Chapter 2

Galaxies in clusters

Astronomers gather information about the past by observing the distant Universe. The images of the Universe at different redshifts are snap shots of the Universe at corresponding ages. Using these images one can study how the Universe evolves with time both spectroscopically and photometrically. We constrain ourself to the photometric study as it is relevant to the main topic of this thesis. Using broad band images of galaxies at different redshift, we can trace back their morphology as a function of both redshift and environment and draw important conclusions on galaxy formation. Clusters can serve as laboratories for this purpose as they are the largest gravitationally bound systems formed by the result of evolution of the primordial density fluctuations. It is interesting to note the following quote by Bradley C. Whitemore (see Oegerle et al., 1990)

“The fact that these three basic galactic properties (morphology, size and mass distribution) all vary as a function of position within a cluster should provide a fundamental clue about the formation of galaxies. If we are going to answer the three questions posed above in the near future it is likely to be from studies of galaxies within clusters.”

In this chapter we explain the observational results of morphological evolution of galaxies in clusters which form the motivation of this work.

2.1 Morphology at high redshifts

From the Butcher-Oemler (BO) effect (see Section 1.3.1), it was understood that significant evolution is going on in the galaxy population. But to study the evolution of galaxies along with their precise morphology was possible only from Hubble Space Telescope (HST) observations. Using the images obtained using HST/WFPC2
in F814W ($\sim$ I) band and F450W ($\sim$ B) band Schade et al. (1995) analysed the morphology of 32 galaxies at $0.5 < z < 1.2$, where the redshifts were obtained from Canada-France Redshift Survey (CFRS). They confirmed the BO effect and found that the disks of normal spiral galaxies are bluer than the nearby spirals by about 1.2 mag. They also found a clear sign of evolution of the morphology, where $\sim 30\%$ of the galaxies show peculiar morphologies. The Medium Deep Survey (Griffiths et al., 1994b) using HST/WFPC2 found that in the field a large fraction of peculiar galaxies with I < 22 mag exist at $\langle z \rangle = 0.5$ (Griffiths et al., 1994a; Driver et al., 1995a). Driver et al. (1995b) extended this study to I < 24.25 using a single ultra deep WFPC2 image of 5.7 hr exposure. They found that 37% of the population is made up of early type spirals and 47% of the population is dominated by late type spirals and irregular galaxies.

More deep images of the sky was obtained by the Hubble Deep Field (HDF) survey (Williams et al., 1996). Using redshifts measured with ground based telescopes of HDF survey images, many authors estimated the evolving fraction of blue galaxies (e.g. Lowenthal et al., 1997). Several other studies made use of photometric redshifts (e.g. Sawicki et al., 1997) and the automated morphological classification (see e.g. Abraham et al., 1996) for such studies.

### 2.2 Observing the high redshift Universe using Hubble Space Telescope

There are several caveats involved in tracing back the galaxy morphology with redshift. To determine the morphology of the galaxy we need images of high resolution and signal-to-noise ratio. The angular size of the galaxies decreases with look back time which essentially implies that light from galaxies at large distance fall only in a very few pixels of CCD of the telescope. Also, due to cosmological dimming the high redshift galaxies appear fainter than their low redshift counter parts. The situation will be much worsen if we use a ground based telescope where the image is further degraded by atmospheric turbulence even at the best telescope site. The remarkable success of the *Hubble Space Telescope (HST)* is that it is even capable of getting images with resolution 0.03 arcsec/pixel with the help of the image processing technique called *drizzling* and therefore, using HST images it is possible to reliably classify galaxies even at $z \sim 1.5$. HST increases the signal-to-noise ratio of the observed images by very long exposure.

Galaxy morphology is a strong function of wavelength. i.e. the same galaxy
observed at visible and UV light may have completely different morphology. Therefore, it is essential to specify the observed passband along with the morphological classification. Historically the morphology of the galaxy is quantified in Johnsons B-band. At this point we must recall that if we use B-band to observe galaxies at different redshift we see light emitted in different wavelength regions of the galaxy spectral energy distribution. So it is not possible to compare galaxy snap shots at different redshifts, as identical galaxies at different redshifts yield different morphology. This effect is called morphological K-correction (Poggianti, 1997). We can overcome this effect significantly by using different passbands for observations, depending on the redshift of the galaxies, which give corresponding rest frame B-band images of galaxies. Therefore, to compare the B-band morphology of galaxies in the nearby Universe with that of galaxies at $z \sim 0.8$, we can use the reddest filter on board HST, i.e. F814W, to observe high redshift galaxies.

Another major problem is that the number of HST observations of high redshift Universe is very limited. Therefore, we have only a small number of objects with reliable visual morphological classification at high redshift compared to low redshift counterparts. The observations of clusters can efficiently utilizes the HST, as we can obtain a number of galaxies in an exposure.

2.3 Evolution of morphology of galaxies in clusters: Medium redshift

Oemler (1974) noticed that the morphological mix of galaxies in clusters is not the same for every cluster. Some clusters are dominated by spiral galaxies while others are dominated by elliptical galaxies. Butcher & Oemler (1978) found that the spiral fraction is a decreasing function of concentration of the clusters. Here concentration is simply the ratio of the radius of the cluster containing 60% of the total population to the radius containing 20% of the total population. Related to the morphology of galaxies in clusters, another important observation was made by Melnick & Sargent (1977). They found that there exists a gradient in the distribution of different morphological types along the projected radius of the clusters. The cluster centre is dominated by ellipticals and their fraction decreases outwards. These observations lead to the conclusion that the morphology of galaxies may have significant connection with their environments.

The classic study of Dressler (1980b) bore out the correlation between galaxy morphology and their environment. He made a sample of 55 low redshift clus-
2.3: Evolution of morphology of galaxies in clusters: Medium redshift

Figure 2.1: The Morphology-Density Relation given by Dressler (1980b). The fraction of ellipticals, lenticulars and spirals are shown against the log the local projected density in unit of galaxies per Mpc$^2$. This image is taken from Dressler (1980b).

Dressler determined the total magnitudes, bulge magnitude, morphology and ellipticity of all these galaxies as a function of their local projected densities. The main result of the study is shown in Figure 2.1. It can be seen that the morphology is a strong function of the local density. While the fractions of elliptical and S0 galaxies increases with the local projected density, the spiral fraction is a decreasing function of the local projected density. He also showed that this relation does not change with the global appearance of the cluster, i.e. whether the cluster is regular or irregular.

The first studies on the evolution of clusters with HST were made by Couch et al. (1994) and Dressler et al. (1994a,b). The former group observed the clusters AC 114 at $z = 0.31$ and ABELL 370 at $z = 0.37$. The important conclusion from their study is that mergers are common in the cores of rich clusters. They found that ~55% of blue galaxies and ~25% of red E/S0 systems are undergoing merger/interaction. From this observation, they speculate that the dynamical interactions of disk systems trigger star formation which could be the cause of the BO effect. The second group of authors observed the cluster Cl 0939 + 4713 at $z = 0.41$ using WFPC1
and WFPC2. They found that the BO effect is caused by the large number of late type populations in the cluster which is in agreement with Couch et al. (1994). These studies using high resolution images confirm the earlier results by Lavery & Henry (1988) who spectroscopically observed three clusters at \( z \sim 0.2 \) and found that as many as 25% of the population are multiple systems. Lavery et al. (1992) made similar conclusions by observing two clusters at \( z \sim 0.4 \) and found 45% of the blue populations in these clusters show dynamical interactions and concluded that the mergers/interactions are the primary mechanism which cause the BO effect. They argued that the starbursts resulting from dynamical interactions cause the galaxies to become brighter and the new stars formed from this process make the galaxies bluer. This process can substantially increase the fraction of blue galaxies in a magnitude-limited sample. Later Smail et al. (1997) presented a catalogue of galaxies in 10 clusters at \( 0.37 < z < 0.56 \) observed using HST/WFPC2. The important results from this study are: (1) Ellipticals are the dominant morphological species in these clusters; (2) Galaxies at \( z \sim 0.5 \) are \( \sim 0.3 \) mag brighter than their low redshift counterparts; (3) At this redshift only 15% of the galaxy population is S0 compared to the 50% of the total population at low redshift.

Using the data given by Smail et al. (1997), morphology-density relation was derived by Dressler et al. (1997). A comparative analysis of these clusters with those of Dressler (1980b) showed that at \( z \sim 0.5 \) the MDR is stronger for centrally concentrated clusters compared to loose clusters in which the MDR is nearly absent. This result suggests that the morphological segregation occurs hierarchically where the clusters formed initially are affected first and those evolve into massive, rich clusters at the present time. On the other hand, the open clusters at the medium redshift are on the way to build up the morphological segregation. They also found that the elliptical fraction remains nearly the same for the high and low redshift clusters, that fraction is a strong function of local projected density and the fraction of asymmetric galaxies decreases with local density. Along with the small scatter (< 0.1 mag) in colour-magnitude diagram (Ellis et al., 1997), they concluded that the elliptical galaxies are not produced by the merger between gas-rich systems. But they did not preclude the possibility of dissipationless mergers between \( z \sim 0.5 \) and \( z = 0.0 \). Another result was that the fraction of S0 galaxies is smaller in these high redshift clusters compared to their local counterparts. This decrease is complemented with a corresponding increase in the spiral fraction. The small scatter of S0 in colour-magnitude relationship in these clusters compared to low redshift counterparts implies that many of the S0 galaxies in low redshift clusters
are formed at $z \sim 0.2$.

Various physical mechanisms have been proposed to explain the morphological transformation of spiral galaxies in clusters to S0. These processes significantly depend on the environment.

### 2.4 Possible mechanisms of morphological transformation

The underlying mechanisms of morphological transformation can be categorised into three types:

1. **Galaxy-ICM interactions**
   
   Ram-pressure striping (Gunn & Gott, 1972; Fujita, 1998; Fujita & Nagashima, 1999) is an efficient mechanism for morphological transformation in the core region of the cluster where the pressure exerted by the ICM removes cold gas from the galaxies and thereby quenches further star formation. This causes the galaxy to evolve passively and ultimately appear as an S0 system. By N-body simulation Abadi et al. (1999) showed that a spiral galaxy can lose 80% of its diffuse gas when it passes through the centre of a cluster similar to Coma. Another possibility is that the external pressure exert by the ICM on the galaxy can compress the gas clouds in the galaxy, which can lead to high star formation rate (Dressler & Gunn, 1983; Evrard, 1991). This process utilizes most of the cold gas and leaves the galaxy to passive evolution without much further star formation. Other than these two processes, the ICM can remove the cold gas by evaporating it. Since the temperature of the ICM is very large it can possibly heat the gas in the galaxy and this hot gas can subsequently ‘evaporate’ out of the galaxy (Cowie & Songaila, 1977), which is also proved to be an efficient process using numerical simulations (Bekki et al., 2002). These processes are generally termed as gas ‘starvation’ which can cause morphological transformation of galaxies in cluster environments.

2. **Galaxy-Galaxy interactions**
   
   The classical numerical simulation by Toomre (1977) showed that collision between galaxies can change the morphology of the systems involved. The study illustrated the formation of Antennae galaxies by the collision of two disk galaxies. Galaxy harassment can also play a major role in the morphological transformation, where the rapid gravitational interaction between two galaxies can start/increase star formation in gas rich galaxies. This process...
can transform spiral galaxies to dwarf spheroids in the cluster environment (Moore et al., 1996). Bekki (1998) demonstrated by simulations that the merger between two unequal mass gas rich disk galaxies can lead to a S0 galaxy. Several recent N-body numerical experiments shed light on the formation of elliptical morphology by dynamical interactions/mergers (e.g. Barnes, 1992; Hernquist, 1992; Scannapieco & Tissera, 2003; Bournaud et al., 2005).

3. Galaxy-Cluster interactions

Byrd & Valtonen (1990) have shown that the tidal field of the cluster has large influence on gas rich spiral galaxies. This can possibly transform these galaxy to passive red galaxies. Henriksen & Byrd (1996) also studied how the cluster potential affects the morphological transformation. They found that within 250 kpc of the cluster, the cluster tidal forces can compress the cold gas in disk system to cause huge star formation. These galaxies progressively evolve into red S0 systems as they will not have enough gas to continue the star formation.

The different mechanisms described here might be acting in different regions of clusters. For example, the ram-pressure striping may be efficient in rich, regular clusters as this process depends on the density of ICM and the velocity of the galaxy with respect to the ICM. Also interactions with cluster potential may be efficient near the centre of clusters. Figure 2.2 shows the relative importance of these mechanisms in different regions of clusters. All these processes can work together to change the morphology mix in the high density regions of clusters which may lead to the observed MDR (Moore et al., 1999).

2.5 High redshift observations

One of the important findings from the studies of morphology at medium redshifts ($z \sim 0.5$) is that the elliptical fraction in such clusters is nearly the same as that of the local clusters. On the other hand, the fraction of S0 galaxies shows a large evolution as is 2-3 times lower than in low redshift clusters, and this decrease is compensated by the fraction of late type galaxies (Smail et al., 1997; Dressler et al., 1997). Therefore, it is necessary to probe higher redshift clusters to check whether the morphological evolution is monotonous.

One of the early attempts to study the morphology of galaxies at high redshift includes 33 galaxies (Hamilton, 1985). Using the ground based data, Hamilton (1985) showed that the early type galaxies are very red even at $z \sim 0.8$, which is
a signature of old stellar population. More comprehensive studies were done by Aragon-Salamanca et al. (1993) using data on 10 rich clusters at $0.5 < z < 0.9$. These studies showed that the cluster galaxies are, on the average, intrinsically bluer at $z \sim 0.9$ than the local cluster galaxies. This implies that significant evolution happened from $z \sim 0.9$ to $z \sim 0.5$, particularly in the case of E/S0 systems for which the colour at $z \sim 0.5$ is as red as nearby cluster ellipticals. Even then, the tight distribution of colours of the galaxies at $z \sim 0.9$ shows that the galaxies are a coeval population. In these studies using ground based data, the exact morphology of the high redshift galaxies are largely unknown.

Lubin et al. (1998) used HST/WFPC2 to observe two clusters at redshift 0.84 and 0.9 to study the evolution of morphological contents in clusters far away from medium redshift. These data are supplemented with ground based observations, both spectroscopically and photometrically. They found that the morphological contents in the cluster CL 0023 + 0423 at $z = 0.84$, which contains two distinct subsystems, is nearly identical to the field population. This cluster is believed to be a merging system of two groups of galaxies (Lubin et al., 1998). At low redshift the early type galaxy fraction in groups of galaxies is a strong function of velocity dispersion of the group. The observed fraction of early type galaxies in
the two subsystems of cluster CL 0023 + 0423 is smaller than the predicted fraction using the empirical relation between early type fraction and velocity dispersion. Therefore, they argue that if galaxy groups are the progenitors of low redshift clusters, then early type galaxies (E+S0) should form even after \( z \sim 0.8 \). This observation contradicts the earlier results where many authors concluded that all the ellipticals are formed at very high redshift and the evolution is only passive after that.

The morphological mix of their second cluster under study, CL 1604 + 4304 at \( z = 0.9 \), is similar to the local relaxed clusters with S0/E ∼ 1.5. This result also contradicts Dressler et al. (1997) who found a deficit of S0 galaxies and small value for S0/E (∼ 0.5) at \( z \sim 0.5 \) and therefore, concluded that the S0 galaxies are under formation. An explanation of this disparity is that this particular cluster is not the progenitor of the intermediate redshift clusters. This result shows that the lack of large number of clusters at high redshift may significantly bias final conclusions.

The observation of cluster MS 1054-03 at \( z = 0.83 \) reveals a large merger fraction (17%) (van Dokkum et al., 1998) which is nearly as high as the elliptical fraction (22%). Along with the estimated values at lower redshift, they concluded that the merger rates are increasing with redshift, which is shown in the Figure 2.3. Combining all these observations at different redshifts, it was possible to conclude that the early type galaxy fraction in clusters shows strong evolution with redshift, which essentially implies that more than 50% of the early type population in the present day clusters are formed/accreted between \( z = 1 \) and \( z = 0 \). The observations of the clusters in this redshift range is summarised in Figure 2.4.

### 2.6 Summary

In this chapter we have summarised the earlier studies which laid the basis of galaxy morphology and their evolution in clusters at medium and high redshifts. The Hubble Space Telescope has acted as a major element in developing such studies. Different mechanisms are proposed to explain the observed evolution of morphology which depend on the environment of the galaxies. It can be seen that we need a large number of clusters at high redshift to disentangle the morphological evolution from cluster properties.

Several studies to understand the morphological evolution of cluster population and its relation with local densities have been done recently and those will be reviewed in the subsequent chapters. Different techniques were used in
Figure 2.3: Merger rates vs redshift. The merger fraction is more than 1% at redshift $\sim 0.84$. This image is take from van Dokkum et al. (1999).

Figure 2.4: Evolution of early type fraction in clusters since $z \sim 1$. The figure includes data from Dressler (1980b); Dressler et al. (1997); Lubin et al. (1998); van Dokkum et al. (2000) This image is take from van Dokkum et al. (2000).
the literature for these purpose which include ‘eye ball’ classification of galaxies, colour-magnitude diagram, magnitude-size relation, fundamental plane relations, automated morphological classification, estimation of luminosity function, pair counting, estimation of two-point correlation etc. These properties of galaxies are studied extensively as a function of redshift, local density and clustercentric radius etc. to put constraints on the different evolutionary scenarios. These studies are supplemented with a variety of numerical simulations which show the importance of merger/interactions, ram pressure, high speed encounters, effect of cluster potential etc.

One of the largely unexplored areas in the field of galaxy morphology is the study of evolution of bulge and disk components of galaxies with redshift and environment. From Chapter 1 it is clear that the Hubble type is strongly correlated to galaxy physical properties. Different galaxy formation theories predict different Hubble types depending on the relative strength of disk part compared to the bulge, where a pure disk galaxy contains no spheroidal component. Therefore, studying the strength of bulges in galaxies can be utilized to constrain the importance of various galaxy formation models. In subsequent chapters we quantify galaxies according to the strength and concentration of galaxy bulges and study their evolution as a function of time and environment.