velocity dispersion, and a relatively large fraction of S0s, shows significant H I deficiency. Willmer *et al.* (1989) indicated that the Eridanus group is in its early phase of cluster formation. If all these results are combined, it appears that the Eridanus group is indeed in an initial phase of cluster formation where physical conditions in the group are favourable for driving the galaxy evolution.

8. Conclusions

- The galaxies in the Eridanus group are H I deficient up to a factor of 2–3. The H I deficiency is inversely correlated to the line-of-sight radial velocity, and directly correlated to the local projected galaxy density.
- The H I deficiency in the Eridanus group is likely to be due to tidal interactions.
- The optical diameters of galaxies are observed to be reduced in the high galaxy density regions indicating the effectiveness of tidal interactions in the Eridanus group.
- If clusters are built via mergers of groups, a fraction of the H I deficiency in cluster galaxies might have been produced in the group environment.
- The co-existence of S0s and H I deficient galaxies in the Eridanus group suggests that tidal interactions may be an effective mechanism for transforming spirals to S0s.
- The environment in the Eridanus group is intermediate between the field and a cluster. Nevertheless, conditions are favourable for driving galaxy evolution in the Eridanus group.

Acknowledgements

We thank Marc Verheijen, Jacqueline van Gorkom, and the referee for useful comments. This research has made use of the HI Parkes All Sky Survey (HIPASS) data and has been benefited by NASA's Astrophysics Data System (ADS) and Extra-galactic Database (NED) services.

Appendix A: The H I detected galaxies

Table 2.

Galaxy	H.T.	D_{UGC} (kpc)	Velocity (km s^{-1})	Proj. density (Mpc^{-2})	log($M_{\rm HI}$ /$M_{\odot}$)	Deficiency
NGC 1076	2	13.9	2102	1.3	9.27	−0.38
NGC 1069	3	25.5	1456	2.5	9.47	0.04
NGC 1140	9	12.4	1496	2.5	962	−0.57
ESO 546-G 034	9	9.5	1568	5.1	9.05	−0.22
NGC 1163	6	21.2	2247	2.5	9.14	0.36
NGC 1187	7	40.1	1396	3.8	9.88	0.12
NGC 1179	8	35.7	1777	5.1	9.78	0.20
UGCA 050	9	13.9	1731	2.5	8.70	0.46
UGCA 051	9	12.4	1672	3.8	8.66	0.39
ESO 547-G 011	9	9.5	2220	3.8	8.92	−0.09
IC 1898	7	26.3	1327	5.1	9.44	0.19
ESO 547-G 020	9	10.2	1991	3.8	8.94	−0.05
NGC 1255	6	30.6	1686	3.8	9.60	0.22
UGCA 061	9	29.2	1735	6.4	9.62	0.18
NGC 1258	8	9.5	1483	5.1	8.77	0.06
UGCA 063	9	8.8	2077	5.1	8.93	−0.17
NGC 1292	7	21.9	1364	2.5	9.43	0.04
UGCA 064	8	21.1	1794	7.6	9.13	0.39
UGCA 065	9	14.6	1537	5.1	9.20	0.00
NGC 1300	6	45.2	1571	5.1	9.72	0.44
NGC 1302	3	28.4	1704	6.4	9.27	0.33
NGC 1306	5	8.0	1454	8.9	9.16	−0.52
MCG-03-09-027	9	11.7	2009	2.5	9.05	−0.04
NGC 1309	6	16.0	2132	2.5	9.56	−0.30
UGCA 068	9	12.4	1848	5.1	9.05	0.01
NGC 1325	6	34.3	1602	11.5	9.53	0.39
NGC 1325A	6	16.0	1333	11.5	8.66	0.60
ESO 548-G 021	8	14.6	1702	17.8	8.82	0.38
NGC 1345	7	10.9	1531	5.1	9.28	−0.41
UGCA 075	9	13.9	1888	1.3	9.44	−0.29
UGCA 077	9	12.4	1952	6.4	9.00	0.05
ESO 482-G 005	8	12.3	1920	6.4	9.00	0.05
NGC 1357	4	20.4	1987	1.3	9.10	0.20

Table 2. *(Continued)*

Galaxy	H.T.	D_{UGC} (kpc)	Velocity (km s^{-1})	Proj. density (Mpc^{-2})	log(M_{HI} /$M_{\odot}$)	Deficiency
IC 1952	6	19.0	1823	3.8	8.87	0.54
IC 1953	8	20.4	1851	12.7	9.19	0.30
NGC 1359	9	17.5	1973	10.2	9.69	−0.33
NGC 1371	3	40.8	1461	6.4	9.94	−0.03
IC 1962	8	19.7	1800	14.0	8.92	0.54
ESO 482-G 013	5	8.2	1854	5.1	8.44	0.22
NGC 1385	8	24.8	1498	8.9	9.56	0.10
NGC 1390	3	10.2	1230	25.5	8.70	0.01
NGC 1398	4	51.8	1388	5.1	9.74	0.38
ESO 482-G 032	9	10.9	1732	3.8	8.79	0.15
NGC 1425	5	42.3	1505	1.3	9.82	0.26
NGC 1421	6	25.5	2069	1.3	9.65	0.01
MCG-03-10-045	9	9.5	1239	3.8	8.75	0.07
UGCA 085	7	24.8	1529	1.3	9.20	0.38
ESO 549-G 035	7	10.2	1794	3.8	9.05	−0.24
IC 2007	7	9.5	1523	1.3	8.81	−0.07
SGC 0401.3-1720	9	12.4	1890	6.4	8.99	0.06
UGCA 087	9	16.8	1884	6.4	9.24	0.08
NGC 1518	8	21.9	922	2.5	9.96	−0.41
UGCA 088	8	13.9	1858	5.1	9.10	0.05
ESO 548-G 049	?	6.7	1510	14.0	8.47	0.14
ESO 549-G 0.35	5	9.4	1778	3.8	8.72	0.06
ESO 548-G 065	1	10.1	1221	25.5	8.46	0.23
NGC 1347	5	7.1	1759	8.6	8.64	−0.03
NGC 1415	1	25.8	1585	12.6	9.05	0.38
NGC 1414	4	11.6	1681	10.2	8.76	0.16
ESO 548-G 072	5	8.7	2034	25.5	8.30	0.65
ESO 482-G 035	2	12.8	1890	9.4	8.64	−0.05
NGC 1422	3	14.8	1637	10.2	8.49	0.44
ESO 549-G 002	9	8.7	1111	16.5	8.27	0.67
ESO 549-G 018	5	17.5	1587	2.4	8.63	0.07

Column 1 – Galaxy name; **Column 2** – Hubble type; **Column 3** – UGC optical diameter; **Column 4** – Systemic velocity; **Column 5** – Projected galaxy density; **Column 6** – H I mass; **Column 7** – H I deficiency.

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