The H\textsc{i} content of the Eridanus group of galaxies

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Abstract.

The H\textsc{i} content of galaxies in the Eridanus group is studied using the GMRT observations and the HIPASS data. A significant H\textsc{i} deficiency up to a factor of 2 – 3 is observed in galaxies in the high galaxy density regions. The H\textsc{i} deficiency in galaxies is observed to be directly correlated with the local projected galaxy density, and inversely correlated with 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 H\textsc{i} 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 H\textsc{i} deficiency in clusters could have originated in groups. The co-existence of S0’s and severely H\textsc{i} deficient galaxies in the Eridanus group suggests that galaxy harassment is likely to be an effective mechanism for transforming spirals to S0’s.

Key words: galaxy: evolution – galaxies: groups, clusters – individual: Eridanus – radio lines: H\textsc{i} 21cm-line

1. Introduction

Spiral galaxies in the cores of clusters are known to be H\textsc{i} 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 H\textsubscript{I} 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 “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 H\textsubscript{I} 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 H\textsubscript{I} 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 H\textsubscript{I} 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 H\textsubscript{I} deficient compared to smaller galaxies in terms of both the fractional number and the amount of gas lost. This behavior 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 H\textsubscript{I} deficiency in clusters is still uncertain. These difficulties have led one to speculate that cluster galaxies were perhaps H\textsubscript{I} 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 H\textsubscript{I}. However, only limited H\textsubscript{I} data exist for large groups. Previous studies on groups were mainly aimed at Hickson Compact Groups (HCG’s), which usually have less than 10 galaxies packed in a small volume. For instance, Verdes-Montenegro et al. (2001) imaged several HCG’s in H\textsubscript{I} and found a significant H\textsubscript{I} deficiency in the galaxies. To our knowledge, the only large group studied in H\textsubscript{I} is Ursa-
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Major, which is rich in spirals, and has a few S0’s and no ellipticals. Verheijen (2001) showed that there is no H I deficiency in the Ursa-Major galaxies. The environment in the Ursa-Major group is similar to that in the field. The H I data for groups in which the environment is intermediate between field and cluster is lacking. Here, we present an H I 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 (2004; hereafter paper-I). The Eridanus group has a significant population of S0’s (paper-I). The origin of S0’s has been the subject of much debate. Usually the population of S0’s is enhanced in clusters where galaxy density is high. There are two hypotheses for the formation of S0’s, one is “Nature” where it is believed that S0’s were formed as such, and the other is “Nurture” (evolution) according to which these galaxies are transformed spirals. The presence of enhanced population of S0’s in the Eridanus group indicates that significant evolution of galaxies has perhaps already happened in the group. In the present study, H I 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 $cz \sim 1500 \text{ km s}^{-1}$ 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 $\sim 200$ galaxies distributed over $\sim 10$ 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-group, NGC 1407 (cf. Willmer et al. 1989), has a population mix of (E+S0’s) and (Sp+Irr’s) in the ratios of 70% & 30% respectively, which is quite similar to those found in clusters. The overall population mix in the Eridanus group is 30% (E+S0) & 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 ($L_B \sim 4 \times 10^{10} \text{ L}_\odot$) elliptical galaxy with diffuse X-ray emission ($L_{\times, 0.1-2.0 \text{ keV}} \sim 2 \times 10^{41} \text{ erg s}^{-1}$) surrounding it. Diffuse x-ray emission($L_{\times, 0.1-2.0 \text{ keV}} \sim 7 \times 10^{40} \text{ erg s}^{-1}$) is also seen around another elliptical galaxy NGC 1395 which belongs to another sub-
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/S0’s have nearly a Gaussian distribution in velocity (Binggeli et al. 1987, Colless & Dunn 1996, Biviano et al. 2002).

### 3. The H\textsc{i} content

A total of 57 galaxies in the Eridanus group were observed with the GMRT in the H\textsc{i} 21 cm-line. The details of the observations and the data analyses are described in paper-I. The H\textsc{i} detections were made for 31 galaxies. It was noticed that the H\textsc{i} 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 H\textsc{i} 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 H\textsc{i} detected galaxies of different morphological types. The H\textsc{i} sample is described in Appendix-A.

The H\textsc{i} masses of galaxies in the field environment are observed to be correlated with their Hubble types and optical diameters \(D_{\text{opt}}\) (e.g., Haynes & Giovanelli 1984, hereafter HG84). The H\textsc{i} deficiency (cf. HG84) for a
galaxy of a given type can be estimated by comparing log($M_{\text{H}}/D_{\text{opt}}^2$) of the galaxy with that observed for field galaxies. In the present study, the ratio log($M_{\text{H}}/D_{\text{opt}}^2$) for each Eridanus galaxy is compared with the mean value of the ratio log($M_{\text{H}}/D_{\text{opt}}^2$) obtained by HG84 for isolated galaxies of similar types. A significant positive difference between the two ratios indicates an H\textsubscript{I} deficiency (def. = <log($M_{\text{H}}/D_{\text{opt}}^2$)>\textsubscript{field} − log($M_{\text{H}}/D_{\text{opt}}^2$)). It should be noted that this deficiency parameter is distance independent. The optical diameters of galaxies used in HG84 were from the 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\textsuperscript{-2} in the B-band. To convert the RC3 diameters or $D_{25}$ to $D_{\text{opt}}$ consistent with the UGC diameters, the conversion relation obtained by Paturel et al. (1991) was used. This relation predicts that the $D_{\text{opt}}$ (UGC) is about 1.09 times the $D_{25}$.

A histogram of the H\textsubscript{I} deficiency for the Eridanus galaxies is plotted in Fig. 1. The H\textsubscript{I} 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 H\textsubscript{I} rich galaxies (def. < −0.5) are also seen in Fig. 1. These turn out to be interacting pairs, and hence the H\textsubscript{I} masses are likely to be overestimated.

Fig. 2 shows the H\textsubscript{I} deficiency plotted against the local projected galaxy density. The projected galaxy density is estimated within a circular region of
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 H\text{\textsc{i}} deficiency greater than 0.3. It can be seen that severely H\text{\textsc{i}} deficient galaxies and early type galaxies are confined to the regions of higher galaxy densities.
Eridanus group: H\textsubscript{i} content

Figure 4. H\textsubscript{i} 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\textsuperscript{-1}.

diameter 1.0 Mpc. It can be seen that in higher galaxy density (> 10 Mpc\textsuperscript{-2}) regions, majority of galaxies are H\textsubscript{i} deficient while in the lower galaxy density regions both normal and deficient galaxies are present. Galaxies are H\textsubscript{i} deficient up to a factor of 2 – 3 (~ 0.3 – 0.5 in log units) in these plots. The correlation between the projected galaxy density and H\textsubscript{i} 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 H\textsubscript{i} deficient galaxies and the early type galaxies are confined to the regions of higher galaxy densities. The H\textsubscript{i} deficiency also shows a strong inverse correlation with the line-of-sight radial velocities (w.r.t. the systemic velocity of the group) of galaxies in the group (Fig. 4). All of these information are 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 H\textsubscript{i} 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 H\textsubscript{i} 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 suggest that the H I deficiency in Eridanus galaxies is due to tidal interactions. Galaxies in higher galaxy density regions will have 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 are 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 H I 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 H I 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 H I 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. Fig. 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 H I deficiency using the \( M_{HI}/D_{opt}^2 \) parameter. Since both \( D_{opt} \) and \( M_{HI} \) are reduced as a result of tidal encounters, the H I gas loss inferred from this deficiency parameter will be a lower limit. In the absence of detailed sim-
Figure 5. The optical disk diameters plotted against the local projected galaxy density.

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 H\textsc{i} extending out of the disk, H\textsc{i} warps, asymmetric H\textsc{i} disks, shrunken or fragmented H\textsc{i} disks, kinematical or H\textsc{i} 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 & 7, and are discussed below.

5.1 Shrunken H\textsc{i} disks

ESO 549- G 002 and NGC 1422 show shrunken H\textsc{i} disks. Both of these galaxies are H\textsc{i} deficient, and are in a region with a galaxy density \(\sim 20 \text{ Mpc}^{-2}\). The H\textsc{i} deficiencies 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 H\textsc{i} 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 much effective in the Eridanus group, it indicates...
Figure 6. GMRT H\textsc{i} column density contours overlaid upon the optical DSS grayscale images of Eridanus galaxies which show peculiar H\textsc{i} morphologies (see Sect. 5 for details). The contours levels increase in units of \(N_{\text{H}\textsc{i}} = 2 \times 10^{20} \text{ cm}^{-2}\). The first contour is at \(N_{\text{H}\textsc{i}} = 10^{20} \text{ cm}^{-2}\).
5.1 Eridanus group : H1 content

Figure 7. GMRT H1 column density contours overlaid upon the optical DSS grayscale images of Eridanus galaxies which have clearly visible tidal tails in optical.

that highly shrunken H1 disk in NGC 1422 is due to some other reasons. Moreover, no tidal features are seen either in optical or in H1. The origin of shrunken H1 disk in NGC 1422 therefore remains elusive.

5.2 Extra-planar gas & warps

Some galaxies in the Eridanus group show H1 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. H1 warps can be noticed in ESO 548-G 021 and NGC 1414.

5.3 Asymmetric H1 disks

NGC 1309 and UGCA 068 have asymmetric H1 disks. These two galaxies have normal H1 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 H1 disks

The H1 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 H1 disks in such galaxies. It is likely that the detected H1 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 H\textsc{i} is seen in isolated clouds. The inclination of the ring is mis-aligned with the inner disk by more than 20°.

The H\textsc{i} disk of NGC 1390 is bent in an arc shape. Some diffuse nebulosity is visible toward the west of this galaxy.

5.5 Polar ring galaxy

ESO 548 -G 036 (S?) has the position angle of the H\textsc{i} disk inferred from H\textsc{i} 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 H\textsc{i} 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 H\textsc{i} tidal tail and some isolated H\textsc{i} 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 H\textsc{i} ring coincident with the dust ring seen in the optical image. The apparent central H\textsc{i} hole in NGC 1482 is due to H\textsc{i} absorption against the radio emission. Stellar tidal features can be seen in NGC 1482. Follow up VLA H\textsc{i} 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 H\textsc{i} images of Eridanus galaxies, no tidal debris in H\textsc{i} 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 neighbors or on galaxies which showed tidal features in optical. The details of the observations are given in Tab. 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
### Table 1. VLA D-config. observations

| #  | Obs. date (d-m-y) | Field centre ($\alpha_{h,m,s}$, J2000) | Galaxies | rms (mJy ($'' \times ''$, $^\circ$)) | $\theta_a \times \theta_b$, PA (bm) |
|----|-----------------|----------------------------------------|----------|-------------------------------------|---------------------------------|
| 1  | 30-05-04        | 03 54 49.0 -20 26 14.0                 | NGC 1482 | 1.4                                 | 74 $\times$ 57, 15.6             |
|    |                 |                                        | NGC 1481 |                                     |                                 |
|    |                 |                                        | ESO 549- G 035 |                       |                                 |
| 2  | 05-06-04        | 03 40 31.5 -19 25 00.0                 | ESO 548- G 072 | 1.0                                 | 67 $\times$ 58, 04.5             |
|    |                 |                                        | ESO 548- G 065 |                       |                                 |
|    |                 |                                        | ESO 548- G 064 |                       |                                 |
| 3  | 11-06-04        | 03 41 12.5 -22 34 30.0                 | NGC 1415 | 1.0                                 | 76 $\times$ 56, 15.1             |
|    |                 |                                        | APM 482+009-132 |                       |                                 |
|    |                 |                                        | ESO 482- G 031 |                       |                                 |
|    |                 |                                        | NGC 1416 |                       |                                 |
| 4  | 12-06-04        | 03 33 34.8 -21 31 23.0                 | ESO 548- G 036 | 1.2                                 | 75 $\times$ 56, 18.6             |
|    |                 |                                        | IC 1953 |                       |                                 |
| 5  | 13-06-04        | 03 37 28.3 -24 30 05.0                 | NGC 1385 | 1.9                                 | 71 $\times$ 57, -8.6             |
| 6  | 13-06-04        | 03 34 00.0 -19 28 36.0                 | NGC 1359 | 1.9                                 | 84 $\times$ 55, 27.0             |
|    |                 |                                        | 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 $\sim 3.2$ hrs for the fields 1, 2, 3, and 4 and $\sim 1.6$ for fields 5 and 6.

The H$_i$ content. The data wereanalysed 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. Tab. 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 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 H$_i$ emission was searched by eye in the channel images. The H$_i$ moment maps were constructed using the AIPS task MOMNT. Field 1 (NGC 1482; Fig. 8) and field 6 (NGC 1359; Fig. 9) show extended H$_i$ tails previously un-
detected in the GMRT images. The H\textsc{i} 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 neighbors, but H\textsc{i} streamers do not connect them. It appears that NGC 1359 has undergone multiple interactions as there are two different H\textsc{i} streamers or tails, one toward the north-east and the other toward the west winding toward the south. An understanding of the H\textsc{i} morphologies in these galaxies requires detailed N-body simulations. Nevertheless, these H\textsc{i} detections indicate that tidal interactions are effective in the Eridanus group.

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

Figure 9. Contours of the VLA H\textsc{i} image of NGC 1359 overlaid upon the optical image from DSS. The contours are at $N_{\text{H}\textsc{i}} = 1, 1.5, 2, 3, 4, 6, 8, 12, 16, 24, 32, 48, 64, 96, 128 \times 10^{19}$ 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.

7. Discussion

Galaxies in the Eridanus group are H\textsc{i} deficient up to a factor of 2 - 3 compared to their field counterparts. The direct correlation of the H\textsc{i} deficiency with the local galaxy density, and the inverse correlation of the H\textsc{i} deficiency with the line-of-sight radial velocities of galaxies suggest that the deficiency is due to tidal interactions. Since the H\textsc{i} deficiency of the Eridanus galaxies is observed in all types of galaxies, the correlation of the H\textsc{i} deficiency with the local galaxy density can not 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 H\textsc{i} 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 \( \sim 1 \text{ Mpc} \) (typical extents of the sub-groups) in \( \sim 5 \text{ Gyr} \) (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 \( \text{H} \alpha \) 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 smaller velocity difference to make the tidal encounters effective.

The observed \( \text{H} \alpha \) deficiency in a loose group like Eridanus has some interesting implications for the evolution of galaxies. Galaxies in clusters are known to be \( \text{H} \alpha \) 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 \( \text{H} \alpha \) 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 \( \text{H} \alpha \) deficient. This implication is particularly important for simulations which try to match the observed \( \text{H} \alpha \) 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 S0’s in high galaxy density regions is not understood. Whether S0’s are due to some evolutionary processes driven by the environment (“\textit{Nurture}”) or due to the result of natural processes of galaxy formation (“\textit{Nature}”) is being debated. Several co-workers (Poggianti et al. 1999, Dressler et al. 1997, Fasano et al. 2000) found in observations of clusters at intermediate redshifts \( (z \sim 0.1 - 0.3) \) that the fraction of S0’s tends to grow at the expense of the spiral population as the redshift decreases. These observations support the “\textit{Nurture}” scenario. Several mechanisms have been proposed for the transformation of spirals into S0’s, e.g., ram-pressure stripping, galaxy harassment, strangulation. The present observations in the Eridanus group indicate that both the severely \( \text{H} \alpha \) deficient galaxies and the S0’s are found in the higher galaxy density regions in the Eridanus group. It may be an indication that both the \( \text{H} \alpha \) deficient and the S0 galaxies originated through similar processes. Since the ram-pressure is not playing any major role in the Eridanus group, the S0’s in Eridanus are produced by some other process. Tidal interactions appear to be a favorable mechanism for transformation of spirals into S0’s in the wake of the current understanding of the Eridanus group from this study.

The \( \text{H} \alpha \) deficiency observed in the Eridanus galaxies is consistent with
the HI 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 \( \sim 0.3 \). 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 S0’s and the HI contents of spirals are similar to the field spirals. However, the Eridanus group which has relatively large velocity dispersion, relatively large fraction of S0’s, shows significant HI 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 favorable for driving the galaxy evolution.

8. Conclusions

- The galaxies in the Eridanus group are HI deficient up to a factor of 2 – 3. The HI deficiency is inversely correlated with the line-of-sight radial velocity, and directly correlated with the local projected galaxy density.

- The HI 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 HI deficiency in cluster galaxies might have been produced in the group environment.

- The co-existence of S0’s and HI deficient galaxies in the Eridanus group suggests that tidal interactions may be an effective mechanism for transforming spirals to S0’s.

- The environment in the Eridanus group is intermediate between the field and a cluster. Nevertheless, conditions are favorable for driving galaxy evolution in the Eridanus group.
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### Table: The H I detected galaxies

| Column 1 – Galaxy name | Column 2 – Hubble Type | Column 3 – UGC optical diameter | Column 4 – Systemic velocity | Column 5 – Projected galaxy density | Column 5 – H I mass | Column 5 – H I deficiency |
|------------------------|------------------------|-------------------------------|-----------------------------|-----------------------------------|--------------------|-------------------------|
### Table 2. The H\textsubscript{i} detected galaxies

| Galaxy          | H.T. | D\textsubscript{UGC} | Velocity | Proj. density | log(M\textsubscript{H\textsubscript{i}}/M\textsubscript{⊙}) | 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           | 9.62                                            | -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    | 22.7                  | 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       |
| 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       |
| Galaxy          | H.T. | $D_{UGC}$ | Velocity | Proj. density | log($M_{\text{H}I}/M_{\odot}$) | Deficiency |
|-----------------|------|-----------|----------|---------------|---------------------------------|------------|
| 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  | 7    | 6.7       | 1510     | 14.0          | 8.47                            | 0.14       |
| ESO 549- G 035  | 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       |