There are two mistakes one can make along the road to truth— not going all the way, and not starting.

–Buddha (563-483 BC)

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Introduction

1.1 Nature of Galaxies

Galaxies are the smallest tassels of luminous matter adorning the fabric of space-time which can be observed beyond the neighbourhood of Milky Way. Composed mainly of stars, gas, dust and the so far undetected entity called Dark Matter (DM), they have been a puzzle for the astronomers till the dawn of the 20th century.

Based on galaxies’ appearance in the visible bands, they have been classified into elliptical and spiral galaxies. Categorising the galaxies into these two broad groups was first proposed by Hubble (Hubble, 1936). A typical elliptical galaxy, as the name suggests, has a featureless elliptical shape in projection; while a spiral galaxy distinguishes itself with a nucleus (or bulge) and an associated, dominant, stellar disk on which a spiral pattern is superposed. The other major differences came to light when multi-wavelength and spectral observations of the galaxies began. The first and foremost among them was the systematic rotation seen in the disk of spiral galaxies. The flatness of the rotation curve (Rubin et al., 1980; Bosma, 1981)
indicated the presence of as yet un-identified form of matter termed dark matter surrounding the galaxy (Fig. 1.1).

At this juncture, it should be mentioned that the scenario described above will be tenable only by assuming the universal validity of the law of gravity at all scales. There are alternative theories which subscribe to a modification to the law of gravity (e.g. MOdified Newtonian Dynamics (MOND) (Milgrom, 1983)). As a result, such theories are able to explain many of the physical and kinematic features of galaxies without invoking the elusive dark matter. In this thesis, however, we presuppose the universal validity of the law of gravity and the standard model of particle physics.

Figure 1.1: Representative picture of a spiral galaxy with Dark Matter halo. Quantities a, b, c represent the major, minor and orthogonal axes respectively.

Random motion of stars dominates over any systematic rotational motion in elliptical galaxies. Hence elliptical galaxies are assumed to be pressure supported systems unlike the spirals. Elliptical galaxies also seem to
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be immersed in a sea of dark matter. In all these cases, from numerical simulations, dark matter is shown to have a universal density profile (Navarro et al., 1997).

Composition of stellar population is another major difference between the elliptical and spiral galaxies belonging to the local universe. Major constitution of the elliptical galaxies is the old stellar population (Population II stars). On the contrary, disks of the spiral galaxies are dominated by young stellar population (Population I). Significant amount of gas and dust are also observed in spiral galaxy disks. Interestingly, the bulge of a typical spiral galaxy has many similarities with the elliptical galaxies. Significant old stellar population, dearth of dust and gas, dominant random motion etc. are some of these similarities.

The Hubble classification scheme (Fig. 1.2), later modified to incorporate finer nuances displayed by the galaxies, reveals not only the physical properties but also, to some extent reflect evolution of galaxies (Baugh, Cole, & Frenk, 1996). This is evident from the strong cor-

Figure 1.2: Hubble classification of galaxies. Images obtained from Digitized Sky Survey (DSS).
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relation that exists between the bulge to disk luminosity ratio, relative mass of atomic Hydrogen (HI) with luminosity, mass concentration, stellar population, nuclear properties, chemical abundance of interstellar medium, star formation history etc. seen right across the Hubble sequence (Roberts & Haynes, 1994). It is not clear, however, whether the suggested evolution is triggered by the intrinsic properties of the galaxies or by the extrinsic effects on the galaxies.

1.2 Time and Space Effects on Galaxies

A large fraction of the galaxies in the local universe is seen to be associated with galaxy clusters or groups. Hence the effect of the environment on the galaxies is easier to study. The first indication of such an evolution that depends on environment came from the density-morphology relation of galaxies (Dressler, 1980) seen in galaxy clusters (Fig. 1.3).

Galaxy clusters are the largest gravitationally bound structures seen in the universe. Typically a cluster consists of ~ 100–1000 galaxies which are gravitationally bound in a region of ~ 2 Mpc. In addition to galaxies, this region consists of hot gas of $10^7 - 10^8$ K (Intra-cluster Medium or ICM) having typical number density of ~ $10^{-3}$ cm$^{-3}$. From the velocity dispersion of galaxies in a cluster (~ 1000 km s$^{-1}$), it is seen that large amount of dark matter is also present in the cluster environment.

From the studies carried out on Virgo cluster (Crowl et al., 2006), it appears that the cluster core, i.e. region within one Abell radius (Abell radius = $1.7'/z$, where $z$=redshift of the cluster) of the cluster centre, is dominated by the early type galaxies and S0 type galaxies. In many compact groups of galaxies containing smaller number of galaxies, the group environment is dominated by a giant elliptical galaxy. The observation that cluster envi-
The density-morphology relation. Here the projected density is shown on the abscissa. High density clusters seem to be dominated by ellipticals and S0 galaxies (Dressler et al., 1997).

The environment stimulates galaxy evolution is also given added impetus by the observed morphological Butcher-Oemler effect (Butcher & Oemler, 1978; Tran et al., 2005) and the HI deficiency studies carried out on spiral galaxies by early observers (Solanes et al., 2001). As one moves away to the outer, less dense regions of the cluster the fraction of spiral galaxies appears to increase. The spiral galaxies often are dominated by the young, massive stars which are bluish in colour. Hence, the spiral galaxies in the outer edge of a cluster often appear bluish. This is called the morphological Butcher-Oemler effect (Butcher & Oemler, 1978; Tran et al., 2005). The heart of BO effect is the spiral to early type transformation.

The causes attributed to gas deficiency in cluster spiral galaxies com-
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pared to field galaxies are many (Haynes et al., 1984). Ram-pressure stripping (Gunn & Gott, 1972), tidal interactions, repetitive encounters with other galaxies in the cluster and cluster potential (galaxy harassment) (Moore et al., 1999), and of late, by large amplitude density-wave perturbations (Zhang & Buta, 2007) etc. are some of the effects that can cause the morphological BO effect. For ram-pressure stripping to be an effective mechanism in removing HI from the outer regions of the galaxy, the galaxy has to move through a high density environment (high ICM density) with a high velocity relative to the medium. The inclination of the galaxy with respect to the direction of motion is also another important parameter. If the motion of the galaxy through the ICM is perpendicular to the disk then, significant HI deficiency can be generated. Tidal interactions on the other hand do not depend on the ICM density, but rather on the separation and mass of interacting galaxies. It has been shown by numerical studies that tidal interaction induced HI stripping will become important when the rotational speed of the galaxy is comparable to the relative speed with which another galaxy goes past it. As the ICM density and the velocity dispersion in cluster environment are high, explanations based on ram-pressure stripping appear to have gained currency for cluster galaxies.

In comparison to clusters, galaxy groups are much smaller entities. They typically contain fewer than 100 galaxies spread over 1-2 Mpc. Another major difference between clusters and groups is the velocity dispersion. Typically in a group the velocity dispersion of galaxies is $\sim 200$ km s$^{-1}$. This velocity dispersion is comparable to the typical rotation velocities of spiral galaxies.

In the case of groups, the important ingredients for ram-pressure stripping to be effective, viz. high velocity dispersion and hot inter-group medium
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are seldom seen. The fraction of spiral galaxies in a group environment is also higher compared to the cluster environment. Does it mean that we are looking at a different mechanism for the evolution of galaxies in a group environment? The answer to this question is not yet fully understood. As mentioned earlier, the velocity dispersion of galaxies belonging to groups is \( \sim 200 \text{ km s}^{-1} \), while the density of Intra-Group Medium (IGM) is \( \leq 10^{-4} \text{ cm}^{-3} \) (Sengupta & Balasubramanyam, 2006). The condition for ram-pressure to be an effective mechanism in stripping HI from a galaxy is that

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\rho_{\text{IGM}} V_{\text{gal}}^2 \geq \Sigma_{\text{gas}} V_{\text{rot}}^2 R^{-1}
\]

where \( \rho_{\text{IGM}} \) is the density of Intra-Group Medium, \( V_{\text{gal}} \) is the speed of the galaxy through the IGM, \( \Sigma_{\text{gas}} \) is the surface density of HI and \( V_{\text{rot}} \) is the rotation velocity of the galaxy at a galactic centric radius \( R \). Using the typical values for the velocity dispersion of galaxies in a group, IGM density and rotation velocity of a galaxy (150 km s\(^{-1}\) at \( R=10 \text{ kpc} \)), the maximum ram-pressure a galaxy is subjected to is \( \sim 10 \text{ cm}^{-3} \text{ km}^2 \text{ s}^{-2} \). This ram-pressure is \( \sim 1 - 2 \) order of magnitude lesser than that seen in galaxy clusters where ram-pressure stripping is found to be effective. In addition, the above mentioned IGM density and velocity dispersion can strip HI surface density less than \( 6 \times 10^{19} \text{ cm}^{-2} \) only. Most of the HI mass associated with the galaxies in groups is above this column density. Hence the HI deficiency is often attributed to tidal interactions (Omar & Dwarakanath, 2005b) which becomes the most efficient mechanism for removing HI when the velocity dispersion becomes comparable to the rotational velocities of galaxies.

Galaxy evolution stimulated by the internal effects are harder to study observationally. This is due to the fact that the evolution triggered by the internal effects of the galaxy will show up only after many years. The only way to address this issue is by numerical simulations of the galaxy. These
1.3. LOPSIDEDNESS IN SPIRAL GALAXIES

Simulations, especially in the case of a spiral galaxy, are often limited by the numerical resolution and the procedure adopted by the simulator. The numerical resolution limitation is due to the number of particles (in the case of numerical simulations using particles) used and the spatial resolution used. The typical N-body simulation takes into account only $10^7$ particles which makes each particle weigh about $10^3 M_\odot$. The procedure adopted in the numerical simulation has implications on the bulge formation and artificial angular momentum loss.

Due to the limitations of numerical simulations the question of galaxy evolution namely whether it results from their internal effects (nature) or due to the influence of the external agents (nurture) is not yet fully answered. In this work, we have been mainly concentrating on understanding the effect of environment on the galaxies. This is because the effect of environment is amenable to observations and is quantifiable. As these evidences are easily available in the case of spiral galaxies, we concentrate on them.

The observational evidence of the importance of environment comes mainly from three sources. The first and the most easily observable effect is the HI deficiency. Next is the star formation rate and associated enhancement of heavier elements in the ISM. The third and the most interesting effect is the observation of lopsidedness, which we estimate in this thesis for various group galaxies.

1.3 Lopsidedness in Spiral Galaxies

Lopsidedness or the asymmetry seen in the matter distribution and in the motion as a function of the galacto-centric radius and azimuthal angle in the galactic disk is an important tool in studying the physical appearance and the history of a galaxy. Another way of interpreting lopsidedness is by
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observing the iso-surface density or iso-surface brightness contours in the
disk of a galaxy. These contours are usually circular and are centred at the
nucleus or about the dynamical centre (or the centre about which the matter
moves) of the galaxy. In lopsided galaxies the centres of these contours are
not concentric and tends to drift away from the nucleus or dynamical centre.
Such behaviour is often seen not only in the case of surface density and sur-
face brightness maps of galaxies but also in the iso-velocity contours of galax-
ies. A premier example for such a system is the spiral galaxy M101 or the
Pinwheel galaxy (Fig. 1.4, Fig. 1.5, Fig. 1.6). Although elliptical galaxies also
indicate lopsidedness to a smaller degree (Hernández-Toledo et al., 2006),
we restrict ourselves to studying the asymmetries in spiral galaxies due to
the ease of studying lopsidedness in them.

Figure 1.4: M101 Optical composite image. This is an example of an opti-
    cally lopsided galaxy.
1.3. LOPSIDEDNESS IN SPIRAL GALAXIES

A large fraction of spiral galaxies shows asymmetries. Some of the earlier works indicate that approximately 50 to 75% of spiral galaxies show lopsidedness (Richter & Sancisi, 1994; Haynes et al., 1998; Matthews et al., 1998). These studies mainly used the global HI spectral line observations (Fig. 1.5, Fig. 1.7) or images obtained using near Infra-Red bands (Rix & Zaritsky, 1995). The observation that a large fraction of spiral galaxies shows lopsidedness also indicates that lopsidedness in spiral galaxies is a long lived phenomenon which has persisted for at least a few rotation period of a galaxy and is not a transient phenomenon.

The lopsidedness studies based on global HI profile can give information of the combined effects of velocity and spatial asymmetries. To decouple
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Figure 1.6: Global HI profile of M101. This profile is asymmetric (Richter & Sancisi, 1994)

the asymmetries due to spatial distribution of matter from velocity asymmetries, spectral line observations alone cannot be used. For this purpose, in this work, we have adopted the surface density maps (moment 0 maps) and velocity field maps (moment 1) from the HI 21 cm-line observations.

The first step in assessing the lopsidedness is to evolve a method for quantifying it. In this work, we have used the Fourier series technique to estimate the lopsidedness. This is the first time that such a technique is being used to analyse the HI 21cm-line emission radio maps (surface density maps) of spiral galaxies. The next step in this progression is to compare the lopsidedness seen in HI maps with that detected in the stellar disks of spiral galaxies. As a result of our analysis, it is demonstrated that for those galaxies where HI disk overlaps with the stellar disk, the lopsidedness of HI disk is comparable to that seen in the stellar disk. Although theoretical
arguments exist to show that lopsidedness of gaseous disk is comparable to that of the stellar disk, it is the first time that this has been observationally confirmed. Performing the lopsidedness analysis on HI maps also has an added advantage. In many galaxies, HI extends far beyond the stellar disk. Hence lopsidedness analysis on HI maps makes us capable of studying and understanding the cause of lopsidedness far beyond the stellar disk.

Although lopsidedness is seen in many galaxies, its physical origin is not clearly understood. The cause of disk lopsidedness has been attributed to a variety of physical processes such as the disk response to halo lopsidedness which could arise due to tidal interactions (Jog, 1997) or due to mergers with satellite galaxies (Zaritsky & Rix, 1997) or asymmetric gas accretion.
1.4. GROUPS SELECTED FOR LOPSIDEDNESS ANALYSIS AND FURTHER OBSERVATIONS

(Bournaud et al., 2005). The asymmetry can also be generated due to the stellar disk being offset in a spherical halo (Noordermeer et al., 2001). A study of HI asymmetry in the outer parts as done in this thesis using HI as a tracer can give a direct handle on the halo asymmetry.

Galaxies in groups were selected for lopsidedness analysis due to the following reasons. Galaxy groups generally have larger fraction of gas-rich spirals compared to clusters. This is because the velocity dispersion of galaxies and the Intra-group Medium (IGM) density in groups is low which makes ram-pressure stripping and the gas loss due to the effect of transport processes like the turbulent and viscous stripping inefficient. The above argument is further aided by the observation that IGM, if it exists, also has low X-ray luminosity and low temperature in a group environment. This implies that the dominant physical process to be concerned about is the tidal interaction.

1.4 Groups Selected for Lopsidedness Analysis and Further Observations

Lopsidedness studies on galaxies belonging to two loose groups viz., Eridanus and Ursa Major and six Hickson Compact Groups (HCGs) were carried out.

1.4.1 Eridanus Group of Galaxies

The Eridanus group was identified during the Southern Sky Redshift Survey (SSRS; da Costa et al., 1988). This group of galaxies are at a mean distance of $\sim 23 \pm 2$ Mpc and is a gravitationally bound structure (Pellegrini et al., 1989; Willmer et al., 1989). The velocity dispersion of this group is $\sim 240$ km s$^{-1}$ (Omar & Dwarakanath, 2005a). This velocity
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dispersion is lesser than the typical cluster velocity dispersion of \( \sim 1000 \) km s\(^{-1}\). In the case of hierarchical structure formation scenario, it is believed that galaxy clusters result from the mergers of groups whose gravitational potential well is smaller compared to that of clusters. Hence the low velocity dispersion implies that Eridanus is dynamically a younger system compared to clusters. This group is expected to be in the process of forming a cluster. If we compare the fraction of S0+E type galaxies in the Eridanus group (0.5) (Omar & Dwarakanath, 2005a), it lies in between a compact cluster like Fornax (0.6) (Tully et al. 1996) and a loose group like the Ursa Major (0.1) (Tully et al. 1996). This factor aids the argument that galaxies in the Eridanus group are interacting with their neighbouring galaxies.

Using the GMRT, about fifty of the galaxies belonging to the Eridanus group have been observed in HI 21 cm line emission (Omar & Dwarakanath, 2005a). Out of these, 18 galaxies were selected based on their inclination and regular appearance for lopsidedness study by us. Four galaxies from this group were used to show the correlation between lopsidedness in their respective HI and stellar disks. As a result of the lopsidedness analysis, it is seen that the estimated lopsidedness in this group is about 3 times higher than that observed in the field galaxies. It is also seen that early type spirals show more lopsidedness compared to the late type galaxies. This trend is opposite to what is observed in the case of field galaxies. Based on the argument that ram-pressure stripping is ineffective in this group, the cause for observed lopsidedness is ascribed to tidal interactions.
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1.4.2 Ursa Major Group of Galaxies

Ursa Major group of galaxies which is at a mean distance of \( \sim 15.5 \) Mpc has 79 galaxies associated with it (Tully et al. 1996). This group has a velocity dispersion of \( \sim 150 \text{ km s}^{-1} \). In this group no HI deficiency is seen (Verheijen & Sancisi, 2001). This might be partially due to the fact that the tidal interactions between the galaxies may not be strong enough to cause the deficiency.

The Ursa Major group was imaged in HI 21cm line emission by Verheijen (Verheijen & Sancisi, 2001) using the Westerbork Synthesis Radio Telescope (WSRT). Eleven galaxies belonging to Ursa Major group were studied for lopsidedness. Here also, galaxies show significant lopsidedness; albeit to a lesser degree compared to the galaxies of the Eridanus group. This group is much more loosely bound than Eridanus. Hence tidal interactions are expected to be much weaker. This might explain the observed lopsidedness. Using the velocity maps available for galaxies belonging to the Ursa Major group, the kinematical lopsidedness was also estimated. For galaxies of this group, we have also estimated the ellipticity of dark matter halo potential from the surface density lopsidedness value. It is observed that the ellipticity of dark matter halo obtained from velocity maps is comparable to that derived from surface density maps.

1.4.3 Hickson Compact Group of Galaxies

HCGs are isolated compact groups that contain typically \( \sim 5 \) galaxies. From early x-ray observations of HCGs using ROSAT, it is known that most of the HCGs are gravitationally bound structures. They show a velocity dispersion of \( \sim 150 \text{ km s}^{-1} \). By virtue of the high number densities in HCGs which are comparable to a cluster environment, they provide us with a laboratory
where the effect of high galaxy density on lopsidedness could be studied. The six HCGs, observed using the GMRT, Pune, India, were selected mainly based on the suitability of their galaxies for lopsidedness analysis and the group size. Based on the earlier studies on Eridanus and Ursa Major group of galaxies, the lopsidedness of HCGs were expected to be much higher than what was seen in a typical group or field galaxies. However, due to the constraints imposed by the Fourier series analysis procedure, the lopsidedness could be estimated only for one galaxy. This galaxy shows a higher degree of lopsidedness compared to the group galaxies. The HI deficiency studies and Far Infra-Red (FIR) - Radio correlation studies on these HCG galaxies were also carried out.

1.5 Thesis Structure

This thesis is mainly divided into five chapters, which will deal with various aspects of Kinematical and Spatial Lopsidedness. The layout of this thesis is as follows:

In Chapter 2 we discuss the nature of kinematical lopsidedness seen in galaxies belonging to Eridanus and Ursa Major groups. Kinematical lopsidedness is an important asymmetry seen in many galaxies which can, in principle, give information about the ellipticity of the dark matter halo potential. In recent times, a similar procedure as adopted here in this thesis has been used to estimate flows in the bars of spiral galaxies.

Chapter 3 will be devoted to the details of the spatial lopsidedness analysis carried out on galaxies of the Eridanus and Ursa Major groups. It is for the first time that such an analysis has ever been carried out using atomic hydrogen as the tracer. In this chapter, we will also show how the spatial lopsidedness derived from optical images compare with that of the atomic
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hydrogen distribution. Interestingly, the early type spirals in group environment seems to be showing more lopsidedness compared to late type spiral galaxies. This trend is seen both in the Eridanus as well as Ursa Major group galaxies.

In Chapter 4 we will be mainly describing our observations of Hickson Compact Group of galaxies using the GMRT and the subsequent analysis. Hickson compact group of galaxies are gravitationally bound systems which are tidally interacting. The study of six selected HCG galaxies have given us information about lopsidedness, HI deficiency and FIR and Radio continuum correlations of these galaxies. This work will be discussed in greater details here.

In Chapter 5, we will discuss our main results and plans for future work. The results can be summarised as follows:

- Spatial and kinematical lopsidedness of spiral galaxies in groups have been estimated using HI as a tracer. The lopsidedness analysis which we carried out quantified asymmetry as a function of galacto-centric radius.

- In spiral galaxies belonging to groups, the early type spirals showed higher spatial lopsidedness than the late type galaxies, measured in the same disk scale length range. Opposite trend, however, is seen in the field galaxies.

- We have shown that the spatial and kinematical lopsidedness are comparable to each other.

- Assuming that the spatial and kinematical lopsidedness stem from lopsided dark matter halo potential, we have estimated the ellipticity of the potential.
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In this chapter we also give the preliminary results of the N-body simulations of galaxies which we carried out. In this analysis particles were allowed to evolve in a background dark matter halo potential. In addition we have given some information about the ongoing research and future work planned.