# Chapter 1

# Introduction

## 1.1 Evolution of galaxies – dependence on environment

Galaxies can form either in isolation or in groups or clusters. A galaxy with the nearest neighbour $\sim$ 1 Mpc away is considered an isolated galaxy. Multiple galaxies ($\sim$ few tens) in a region of diameter 1 Mpc, with a velocity dispersion of $\sim$ 200 km s$^{-1}$ are called groups of galaxies. Galaxy clusters are even denser systems with $\sim$ few hundreds of galaxies in a region of similar or larger diameter and a velocity dispersion $\sim$ 1000 km s$^{-1}$. The medium that fills the space between the galaxies in groups or clusters is called the intra-group or the intra-cluster medium respectively. X-ray observations of clusters have revealed that this medium is made up of a hot, tenuous $\sim 10^7$ to $10^8$ K gas, which emits in mostly thermal bremsstrahlung and also in atomic lines. This medium is known to have a marked influence on the galaxy evolution in clusters.

There exists about three decades of study of the effect of cluster environment on the evolution and properties of galaxies. The possibility that cluster environment will affect the gas content of galaxies, was considered in the early fifties by Spitzer & Bade (1951) [135] and a decade later by Osterbrock (1960) [105]. But it was not until the mid sixties, that an observational evidence was found to suggest that cluster galaxies can be different from field galaxies in certain respects. Robinson (1965) [119], made a survey of 18 galaxies in the Virgo cluster, and found them to be H I deficient, compared to field galaxies. H I deficiency is a term used to denote the relative H I content of a cluster or a group galaxy compared to the average value found in a field galaxy of similar size and morphological type. This term will be discussed in detail in CHAPTER TWO. The result was confirmed by Davies & Lewis (1973), with fresh observation of 25 galaxies in the Virgo cluster. They made detailed comparison of the gas content of the sample galaxies, with respect to the field galaxies, in terms of distance independent parameters ( H I surface density: $\Sigma_{Hi}$). The parameters were compared within each morphological types for the sample galaxies and field galaxies. The authors came to the conclusion, that the galaxies are indeed deficient in H I , and cited galactic collisions or the effect of the intergalactic gas as the reason for this deficiency [38].

Though galactic collisions or tidal interactions (gravitational interaction between galaxies) can strip off substantial amount of gas from galaxies, in cluster environment this process was not considered the main gas removal mechanism, mainly because of the large relative velocities and small interaction timescales of the galaxies. Depending upon the local environment, studies showed, there could be several processes, responsible for removing gas from cluster galaxies. Observationally the most favourable process till now, ram pressure stripping, was proposed by Gunn & Gott (1972). When a galaxy moves through the hot intra-cluster medium (ICM) with a velocity $\sim$ 1000 km s$^{-1}$, the ram pressure due to the (ICM) can very effectively remove gas from the galaxies [58]. Ram pressure stripping [58] is effective for a galaxy when the H I surface density is less than $\rho_0 \mathrm{v}^2/(2\pi G\sigma_*)$, where $\sigma_*$ is the stellar surface mass density, $\rho_0$ is the ICM density and v is the velocity with which the galaxy is moving through the medium.

Gas in cluster galaxies can be lost in other ways too. Evaporation via thermal conduction [34], or viscous forces and turbulence created when the galaxy moves through the hot ICM [100] can strip off gas from galaxies. Recent studies show, a form of galaxy interaction, called galaxy harassment, can also remove gas from the galaxies. At speeds of about 1000 km s$^{-1}$, close and repeated encounters with bright large galaxies, can cause impulsive gravitational shocks that can severely damage the gas disks of late type spirals. Because of large number density in clusters, these interactions are frequent, and can lead to substantial gas loss [94].

Several observation and simulation studies have detected the effects of ram pressure in many of the H I deficienct clusters. Giovanelli & Haynes (1985) observed H I in nine clusters and found marked H I deficiency in five of them. The H I deficiency was seen to correlate well with the projected radial distance from the cluster centre and the deficiency fraction with the observed X-ray luminosity of the cluster. Their conclusions suggested the effect of either ram pressure or evaporative processes to be responsible for this gas loss, ram pressure being marginally favoured [53]. For a better understanding of the gas removal process, high resolution H I images were necessary at this point of time. The first exploratory observation of this kind was a Very Large Array (VLA) survey of ten spirals towards the centre of the Virgo cluster [154]. The results showed that the size of the H I disks were strongly dependent on the projected distance from the centre of the Virgo cluster. Galaxies towards the centre were seen to have H I disks smaller in size than the optical diameter of the galaxy, whereas galaxies at larger distances from M87, had H I disks similar in size to those of spirals in the field. A more extended survey of the Virgo cluster also showed the shrunk H I disks in deficienct galaxies which could be explained by ram pressure stripping or thermal conduction and viscous stripping processes [23]. Fig 1. represents the morphology of H I in a ram pressure stripped galaxy, in cluster cores. Several similar, observational and/or simulation studies followed, trying to figure out the most favoured gas removal mechanism operational in clusters [22], [1], [156], [132], and all concluded ram pressure to be the dominant gas removal process in clusters.

However, not all observations of cluster galaxies match the predictions. For example, ram pressure stripping was expected to correlate well with the relative radial velocities of the galaxies, and also smaller, low surface brightness galaxies were expected to be more affected by ram pressure than the larger ones as they have lower stellar surface density to hold back the gas to their disks. But observations revealed that this was not always true. H I deficiencies of dwarfs and less massive spirals were found to be not too different from massive spirals

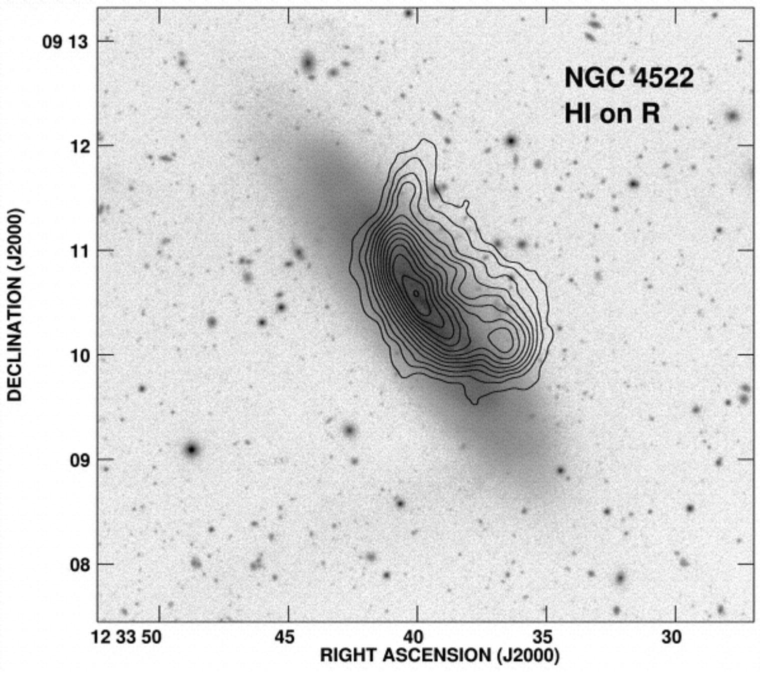

Figure 1.1: VLA observation of NGC 4522, a ram pressure stripped galaxy in the Virgo Cluster, taken from Kenney et al, 2004, AJ, 127, 3361

[65]. Infact in Virgo and some other rich clusters, galaxies with medium to large sizes had been found to be more deficienct than small sized galaxies [151]. These observations were contradictory to what was expected if ram pressure was the dominant process for removing gas from galaxies, but were consistent with the effects of tidal interactions amongst galaxies. Tidal interactions however, can effectively work in low velocity dispersion environment, i.e in groups, and that implied these galaxies could be already deficient before they fell into the cluster potential. This suggested that there were no single accepted mechanism that could lead to gas deficiency in these galaxies and also was an observational evidence to the idea of *sub-clustering*– evolution of galaxies in groups, and merger of groups to form larger clusters– an idea which was relatively observationally unexplored.

While a wealth of studies is available on evolution of cluster galaxies, not many studies exist on the properties of groups in galaxies. Once a cluster is formed it is impossible to discern the pre-merger evolution of galaxies with the ongoing evolution in the cluster. Observations by Geller & Beers (1982) [50], suggested subclustering to be a common phenomenon. While studying galaxy evolution in clusters, this is an important issue, as the cluster environment in many cases may not be responsible in the evolution of the observed galaxy. Relatively recent X-ray observations of the intragroup medium (IGM) of several groups indicate the metallicity to vary from 0.1 to 0.6 solar metalicity [95]. Another study finds the average metallicity of the IGM of a set of groups to be 0.3 [18]. Since stars can be the only source of these heavy elements, it is obvious that part of this gas is contributed by the group members, indicating that clusters are not the only environment where gas is lost from the galaxies. Redshift surveys indicate that most galaxies occur in small groups [66],[67]. Groups can merge to form subclusters and subsequent merger of these subclusters can form clusters. In groups, galaxies have low velocity dispersion and can interact tidally, which can affect their gas content, morphology and star formation rate. In view of this hierarchy, it becomes very important to study possible ways of galaxy evolution in groups.

Till date there have been only a few observational studies about galaxy evolution in groups, especially those related to the gas removal processes. Most of these are on the compact groups. Williams & Rood (1987) studied 51 Hickson Compact groups (HCG) and concluded them to be H I deficienct [160]. Subsequent studies by Huchtmeier (1997) [69] and verdes Montenegro et al (2001) [155] confirmed H I deficiency in HCGs. An important result that came out of this study by Verdes Montenegro et al (2001), was the relation of H I deficiency of a group and the presence of a hot intra-group medium (IGM). The H I deficiency levels found in the HCGs were similar to the ones found in the central galaxies of Coma and Virgo clusters. In these clusters the deficiencies were related to the existence of a hot intragroup medium. Among the 44 HCGs observed in X-ray, in search for a hot IGM, the detection rate was higher for the HI deficient groups, and it was confirmed that this detection was not due to closer distances or longer exposure times. This information was an important clue in understanding the gas removal processes working in this environment. In clusters H I deficiencies had been already seen to correlate well with the X-ray emission from the ICM. Fig 2 [53], illustrates the relationship between the deficient fraction ($f$) and the cluster X-ray luminosity in the 0.5 to 3.0 keV band. This correlation suggested that the ICM had a

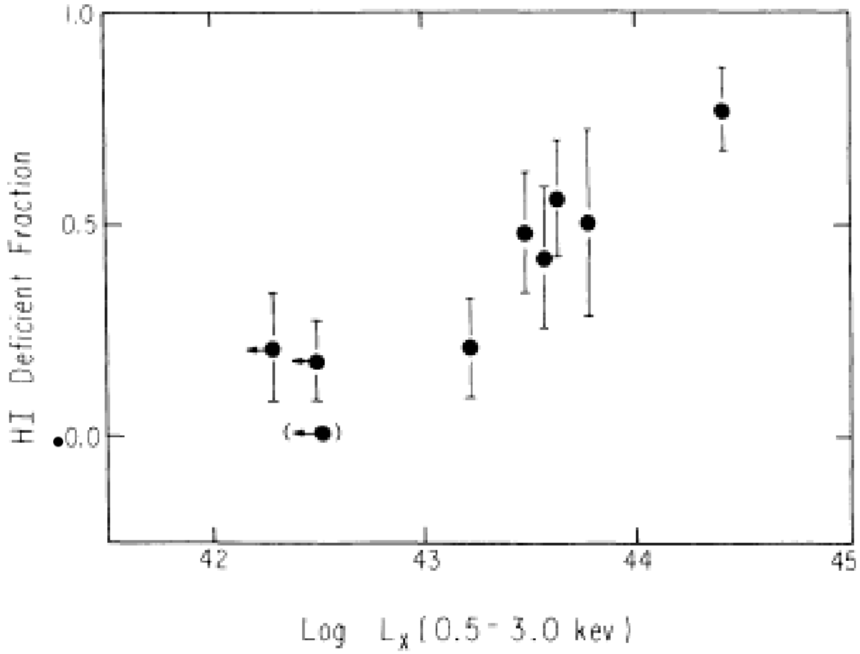

Figure 1.2: Relationship between the deficient fraction f [53] and the cluster X-ray luminosity, taken from Giovanelli & Haynes, 1985, ApJ, 292, 404

role to play in the gas content of the galaxies. Clusters that were denser, could expect a higher rate of grazing encounters of galaxies. Also higher the velocity dispersion and ICM density, more effective the ram pressure will be. Since it was well known by that time, that velocity dispersion increases with increasing X-ray luminosity [111], so the correlation between the deficiency factor and the X-ray luminosity was understood as a secondary step in the causal chain [53].

In non-compact, loose groups however, because of low dispersion (~ 200 km $s^{-1}$) and low IGM density, processes like ram pressure or thermal conduction were ruled out as the predominant gas removal mechanism. In this environment tidal interaction was seen as the most favourable mechanism to cause gas depletion from galaxies. The first case of H I deficiency by a factor more than 1.6, was reported in some members of a non-compact group in the Puppis region [29]. Omar & Dwarakanath (2005) carried out a detailed radio study of Eridanus, an extended large group with significant sub-structures, which revealed a lot of information about the evolution of galaxies in low density environment [102]. About 31 galaxies from the

Eridanus group were imaged in H I using the Giant Metrewave Radio Telescope (GMRT). It was found on an average the galaxies were H I deficient up to a factor of 2-3, compared to their counterparts in the isolated environment. The deficiency was found in all morphological types. Because of the low density and low dispersion of the group, tidal interaction was suspected to be the main process at work. H I tidal tails and debris found in the group, supported the idea observationally.

The discovery that many groups are X-ray sources provided considerable new insight into these important systems. X-ray observations indicated that about half of all poor groups were X-ray luminous. In many cases, the X-ray emission was extended, often beyond the optical extent of the group. The spatial and spectral properties of the X-ray emission suggested the entire volume of groups is filled with hot, low-density gas, emitted by a combination of thermal bremsstrahlung and line emission from highly ionized trace elements. This gas component was referred to as the intragroup medium (IGM), in analogy to the diffuse X-ray emitting intra-cluster medium found in rich clusters [95]. The idea that poor groups might contain diffuse hot gas dates back to the early sixties, to the work on the ”timing mass” of the Local Group [76]. Though the earliest claims for X-ray detections of groups came from the non-imaging X-ray telescopes Uhuru, Ariel 5, and HEAO 1 (1970s), X-ray emission from groups were for the first time detected by the Einstein observatory results, when Biermann et al found extended emission in two nearby elliptical-dominated groups ([11], [10]). Because of the limitation in spatial resolution, it was not possible to unambiguously separate a diffuse component from galaxy emission with Einstein, but there were strong indications that intragroup gas was present in some groups.

It was not until the 1990s that the presence of diffuse gas in groups was firmly established. The ROSAT Position Sensitive Proportional Counter (PSPC) survey revealed the existence of a hot IGM in several groups [96], [108]. Over 100 nearby groups were observed by the ROSAT PSPC during its lifetime, subsequent data analysis indicated $\sim 60$ groups had diffuse X-ray emitting hot IGM [97].

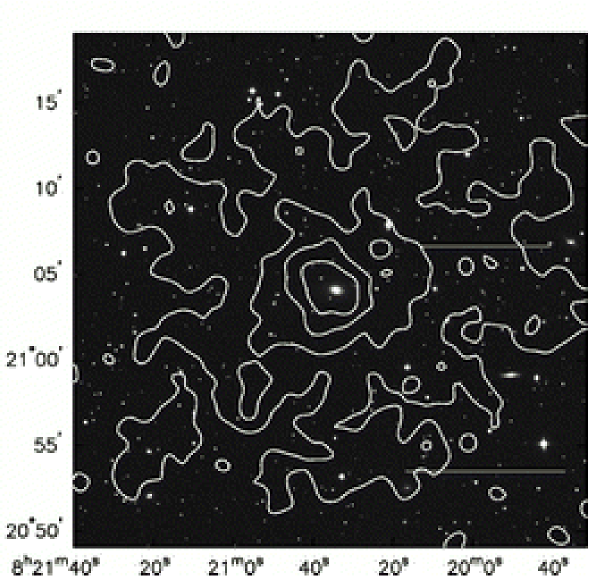

Figure 1.3: Contour map of the diffuse X-ray emission as traced by the ROSAT PSPC in NGC 2563 group overlayed on the STScI Digitized Sky Survey, taken from Mulchaey, 2000, ARA&A,38,289

To first order, these groups were viewed as scaled-down versions of rich clusters. Many of the fundamental properties of groups, such as X-ray luminosity and temperature, were similar to what one expects if a ”cluster” had a velocity dispersion of several hundred kilometers per second. The differences were in the velocity dispersion, which were order of magnitude less in groups than clusters. This obviously would affect the processes responsible for galaxy evolution in group environment.

Thus it became interesting at this point to study the evolution of gas in such conditions. These groups, with hot IGM, could be visualized as an intermediate environment between clusters and normal groups, without a hot IGM. While these environments can allow galaxy-galaxy mergers and interactions, because of their comparatively lower dispersion, the X-ray emitting hot medium could as well assist gas stripping from the galaxies, which is not normally expected to happen in groups without this hot medium. However, though unexpected, ram pressure stripping was not unheard of in group environment. There were a few cases where ram pressure was seen to remove gas from galaxies in groups. GMRT observations of Holmberg 124 (Ho 124) indicated that the galaxy NGC 2820 was affected by ram pressure

[78]. In another case, NGC 2276, in the X-ray bright group NGC 2300, showed signs of ram pressure stripping [113]. Therefore, it was important to understand statistically, if at all this X-ray gas, can affect the gas content of galaxies, like it does in clusters. With this quest, we started a quantitative comparative analysis, of the H I content of galaxies in X-ray bright groups and in non X-ray bright groups. The motivation was to study and quantify the effect of the hot IGM on the H I contents of galaxies in groups and to understand the gas removal processes active in such environment. The first three chapters of this thesis would address the following questions,

- Do H I contents of groups with hot IGM differ from those in groups without the hot IGM?
- Is there any correlation of the H I deficiency with the X-ray luminosity of the IGM?
- Is there any signature of IGM assisted stripping on the galaxies?
- Can we estimate the possible gas loss due to IGM assisted ram pressure stripping?

## 1.2 Relation of cold gas and hot gas in spiral galaxies

Having studied the effect of the hot gas of the IGM on the H I content of the galaxies, we would explore the relation of the hot gas and H I within a galaxy. The presence of a hot diffuse X-ray gas in galaxies has been predicted for decades. Yet, the limitation in the spatial resolution and the sensitivity of early X-ray telescopes, forbade a proper study of this hot gas, till the advent of *Einstein Observatory*. Elliptical galaxies were thought to be purely stellar systems, till Einstein Observatory saw significant amount of X-ray emission from them [44]. Because of the rather poor spatial and spectral resolution of the Einstein Imaging Proportional Counter (IPC), detailed study of X-ray morphology and spectral characteristic were only possible for very nearby galaxies. Many systems observed by Einstein suggested that normal spiral galaxies do indeed emit X-rays [43] and that the emission is dominated by the integrated output of supernova remnants and close accreting binaries.

With the advent of ROSAT, equipped with a relatively softer band that facilitates the study of the hot diffuse ISM, first firm evidence of this hot gas was seen in normal spiral galaxies. Bregman & Pildis (1994) observation of NGC 891, was the first evidence for diffuse hot gas around a spiral galaxy. The authors reported the gas to be bound to the galaxy, to have a temperature of 3-4 $\times 10^6$ K and a density of $2 \times 10^{-3}$ cm$^{-3}$ and a vertical density scale height of 7 kpc. The gas mass occupied a radial extent of 6-7 kpc and had a luminosity $\sim 4\times 10^{39}$ ergs s$^{-1}$ [15].

After the existence of this hot X-ray emitting ISM was established the next obvious question was: the origin of this gas. Large majority of previous studies carried out on this subject suggest that this gas is supernova powered. The purely mechanical feedback from the SNe and stellar winds (commonly termed SN feedback) in the disk of star forming galaxies, can produce, via blow-out or venting of hot gas from the disk, tenuous exponential atmospheres of density scale height 4-8 kpc. Thus the soft thermal X-ray emission observed in the halos of the starburst galaxies is either from this halo medium, which has been swept up and shock heated by the starburst driven wind, or wind material compressed near the walls of the outflow by reverse shocks within the wind ([137]).

An indirect way to know this is to understand the relation of this gas with the emissions in other wavelengths. Read & Ponman (2001) carried out a statistical study with a sample of 17 ROSAT observed normal galaxies, the first quantitative comparative study of the diffuse X-rays from spiral galaxies. They used optical luminosity $L_B$ and the SFR per unit mass, measured by $L_{FIR}/L_B$ as an estimator of 'mass' and 'activity' respectively, of the sample galaxies. They found large normal galaxies, irrespective of activity, appeared to possess more diffuse emission than smaller galaxies. This was not merely due to scaling by size, as the X-ray luminosity per unit galaxy mass and the diffuse emission fraction both increased with $L_B$. The large galaxies seemed to be able to heat or retain a larger fraction of their gas than do smaller galaxies, or they compress it to higher mean densities. A possible explanation was that hot gas from active star forming regions was able to escape more readily from the shallower potentials of smaller galaxies, systematically lowering their hot gas fraction. However, in the case of starburst galaxies, the fraction of diffuse emission was primarily determined by activity rather than galaxy mass, suggesting that the influence of the galaxy potential, important for the normal galaxies, was no longer as important for starbursts. In case of starbursts, the activity was the only dominant property, and whether the galactic potential is shallow or deeper had little effect [116].

An important aspect of studying diffuse emission is point source removal from the region of interest. The estimates of diffuse X-ray flux from the galaxy are likely to be heavily contaminated by the point source emission. This is the main reason why many of the early estimates of diffuse X-ray emission needed to be revisited, once Chandra was launched. The second detailed statistical study carried out using Chandra data (Strickland et al, 2004) [138] helped to reveal many of the properties of this gas.

Strickland et al (2004) studied a sample of 10 spirals, mostly starburst galaxies. The sample had 7 starbursts and 3 normal galaxies. They found the correlation between the X-ray luminosities and the optical B- and NIR K-band luminosities to be weaker than the correlation between the soft X-ray luminosity and the total galactic FIR and 1.4 GHz radio luminosities. This suggested the influence of SFR on the X-ray emission to be stronger than mass of the galaxy. Estimates of the stellar mass of the galaxy were made using the Two Micron All Sky Survey (2MASS) K-band Tully-Fisher relationship derived by Bell & de Jong (2001) [9], and parameters were scaled by the mass, to remove bias due to size dependence of any kind. Plots showed a strong correlation between diffuse X-ray luminosity per unit mass and SF rate per unit mass of the galaxies. Their findings also included correlations between the halo X-ray luminosity and total SF rate, as well as the vertical extent of the X-ray emitting gas to the total size of the host galaxy. These results led to a study of correlations between the diffuse X-ray surface brightness and estimates of the SF rate per unit area in the host galaxy.

A strong correlation was noted between X-ray surface brightness and FIR luminosity scaled by ${D_{25}}^2$, whereas no correlation was found between the X-ray surface brightness and the circular velocity of the galaxy which is used as a measure of the mass of the galaxy. All their results point to the fact that X-ray gas in spirals, especially the hot gas in halos were connected to the star formation in the galaxy. However the sample size of this study was only 10 with 7 starbursts and 3 non-starburts, making it difficult to conclude anything about galaxies that are not starbursts.

The next issue of interest was understanding the role of cold gas, more precisely H I , in this environment. The most widely applied star formation law remains the simple gas-density power law introduced by Schmidt (1959) [122], which for external galaxies is usually expressed in terms of the observable surface densities of gas and star formation.

$$\sigma_{SFR} = A{\sigma_{gas}}^N \tag{1.1}$$

Several previous observational studies have explored the relation between SFR and cold gas in the galaxies. Mirabel & Sanders (1988) conducted an Arecibo survey of the atomic hydrogen in the H I 21 cm line and radio continuum in the most luminous IRAS galaxies of the local universe. Their sample consisted of 92 galaxies, of which 88 were H I detected, and the H I masses varied between two orders of magnitude. A loose correlation of H I mass and FIR luminosity was found, implying SFR to be not a simple function of the H I mass [92]. Kennicutt (1998), examined the H I Schmidt law, with a sample of 88 galaxies. One of his observations was, the effect of the differences in the star formation in starbursts and in normal galaxies and its correlation with the cold gas content. In normal disk galaxies, the relationship between the FIR luminosity and the SFR is complex because stars with a variety of ages can contribute to the dust heating, and only a fraction of the bolometric luminosity of the young stellar population is absorbed by dust. In starbursts, young stars dominate the radiation field that heats the dust, and the dust optical depths are so large that almost all of the bolometric luminosity of the starburst is reradiated in the infrared. Thus in this case,

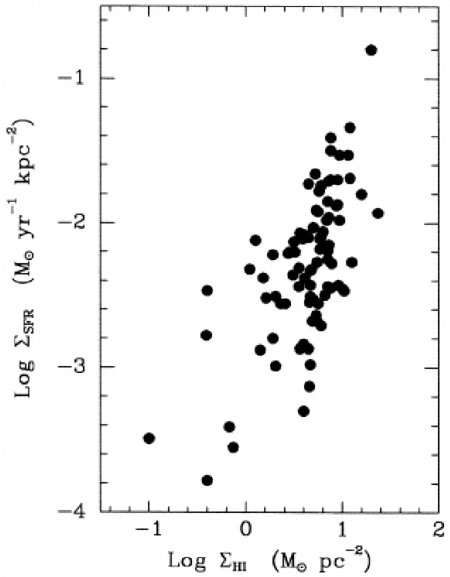

Figure 1.4: Relation of H I and SFR, plot taken from Kennicutt, 1998, ApJ, 498, 541

SFR from the FIR luminosity relation is much more direct than in normal galaxies. Fig 4, from Kennicutt (1998)[79] shows the relationship between the disk-averaged SFR and the total H I density. The corresponding correlation coefficient is 0.66, implying a very low probability that the data are uncorrelated.

Recent studies confirmed the correlation of H I and SFR [41], [86]. The H I mass and SFR have been seen to be related by the following equation,

$$log(HImass) = 0.59log(SFR) + 9.55 \tag{1.2}$$

These relations stated above, in a way acts as a bridge between the H I content of a galaxy and its X-ray luminosity, under the assumption that the X-ray emitting gas has direct correlation with the star formation rate in the galaxy. With a bigger sample than the previous two statistical studies, we revisited the issue of the origin of the X-ray gas in spiral galaxies, its connection with star formation rate and its relation with the H I content of the galaxy. Ours is a comparative study of the diffuse hot gas in spirals. Following reasons highlight the relevance of this work. There were only two previous studies addressing these issues, both with smaller sample size, 17 [116] and 10 [137]. Of this the first study with 17 galaxies was carried out using ROSAT data [116]. The diffuse X-ray estimates are likely to suffer from point source contamination in ROSAT data. Chandra, on the other hand is an ideal instrument for this kind of study. The second statistical study carried out using Chandra data [137], but the sample size was just 10, and biases towards starbursts. So a bigger sample, with the highest spatial resolution available was a necessity to revisit some of the results of these two previous studies. In addition, this work statistically studies for the first time the relation of H I and the hot gas in these galaxies, the effect of environment as well as the effect of the presence of AGNs. This work addresses the following questions

- The effect of mass and star formation on the hot gas: do galaxies with higher SFR have different X-ray properties than galaxies with low SFR?
- Relation of the hot gas with the H I content of the galaxy.
- Do other properties like the presence of AGN or the environment affect the presence of the hot gas.

## 1.3 Layout of the Thesis

- Chapter 1. Introduction : A short write up discussing the motivation and the necessity to carry out this research.
- Chapter 2. H I deficiency in X-ray bright groups - a statistical study : This chapter contains the work done with a sample of 27 groups, to study if the hot X-ray emitting intra-group medium, affects the H I content of the group members.
- Chapter 3. GMRT H I imaging of galaxies in X-ray bright groups: Thirteen galaxies from four X-ray bright groups were imaged in H I using the GMRT, to see if IGM assisted gas stripping has left its signature on them. This chapter presents the details of the observations, the H I images and velocity fields and the results from the analysis.

- Chapter 4. H I in intermediate redshift groups : Analysis of GMRT H I observations of two groups at a redshift of 0.06 are presented in this chapter. This piece of work is part of an ongoing multi-wavelength study of groups of galaxies at intermediate redshift.

- Chapter 5. H I and diffuse X-ray in spiral galaxies : Archived Chandra data for 34 spiral galaxies were analysed to create a uniform sample of X-ray dataset. Existing H I , IRAS and 2MASS K-band data were used to compute the necessary quantities for a comparative statistical study of the properties of the hot gas in spiral galaxies and its relation with the H I content of the galaxy. This chapter presents all the analysed images, the diffuse X-ray spectra and the results from the analysis.

- Summary : A brief summary of the conclusions from this thesis.