A GMRT synthesis survey of radio continuum and atomic Hydrogen in the Eridanus group of galaxies

by

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Certificate

This is to certify that the thesis entitled "A GMRT synthesis survey of radio continuum and atomic Hydrogen in the Eridanus group of galaxies" submitted by Amitesh Omar for the award of the degree of Doctor of Philosophy of Jawaharlal Nehru University, New Delhi is his original work. This has not been published or submitted to any other University for any other Degree or Diploma.

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Declaration

I hereby declare that the work reported in this thesis is entirely original. This thesis is composed independently by me at Raman Research Institute, Bangalore under the supervision of Dr. K.S. Dwarakanath. I further declare that the subject matter presented in the thesis has not previously formed the basis for the award of any degree, diploma, membership, associateship, fellowship, or any other similar title of any University or Institution.

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Dedicated to my parents

Propositions

- *Galaxies in the group environment can be* H I *deficient compared to their counterparts in the field.*
- *The* H I *deficiency in the Eridanus group is due to tidal interactions.*
- *Not all of the gas deficiency observed in the rich clusters originates in the cluster environment if clusters form via mergers of groups.*
- *Extra-planar* H I *gas is quite common in galaxies. Almost all edge-on galaxies in the Eridanus group have* H I *in their halos in the form of wisps.*
- *Galaxies often have mild kinematical lopsidedness.*
- *The disk central surface brightnesses of galaxies follow a linear relation with the logarithm of the disk scale length.*
- *The distribution of the K-band disk central surface brightness is bi-modal where HSBs and LSBs are separated by* ~ 2 *magnitude at a given scale-length.*
- *Loose groups of galaxies show large scatter in the Tully-Fisher relation.*
- *The Eridanus galaxies follow the well-known radio-FIR correlation.*
- *Eridanus galaxies having more than 5 times excess radio continuum emission than that expected from the radio-FIR correlation are identified as radio AGNs.*
- *Dynamically young groups lack in powerful radio galaxies which are more commonly observed in galaxy clusters.*
- *Some far-infrared luminous galaxies in the Eridanus group are synchrotron deficient. It is believed that such galaxies are undergoing a recent (*~ 1 *Myr) star-burst.*

Synopsis

This thesis describes the results of H I 21cm-line and radio continuum studies of the Eridanus group of galaxies using ~ 200 hour of observations with the Giant Meterwave Radio Telescope (GMRT).

Galaxies are not distributed homogeneously in the local Universe. The regions of highest galaxy densities are known as super-clusters and clusters. However, the majority of galaxies in the local Universe are found in less dense regions called groups. In the hierarchical Universe, clusters with a few hundred to a few thousand of galaxies are formed via mergers of groups. Clusters differ from groups in several aspects. One of the differences between groups and clusters is their morphological mix. Clusters population is mostly the "featureless" ellipticals (Es) and lenticulars (S0's) while groups are generally populated with the "spectacular" spiral galaxies. Spirals are rich in gas, and are forming stars at the current epoch, but, ellipticals and S0's are left with a little gas, and are evolving passively. Studies in early 80's indicated that the fraction of early type (E+S0) galaxies increases with increasing galaxy density spanning five orders of magnitudes. The origin of the enhanced population of E+S0's in high galaxy density regions has been the subject of much debate. There are two hypotheses for the formation of S0's, one is "Nature" where it is believed that early types were formed as such, and other is "Nurture" according to which S0's are transformed spirals which have lost their gas via some mechanism(s). As a result of the gas depletion, spirals no longer form the new stars and their spiral arms slowly fade. Recent observations indicate that the clusters at their earlier epochs of evolution tend to have a higher fraction of S0's at the expense of spirals. These observations support the "Nurture" hypothesis. Several of the spirals in clusters are also found to be H I deficient as compared to those in the field of similar types. It indicates that gas is being lost from galaxies in the cluster environment. Several gas-removal mechanisms, e.g., ram-pressure stripping, thermal conduction and viscous stripping collectively referred as the transport processes, harassment (repetitive fast tidal encounters), strangulation (stripping of the gas from galaxy halos) etc. have been proposed to explain the H I deficiency in cluster spirals. Ram-pressure and transport processes are most effective in the hot (10^8 K) and dense ($10^{-2} - 10^{-3}$ cm^{-3}) cluster environment, and are able to explain some but not all of the observed H I deficiency in cluster spirals. It is realized that there could be other processes causing H I deficiency, but, the details are unclear.

The galaxy groups have a *not so* hot and *not so* dense environment for ram-pressure stripping and the transport processes to be effective. The velocity dispersions of galaxies in groups are also a factor of 3–4 lower than that in clusters, making ram-pressure further ineffective by at least an order of magnitude. Then, a group like Eridanus which has ~ 50 ellipticals and S0's as compared to a total of ~ 180 galaxies over an extent of ~ 10 Mpc raises questions on the origin of the ellipticals and the S0's in the group. The Eridanus group has significant sub-clustering in the inner ~ 4 Mpc region. The Eridanus group is in earlier stage of the cluster formation where the small groups are merging together, and more galaxies from the outer regions are being accreted. Our observations of H I in the Eridanus group revealed that the spiral galaxies in the high galaxy density regions are H I deficient by a factor of $2-3$. The H 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. This was a *hitherto* unknown result in large groups like Eridanus. It is also noticed that galaxies with larger optical diameters are predominantly in the lower galaxy density regions. It is suggested that the H I deficiency in Eridanus is due to tidal interactions. The detailed H I morphologies of the gas deficient galaxies showed tidal features. Although qualitatively all the results can be understood by tidal interactions, quantitatively it still remains to be shown that galaxies can lose large amount of H I over their life-times via tidal interactions. The immediate conclusion is that in the hierarchical Universe, a good fraction of the H I deficiency in cluster galaxies could have originated in the group environment.

The near-infrared properties of the disk galaxies in the Eridanus group suggest that the inclination corrected disk central surface brightnesses of galaxies have a scaling relationship with the disk scale lengths. The results hint that the high surface brightness galaxies (HSBs) and the low surface brightness galaxies (LSBs) occupy two distinct regions in their central surface brightnesses with a difference of ~ 2 mag at any given disk scale length. This result, if correct, can be an important input for theories of galaxy formation.

In this thesis, studies are also carried out on the Tully-Fisher (TF) relations in the Eridanus galaxies. The slopes of the TF relations (absolute magnitude vs log2$\times$ rot-vel.) are -7.1 ± 0.9 in the B-band, -10.0 ± 1.1 in the R-band, -10.1 ± 1.5 in the I-band, -11.8 ± 1.5 in the J-band, -11.3 ± 1.8 in the H-band, and -10.9 ± 1.5 in the K-band for a galaxy sample with flat H I rotation curves. These estimates of slopes are in general consistent with other similar studies of field galaxies, and galaxies in the group. The TF relations in the Eridanus galaxies are found to have larger scatter ($\sigma \sim 0.5 - 0.8$) compared to that in other groups and clusters ($\sigma \sim 0.3$). The *large* TF scatter in the Eridanus group is seen both in the optical and in the near-infrared. This large scatter *perhaps* indicates that galaxies in the Eridanus group are not at similar distances. This result is not very surprising as the Eridanus group is loose and has an irregular appearance. The baryonic TF relations (baryonic mass vs log2$\times$ rot-vel.) are constructed using the stellar and gas mass in galaxies. The baryonic TF relations have *more or less* identical slopes in all the wave-bands The mean slope of the baryonic TF relation is 4.2 ± 0.7.

The radio -far infrared (FIR) correlation is also constructed for the Eridanus galaxies. The galaxies in the Eridanus group *in general* follow the well-known radio-FIR correlation. Two galaxies, *viz.*, NGC 1407 (E), the brightest galaxy in the group, and NGC 1371 (S0/a) have *significant* radio-excess compared to that expected from the radio-FIR correlation. NGC 1371 has 5 times radio-excess, and NGC 1407 has more than 70 times radio-excess. The GMRT 1.4 GHz radio continuum morphologies of these two galaxies revealed *for the first time* a low radio luminosity (log $L_{1.4GHz} \sim 21 - 22$ W Hz^{-1}) active galactic nucleus (AGN) with *kpc-scale* radio structures in both the galaxies. Two galaxies, *viz.*, NGC 1377 (S0) and IC 1953 (SBc) are radio-deficient by factors of 40 and 4 respectively. It is believed that these galaxies are observed within a few Myr of the onset of an intense star formation episode after being quiescent for at least 100 Myr. The Eridanus group lacks in the *powerful* radio galaxies (log $L_{1.4GHz} > 23$ W Hz^{-1}), more commonly seen in the clusters. Majority (70%) of galaxies have their star formation rates below that of the Milky-way.

At the end of the thesis, three *published* research papers are presented. These three publications, based on the radio observations from the GMRT and the VLA, have no *direct* relevance to the main theme of the thesis. The first one is on the electron temperatures of some Galactic H II regions. It presents *high* resolution multi-frequency GMRT radio continuum images of three H II regions. The other two papers discuss H I and 18cm-OH lines from the two AGNs, *viz.*, NGC 1052 and Mrk 1.

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When looking over my five and half years at the Raman Research Institute, it strikes me that so little of it was planned which is being presented in this bound volume. I surely made plans, some of them materialized, some failed and others could never take off. Many events happened, some predictable, some wanted, and some shocking. Several turns were taken, some well thought and some just happened. But, it all continued amid new ideas, new challenges, new perspectives often with the timely advices of my seniors and help from friends who are instrumental in bringing up this work. While being and working with several people, we slowly recognize and start appreciating each individual event and person. In the following lines, I try to relate those events and remember several persons who made this thesis possible.

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List of Notations, Units, and Constants

Notations and Definitions

Apparent magnitude	$m = -2.5\log(\text{intensity})$
Absolute magnitude	$M = m - 5\log(\text{distance in pc}) + 5$
Stellar mass to light ratio	M^*/L
Total mass to light ratio	M/L
Intra group medium	IGM
Noise (root mean square)	σ
Wavelength	λ
Redshift	$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$
Velocity of light	c
Radial velocity	$v_{opt} = cz$;(Optical)
Spatial frequency	(u, v)

Units and Constants

Solar mass	$1\ M_\odot = 1.989 \times 10^{33}$ g
Solar luminosity	$1\ L_\odot = 3.827 \times 10^{33}$ erg s^{-1}
Year	3.156×10^7 s
Myr, Gyr	10^6,10^9 year
Parsec	1 pc = 3.086×10^{18} cm
kpc, Mpc	10^3,10^6 pc
Jansky	1 Jy = 10^{-26} W m^{-2} Hz^{-1}
mJy	1 mJy = 10^{-3} Jy
Electron Volt	1 eV = 1.602×10^{-12} erg
Mega Hertz	1 MHz = 10^6 s^{-1}
Micron	1 μm = 10^{-4} cm
Velocity of light	2.997925×10^{10} cm s^{-1}
mass of Hydrogen atom	$m_H = 1.6735 \times 10^{-24}$ g