As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Lei Bai entitled THE EFFECTS OF DENSE CLUSTER ENVIRONMENTS ON GALAXIES AND INTRACLUSTER DUST and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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Lei Bai
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DEDICATION

I dedicate this dissertation to my mother, Lifen Li.
She is an extraordinary woman and the best mom I could ever imagine.
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Dense cluster environment influences the properties of galaxies and their evolution. In order to understand this environmental effect and how it evolves with time, we study the infrared (IR) properties of galaxies in three rich clusters. The IR luminosities provide us with extinction-free measurements of the star formation rates (SFRs) of these cluster galaxies. We find a strong evolution in the IR luminosity function (LF) of two $z \sim 0.8$ clusters when compared to two local clusters. The evolution rate of the IR LF found in these clusters is consistent with the evolution in field IR LFs. The similar evolution rate found in very different environments favors some internal mechanism, e.g., the gradual consumption of the gas fuel in galaxies, as being responsible for much of the star formation evolution. The mass-normalized integrated SFRs within $0.5R_{200}$ of these clusters also shows an evolution trend, $\propto (1 + z)^{5}$. But this evolution has large scatter and may be affected by the mass selection effect of the sample. In the dense cluster core regions ($r < 0.3$ Mpc), we find evidence for enhanced SFR suppression. A substantial fraction of members in MS 1054-03 ($z \sim 0.8$) are still forming stars actively. This cannot be explained by the scenario where the cluster is only passively accreting star-forming galaxies from the surrounding field, after which their star formation is quenched quickly. We also study the extended IR emission from the intracluster dust (ICD) in A2029. We only find weak signals at 24 and 70 $\mu$m and obtain upper limits for the ICD emission.
Galaxy clusters are ideal laboratories to study the influence of the environment on galaxy evolution. They provide a large sample of galaxies in a limited volume for efficient observation and their high densities have a marked effect on the star formation properties of their member galaxies, compared with those in the field.

1.1 Environmental Effects on Star Formation

Many environment-related differences in galaxy properties have been found by comparing galaxies in clusters and the field.

**Density-Morphology relation (DMR)** Clusters are well known to be composed mostly of S0 and elliptical galaxies while the field population is largely spiral galaxies (e.g., Hubble & Humason, 1931; Dressler, 1980). This is the clearest evidence that the environment might shape the evolution of galaxies and drive the transformation of galaxy type.

**Density-SFR relation** Galaxies in clusters generally have less star formation compared to galaxies in the field (e.g., Kennicutt, 1983; Balogh et al., 1997; Hashimoto et al., 1998; Poggianti et al., 1999; Postman et al., 2001; Gómez et al., 2003). This relation has two levels of meaning: one is that the fraction the star forming galaxies is lower in the clusters than in the field; the other is that for galaxies of the same type, those in clusters have relatively lower SFR (Balogh et al., 1997, 1998). Although the lower fraction of star forming galaxies can be induced by the DMR, the second level of the density-SFR relation is independent of the DMR. In addition, Couch et al. (2001) found a large fraction of the cluster spirals have no detectable H$_\alpha$ emission and suggest that the star formation and morphological transformation in cluster galaxies are largely decoupled. Many studies (e.g., Balogh
et al., 1997, 1998; Gómez et al., 2003; Lewis et al., 2002) also found that density-SFR
relation is not limited to clusters, but is a universal phenomenon extended to much
lower density regions, e.g., the outskirt region of clusters and groups. It indicates
the properties presented by cluster galaxies, which are only a small fraction of all
the galaxies in the universe (~ 20%), are not isolated and the study of these galaxies
will help to understand the galaxy evolution in general.

Several physical processes have been proposed to influence galaxy evolution in
dense environments. However, which mechanism dominates and where the suppress-
ion first occurs are still controversial (e.g., Lewis et al., 2002; Balogh et al., 2004b;
Kauffmann et al., 2004).

**Ram pressure stripping** When a galaxy falls into the high density region of
a cluster, the ram pressure caused by the hot intrachuster medium (ICM) will strip
away the ISM in its disk and quench the star formation (Gunn & Gott, 1972). This
gas stripping can be quite efficient in the cores of rich clusters and will remove most
of the gas in a time scale of $10^7$ yrs (Abadi et al., 1999). The ram pressure can
also compress the molecular gas of the galaxy and trigger star formation, which
will consume the gas that has not been stripped (Fujita & Nagashima, 1999). The
characteristic short timescale of the ram pressure stripping indicates a quick trans-
formation from blue/gas-rich galaxies to red/gas-poor ones and may help to explain
the simple Gaussian distribution of the blue galaxy color in the high density region
(Balogh et al., 2004b). A quick truncation of the star formation following the gas
stripping would also help to explain a significant population (21%) of post-starburst
galaxies found in some distant clusters (Poggianti et al., 1999). However, since ram
pressure stripping was thought to be efficient only in the high density region, it
has difficulty being reconciled with the observed star formation suppression effect
out to the much lower-density region of the cluster, e.g., $\sim R_{\text{vir}}$, or in the group
environment (Gómez et al., 2003; Balogh et al., 1998). Recently, new numerical
simulations have shown that although more prominent in the high density region,
ram pressure stripping is still very important out to the virial radius of the cluster
and the timescale for complete gas removal is $\geq 1$ Gyr (Tonnesen et al., 2007;
Galaxy-galaxy interaction The tidal force generated by the close encounters of galaxies can cause instability in a disk and trigger a starburst. The star formation quickly consumes the gas in a galaxy and changes the properties of the galaxy on short time scales ($\sim 100$ Myr). The direct encounter of galaxies is more common in a group environment than in a cluster due to the much smaller velocity dispersion. It provides an efficient mechanism to ‘preprocess’ galaxies in the group environment (Zabludoff & Mulchaey, 1998) and can produce the universal trend of decreasing SFR over a wide range of densities Gómez et al. (2003); Lewis et al. (2002). In a cluster, Moore et al. (1996, 1998) show that multiple highspeed encounters between cluster galaxies—‘galaxy harassment’—can transform small disk galaxies into dwarf spheroidals over a period of a few Gyr.

Strangulation The hot halo gas of a galaxy replenishes the cold gas consumed by star formation. But when a galaxy encounters hot intracluster gas, it loses its hot gas halo and the star formation gets strangled due to the cutoff of the cold gas supply (Larson et al., 1980; Bekki et al., 2002). This process can strip the halo gas of the galaxy far away from the cluster center in a few Gyr. A new simulation (Kawata & Mulchaey, 2007) shows this mechanism even works in low mass groups where ram pressure is not sufficient to remove the cold gas.

1.2 Evolution of Star Formation in Clusters

The average cosmic SFR has experienced a rapid decline since $z \sim 1$ (Lilly et al., 1996; Madau et al., 1998; Hopkins, 2004; Le Floc’h et al., 2005; Pérez-González et al., 2005). In parallel to this trend, cluster galaxies, although generally less active than field galaxies, also show increased star formation at higher redshifts. This behavior was first discovered as the increasing number of blue galaxies in distant clusters compared to nearby clusters, the so-called Butcher-Oemler effect (Butcher & Oemler, 1978, 1984). Spectroscopic studies (Dressler & Gunn, 1982, 1983; Ellingson et al., 2001; Tran et al., 2005) reveal those blue galaxies as star-forming galaxies...
and indicate increased star forming activity in distant clusters compared to their relatively ‘quiet’ local kin. In addition, the fraction of star forming galaxies in distant groups was also shown to be higher than that in local groups (Wilman et al., 2005).

The differences of evolution of star formation in different environments raises interesting questions of what drives the evolution and how these evolutions are related to each other. Does the increasing star formation in clusters simply reflect a greater level of activity in field galaxies which provide the reservoir of new cluster members, or, does it actually suggest a change of the suppression mechanism imposed by the cluster environments with redshift? If clusters only passively accrete star forming galaxies from the field, then the increased number of star forming galaxies in distant clusters may merely result from the increased number of blue galaxies in the field and clusters would show a similar evolution in SFR as in the field. Also, if the cosmic decline of the SFR is mainly caused by an overall progressive gas consumption in galaxies, the same evolutionary trend in different environments will be a natural consequence. On the other hand, if the SFR suppression is largely caused by an environment-dependent mechanism, the rate of decline of the cosmic SFR is expected to be correlated with the hierarchical growth of structure.

To answer these questions, we need to have a quantitative analysis of the star formation in clusters over a large redshift range and compare it with galaxies in groups and the field.

1.3 Study Star Formation in Clusters with IR Observations

1.3.1 SFR Indicators

There are many different SFR indicators widely used to study the star formation properties of clusters, e.g., the galaxy colors, UV luminosity, emission-line measurements and IR luminosity. The colors of galaxies depend on the star formation history, as well as reddening, initial mass function (IMF), age, and metallicity. They can only provide an approximate estimate of the star formation history of the galax-
ies. The UV continuum directly traces the emission of the young stellar population (< 100 Myr), but it is heavily attenuated by dust and represents only the unobscured star formation, which is usually a small fraction of the total star formation in galaxies (e.g., Buat et al., 2005).

Several nebular recombination lines provide sensitive, instantaneous measurement (< 10 Myr) of star formation (SF). Among them, $H\alpha$ is the most widely used and one of the best understood indicators. Its luminosity is directly proportional to the ionizing radiation from the young stars. The spectroscopic surveys of $H\alpha$ lines are mostly limited to galaxies with $z < 0.4$ where it is in the optical band. The $H\alpha$ narrow-band imaging technique (e.g., Kennicutt, 1983; Gavazzi et al., 1998; Balogh & Morris, 2000) is more efficient than spectroscopic surveys. This method becomes extremely useful at $z \sim 0.8$, when the $H\alpha$ line moves into the near-IR band (Finn et al., 2004, 2005). However, this technique is limited to specific redshifts; also, the continuum measurement and the contamination from [N II] could bring extra uncertainties. For clusters with $z > 0.4$, most of the studies use [O II]$\lambda$3727 emission lines to measure the SFR. It is a strong emission line which can be easily accessed in the optical band for clusters with $z > 0.4$ up to $z < 1.5$. However, the [O II] lines are a less precise SFR tracer than $H\alpha$. Their strength depends explicitly on the metallicity of galaxies and they have a higher dust extinction compared to $H\alpha$. The ratio of [O II]/$H\alpha$ can vary by a factor of 7 at $M_B^*$ (Jansen et al., 2001). The SFRs measured from [O II] lines in the high redshift clusters therefore have large uncertainties and pose serious problem for comparisons with SFRs measured from $H\alpha$ lines. Although to a much lesser degree than the UV and the [O II] line, the $H\alpha$ line is still affected by dust extinction, which can be very high for strongly star-forming galaxies (e.g., Choi et al., 2006). As a result, robust measurements of the SFR unaffected by extinction in clusters are still lacking, especially at high redshift ($z > 0.5$).

Different from all the methods mentioned above, the infrared (IR) bolometric luminosity from the interstellar dust heated by the young stars in galaxies can provide a sensitive SFR indicator minimally affected by extinction (Kennicutt, 1998a).
Moreover, because mid-IR broadband emission shows a good correlation with the total IR luminosity (e.g., Takeuchi et al., 2005; Dale et al., 2005), it has become common practice to use single band mid-IR emission as a star formation indicator. The mid-IR correlates well over a large luminosity range with the extinction corrected optical and near infrared SFR indicators (e.g., Alonso-Herrero et al., 2006; Calzetti et al., 2007). Although there are many uncertainties involved in this method, e.g., the escape of the UV photons in optically thin regions, the heating of dust due to the ionizing photons from older stellar populations and the uncertainties in converting single band emission into the total IR luminosity (e.g., Pérez-González et al., 2006), it is still a robust method to measure obscured SF in luminous galaxies.

ISO data for a few clusters with \( z < 0.5 \) have shown that star formation in many cluster galaxies is heavily obscured, with no trace in the optical spectra. For example, at least 90% of the star formation in A1689 is obscured by dust (Duc et al., 2002). These results demonstrate that the study of IR emission is very critical for us to fully evaluate the star formation in clusters. Although ISO led to important advances in our knowledge of star formation in clusters (see the review by Metcalfe et al., 2005), it was not until the launch of Spitzer, with its sensitive Multiband Imaging Photometer (MIPS, Rieke et al., 2004), that we are able to study the IR emission of a statistically large sample of clusters up to a high redshift (\( z \sim 1 \)).

### 1.3.2 IR Luminosity Function as an Analysis Tool

The study of the luminosity functions (LFs) is one of the most fundamental methods to quantify the properties of a galaxy population. It has been widely used to compare the properties of galaxies in clusters with those in the field at many different wavelengths. Because of the direct correlation of the IR luminosity to SFR, the IR LF is particularly useful for studying star formation in clusters. Most of the previous star formation comparisons between cluster and field galaxies are focused on the fraction of star forming galaxies and the total/average SFRs, which are all integrated properties and may not accurately reflect the star formation properties in different populations. In comparison, the IR LF provides a quantitative description
of the frequencies of galaxy SFRs at different intensities at the same time and is a powerful tool for easy comparisons.

Using MIPS 24 μm data, Le Floc’h et al. (2005) and Pérez-González et al. (2005) studied the evolution of the IR Luminosity function for galaxies in the field. Le Floc’h et al. (2005) quantified the evolution of the IR LF in the CDF-S field in both density and luminosity as \[ L^*_{IR} \propto (1 + z)^3.2, \phi^*_{IR} \propto (1 + z)^{0.7} \] up to \( z \sim 1 \). These studies provide a good reference frame for studying the IR LF in clusters.

1.4 This Dissertation

This dissertation is composed of two parts. In the first part (chapter 2, 3, and 4), which is also the major part of the dissertation, we analysis the 24 μm observation of a sample of rich clusters and present their IR LFs. This is the first time the IR LFs in clusters have been studied and it is the first step in our systematic study of the evolution of star formation in rich clusters. Our sample of clusters includes two local rich clusters: Coma and A3266, and one cluster at \( z \sim 0.8 \), MS1054-03. We also include the data from another \( z \sim 0.8 \) cluster RXJ0152-13 (Marcillac et al., 2007) in this study.

These clusters are all very massive (\( M > 4 \times 10^{14} \text{ M}_\odot \)) and have a large number of spectroscopically confirmed cluster members (> 100), which are critical to exclude the contamination from the field galaxies. Using 24 μm emission, we are able to build extinction-free star forming galaxy samples complete down to 0.2 \( \text{M}_\odot \text{ yr}^{-1} \) for the two local clusters and \( \sim 10 \text{ M}_\odot \text{ yr}^{-1} \) for the two high redshift ones.

With these IR LFs, we can 1) compare with the field IR LFs at the same redshifts; 2) study their evolution and compare it with the evolution found in the field IR LFs. These comparisons will help us to answer the questions posed before and provide important information on galaxy evolution.

We will also study the detailed properties of these star forming galaxies in each cluster, e.g., their spatial distribution and the change of the IR-emitting fraction at different radii. These studies will enable us to disentangle the effect of different star
formation suppressing mechanisms.

In the second part of the dissertation (chapter 5), we studied the extended IR emission from intracluster dust (ICD) heated by the X-ray hot gas in A2029. The detection of this emission has been a controversial issue. With the MIPS observation, we are able to put upper limits on the intensities at 24 and 70 μm and provide constraints on the properties of ICD.
CHAPTER 2

IR Properties of Galaxies in Rich clusters: the Coma Cluster

2.1 INTRODUCTION

In this chapter, the first one of a series studying the IR LF of clusters up to $z \approx 0.8$ using MIPS observations, we present the IR LF of the Coma cluster. The Coma cluster, as the nearest rich cluster, provides us an excellent chance to study the IR properties of a large number of cluster galaxies down to a very faint limit. It is one of the most studied clusters in the sky and there are extensive photometric and spectroscopic data available in the literature.

These data combined with the IR data enable us to study the change of IR LF in different regions of the cluster, as well as the contributions to the total IR LF from different types of galaxies. The Coma Cluster is also one of the most regular clusters known and was once thought to be a prototype of the fully relaxed virial system, but many studies have shown evidence for substructures (Mellier et al., 1988; White et al., 1993; Neumann et al., 2003) and suggest the cluster is probably still in the process of relaxing. These interesting features of the cluster may affect the IR properties of the galaxies. In this chapter we will show how the cluster environment shapes the current star formation in this prototypical dense cluster and provide a foundation for the future studies of the SFR patterns in other clusters, both nearby and at high redshift.

The organization of this chapter is as follows. In sect 1.2, we describe how we analysis the data; in sect 1.3, we present the IR LF and its variation in different region of the cluster. We also study the contribution of the early- and late-type of galaxies toward the total IR LF. We discuss these results in comparing with the field IR LF in sect 1.4. Throughout this work, we assume a distance modulus of $m - M = 35.0$ mag for the Coma cluster at $z=0.023$ (Struble & Rood, 1999).
2.2 DATA

2.2.1 Observations

We used MIPS to observe the Coma cluster in medium scan map mode on Jun 6, 2004. Our map covered a 4 deg$^2$ area centered at $\alpha = 12^{h}59^{m}27^{s}, \delta = +27^{\circ}51'53''$, which included both the cluster core region and the NGC 4839 region. Fig. 2.1 shows the region of the map. The 24 $\mu$m and 70 $\mu$m reductions were carried out with the MIPS Data Analysis Tool (Gordon et al., 2005). The total exposure time was about 88 seconds per pixel for the 24 $\mu$m observations and about 40 seconds for the 70 $\mu$m ones.

2.2.2 Source Detection

SExtractor was applied to the images to detect sources automatically and to obtain photometry parameters. First, the images were analyzed and sky background models were built. Then the images were background-subtracted and filtered with Gaussian functions with the full width at half maximum (FWHM) matching the FWHM of the MIPS 24 $\mu$m and 70 $\mu$m point spread functions (PSFs). All the objects with values exceeding a certain threshold of local background were extracted. We set this detection threshold, relative to the root-mean-square background noise, at 0.65 for the 24 $\mu$m image and 2 for the 70 $\mu$m image. After deblending the adjacent objects and ‘cleaning’ the artifacts due to bright objects, SExtractor gave a final catalog of sources. SExtractor provides several types of magnitude measurements. We adopted the MAG\_BEST magnitude. In most of the cases, the MAG\_BEST magnitude is measured in an adaptive aperture of 2.5 times the Kron aperture, but in crowded fields, it is measured in an isophotal aperture and corrected for aperture losses. In our data, few regions are crowded.

2.2.3 Completeness

The completeness of source detection affects the LF directly, so it is important to know the detection limit of the observations. Papovich et al. (2004) studied the
Figure 2.1 The sky map of the Coma cluster. The dots are the galaxy members detected at 24 $\mu$m in the BvdHC. The stars designate the sources with $L_{1R} > 10^{43.3}$ ergs s$^{-1}$. The circle in the center defines the Coma core region, with $r < 0.2\degree$, and the surrounding annulus is defined as $0.2\degree < r < 0.4\degree$. The circular region southwest of the Coma core is centered at NGC 4839 with same radius as the Coma core. The dotted rectangular region is the MIPS 24 $\mu$m coverage. The dashed region is the survey region of the BvdHC, and the two dash-dotted rectangular regions are of the MBC.
source detection completeness of MIPS 24 μm images in several different fields. Among these fields, the Boötes image has almost the same exposure time as the Coma image and the background levels are also similar, with a mean value of 22.7 MJy sr$^{-1}$ for the Boötes field and 33.4 MJy sr$^{-1}$ for the Coma field. By inserting artificial sources in the images and performing source extraction on them, Papovich et al. (2004) found a 80% completeness flux density limit of 0.27 mJy in the Boötes field. As a rough approximation, a simple linear scaling with the square root of the background level gives us a detection limit of 80% completeness at 0.33 mJy for the Coma field.

At 70 μm, the Coma data were obtained at a lower detector bias than those in Boötes, resulting in an improvement in overall performance. Therefore, we ignore the background difference and adopt the completeness limit of about 80 mJy obtained in the Boötes field with the same exposure time (Dole et al., 2004).

2.2.4 Matching Spectroscopic Surveys of the Coma Cluster with 24 μm Sources

To study the infrared LF of the Coma cluster galaxies, we used a spectroscopic sample so that cluster membership could be confirmed. Fortunately many spectroscopic surveys have been carried out in this region. Among them, the catalogs from Beijersbergen & van der Hulst (2003) and Mobasher et al. (2001) have the largest overlapping area with the MIPS 24 μm observations and also go to fairly deep detection limits. Beijersbergen & van der Hulst (2003) generated a catalog (hereafter BvdHC) using all known Coma cluster redshifts in a 5.2 deg$^2$ region. This catalog covers almost the whole region of the MIPS 24 μm image except a few small patches at the edge and has a 93% completeness down to Sloan $r' = 16.27$ mag. Mobasher et al. (2001) performed spectroscopic observations on two rectangular regions, one at the cluster core and the other near the NGC 4839 group, each 32.5 × 50.8 arcmin$^2$. The core region is totally covered by MIPS observations, and the region near the NGC 4839 group is partly covered. Its completeness is about 60% for the bright galaxies ($R < 17$) and decreases towards the faint end. The difference between the Sloan $r'$ filter BvdHC used and the Cousins $R$ filter Mobasher et al. (2001) used is
small. Comparing the common objects in these two catalogs gives a difference of $R - r' \sim 0.03$ mag, so we do not differentiate them and just use $R$ to refer to both of them in this chapter. Furthermore, we complemented Mobasher’s catalog with the BvdHC down to $R = 16.27$ mag, and generated a merged catalog in these regions (hereafter MBC).

We selected all the galaxies from these two catalogs (BvdHC & MBC) with $4000$ km s$^{-1} \leq c z \leq 10000$ km s$^{-1}$ as cluster members (Colless & Dunn, 1996) and cross matched them with our 24 $\mu$m and 70 $\mu$m sources. Any 24 $\mu$m or 70 $\mu$m source within 10" of the optical galaxy was identified as the IR emission from this galaxy. This search radius is about twice as large as the FWHM of the MIPS PSF at 24 $\mu$m and half of the FWHM at 70 $\mu$m. It allows a displacement in projected distance up to 5 kpc between the optical centers of galaxies and the peaks of their IR emission. About 90% of the cluster members with 24 $\mu$m emission above the completeness limit have a displacement between optical center and IR emission peak smaller than 5", i.e., 2.5 kpc. When multiple identifications occurred, the one with the smallest distance from the optical galaxy was selected. Less than 2% of the sources had multiple identifications. Therefore, our final sample is not sensitive to the details of matching infrared and optical sources; few cases yield ambiguous associations, and moderate changes in the acceptance radius have little effect on the results.

Among the 498 Coma galaxies in the BvdHC within the MIPS 24 $\mu$m field, 217 have 24 $\mu$m counterparts. In the part of the field covered at 70 $\mu$m, 58 were detected out of 477 members. In the MBC, there were 123 galaxies detected at 24 $\mu$m out of 333 galaxies and 33 at 70 $\mu$m out of 302 galaxies. The number of galaxies detected in both bands was 56 for the BvdHC and 33 for the MBC. Although the total number of galaxies detected in the MBC is less than in the BvdHC, the overlapping area with MIPS observations is also smaller: it is about 0.8 deg$^2$ for the MBC and about 3 deg$^2$ for the BvdHC. Therefore, the number density of galaxies detected in the MBC is still larger than in the BvdHC, consistent with their different detection limits.
2.3 IR LUMINOSITY FUNCTION

2.3.1 Determination of total IR luminosity

Since we detected relatively fewer galaxies at 70 \( \mu m \) than at 24 \( \mu m \), we based our LF calculations mainly on 24 \( \mu m \) sources.

To obtain the total IR luminosities of galaxies, which relate to the total flux from 8 - 1000 \( \mu m \), a single measurement of flux density at 24 \( \mu m \) is not enough. We need more constraints. Using a self-consistent modelling of the spectral energy distributions (SEDs) of galaxies over a broad range of wavelength, Devriendt et al. (1999) published a sequence of galaxy SEDs with different IR luminosities based on a sample of nearby galaxies. Their sample includes normal spirals, luminous IR galaxies (LIRGs) and ultraluminous IR galaxies (ULIRGs). If we assume these SEDs are a complete assembly of representatives of nearby galaxies, the color correlation of these SEDs should be the same as the color correlation of the Coma galaxies. More specifically, if we know the color correlation between the ratio of IR luminosity \( (L_{IR}) \) and 24 \( \mu m \) luminosity \( (L_{24}) \) and the ratio of flux density at 24 \( \mu m \) \( (S_{24}) \) and R band \( (S_R) \) from the template SEDs, we will know the color correlation of the Coma galaxies as well. Therefore, we can use observational data regarding \( L_{24}, S_R \) and \( S_{24} \) to get the total infrared luminosity \( L_{IR} \).

However, the assumption that the template SEDs include all the galaxy types in Coma is not correct. For a cluster as rich as Coma, the early type (E/S0) galaxies dominate the optical emission of the cluster. In the infrared, the spiral galaxies are generally more luminous than the early type galaxies and hence are the majority of the IR sources. However, given the sensitivity of MIPS and the closeness of the Coma cluster, we still detected the 24 \( \mu m \) emission from many elliptical galaxies and S0 galaxies. In the BvdHC, which gives information on the galaxy type, about half of the galaxies detected at 24 \( \mu m \) are early type galaxies, and the rest are mostly spiral galaxies or galaxies without type identification. The infrared emissions of the early-type galaxies may come from different physical mechanisms or different dust geometry than that of the spirals, and their SEDs may have different shapes and
colors than those of the template SEDs.

To check for possible differences between the early-type galaxies and the spiral galaxies in the colors that are crucial to determine the total infrared luminosity, we plot in Fig. 2.3.1 the color correlation of the different types of galaxies in the BvdHC. Panel a in Fig. 2.3.1 is the color-color plot of $S_{70}/S_{24}$ vs. $S_{24}/S_R$ for the galaxies detected both at 24 $\mu$m and 70 $\mu$m and with a morphology identification. The plot shows that early type galaxies (open circles) have smaller $S_{24}/S_R$ ratios on average than the spiral galaxies (open triangles), but their $S_{70}/S_{24}$ ratios are similar to the spiral galaxies. Although with a large dispersion, the template SED’s (crosses) color correlation represents the average value for the whole galaxy sample fairly well. If the IR emission of the galaxy mainly comes from dust at a single temperature, then small differences in the $S_{70}/S_{24}$ color indicate a small difference in the $L_{IR}/L_{24}$ ratio for these galaxies. In panel b, we show the 24 $\mu$m flux density vs. $S_{24}/S_R$ color of all the galaxies. The early type galaxies mostly reside in the lower corner of the plot but they are well mixed with the spiral galaxies and show no difference in this correlation from the faint spiral galaxies. The plot also shows that most of the galaxies with 24 $\mu$m flux density larger than 6 mJy are also detected at 70 $\mu$m (indicated by the filled symbols). This result is consistent with the detection completeness at 70 $\mu$m assuming the average $S_{70}/S_{24}$ color. There also appears to be a trend between the 24 $\mu$m flux and the $S_{24}/S_R$ color of the galaxies, which indicates larger IR emission from the redder galaxies. Using this trend, we can also obtain a detection limit set by the completeness of the 70 $\mu$m observation for panel a shown as the dotted line; the region at the left and below the line is affected by the incompleteness and large uncertainties of the 70 $\mu$m measurements. From both plots, we find that the early type galaxies are generally less luminous at 24 $\mu$m than the spiral galaxies and therefore have lower $S_{24}/S_R$ ratios, but their color correlation does not differ from that of the spiral galaxies with similar 24 $\mu$m flux density. This justifies the use of the template SEDs as a complete assembly of all types of galaxies to deduce the total IR luminosity from the $L_{IR}/L_{24}$ vs. $S_{24}/S_R$ correlation.

To obtain the flux densities of the SEDs at different bands, we convolved the
Figure 2.2 The color - color/flux plot of the early- and late- type galaxies. The open circles and open triangles represent early- and late- type galaxies, respectively. (a) the 70 - 24 color vs. 24 - R color. The crosses are the color of the template SEDs. The dotted line is the detection limit set by the completeness of the 70 \( \mu \text{m} \) observations. (b) the 24 \( \mu \text{m} \) flux density vs. 24 - R color. The galaxies also detected at 70 \( \mu \text{m} \) are plotted as filled symbols.
SEDs with the response functions of the filters. For the 24 µm and 70 µm bands, we also account for the color corrections as described in the MIPS Data Handbook. In Fig. 2.3.1, we plot the correlation of $L_{IR}/L_{24}$ vs. $S_{24}/S_R$ obtained from template SEDs as well as the value interpolated from the Coma galaxies. The log($S_{24}/S_R$) ratios of the template spirals range from about −0.5 to 1 and those of the LIRGs and ULIRGs from about 2 to 3.5. Most of the Coma galaxies have log($S_{24}/S_R$) ratios smaller than 1.5 and only one source has a color similar to the LIRGs/ULIRGs. The log($L_{IR}/L_{24}$) ratios of the LIRGs/ULIRGs are almost a constant of $\sim$ 1.5. These ratios for the normal spirals increase slowly with the decrease of $S_{24}/S_R$ ratios, with a little (and insignificant) dip at about log($S_{24}/S_R$) $\approx$ 0. Although a simple interpolation onto the correlation works for many of the Coma galaxies, our template SEDs do not cover the range with log($S_{24}/S_R$) < −0.5 as the data do, so the color correlation at this end is an extrapolation from the last few points of the template SEDs. This unbounded extrapolation may cause systematic errors when deducing the $L_{IR}$ from the $L_{IR}/L_{24}$ ratio. However, we can find some support for the higher value of the $L_{IR}/L_{24}$ ratio at this end from panel a of Fig. 2.3.1. Despite the incompleteness and large uncertainties, the panel shows a slightly higher value of the $S_{70}/S_{24}$ ratio than the ratio given by template SEDs towards the lower end of $S_{24}/S_R$ ratio. It is worth noticing that this extrapolation is also consistent with the general expectations for thermal emission: galaxies with smaller values of $S_{24}/S_R$ have relatively less emission by warm dust and therefore a higher value of $L_{IR}/L_{24}$. In the future, a template SED with lower $S_{24}/S_R$ ratios will be needed to further constrain the $L_{IR}/L_{24}$ color at this end, but for now we rely on the simple extrapolation. With the $L_{IR}/L_{24}$ ratio of each galaxy in hand, we can directly deduce the $L_{IR}$ of each galaxy from its $L_{24}$.

An important result from Fig. 2.3.1 is that $S_{24}/S_R$ is nearly independent of $L_{IR}/L_{24}$ over the luminosity range of interest to us. Therefore, our initial galaxy selection on the basis of a visible spectroscopic study will not introduce biases in the infrared properties of the sample.

To test the method we used here to determine $L_{IR}$, we compare our result with
the IR luminosities obtained with the method used by Le Floc’h et al. (2005). They adopt a different set of SED templates that are luminosity dependent, e.g., the templates given by Lagache et al. (2003). Lagache et al.’s galaxy templates include separate SEDs for normal galaxies and starburst galaxies. Their normal galaxies, again, only include spiral galaxies. As we can see from Fig. 2.3.1, most of the galaxies in the Coma cluster are normal galaxies and only one galaxy has a $S_R/S_{24}$ color similar to LIRGs/ULIRGs, so we plot Lagache et al.’s correlation between $L_{IR}/L_{24}$ for normal galaxies in Fig. 2.3.1 as the dashed line. This correlation agrees well with the $L_{IR}/L_{24}$ ratios given by the template spirals and thus demonstrates the consistency between our method and that of Le Floc’h.

To test the self-consistency of our method, we use the data for the members of the BvdHC detected both in the 24 $\mu$m and 70 $\mu$m bands. Using the same SED mapping method as before, but, using different combinations of bands, we estimated new values of $L_{IR}$ for these objects. We plot them against the previous $L_{IR}$ ob-
tained from the correlation between $L_{IR}/L_{24}$ and $S_{24}/S_R$ in Fig. 2.4. The top panel in Fig. 2.4 is the $L_{IR}$ obtained from the correlation between $L_{IR}/L_{70}$ and $S_{70}/S_R$ compared with the previous one. The bottom panel is the $L_{IR}$ obtained using the correlation between $L_{IR}/L_{70}$ and $S_{70}/S_{24}$. The $L_{IR}$ values obtained from different color correlations are generally consistent with a standard deviation of about 0.10 dex for the top panel and 0.16 dex for the bottom panel. The galaxies with $S_{70}$ under the 80 mJy completeness limit, shown as the open circles in the figure, have large uncertainties in their $S_{70}$ measurement (with errors up to 40 %) and therefore show a more scattered correlation. The dispersions of the correlations are generally consistent with the dispersion caused by the uncertainties in the photometric measurements. It is also possible there are significant contributions to the dispersions by intrinsic color dispersions of the galaxies, as opposed to the tight correlation we assumed in Fig. 2.3.1. Since the dispersions are modest and have zero averages, they will in any case have little effect on the LF we deduce.

2.3.2 Contamination from AGNs

When we measure the IR emission from galaxies and study their star forming activities, contamination from AGNs is always an issue. The IR emission of AGNs comes from dust heated by the soft X-ray and ultraviolet emission of the active nuclei rather than from star forming activities; therefore, their SEDs could be very different from the template SEDs we used.

To search for the AGNs in the Coma cluster, we cross matched the Quasars and Active Galactic Nuclei catalog (Véron-Cetty & Véron, 2003) with the BvdHC and MBC. The Véron-Cetty & Véron (2003) catalog is not complete but it includes almost all the AGNs in the literature. There are three AGNs detected at 24 μm: D 16, Sy1; NGC 4853, Sy and KUG 1259+280 Sy. Among them, only NGC 4853 has a $L_{IR}$ greater $10^{43}$ ergs s$^{-1}$. These AGNs, so few in number, do not have a noticeable effect on the IR LFs we obtain.
Figure 2.4 Comparisons of $L_{IR}$ obtained from different color correlations. The filled circles are the galaxies with $S_{70}$ greater than the 80 mJy completeness limit, and the open circles are the galaxies under the limit.
2.3.3 Total IR Luminosity Function

After testing for the method we used to deduce the total IR luminosity as described above, we calculated the projected IR luminosity function of the Coma cluster.

For the BvdHC, we obtained the number density of galaxies per projected area by directly counting the number of galaxies in each luminosity bin and dividing the number by the projection area. For the MBC, we assume the completeness function is unity for $R < 16.27$ mag and behaves as described in Mobasher et al. (2001) for galaxies fainter than $R = 16.27$ mag. In calculating the number counts of galaxies, we used the inverse of this completeness function as a weighting factor to correct for the incompleteness.

Both LFs are affected by the completeness of the spectroscopic surveys as well as the IR observations. The BvdHC spectroscopic completeness is about $R = 16.27$ mag, and for the MBC, since we already correct for the incompleteness, the completeness limit can be extended to $R = 19$ mag. The spectroscopic completeness levels of the BvdHC and the MBC are both well above the detection limits in surface brightness for the two surveys (Beijersbergen et al., 2002a; Komiyama et al., 2002), suggesting our samples are not limited by the galaxy surface brightness. In the end, we need to estimate the IR completeness of samples selected in the optical for the spectroscopic surveys. We therefore need to relate the two spectral ranges. About 93% of our galaxy sample has a $S_{24}/S_R$ ratio smaller than 6.5, so we can use this value to set the upper limit of the $24\mu$m flux density corresponding to the completeness in $R$ band. With the linear correlation between $L_{IR}$ and $L_{24}$ given by Lagache et al. (2003), we find the completeness limits of the two spectroscopic surveys in total IR luminosity are $2.6 \times 10^9$ $L_\odot$ and $2.2 \times 10^8$ $L_\odot$, respectively. From section 2.2.3, we already know that the 80% detection limit of the $24\mu$m observations is about 0.33 mJy, which corresponds to a total IR luminosity of about $1.41 \times 10^8$ $L_\odot$. This detection limit is lower than the completeness levels set by spectroscopic surveys. Thus, the spectroscopic data are the primary limit on the range at which the LFs are free from the effects of incompleteness, with only $\sim 7\%$ incompleteness at
the lowest luminosities from the dispersion in IR properties.

In the above calculations of the completeness, we utilize the $S_{24}/S_R$ color distribution of our Coma galaxy samples. However, an issue with these samples is that they are optically selected and therefore they are likely to miss galaxies faint in the optical while bright in the IR. The IR/optical color distribution of our samples might be tilted towards lower values and we might underestimate the number of galaxies we missed in the calculation of the completeness limit. To check the color bias of our optically selected samples, we use the catalog of Karachentsev (2004), which provides a nearly complete listing of local galaxies within 10 Mpc. The catalog gives the $B$-band magnitude of each galaxy. We obtained the IRAS data for these galaxies, and therefore have a complete sample which is not constrained at the levels of interest by the optical and/or IR detection limits. We calculated the IR/optical colors $S_{24}/S_B$ of the normal galaxies (not dominated by AGN and below the LIRG luminosity range) in the sample and compared them with those of the BvdHC. In $B$ band, the BvdHC is complete down to $B = 17.5$ mag, and the IR completeness limit of $2.6 \times 10^9 L_\odot$ corresponds to a $S_{24}/S_B$ color of $\sim 14.6$. About 95±9% of galaxies in BvdHC have $S_{24}/S_B$ color smaller than this value, while in the Karachentsev’s catalog, this ratio is only slightly lower, 89±14%, among the galaxies with same $B$ band magnitude cutoff. That is, the small effect of the dispersion in infrared properties on the overall completeness is confirmed by the behavior of the complete sample of local galaxies.

In Fig. 2.5, we plot the LFs obtained from the two spectroscopic catalogs along with the completeness limits. The filled circles are results from the BvdHC and the open squares from the MBC. The dotted vertical line is the detection limit at 24 μm, the solid line is the limit of the MBC, and the dashed one is the limit of the BvdHC. The shapes of these two LFs are similar, but the LF from the MBC has an overall higher number density than that from the BvdHC. The reason for this difference is that Mobasher’s spectroscopic survey covered the whole cluster core, where the galaxy number density is the highest, but only a small portion of the outer region, while the BvdHC is based on a much larger area including both the core and the
Figure 2.5 (a) The IR luminosity function of the Coma galaxies. The filled circles and the open squares represent the LF from the BvdHC and the MBC, respectively. The error bars denote the statistical error. The three vertical lines are completeness limits: the dotted vertical line shows the completeness of the 24 μm detections, the solid vertical line shows the completeness of the MBC after correcting so far as possible for incompleteness, and the dashed vertical line shows the completeness of the BvdHC. The solid curves are the results of fitting the LF with the Schechter function and the dashed curves are the results of fitting with a two-power-law function with a fixed slope at the bright end. (b),(c),(d) and (e) are the error contours for the fitting parameters $L^\star_{IR}$ and $\alpha$. The contour levels are 1, 2 and 3 $\sigma$. The best-fitting parameters are indicated by the cross symbols.
outer region. Also, the LF from the MBC has a larger variance compared to the LF from the BvdHC because it is based on a smaller sample. Below the 24 \( \mu \text{m} \) detection limit, the loss of faint galaxies due to the limit of the IR observations causes quick drops in both LFs. Above this limit, the faint end slope of the MBC LF is steeper than the BvdHC LF, which is consistent with the different completeness limits of these two LFs.

To have a more quantitative comparison, we fitted these two LFs with some analytical functions. We discarded all the data points below \( 10^{42} \text{ ergs s}^{-1} \) and use a chi-square minimization method to find the best fitting parameters. Since we do not have many data points at the bright ends which are critical to determine \( L_{\text{IR}}^{*} \), it is important to constrain the fitting beyond the last bin for the non-detection of brighter galaxies. In order to incorporate this factor into the fitting, we calculate the integrated expected galaxy number brighter than the brightest galaxy actually observed for each trial function and use this number to estimate the probability of the non-detection. This integration is carried out from the brightest luminosity observed to a luminosity 2 orders of magnitude brighter. The results change little when we extend the integration to a higher upper limit. We include the chi-square of this non-detection into the total chi-square value for the minimization process. We first fitted the LFs with the Schechter function (Schechter, 1976) and the best-fitting parameters we found are:

\[
\alpha = 1.49^{+0.11}_{-0.11}; \quad \log(L_{\text{IR}}^{*}/L_{\odot}) = 10.48^{+0.48}_{-0.31}, \text{ for the MBC; } (2.1)
\]

\[
\alpha = 1.41^{+0.08}_{-0.08}; \quad \log(L_{\text{IR}}^{*}/L_{\odot}) = 10.49^{+0.27}_{-0.24}, \text{ for the BvdHC. } (2.2)
\]

The fitting results are shown as the solid curves in Fig. 2.5. The \( L_{\text{IR}}^{*} \) values of these two LFs are very similar. The parameters of the MBC LF have larger uncertainties due to the few data points at the bright end to constrain the fitting. It also has a steeper faint end slope than the LF for the BvdHC, which is in agreement with the fact that the MBC has been corrected for incompleteness at the faint end while the BvdHC has not. Considering this factor, we expect that the IR LF for the MBC
gives a better estimate of the faint end slope than the IR LF for the BvdHC.

A recent work of Pérez-González et al. (2005) studies the 12 µm LF from the 24 µm emission of galaxies using the Spitzer data in two deep field surveys, the Chandra Deep Field South and the Hubble Deep Field North. Their results, coming from galaxies in the general field, provide a good comparison to our LF in a dense cluster. Their LF for galaxies with \(0.0 < z < 0.2\) gives the Schechter parameter of \(\alpha = 1.23 \pm 0.07\) and \(\log(L_{12}^*/L_\odot) = 9.61 \pm 0.14\). With a relation between \(L_{IR}\) and \(L_{12}\) given by Takeuchi et al. (2005), \(\log L_{IR} = 1.02 + 0.972 \log L_{12}\), the \(L_{12}^*\) obtained by Pérez-González et al. (2005) corresponds to a total IR luminosity of \(\log(L_{IR}^*/L_\odot) = 10.36 \pm 0.14\), which is only slightly smaller than the value we got; the difference is well within the one sigma error. However, we found a somewhat steeper slope at the low luminosity end (at about 2\(\sigma\) significance). Pérez-González et al. (2005) suggest that incompleteness may have reduced the value of \(\alpha\) in their LF.

Rush, Malkan & Spinoglio (1993) obtained a LF using an all-sky 12 µm survey from the IRAS Faint Source Catalog, Version 2, and fitted it with a two-power-law function

\[
\Phi(L) = CL^{1-\alpha}(1 + \frac{L}{L^*\beta})^{-\beta}
\]

For the non-Seyfert subsample (the majority are normal galaxies, and about 5% are starburst galaxies), they found the best-fitting parameters are \(\alpha = 1.7\), \(\beta = 3.6\), and \(\log(L_{12}^*/L_\odot) = 9.8\). The average redshift of their non-Seyfert subsample is 0.013, comparable to our sample’s average redshift. Their result has a much steeper slope at the faint end compared to the Pérez-González et al. (2005) result and a little larger \(L_{12}^*\), which corresponds to \(\log(L_{IR}^*/L_\odot) = 10.55\). To make a fair comparison to their result, we tried to fit our LFs with the same two-power-law function. However, since the two-power-law function has too many free parameters and our small sample size gives poor constraints at the high luminosity end, a free fitting failed to give a reasonable result. We fixed the slope index at the high luminosity end to the best-fitting value given by Rush, Malkan & Spinoglio (1993) and kept \(L_{IR}^*, \alpha\) and the normalization free. The fitting gives very similar results to the Schechter fitting; the
The best-fitting parameters are

\[ \alpha = 1.48^{+0.12}_{-0.13}, \quad \log(L_{IR}^*/L_\odot) = 10.24^{+0.58}_{-0.39}, \quad \beta = 3.6 \ (fixed), \quad \text{for MBC}; \quad (2.3) \]

\[ \alpha = 1.38^{+0.10}_{-0.12}, \quad \log(L_{IR}^*/L_\odot) = 10.15^{+0.33}_{-0.31}, \quad \beta = 3.6 \ (fixed), \quad \text{for BvdHC}. \quad (2.4) \]

Again, we note that the MBC LF gives a larger value for the faint end slope and the BvdHC LF gives a more reliable estimate for the \( L_{IR}^* \) value. The MBC LF has a faint end slope a little flatter than Rush’s LF, and both LFs give \( L_{IR}^* \) values smaller than Rush’s \( L_{IR}^* \), with significance about one sigma.

Takeuchi et al. (2003) estimated the 60 \( \mu \text{m} \) LF of the local galaxies in the Point Source Redshift survey of IRAS. Based on this LF, Le Floc’h et al. (2005) calculate the total IR LF using the 60 \( \mu \text{m} \) total-IR IRAS correlation (e.g., Chary & Elbaz, 2001) and fit the IR LF with a double-exponential function. The fitting gives a faint end slope index of 1.23, \( \log(L_{IR}^*/L_\odot) = 9.25 \) and \( \sigma = 0.72 \), where \( \sigma \) is the parameter used to adjust the shape of the bright end of the LF (e.g., Le Floc’h et al., 2005). To compare to their result, we fitted our LFs with the same double-exponential function. Since neither of our LFs has enough data points at the bright end, we have to fix \( \sigma = 0.72 \), the value they gave. By doing this, we found a faint end slope index of 1.52 \( \pm 0.13 \) for the MBC LF and \( \log(L_{IR}^*/L_\odot) = 9.39 \pm 0.37 \) for the BvdHC LF. Again, the Coma IR LF has a very similar \( L_{IR}^* \) to the field LF. The faint end slope of Takeuchi’s LF is similar to that of Pérez-González et al. (2005), and they both are flatter than the Coma LF.

The comparisons between the Coma IR LFs and the IR LFs from the general field do not show significant variation of the \( L_{IR}^* \) value in different environments. However, a difference in the IR luminosity as small as the 0.3 mag (0.12 dex in luminosity) difference in \( M_{b_J}^* \) of cluster LF and field LF shown by De Propris et al. (2003), is beyond the capability of our study. The faint end slope of the Coma IR LF is steeper than that of Pérez-González et al. (2005) and Takeuchi et al. (2003), but a little shallower than that of Rush, Malkan & Spinoglio (1993). This comparison, although complicated by completeness issues, does not support a strong dependence of the shape of the IR LF on environment.
Despite the similarity in the shape of the Coma IR LF and the field IR LF, there might be a large portion of IR-inactive galaxies in the cluster compared with the field. Assuming a line-of-sight dimension of the Coma cluster of 13 Mpc, the BvdHC IR LF has a $\phi^*$ value - the space density at $L^*_{IR}$ - about 45 times larger than the $\phi^*$ value given by Pérez-González et al. (2005). Because $L^*_{IR}$ is far above our detection limits and those of the spectroscopic surveys (using the proportionality we found for local galaxies between optical and IR luminosities), our study should be complete there. With the same assumptions, we find that the average density at $L^*_{R}$ is $62.9 \pm 15.2$ times that in the field (Geller et al., 1997; Beijersbergen et al., 2002a). That is, the infrared-emitting galaxy density is only slightly less enhanced in the cluster than the optical galaxy density; there are few extra IR-inactive galaxies in the cluster.

A second approach to this issue is to examine a sample of field galaxies, and see how many would be detected in the infrared using the same selection method as we have used in the Coma Cluster. To implement this approach, we have again used the catalog of galaxies within 10 Mpc from Karachentsev (2004). We have compiled the IRAS data for galaxies down to $M_B = -17.5$ mag, the completeness limit of the BvdHC. If these galaxies were at the distance of the Coma Cluster, we find that $0.89 \pm 0.12$ would be detected above our $24 \mu$m limit, whereas the portion of infrared-detected galaxies in the BvdHC down to $M_B = -17.5$ mag is $0.56 \pm 0.05$. In agreement with our first estimate, there is only a small deficit of IR-active galaxies compared with the behavior in the field.

It is possible that this difference is partly due to the morphology-environment correlation of galaxies because our Coma sample has about 53% early-type galaxies while Karachentsev’s field galaxy sample only has about 17% early-type galaxies. So we divided our sample into early- and late-type subsamples and calculated the portion respectively. It turns out this portion just slightly increases in the late-type subsample compared with early-type subsample (57% vs. 55%). Therefore, the morphology-environment correlation can not account for the different portion of IR-active galaxies in Coma and the field.
2.3.4 Luminosity Function in Different Regions of the Cluster

Given the large coverage of the BvdHC, we can study the LFs in different regions of the cluster. Although the BvdHC is only complete down to $R = 16.27$, our previous results show the incompleteness probably will only make the faint end slope a little shallower. Since the completeness does not change very much across the cluster, incompleteness will not bias the comparison of LFs in the different regions. Following Beijersbergen et al. (2002a), we define the core region of Coma as the area with $r < 12' \, (\sim 0.3 \, \text{Mpc})$ centered at $\alpha = 12^h59^m43^s$, $\delta = +27^\circ58'14''$. We also define an annulus region outside of the core for $12' < r < 24' \, (\sim 0.6 \, \text{Mpc})$. Another interesting area is the group of galaxies around NGC 4839. It is the second densest region in the cluster and its X-ray emission suggests that the group is falling into the cluster (Neumann et al., 2001). The interaction between the group and the cluster may trigger star forming activities and therefore affect the IR LF. Therefore, we also select the circular region centered at NGC 4839 with the same radius as the Coma core region. We constructed LFs in these three regions. Apart from these regions, we took the rest of the area with MIPS coverage as a whole to be the outskirt region of the cluster. A sky map of these regions and all the galaxy members detected at $24 \, \mu\text{m}$ is shown in Fig. 2.1. There are 40, 56 and 28 galaxies detected in the IR in the Coma core, the surrounding annulus and the NGC 4839 region. In the outskirt region, 101 galaxies are detected. The two circular regions have an area of $0.13 \, \text{deg}^2$, the annulus region has an area of $0.38 \, \text{deg}^2$, and the outskirt has an area of about $2.41 \, \text{deg}^2$. Therefore, the ratios of the projected number density of infrared emitting galaxies in the Coma core, NGC 4839 region, annulus, and outskirt region are about 6:4:3:1. Even the lowest-density region has a space density of infrared galaxies roughly 40 times that in the field.

All the LFs were fitted with the Schechter function. The results are shown in Fig. 2.6 and the best fitting parameters are listed in Table 2.3.4. Because the small number statistics in small regions cause large uncertainties in the Schechter function fitting, simple comparisons of the best fitting parameters between these LFs
Figure 2.6 The LFs of the galaxies from the BvdHC in different regions of the Coma cluster and the corresponding 1, 2, 3 σ error contour maps for the Schechter function fitting. The vertical lines are the same as in Fig. 2.5 and the solid curves are the best fitting Schechter functions. The best-fitting parameters are indicated by the cross symbols on the error contour maps.
are ambiguous and need to be taken with care. The large uncertainties at the bright end of the LFs may cause very different fitting results for the exponential cut-off of the Schechter function and, therefore, unreliable $L_*$ values. However, interesting variations are apparent in other aspects of the LFs. The Coma core region has a flatter faint end and fewer luminous galaxies compared to the LFs in the other regions. In particular, when we compare it with the LF in the annulus region, which has similar total number counts as in the core, it is apparent that galaxies in the core region are lacking at the high luminosity end. A flatter faint end in the core indicates a lack of faint galaxies as well. The NGC 4839 and the annulus regions have similar number densities and their LFs are not very different from each other at the faint end. They both have a steeper faint end LF than the Coma core. At the bright end, it seems that the annulus region has more luminous galaxies than the NGC 4839 region does, but the difference is not significant given the uncertainties. The LF in the outskirt region is better constrained at both faint and bright ends due to its larger number of galaxies. Its faint end slope is steeper than the Coma core region but shallower than the annulus and NGC 4839 region. However, this faint end slope is largely constrained by the lowest point in our fitting process (the point at $L_{IR} = 10^{42.05}\,\text{ergs s}^{-1}$) and we suspect that incompleteness may have a more severe effect on this point in the outskirt region than in the other regions (e.g., because of the lower density of cluster members on the sky). If we discard this point in our fitting, we have a much steeper faint end slope with $\alpha = 1.52^{+0.16}_{-0.17}$. With this correction, there appears to be a trend of steeper faint end slope toward the outer regions of the cluster, similar to the behavior in the optical bands (Beijersbergen et al., 2002a; Beijersbergen & van der Hulst, 2003). Although the faint end slope may be questionable, the bright end of the LF in outskirt region is well constrained and has a very similar $L_*$ value as the total LF. In summary, we found that the Coma core region lacks both very faint and very bright galaxies compared with the outer regions. The NGC 4839 region does not show significant difference in the LF from that of the annulus region with similar number density. It is also worth noting that all the galaxies with $L_{IR} > 10^{44}\,\text{ergs s}^{-1}$ reside outside of the core region.
Table 2.1 The best fitting parameters of the LFs in different regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>$\log(L_{\text{IR}}^*/L_{\odot})$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4839 $r &lt; 12'$</td>
<td>$10.21^{+0.48}_{-0.47}$</td>
<td>$1.34^{+0.30}_{-0.33}$</td>
</tr>
<tr>
<td>core $r &lt; 12'$</td>
<td>$9.44^{+0.27}_{-0.37}$</td>
<td>$0.99^{+0.34}_{-0.52}$</td>
</tr>
<tr>
<td>$12' &lt; r &lt; 24'$</td>
<td>$10.68^{+0.51}_{-0.40}$</td>
<td>$1.42^{+0.20}_{-0.19}$</td>
</tr>
<tr>
<td>outskirt</td>
<td>$10.50^{+0.36}_{-0.36}$</td>
<td>$1.32^{+0.11}_{-0.14}$</td>
</tr>
</tbody>
</table>

All the LFs in the Coma cluster calculated above are actually the 2-D projection of the real LF, and therefore will be affected by projection effects (Valotto, Moore & Lambas, 2001; Beijersbergen et al., 2002b). The projection effect is most serious in the core region and it will probably make the faint end slope steeper. That is, the flat faint end slope of the core region may become even flatter after deprojection. On the other hand, the projection effect will make the lack of bright galaxies in the core region more severe. Fig. 2.1 also shows the galaxies with $L_{\text{IR}} > 10^{43.3}$ ergs s$^{-1}$ as star signs. They are more or less uniformly distributed in the whole region, without any concentration in the core region or the NGC 4839 region. The deprojection from this 2-D distribution will make the bright galaxies move further outward.

The interpretation of the galaxy population variations across the cluster only from the change of the shape of the LFs may be misleading without knowledge of the fraction of galaxy members detected in the IR. We already know that the overall fraction of optical galaxy members detected at 24 $\mu$m is about 44% for the BvdHC. This fraction is smallest in the core region, at about 37 $\pm$ 7%, and it is about 46 $\pm$ 4% in the outer region. The difference is not very significant considering the large statistical errors. If we only consider the fraction for the galaxies brighter than the completeness of the BvdHC, the difference is even smaller, with the fraction about 54 $\pm$ 9% in the core and 57 $\pm$ 5% in the outer region. Also, a correction for the projection effect, if possible, would make the difference even smaller. Thus, the fraction of the galaxy members detected in the IR does not change very much across the cluster, providing a uniform foundation for the comparison of the shape of the
2.3.5 Contribution of the Different Types of Galaxies to the Total LF

Since the BvdHC also has morphology information for each galaxy, we can study the contribution of early type (E/S0) and late type galaxies to the total LF. In Fig. 2.7, we plot the LF of the late type galaxies and early type galaxies along with the total LF for comparison. The late type galaxies here include all spirals and irregulars.

From Fig. 2.7, we find that the early type galaxies make a larger contribution to the number counts of the LF than the late type galaxies at $L_{IR} < 10^{43}$ ergs s$^{-1}$, while the late type galaxies dominate the bright end of the total LF. This behavior indicates that although the late-type galaxies dominate the bright population, there are more faint early-type galaxies than faint late-type galaxies. However, we note that at the faint end, it is possible to misidentify a spiral as an S0 galaxy and, therefore, the number of early-type galaxies may be overestimated. We fit the LF of late type galaxies with the Schechter function, and the best-fitting parameters are

$$
\alpha = 1.15^{+0.24}_{-0.28}; \quad \log(L_{15}/L_{\odot}) = 10.44^{+0.50}_{-0.42} \quad (2.5)
$$

This LF has a flat faint end and a similar $L_{15}$ to the total LF. Although the $\alpha$ we derive would have a higher value if the incompleteness were taken into account, it is still smaller than the index of the total LF that is affected by the incompleteness in the same way. The steeply rising faint end of the total LF is boosted by the increasing number of early type galaxies with low IR luminosity.

Using ISO data, Pozzi et al. (2004) deduced the 15 $\mu$m LF of the European Large Area ISO survey (ELAIS). The index of the faint end slope they found for the spiral galaxies with $z < 0.2$ is very close to our value, with $\alpha = 1.10 \pm 0.25$.

Using the LFs of early type and late type galaxies, we can calculate the surface density of the total IR luminosity of these two groups down to the detection limit of the 24 $\mu$m observations. It turns out that the surface density of IR luminosity contributed by early type galaxies is only about 15% of the total surface density. Therefore, the early type galaxies make a rather small contribution to the total IR LFs.
Figure 2.7 The contributions of the early- and late-type galaxies to the LF. The galaxies are all from the BvdHC. The vertical lines are the same as in Fig. 2.5. The total LF and the LF of the late-type galaxies are fitted with the Schechter function, and the results are shown as the solid curves.
luminosity of the cluster, but they make a significant contribution to the number counts of faint galaxies and therefore affect the shape of the LF.

2.3.6 Measuring the SFR from the IR LF

Since IR luminosity is a good tracer for star-forming activity, the IR LF allows us to estimate the total SFR of the cluster. Although this chapter is the first work reaching such a depth in the IR luminosity of the Coma galaxies, which means detecting a lower level of star forming activities, there are other works measuring the SFR at a higher level by measuring the ionization lines. Iglesias-Paramo et al. (2002) used a deep wide field Hα survey of the Coma cluster to deduce the Hα LF. They detected 22 sources in the Hα band. Five of them are not in either the BvdHC or the MBC. We detected all the rest of them at 24 μm and hence obtained the $L_{IR}$ for them. Using the conversion formula given by Kennicutt (1998b)

$$SFR(\, M_{\odot} \text{yr}^{-1}) = 4.5 \times 10^{-44} L_{IR}(\text{ergs s}^{-1})$$

we deduce the SFR for these objects and compare them with the SFR given by Iglesias-Paramo et al. (2002). The result is shown in Fig. 2.8. The two results are basically consistent, but the SFRs measured from $L_{IR}$ are larger on average, and this discrepancy is more pronounced in the galaxies with higher SFR. This discrepancy was also found by Kennicutt (1998a) when he compared the SFR deduced from the measurement of $L_{IR}$ and the Brγ emission line. He justified the discrepancy by citing effects of extinction and the heating of dust by longer lived stars than those exciting the emission lines. These arguments are also applicable to our case.

The Hα survey has a smaller area coverage than the MIPS observations and is much less complete than the IR survey. For the 18 objects detected with both Hα and 24 μm emission, 16 have $L_{IR} > 10^{43}$ ergs s$^{-1}$, but in our sample we have 40 sources with $L_{IR} > 10^{43}$ ergs s$^{-1}$. Using the Hα LF, Iglesias-Paramo et al. (2002) showed the SFR density of the Coma cluster to be $1.36 \, M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$ by integrating the best fitting function over the whole range of luminosities and assuming the radius of the Coma cluster to be 6.5 Mpc. In our case, we calculate
Figure 2.8 Comparison of the SFR measured from $L_{IR}$ and Hα luminosity.
the total IR luminosities from the best fitting Schechter functions in the range of $10^{42} \text{ ergs s}^{-1} < L_{IR} < 10^{45} \text{ ergs s}^{-1}$. The upper limit corresponds to the brightest galaxies actually observed and the lower limit excludes the part of the LF with serious incompleteness. The formula we used to convert the IR luminosity to SFR will also become problematic below this lower limit. Fortunately, from the shape of the LF, the galaxies in the $10^{42} \text{ ergs s}^{-1} < L_{IR} < 10^{45} \text{ ergs s}^{-1}$ luminosity range dominate the total luminosity and there is only a small difference between our integration and an integration over the whole luminosity range. The total SFRs of the cluster, deduced from the best fitted Schechter functions of the MBC and the BvdHC IR LFs, are $24.48 \, M_{\odot} \text{yr}^{-1} \text{Mpc}^{-2}$ and $11.41 \, M_{\odot} \text{yr}^{-1} \text{Mpc}^{-2}$ respectively. The lower value given by the BvdHC LF is because the BvdHC covers more outskirt regions where the IR galaxy densities are relatively smaller. The BvdHC is also less complete than the MBC, and thus underestimates the contribution from the faint IR galaxies. The total SFR in the 8.5 Mpc$^2$ area of the BvdHC survey and MIPS observation is about $97.0 \, M_{\odot} \text{yr}^{-1}$.

If we assume the region we observed in the IR has the same line-of-sight dimension as assumed by Iglesias-Paramo et al. (2002), e.g., $\sim 13$ Mpc, these two IR LFs give SFR densities of about $1.88 \, M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$ and $0.88 \, M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$. The SFR density deduced from the H$\alpha$ LF is smaller than the value given by MBC but larger than that given by BvdHC. However, considering the Iglesias-Paramo et al. (2002) survey also covers mostly the central region, we calculate the SFR from the BvdHC in the region of the H$\alpha$ survey coverage and obtain a larger SFR of $1.7 \, M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$. Therefore, the IR LF gives a more complete estimate of the total SFR of the cluster than the available H$\alpha$ LF. If we adopt $0.88 \, M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$ as the general SFR density of the Coma cluster, we find it to be about 60 times larger than the SFR density of the general field (Pérez-González et al., 2005). This difference is comparable to the difference in $\phi^*$ between these two LFs. Thus, the higher SFR density in the Coma cluster is mainly due to the overall higher IR galaxy density in the cluster than in the field, not to any differences in the shape of the IR LF.
2.4 DISCUSSION

Despite the evidence that the SFRs of galaxies are different in cluster and field regions (Gómez et al., 2003; Balogh et al., 1998), the comparison of our IR LFs of the Coma cluster with the IR LFs of field galaxies does not support a strong dependence of the shape of the IR LF on environment. However, the measurements of the SFR in Gómez et al. (2003) and Balogh et al. (1998) are based on the bright galaxies ($R < 17$ mag) with ionizing emission lines, which approximately corresponds to the galaxies with $L_{IR} > 10^{43}$ ergs s$^{-1}$. In fact, Gómez et al. (2003) found that the correlation of the SFR and the environment is most noticeable for the strongly star-forming galaxies. So, it is very possible that our IR LF, because it is not well constrained at the bright end, does not show a difference from the field LF simply because of the lack of enough very luminous IR galaxies in the small sample to draw any meaningful conclusions. In any case, the similar $L_{IR}$ of the Coma cluster to that of the general field LF, as well as the fairly good fit with similar functions up to $L_{IR} \approx 10^{44}$ ergs s$^{-1}$, are evidence against a strong correlation between the global SFR for infrared-bright galaxies and their environment.

Explanations for this behavior may come from some recent works by Balogh et al. (2004a,b). Balogh et al. (2004a) studied SFRs of galaxies in group and low-density environments and found that although the fraction of the star-forming galaxies is very sensitive to the galaxy density, the distribution of $W_0$(H$_\alpha$), the equivalent width of H$_\alpha$, in the star-forming galaxies is independent of environment. Balogh et al. (2004b) studied the color distributions of galaxies in different environments including the typical environment of a cluster core. After dividing their sample into red and blue components in several luminosity bins, they found that the ratio of these two components is a strong function of the local density but the mean value and the shape of the color distribution of each component are nearly independent of environment. They proposed that most star-forming galaxies today evolve independently from their environment. Both these works suggest that interactions of the galaxies, probably happening in a very short time scale ($\tau < 0.5$ Gyr), may be
responsible for triggering star formation and leave the galaxies to evolve afterwards independently from their environments. Our results appear to agree well with these works and push the independence of the global SFR of IR galaxies on environment to an even lower level of SFR.

It is also possible that the lack of difference between the shape of the Coma LF and LFs from the general field results in part from the effects of averaging. First, the general field also includes galaxies in clusters. Secondly, and more importantly, the galaxies in the outskirt region have evolved largely in the field and are only beginning to fall into the cluster. However, their LF of dominates the total LF of the cluster at luminosities above $L_{IR}^*$. Since the outskirt LF has a similar $L_{IR}^*$ and a little smaller $\alpha$ compared with the total LF, it is possible that the contribution from the dense region mostly goes to the faint end of the LF where we do detect an environmental effect. The early-type galaxies also contribute greatly to the number counts in this range. However, exact comparisons are complicated by the incompleteness. It has been reported that there is a group of dwarf galaxies contributing to the steeply rising faint end slope of the optical and near-IR LF in the Coma cluster (Bernstein et al., 1995; Secker & Harris, 1996; Trentham, 1998; Mobasher & Trenthan, 1998; De Propris et al., 1998). These dwarf galaxies are beyond our completeness limit ($R < 19$ mag) and are not the contributors of the steeply rising faint end of the IR LF.

Although we did not obtain any direct evidence of a correlation of SFR and environment in the comparison of the shape of the Coma IR LF and the general field IR LF, there is some evidence of a change in SFR with the environment inside the cluster. We found that although the fractions of the galaxy members detected at 24 $\mu$m do not change very much across the cluster, the LF in the core region has a flatter faint end and is lacking the bright IR galaxies compared to the LF in the outer region. In addition, all the galaxies with $L_{IR}^* > 10^{44}$ ergs s$^{-1}$ lie outside of the core region. This behavior shows that the strongest star-forming activity happens in the lower density region of the cluster. This is consistent with the speculation that galaxies in a crowded environment lack gas and dust due to the interactions between
the galaxies or between the galaxies and the cluster potential well and therefore can not support a large SFR. The flatter faint end in the core region, on the other hand, suggests a deficiency of faint IR galaxies as well.

Mori & Burkert (2000) studied the gas stripping of dwarf galaxies by ram pressure in the cluster and found that dwarf galaxies will lose virtually all of their gas instantaneously if their core mass is smaller than a critical mass ($M_{cr}$). For the Coma cluster, $\log(M_{cr}/M_\odot)$ is about 10.9 at the median distance of the cluster galaxies. This value increases to about 11.7 and 12.9 at $r = 24'$ ($\sim 0.6$ Mpc) and $r = 12'$ ($\sim 0.3$ Mpc). Mori & Burkert (2000) would argue that galaxies with core masses smaller than these values will lose all of their gas very quickly ($\tau \approx 10^8$ yr). Thus, even if the triggering of the star-forming activities in these galaxies happens in the galaxy group before they fall into the cluster core, gas stripping will prohibit them from keeping up such activities by depriving them of fuel.

However, such an effective stripping contradicts our result. The faint IR galaxies in our LFs ($41.9 < \log L_{IR} < 42.6$, about the range of the lowest two points in the LFs above the incompleteness) have $R \approx 15$ mag on average. The early type galaxies in the Coma cluster usually have a stellar mass-to-light ratio smaller than 8 (Jørgensen, 1999). The stellar mass is comparable to the core mass of a galaxy, so we can use this ratio to estimate the core mass of a galaxy from its luminosity. Considering that faint galaxies usually have relatively large M/L, we take M/L $\approx 20$ as a conservative upper limit for these galaxies. We also assume all cluster galaxies have similar M/L ratios. With this ratio and the average $R$ magnitude of the faint IR galaxies, we obtained the upper limit of the mass for these galaxies as $\log(M/M_\odot) \approx 11.0$. This mass is smaller than the critical mass for gas stripping at $r < 24'$ ($\sim 0.6$ Mpc), which means most of the faint galaxies in this region should already have lost all of their gas, so we would expect a drop in the number counts of the IR LF. However, the IR LF in the annulus region does not show such a drop, although we do see a flattening of the slope in the core region. If this flattening of the faint end slope is the result of the total gas stripping, there seems to be a factor of ten discrepancy between the critical mass Mori & Burkert deduced and the one suggested by the IR
LFS. A smaller critical mass for these IR galaxies is also consistent with the small difference we found in the Coma IR LF and the IR LF of general field. Mori & Burkert (2000) also pointed out that there were some issues they did not consider in their simulation that may affect the critical mass, e.g., the heating of the gas from star forming activities. For the IR galaxies, this effect may be very important because it would lower the critical mass and provide a possible explanation of why these faint galaxies still have star forming activities. An underestimated M/L ratio can also contribute to this difference. However, to resolve the discrepancy in this way, the M/L would need to be as high as 100, which seems unlikely.

We also observed a high ratio of early-type galaxies in the core region of the Coma cluster, ~80%; this ratio drops to about 50% for the other regions. The change of the shape of IR LF in the core region is also possibly caused by a morphology-environment correlation rather than a SFR-environment correlation.

2.5 CONCLUSIONS

Using MIPS 24 μm observations and two spectroscopic surveys of the Coma cluster, we present the IR LF of the cluster. The shape of the Coma cluster LF does not differ from that of the general field significantly. The $L^{*}_{IR}$ value of our LF is very similar to those given by Rush, Malkan & Spinoglio (1993) and Pérez-González et al. (2005), which are both based on surveys of general fields. The faint end slope of the Coma cluster is shallower than the slope of Rush, Malkan & Spinoglio (1993) but steeper than that of Pérez-González et al. (2005) and Takeuchi et al. (2003), again indicating little variation between field and cluster. In addition, the overall proportion of IR-active galaxies in the cluster is only slightly less than in the field. Thus, the overall pattern of star formation in cluster members is surprisingly similar to that in the field, despite an increased galaxy space density by an average factor of ~40.

However, in the cluster core where the galaxy density is six times higher still, we found a shallower faint end slope and a smaller $L^{*}_{IR}$ compared to the outer region
of the cluster, which indicates a decrease in the number of faint IR galaxies as well as in the very bright ones. The IR-bright galaxies are distributed around the outer region of the cluster. All the galaxies with $L_{IR} > 10^{44}$ ergs s$^{-1}$ lie outside of the core region, e.g., $r > 340$ kpc. No special feature of the IR LF was found in the NGC 4839 region.

In determining the LF of different morphological types, we found that early type galaxies only make about a 15% contribution to the total IR luminosity density, but they dominate the number density at the low luminosity end. The global SFR density in the cluster is about $0.88 \, M_\odot \, yr^{-1} \, Mpc^{-3}$ and the total SFR in the 8.5 Mpc$^2$ area of the central cluster is about $97.0 \, M_\odot \, yr^{-1}$. 
3.1 INTRODUCTION

In the last chapter, we studied the IR LF in the Coma cluster and compared it with the local field IR LF. In this chapter, we move to a rich cluster MS 1054-03 at a much higher redshift \((z = 0.83)\) to look for the evidence of evolution. MS 1054-03 is bright in the X-ray and has a mass comparable to the Coma Cluster (Jee et al., 2005a, \(1 \times 10^{15} \, M_\odot\)). Tran et al. (2007) carried out an extensive spectroscopic survey in this cluster and obtained redshifts for about 150 cluster members. The large spectroscopically confirmed cluster sample, which is rare at this redshift, makes MS 1054-03 a great target for studying the evolution of IR LFs in rich clusters. Recently, Marcillac et al. (2007) studied the IR properties of another high redshift cluster RXJ0152.7-1357 (RXJ0152 hereafter) at a similar redshift. The study of MS 1054-03, along with the results from RXJ0152, will provide a good constraint on the IR LF in rich clusters at this redshift and make a good comparison with IR LF in Coma.

The chapter is organized as follows. In sect 2.2 and 2.3, we describe the observation and data analysis. In sect 2.4, we present the IR LF and additional IR properties of the cluster. We also compare the IR LF of MS 1054-03 with the Coma IR LF and the field IR LF at the same redshift. In sect 2.5, we discuss the results and we summarize them in sect 2.6.
3.2 DATA

3.2.1 Observations

The MS 1054-03 field was observed at 24 μm by MIPS on June 2005 in photometry mode. The total MIPS field has a size of 5′ × 10′. The integration time is about 3600 second pixel$^{-1}$ in the central 5′ × 5′ region, and is about 1200 second pixel$^{-1}$ in the rest of the field. The data were processed with the MIPS instrument team Data Analysis Tool (Gordon et al., 2005; Engelbracht et al., 2007) and scan-mirror-dependent flats were used. The final mosaic has a pixel scale of \(~1.25″\) pixel$^{-1}$ and a point-spread function (PSF) with FWHM \(~6″\).

The spectroscopic data were obtained with the Low Resolution Imaging Spectrograph on the Keck Telescope based on the wide-field images taken by the Hubble Space Telescope (HST) WFPC2 in F606W and F814W (van Dokkum et al., 2000; Tran et al., 2007). They cover the 5′ × 5′ central region of the cluster and yield more than 300 redshifts, adding to a total of more than 400 galaxies with previously known redshifts. Among them, 144 sources with reliable redshifts are identified as cluster members. The spectroscopic survey is about 50% complete down to $I_{814}=22$ mag and it is mostly coincident with the central deep region of the 24 μm observations.

Along with the HST photometric data, $UBV$ and near-IR $J_{s}HK_{s}$ data in a similar region of this field were obtained with FORS1 and ISAAC on the Very Large Telescope (VLT) as the part of the Faint InfraRed Extragalactic Survey (FIRES). From these data a K-band selected catalog with 1859 sources was extracted. The photometric catalog is presented in Förster Schreiber et al. (2006) and it is 90% complete to $K_{s,AB} \approx 24.1$ mag. Photometric redshifts ($z_{ph}$) were derived from this catalog using the method presented by Rudnick et al. (2001, 2003). The photometric redshifts are less accurate than the spectroscopic redshifts ($z_{sp}$), with $\delta z/(1+z_{sp}) = 0.074$ for $z < 1$, but the FIRES catalog is much deeper than the spectroscopic data. Therefore, we use photometric redshifts to supplement the spectroscopic catalog.
3.2.2 Source Detection and Completeness

Since the cluster members are not resolved at 24 μm, we used DAOPHOT II (Stetson, 1987), a package for PSF fitting photometry, to detect sources and measure their fluxes. We follow the same strategy as described in Papovich et al. (2004). Because of the significant zodiacal IR emission at low ecliptic latitudes, the 24 μm background level in the MS 1054-03 field is fairly high, averaged at about 40 MJy sr$^{-1}$. Even with more than 3000 seconds of integration time, the detection limit is not as deep as in some low background regions. By adding artificial point sources into the image, we found a 80% completeness limit at about 80 μJy. In the left panel of Fig. 3.1, we plot the completeness of the 24 μm detections vs. the flux density. The completeness drops from 80% at about 80 μJy to only 50% at 50 μJy. We detected about 240 sources with $f_{24} > 50$ μJy in the central region that is covered both by IR and optical data, about 180 of them with $f_{24} > 80$ μJy.

3.3 ANALYSIS

3.3.1 Spectroscopically Confirmed Cluster Members

We select the galaxies with 0.81 < $z_{sp}$ < 0.85 as cluster members, which corresponds to a 3-σ line-of-sight velocity dispersion of 1156 ± 82 km s$^{-1}$ (Tran et al., 2007). We select 144 cluster members out of around 400 galaxies with spectroscopic data. Since the spectroscopic data are only 80% complete down to $I_{814} = 21$, we need to correct for the incompleteness to avoid bias. In the right panel of Fig. 3.1, we plot the ratio of galaxies with successful spectroscopic redshift measurements among all galaxies in the imaging data as a function of $I_{814}$. We use this curve to correct for the spectroscopic incompleteness when calculating the IR luminosity function (LF).

3.3.2 Photometrically Identified Candidate Cluster Members

Even though we can roughly correct for the spectroscopic incompleteness of our IR sample using the completeness curve, about one third of the IR luminous members
Figure 3.1 The completeness of the IR and spectroscopic surveys. The left panel is the completeness at 24 μm. The sample is about 80% complete down to $f_{24} \approx 80$ μJy. The right panel is the completeness of the spectroscopic survey as a function of $I_{814}$ magnitude. The dashed vertical line is approximately the 90% completeness limit of the photometric survey.
have a magnitude of $I_{814} > 22$, where the incompleteness is larger than 50% and a simple correction can be erroneous. In addition, the $I_{814}$ band selection is biased toward the blue galaxies and may miss some dusty star forming galaxies with extreme red colors. This would make the incompleteness correction based on the $I_{814}$ magnitudes inadequate. Therefore, we also use photometric redshifts to help select the cluster member sample.

Because most of the cluster members have $I_{814} - K_{s,AB} \approx 1.0$, the 90% completeness limit ($K_{s,AB} \approx 24.1$) of the photometric survey corresponds to $I_{814} \approx 25.1$, indicated as a dashed vertical line in the right panel of Fig. 3.1. This limit is about three magnitudes deeper than the spectroscopic survey. However, the uncertainties in the photometric redshifts are large ($\delta z \sim 0.14$ at the cluster redshift $z_{cl} = 0.83$) compared to those of the spectroscopic redshifts and their distribution is non-Gaussian. Because of this, a simple cut in $z_{ph}$ is not effective to select cluster members and would cause large contamination. Therefore, we use the probability curve of the $z_{ph}$ deduced from Monte-Carlo simulations (Rudnick et al., 2003) to select the cluster members. If the integrated probability of cluster membership for a galaxy with $K_{s,AB} < 24.1$ over the range of $z_{cl} - 0.14 < z < z_{cl} + 0.14$ is larger than 60% (normalized by the total probability), we designate this galaxy as a cluster member. The 60% threshold is selected to best balance between maximizing correct selections and meanwhile minimizing incorrect selections when applied to galaxies with spectroscopic measurements. When the threshold is set to 70%, the incorrect selection drops from 17% to 15%, but the correct selection also drops from 83% to 73%. Altogether, we select 454 candidate cluster members from 1858 sources in this region, three times more than the members selected by spectroscopic redshifts alone.

The performance of the photo-z selection is expected to decrease for faint $K$ band sources. As the uncertainties in the fluxes increase, the internal uncertainties in the photo-z increase too. Therefore, the probability curve of $z_{ph}$ broadens and its integrated value in the same redshift range will be lower. As a result, more faint galaxies will be rejected given the same threshold.
3.3.3 Crossmatch between Optical/NIR Sources and 24 μm Sources

In a crowded field such as MS 1054-03, we need to be careful in crossmatching between the Optical/NIR sources and the 24 μm sources. The optical and NIR images have an absolute astrometric accuracy of < 0′′.5 (Förster Schreiber et al., 2006). The astrometry of the 24 μm image is calibrated using the USNO-B1.0 catalog (Monet et al., 2003), and has an accuracy of rms < 0′′.6. However, due to the rather large FWHM (∼ 6″) of the 24 μm image, this accuracy in position can only be achieved for bright IR point sources, namely with a 24 μm flux > 100 μJy. For faint sources, as shown by our simulations, the average uncertainties of the positions are about 1″. We use a radius of 2″ (∼ 15 kpc at z = 0.83) to correlate the optical/NIR cluster members with their IR counterparts. This matching radius accounts for the possible displacement between the optical/NIR and 24 μm brightness centroids, the astrometric uncertainties and local astrometric offsets. If more than one counterpart is found in this radius, the nearest one is picked. We estimate the chance of random matches by randomly re-distributing the IR sources and matching them with the same criteria. We found only 4.8 ± 0.9% random matches. Using this criterion, we obtain the preliminary matching lists for both spectroscopic and photometric samples. We then carefully check each individual source by eye to exclude any apparent mis-identification, e.g., contamination from nearby bright IR sources. Finally, we identify 19 sources selected by spectroscopic redshift and an additional 15 sources selected by photometric redshift with IR emission ≥ 50 μJy. We refer to those 19 IR galaxies with spectroscopic redshifts as our spectroscopic sample, and those 19 sources plus 15 sources selected by photometric redshifts as our combined sample. For the 15 photometrically selected galaxies, we will use the cluster redshift as their redshifts in the following study. In addition, for most of these IR galaxies, we use the IRAC data kindly provided by the FIRES group to confirm the crossmatching.
3.3.4 Incompleteness Correction

Many of the sources in our final samples are fainter than the 80% completeness limit of the spectroscopic and 24 µm surveys. It is therefore necessary to correct for the incompleteness of both surveys to have an unbiased number count. To do this, we use the inverse of the completeness curves in the 24 µm and \( I_{814} \) bands given in Fig. 3.1 as the weighting functions to calculate LFs. For the 19 galaxies in the spectroscopic sample, we correct both for the spectroscopic incompleteness and 24 µm incompleteness according to each galaxy’s \( I_{814} \) magnitude and 24 µm flux density. All the galaxies in the combined sample are brighter than the 90% completeness limit of the photometric survey, so we only correct for the incompleteness in the 24 µm detections.

The incompleteness correction can be very large (see Fig. 3.1), especially for faint galaxies in the spectroscopic sample. It boosts the number density up to 3 times at the faint end of the luminosity function. We will discuss the effect of the incompleteness correction in §4.1.

3.3.5 Deduction of the Total IR Luminosity

To maintain continuity with Bai et al. (2006), we use their method to determine total IR luminosities. We shift the SEDs given by Devriendt et al. (1999) to the cluster redshift to deduce the rest-frame total IR luminosities (\( L_{IR}, \lambda = 8 - 1000\) µm) of the galaxies. Those SEDs are based on a sample of nearby galaxies and include three types: normal spirals, luminous IR galaxies (LIRGs) and ultraluminous IR galaxies (ULIRGs). The deduction of the total IR luminosity depends primarily on the ratio between the rest frame \( L_{IR} \) and the 13 µm luminosity (\( L_{24/(1+z)} \sim L_{13} \)) for each galaxy. The template SEDs indicate that this ratio is almost constant within each type, but increases by three times from normal spirals to ULIRGs (see Fig. 3.2). Since the \( K_s \) band (similar to rest frame \( J \) band) flux and 24 µm (similar to rest frame 13 µm) flux are good indicators of the old and star-forming components of galaxies respectively, the color between these two bands (\( f_{K_s}/f_{24} \)) can be used to...
Figure 3.2 The rest frame $L_{IR}/L_{24/(1+z)}$ ratio as a function of $K_s$ - 24 color. The open symbols are the data points deduced from the template SEDs given by Devriendt et al. (1999). Upward triangles, square, and stars denote the normal spirals, LIRG and ULIRGs. The filled circle and the downward triangle are the results of the interpolation of the galaxies of the spectroscopic and combined samples from their $K_s$ - 24 colors. The small dots are the $L_{IR}/L_{24/(1+z)}$ ratio of galaxies deduced from the second method in §3.5.

distinguish different types of galaxies. In Fig. 3.2, we show the correlation between $L_{IR}/L_{24/(1+z)}$ and $f_{K_s}/f_{24}$ for each type of SED. The open stars are ULIRGs, the square is a LIRG, and the open triangles are normal spirals. We interpolate the $f_{K_s}/f_{24}$ colors of the cluster members linearly into the correlation given by template SEDs and get a $L_{IR}/L_{24/(1+z)}$ ratio for each galaxy. The filled circles are the spectroscopic sample and the filled upside down triangles are the combined sample. According to their $f_{K_s}/f_{24}$ colors, about one third of the galaxies in our spectroscopic sample and about half in the combined sample have ULIRG or LIRG SEDs. Using the $L_{IR}/L_{24/(1+z)}$ ratio given by the interpolation, we deduce the total IR luminosity from the 24 µm flux of each galaxy in our samples (see Table 3.1).

The method we used above basically assumes that there is no intrinsic variation in SEDs for galaxies with same $f_{K_s}/f_{24}$ colors and that the templates represent a
complete sample of IR galaxies up to $z \sim 0.8$. However, both of these assumptions are questionable, given the large variation of IR SEDs among star forming galaxies and the possible evolution of galaxy properties from $z = 0.8$ to $z = 0$. To estimate the uncertainties of $L_{IR}$ caused by the limitations of the SED templates, we used a different set of SEDs from Dale & Helou (2002) and a strategy described in Marcillac et al. (2006b) to deduce the total IR luminosities. Marcillac et al. (2007) use this method to deduce the total IR luminosities in another cluster, RXJ0152, at a similar redshift. We plot the deduced $L_{IR}/L_{24/(1+z)}$ ratio of galaxies vs. $f_{K_s}/f_{24}$ colors as small dots in Fig. 3.2 for comparison, though the analysis itself does not depend on $f_{K_s}/f_{24}$ color. This method gives a slightly smaller typical $L_{IR}$ compared to the first method, by a factor of $0.9 \pm 0.3$ on average. The difference is more pronounced for those galaxies with a smaller $f_{K_s}/f_{24}$ color ($< -1$), where the difference is up to a factor of 2, and may be caused by the mis-classification of SED types with only one color. To exclude this possibility, we compared the multi-wavelength photometry of sample galaxies (optical + NIR + IRAC + MIPS 24 $\mu$m ) with the model SEDs from Devriendt et al. (1999) and confirmed they do have LIRG/ULIRG type SEDs. The difference, caused by the wide SED variations from galaxy to galaxy, is typical of methods to estimate total IR luminosities from 24 $\mu$m measurements (e.g., Papovich & Bell, 2002; Dale et al., 2005). It does not affect the results of this chapter significantly. If we do not consider the uncertainties caused by the SED fitting, the error of $L_{IR}$ is dominated by the flux uncertainties at 24 $\mu$m, which are typically 50% for the galaxies studied in this chapter.
Table 3.1. Cluster galaxies with 24 \( \mu \text{m} \) emission

<table>
<thead>
<tr>
<th>ID(^a)</th>
<th>( K_{s,AB}^a ) (Mag)</th>
<th>( f_{24}^b ) (( \mu \text{Jy} ))</th>
<th>( \log L_{1\text{R}} ) (ergs s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectroscopic Sample</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1140</td>
<td>20.24± 0.06</td>
<td>363± 33</td>
<td>45.37</td>
</tr>
<tr>
<td>553</td>
<td>19.83± 0.02</td>
<td>317± 30</td>
<td>45.13</td>
</tr>
<tr>
<td>1663</td>
<td>20.51± 0.05</td>
<td>140± 28</td>
<td>44.69</td>
</tr>
<tr>
<td>791</td>
<td>21.90± 0.09</td>
<td>76± 44</td>
<td>44.68</td>
</tr>
<tr>
<td>102</td>
<td>19.86± 0.06</td>
<td>184± 32</td>
<td>44.68</td>
</tr>
<tr>
<td>909</td>
<td>20.76± 0.01</td>
<td>116± 24</td>
<td>44.63</td>
</tr>
<tr>
<td>1316</td>
<td>20.91± 0.01</td>
<td>96± 26</td>
<td>44.52</td>
</tr>
<tr>
<td>1200</td>
<td>20.07± 0.07</td>
<td>107± 36</td>
<td>44.45</td>
</tr>
<tr>
<td>581</td>
<td>21.61± 0.03</td>
<td>62± 30</td>
<td>44.43</td>
</tr>
<tr>
<td>1357</td>
<td>20.86± 0.04</td>
<td>82± 25</td>
<td>44.32</td>
</tr>
<tr>
<td>695</td>
<td>20.85± 0.02</td>
<td>76± 22</td>
<td>44.29</td>
</tr>
<tr>
<td>874</td>
<td>20.68± 0.04</td>
<td>68± 28</td>
<td>44.25</td>
</tr>
<tr>
<td>211</td>
<td>19.97± 0.02</td>
<td>63± 31</td>
<td>44.22</td>
</tr>
<tr>
<td>725</td>
<td>21.50± 0.08</td>
<td>51± 34</td>
<td>44.21</td>
</tr>
<tr>
<td>170</td>
<td>21.14± 0.06</td>
<td>59± 25</td>
<td>44.19</td>
</tr>
<tr>
<td>107</td>
<td>20.04± 0.01</td>
<td>56± 31</td>
<td>44.17</td>
</tr>
<tr>
<td>1108</td>
<td>20.64± 0.04</td>
<td>54± 25</td>
<td>44.16</td>
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<tr>
<td>166</td>
<td>21.25± 0.01</td>
<td>55± 24</td>
<td>44.15</td>
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<tr>
<td>195</td>
<td>21.01± 0.05</td>
<td>52± 17</td>
<td>44.14</td>
</tr>
<tr>
<td>Photometric Sample</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>21.19± 0.05</td>
<td>510± 36</td>
<td>45.59</td>
</tr>
</tbody>
</table>
3.3.6 Contamination from AGNs

When we deduce total IR luminosities for the galaxies, we assume their IR emission is entirely from emission by dust heated by star forming activity, neglecting the possible contribution from active galactic nuclei (AGNs). Although optical studies suggest that AGNs reside in only about one percent of galaxies in clusters up to $z \sim 0.5$ (Dressler et al., 1999), recent X-ray surveys have found an excess of point sources in cluster fields, many of which are confirmed as cluster AGNs (e.g., Martini et al., 2002). These discoveries suggest that AGN contamination may be an issue, especially for our small number samples.

In the MS 1054-03 field, surveys in the radio and the X-ray bands have been analyzed to identify the possible AGNs. Best et al. (2002) conducted an extremely deep 5-GHz radio observation and found 34 radio sources, 8 of which are confirmed as cluster members by their spectroscopic data. On the basis of the [O II] emission line flux and radio flux density ratio, they further conclude that 6 of these 8 radio sources are AGNs, one source (No 5) is a star-forming galaxy and one (No 14) is ambiguous. Johnson et al. (2003) analyzed the 91 ks Chandra observations of the cluster and detected 47 X-ray sources. Among them, two sources are confirmed as AGNs (source 7 and source 19); source 19 is also detected in the radio. Altogether, there are 8 possible AGN members in the cluster. To avoid losing possible AGN candidates in our IR galaxy sample due to the incompleteness of the spectroscopic survey, we crossmatched the IR galaxies with all the 34 radio sources and the 47 X-ray sources. The two confirmed AGNs (X-ray source 7 and source 19) and the No 5 radio source are detected in the IR. We exclude the two AGNs from both of our samples. For the No 5 radio source, we use a radio spectral index of -0.8 and the formula given by Hopkins et al. (2003) to convert the radio flux to the SFR. We deduce a SFR of about 88 $M_\odot$ yr$^{-1}$ from its radio flux, which is consistent with the SFR estimated from the total IR luminosity, $\sim 61$ $M_\odot$ yr$^{-1}$, using the conversion formula given by Kennicutt (1998a). This agreement further confirms radio source No 5 as a star-forming galaxy. Due to the limitations of the spectroscopic data and the sensitivity
Table 3.1 (cont’d)

<table>
<thead>
<tr>
<th>ID (^{a})</th>
<th>(K_{s,AB}^{a}) ((\text{Mag}))</th>
<th>(f_{24}^{b}) ((\mu\text{Jy}))</th>
<th>(\log L_{IR}) ((\text{ergs s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1098</td>
<td>20.55± 0.04</td>
<td>365± 33</td>
<td>45.43</td>
</tr>
<tr>
<td>870</td>
<td>21.89± 0.06</td>
<td>144± 15</td>
<td>45.04</td>
</tr>
<tr>
<td>1546</td>
<td>22.09± 0.11</td>
<td>89± 33</td>
<td>44.82</td>
</tr>
<tr>
<td>1528</td>
<td>21.87± 0.17</td>
<td>84± 39</td>
<td>44.75</td>
</tr>
<tr>
<td>1849</td>
<td>20.85± 0.02</td>
<td>124± 29</td>
<td>44.72</td>
</tr>
<tr>
<td>1121</td>
<td>22.82± 0.26</td>
<td>61± 21</td>
<td>44.67</td>
</tr>
<tr>
<td>788</td>
<td>23.09± 0.21</td>
<td>54± 10</td>
<td>44.61</td>
</tr>
<tr>
<td>828</td>
<td>20.63± 0.04</td>
<td>116± 25</td>
<td>44.56</td>
</tr>
<tr>
<td>950</td>
<td>21.89± 0.10</td>
<td>63± 23</td>
<td>44.55</td>
</tr>
<tr>
<td>420</td>
<td>21.50± 0.13</td>
<td>63± 27</td>
<td>44.41</td>
</tr>
<tr>
<td>278</td>
<td>21.93± 0.11</td>
<td>51± 34</td>
<td>44.40</td>
</tr>
<tr>
<td>1716</td>
<td>20.38± 0.03</td>
<td>88± 17</td>
<td>44.37</td>
</tr>
<tr>
<td>1750</td>
<td>21.56± 0.11</td>
<td>58± 29</td>
<td>44.35</td>
</tr>
<tr>
<td>1846</td>
<td>20.62± 0.02</td>
<td>76± 60(^{c})</td>
<td>44.30</td>
</tr>
</tbody>
</table>

\(^{a}\)Galaxy IDs and \(K_{s,AB}\) are taken from Förster Schreiber et al. (2006).

\(^{b}\)The 24 \(\mu\text{m}\) flux errors are estimated within a fixed aperture \((r < 5''\) and are scaled by the ratio of the DAOPHOT PSF fitting flux vs. the fixed aperture flux. The method would overestimate the error for some faint sources.

\(^{c}\)The source has a low nominal SNR of 1.3 due to the reason mentioned in note b; it has been visually confirmed as a secure detection.
of the X-ray survey, we can not totally exclude all AGN contamination from our IR galaxy samples, but the fact that only one star forming IR galaxy in our sample is detected either in the radio or in the X-ray band indicates the contamination is negligible.

3.3.7 Comparison of the IR and [O II] emission line deduced SFRs

Many previous studies of the SFR in clusters at \( z > 0.4 \) rely on the [O II] emission line as an indicator, which is very sensitive to extinction and metallicity. We compare the SFR deduced from the [O II] emission line luminosity and that from the total IR luminosity in Fig. 3.3 for the IR galaxies in the spectroscopic sample. Among 15 IR galaxies with [O II] data, 12 galaxies have emission lines. The [O II] emission line luminosity is estimated by multiplying the equivalent width of the emission line by the continuum flux. The continuum flux at the rest frame of the [O II] line is approximated by the continuum flux in \( V_{606} \). The [O II] emission line luminosity is converted to a SFR using the formula \( SFR_{\text{[OII]}} = (6.58 \pm 1.65) \times 10^{-42} L_{\text{[OII]}} \) (Kewley et al., 2004), where \( L_{\text{[OII]}} \) is the luminosity corrected for extinction. Without any extinction correction, the SFR_{[OII]} is smaller than the SFR_{IR} by more than one dex on average (the open circles), but with large scatter. Since we do not have enough optical data to deduce extinction, we used the IR-luminosity-dependent extinction \( A_V^{\text{IR}} = 0.75 \log(L_{\text{IR}}/L_\odot) - 6.35 \) mag given by Choi et al. (2006) to correct for the dust attenuation. This extinction formula is deduced from the ratio of the \( SFR_{\text{IR}} \) and the SFR measured from emission lines, assuming \( SFR_{\text{IR}} \) approximate the true SFR. The galaxies in our sample all have a \( A_V^{\text{IR}} \) greater than 1.5. We convert \( A_V^{\text{IR}} \) to the extinction of [O II] line using the reddening curve of Calzetti et al. (2000), the same one used by Choi et al. (2006). The extinction-corrected SFR_{[OII]} agrees with the SFR_{IR} reasonably well (the filled circles), with a scatter of about 0.5 dex.

For the three IR galaxies without emission lines, we plot the SFR_{IR} as the upper limits of their SFR_{[OII]} (the open circles with downward arrows). There are also about a dozen [O II] emission line galaxies (EW_{[OII]} > 5Å) not detected at 24 \( \mu \)m. For these galaxies, the lack of IR emission probably suggests relatively less dust and
Figure 3.3 The comparison of SFR\textsubscript{IR} and SFR\textsubscript{[OII]}. The filled and open circles are the SFRs of the IR galaxies in MS 1054-03, with and without extinction correction for SFR\textsubscript{[OII]}. For the three IR galaxies without [O II] emission lines, SFR\textsubscript{IR} are used as the upper limit of SFR\textsubscript{[OII]} and they are plotted as open circles with downward arrows. The filled and open triangles are the SFRs of the IR galaxies in RXJ0152, with and without extinction correction for SFR\textsubscript{[OII]}. The dotted vertical line is the SFR approximately corresponding to the 80% completeness limit of the 24 μm observation. The solid line indicates the one-to-one correlation.
smaller extinction, so we used a fixed $A_V = 1.0$ to deduce their SFR$_{[O\text{II}]}$. Their SFR$_{[O\text{II}]}$ are all quite small, with a maximum value of $7 \, M_\odot \, \text{yr}^{-1}$, well below the 80% detection completeness limit.

We also compared the SFR$_{[\text{IR}]}$ of galaxies in RXJ0152 with the SFR$_{[O\text{II}]}$ given by Homeier et al. (2005), correcting for extinction with $A_{[\text{IR}]}^V$. The open and filled triangles in Fig. 3.3 are the data without and with extinction correction. Again, the extinction corrected SFR$_{[O\text{II}]}$ shows a better consistency with the SFR$_{[\text{IR}]}$. This agrees with the results of Marcillac et al. (2007), who also found a large amount of dust-embedded SF in RXJ0152.

The median values of $A_{[\text{IR}]}^V$ for the IR galaxies with [O II] emission lines in MS 1054-03 and in RXJ0152 are both about 2, corresponding to a correction factor of $\sim 14$ for the SFR$_{[O\text{II}]}$. This result implies the star-forming galaxies in these clusters are enshrouded heavily by dust and the SFR$_{[O\text{II}]}$ without extinction correction only measures a small portion of the total SFR. Even with the widely adopted extinction of 1 mag at H$\alpha$ ($A_V \sim 1.2$), the emission line SFRs still underestimate the SFR by a factor of 4 for these IR bright galaxies.

3.3.8 Comparison of the IR and Ultraviolet continuum deduced SFRs

UV luminosity is also widely used to estimate the SFR of galaxies. Although it is very sensitive to the dust extinction, it gives us access to the "non dusty" star formation and is therefore complementary to the IR-deduced SFR. For the cluster members, we have derived the rest-frame 2200Å luminosity ($L_{\nu,2200\AA}$) from the galactic extinction corrected $U - K$ photometry from Förster Schreiber et al. (2006), using the methodology presented in Rudnick et al. (2003). We estimate the SFR from $L_{\nu,2200\AA}$ using the formula given by Kennicutt (1998a). The conversion assumes a Salpeter IMF and a constant SFR, with UV emission dominated by a stellar population younger than 100 Myr. These assumptions are consistent with those used to deduce the IR SFR conversion formula we adopt in this work (Kennicutt, 1998a).

In Fig. 3.4, we show the comparison between the UV continuum-deduced SFRs and the IR-deduced SFRs. For the IR bright cluster members, the unobscured star
formation are only a small fraction of the total star formation. The median value of \( \text{SFR}_{\text{IR}} / \text{SFR}_{\text{UV}} \) is \( \sim 12 \) for the spectroscopic sample and \( \sim 16 \) for the combined sample. Such a large \( \text{SFR}_{\text{IR}} / \text{SFR}_{\text{UV}} \) ratio is mainly due to the fact that our IR data is only sensitive to galaxies with \( SFR > 10 ~ M_\odot \text{yr}^{-1} \), where extinction is known to be large. The combined sample has a larger \( \text{SFR}_{\text{IR}} / \text{SFR}_{\text{UV}} \) ratio on average because the spectroscopic survey is \( I \)-band magnitude limited and is biased against the most dusty star forming galaxies. If we calculate the visual gas medium extinction from \( L_{\text{IR}} \) using the formula given by Choi et al. (2006) (all the extinctions we mentioned in §3.7 are for the gas medium) and apply the corresponding UV stellar continuum extinction to \( \text{SFR}_{\text{UV}} \), we will have a better agreement between \( \text{SFR}_{\text{IR}} \) and \( \text{SFR}_{\text{UV}} \), as shown in Fig. 3.4. However, even after this extinction correction, there are still many galaxies, especially the ones selected by photometric redshifts, showing a much smaller \( \text{SFR}_{\text{UV}} \) compared to \( \text{SFR}_{\text{IR}} \).

If we assume \( \text{SFR}_{\text{IR}} \) is the total SFR and directly estimate the NUV extinction by \( 2.5 \log(\text{SFR}_{\text{IR}} / \text{SFR}_{\text{UV}}) \), we will have a median \( A_{\text{NUV}} \) of \( 2.7 \pm 0.5 \) mag and \( 3.0 \pm 1.0 \) mag for the spectroscopic sample and the combined sample respectively. The high extinction we found here supports our assumption that \( \text{SFR}_{\text{IR}} \) provides a reasonable estimate of the total SFR. The NUV extinction of the stellar continuum can be translated into the visual extinction of the gas medium using the reddening curve of Calzetti et al. (2000), \( A_V = 2.9 \pm 0.5 \) mag and \( A_V = 3.3 \pm 1.1 \) mag respectively for our two samples. Buat et al. (2007) studied the extinction of a sample of LIRGs detected in the Chandara Deep Field South at \( z = 0.7 \) using the ratio of the total IR and FUV luminosity. They found an average FUV extinction of \( 3.33 \pm 0.08 \) mag for their sample, corresponding to a gas medium visual extinction of \( A_V = 2.97 \pm 0.07 \) mag \(^1\), which is in very good agreement with our results.

\(^1\)To be consistent with Choi et al. (2006), we use the reddening curve of Calzetti et al. (2000) for all the extinction conversion in this work, which indicates \( A_V = 4.05 E(B-V)_g \). It is different from \( A_V = 3.1E(B-V)_g \) used by Buat et al. (2007). If we adopt their conversion method, the absolute value of the visual extinctions corresponding to the NUV and FUV extinctions will change, but the results of the comparison will remain the same.
Figure 3.4 The comparison of SFR$_{IR}$ and SFR$_{UV}$. The open circles are the spectroscopically confirmed IR cluster members, and the open squares are the ones selected by their photometric redshifts. The filled circles and squares are the results after applying extinction correction. The dotted vertical line is the SFR approximately corresponding to the 80% completeness limit of the 24 $\mu$m observation. The solid line indicates the one-to-one correlation.
In addition to the IR cluster members, we also calculate the SFR$_{UV}$ for all the cluster members (spectroscopic + photometric) without detectable IR emission. Their SFR$_{UV}$ are all at least two times smaller the detection limit of the SFR$_{IR}$, which confirms there is no galaxy with a high level of star formation that is missed by IR selection due to the lack of dust.

3.4 RESULTS

3.4.1 IR Luminosity Function

After obtaining the total IR luminosity of each galaxy, we calculate the LF for each sample. For the spectroscopic sample, we correct the number counts for the incompleteness in both the $I_{814}$ and 24 $\mu$m bands. We only correct for incompleteness in the 24 $\mu$m detections for the combined sample. The overlapping area between the spectroscopic survey and the 24 $\mu$m observations is about 4.8 Mpc$^2$, and the overlapping area between the photometric survey and the 24 $\mu$m observations is 5.5 Mpc$^2$.

The IR LFs are shown in Fig. 3.5. The open circles are the LF deduced from the spectroscopic sample without any incompleteness correction and the error bars are estimated by Poisson statistics (Gehrels, 1986); the filled circles are the results corrected for the incompletenesses in both the spectroscopic and IR surveys. The correction is quite significant except for the brightest data point. The error for the incompleteness corrected LF is obtained by multiplying the original error by the incompleteness correction made at each data point. Since we do not consider the error caused by the incompleteness estimate itself, the error bars should be considered to be lower limits to the actual errors. Similarly, the incompleteness uncorrected and corrected data points of the combined sample are shown as open and filled squares respectively. Even though the uncorrected LFs of the spectroscopic and combined samples exhibit a large difference, their incompleteness corrected ones agree with each other quite well. This good agreement demonstrates that neither the simplified spectroscopic incompleteness correction nor the uncertainty of the
photometric redshifts affects our resulting IR LFs significantly. It also shows that there are few galaxies with extremely red optical-IR colors missed by the selection limit in the $I_{814}$ band.

Despite this general agreement, the difference in the brightest data point may cause quite a large discrepancy when we try to fit the LF. It also raises questions about the incompleteness correction because we expect it to be least significant for the brightest galaxies. Two spectroscopically and two photometrically selected IR galaxies contribute to this data point. The two galaxies selected by spectroscopic redshifts are both very bright ($I_{814} \approx 20$) late type galaxies, and the two selected by photometric redshifts are both about two magnitudes fainter in the $I_{814}$ band and slightly brighter in the IR. Even though the probability of the photometric redshifts of those two galaxies falling into the one sigma error range of the cluster redshift is more than 70%, their best fitting photometric redshifts are both about 0.95. As an independent check, P. G. Pérez-González helped us get another set of photometric redshifts for these two IR galaxies using a different fitting strategy (Pérez-González et al., 2005) and with IRAC photometric data as an addition. These photometric redshifts have an average accuracy of $\Delta z = 0.08$. The best fitting redshifts of those two galaxies are $0.97 \pm 0.09$ and $1.00 \pm 0.11$, both more than 1 $\sigma$ above the cluster redshift. Their extremely large SFR$_{IR}$/SFR$_{UV}$ ratio, as shown in Fig. 3.4, also suggest them as background sources. In addition, among the 20% of photometric sources with spectroscopic data, one galaxy as bright as those two at 24 $\mu$m is selected as a cluster member by its photometric redshift but shown to be a non-member by its spectroscopic redshift. Statistically, it is possible that four more foreground or background contaminations may occur in the whole sample. However, we still can not rule out the possibility of those two sources as real cluster members given the uncertainties of the photometric redshifts. Spectroscopic data are needed to clarify the ambiguity.

Because the incompleteness-corrected IR LF of the spectroscopic and combined sample are generally consistent, while the combined sample has larger uncertainties at the brightest end (the spectroscopic sample, on the other hand, should have the
Figure 3.5 The IR luminosity function of MS 1054-03. The open and filled circles are the result of the spectroscopic sample without and with spectroscopic and IR incompleteness correction. The open and filled triangles are the result of the spectroscopic sample deduced from the second method in §3.5, without and with incompleteness correction. The open and filled squares (shifted to the bright end by 0.04 for clarity) are the result of the combined sample without and with IR incompleteness correction. The open stars (shifted to the faint end by 0.04 for clarity) are the IR LF of RXJ0152 from Marcillac et al. (2007). Since they only include galaxies with $f_{24} > 80 \mu$Jy and the data are very incomplete at $\log L_{\text{IR}} < 44$, we draw the faintest point as a lower limit. The solid curve is the best fitting Schechter function to the corrected spectroscopic IR LF. The dotted curve is the best fitting Schechter function to the IR LF of the Coma cluster. The dashed curve is the Coma LF evolved to $z = 0.83$ with the same evolution trend as the field IR LF. The vertical dashed line is the IR luminosity corresponding to the 80% detection limit at 24 $\mu$m.
smallest uncertainties due to the incompleteness correction at this point), we select the incompleteness-corrected IR LF of the spectroscopic sample as the IR LF of the cluster. We fit this LF with a Schechter function (Schechter, 1976). Since we only have three data points, we fix the faint end slope to the same value as the IR LF of the Coma cluster (Bai et al., 2006). We adopted a chi-square minimization method for the fitting. We also use the non-detection of the brighter galaxies beyond the brightest bin as a constraint during the fitting (Bai et al., 2006). The best fitted parameters are:

\[ \alpha = 1.41 \ (\text{fixed}); \ \log(L_{IR}^*/L_\odot) = 11.49_{-0.29}^{+0.30}. \]  

(3.1)

The resulting fit is shown as the solid curve in Fig. 3.5. Fitting the incompleteness-corrected IR LF of the combined sample gives an even larger \( L_{IR}^* \), with \( \log(L_{IR}^*/L_\odot) = 11.73_{-0.23}^{+0.34} \). We only use the Poisson statistical errors for the fitting and do not consider the uncertainties caused by the errors in \( L_{IR} \) estimation. The best-fitting parameters have large uncertainties, because the Schechter function fitting depends strongly on the brightest bin, which only includes two galaxies to constrain \( L_{IR}^* \), and even small changes of the \( L_{IR} \) of those galaxies can cause large changes in the best fitting parameters. We also note that due to the degeneracy between the faint end slope and the characteristic IR luminosity (\( L_{IR}^* \)), the best-fitting \( L_{IR}^* \) value we obtained here depends on the assumed faint end slope. If we vary the faint end slope from its current value by \( \pm 0.2 \), the best-fitting \( L_{IR}^* \) would vary by \( \pm 0.13 \). However, by fixing the faint end slope and fitting to a Schechter function, we can quantify the difference between LFs. Because no available infrared data in this redshift range penetrate significantly below the LIRG range, virtually all studies use a fixed low luminosity slope, including the field IR LF we compare with in this work (Le Floc’h et al., 2005).

We have tested the dependence of these fits on the uncertainties in the deduction of \( L_{IR} \) with different methods. If we use the \( L_{IR} \) of the spectroscopic sample deduced from the second method listed in Sect. 3.5, the IR LF does not change significantly, as shown by open and filled triangles in Fig. 3.5. The best fitting function has
a smaller $\log(L_{IR}^*/L_\odot) = 11.41^{+0.33}_{-0.52}$. The difference is still within the one sigma Poisson error, suggesting that small number statistics dominate the uncertainty to define a best fitting LF, and the systematic error caused by different $L_{IR}$ deduction methods is negligible. Therefore, we only use the results from the first method.

3.4.2 Comparison with Coma IR LF

We compare the IR LF of MS 1054-03 to that of the Coma cluster, which has similar mass as MS 1054-03 (Lokas & Mamon, 2003; Jee et al., 2005a) and whose galaxy infrared luminosities are deduced using the same set of SEDs as the first method in this chapter. We plot the best fitted Schechter function of the Coma cluster IR LF as the dotted curve in Fig. 3.5. The characteristic IR luminosity in MS 1054-03 is ten times larger than that of the Coma cluster ($\log(L_{IR}^*/L_\odot) = 10.49^{+0.27}_{-0.24}$). The surface density of the IR galaxies with $\log L_{IR} \geq 43.5$ expected from the MS 1054-03 LF is about 5 times larger than that in Coma. We integrate the best fitted Schechter function of the MS 1054-03 IR LF from $\log L_{IR} = 44$ to $\log L_{IR} = 46$ and get a SFR density of $190 \ M_\odot \ yr^{-1} \ Mpc^{-2}$, about 16 times larger than the SFR density of the Coma cluster ($\sim 11.4 \ M_\odot \ yr^{-1} \ Mpc^{-2}$).

The significant difference between the IR LFs of MS 1054-03 and of Coma agrees with the general evolution trend found in the field IR LF (Le Floc’h et al., 2005; Pérez-González et al., 2005). Le Floc’h et al. (2005) quantified the evolution of the IR LF in the CDF-S field in both density and luminosity as $[L_{IR}^* \propto (1+z)^{\alpha_L}, \phi_{IR}^* \propto (1+z)^{\alpha_D}]$, with the best fitting parameters $\alpha_L = 3.15 \pm 1.6, \alpha_D = 1.02 \pm 1.6$. Corresponding to this, we estimate the difference of the two cluster IR LFs using the same parameters and get $\alpha_L = 4.0^{+2.1}_{-2.2}, \alpha_D = 1.4$. For $\alpha_D$, we do not give an error estimate due to the large uncertainties of the best fitting $\phi_{IR}^*$ value. The results agree within the errors and even suggest a slightly stronger evolution of these two cluster IR LFs compared to the field IR LF. This is also demonstrated in Fig. 3.5, where the dashed curve corresponds to the LF of the Coma cluster evolved to $z = 0.83$ using the field IR LF evolution law. Both the incompleteness-corrected IR LFs of the spectroscopic and combined sample of MS 1054-03 fall above this curve.
The agreement between the evolution of the IR LF in these two clusters and the evolution in the field might suggest that the population of star forming galaxies in clusters is dominated by recently accreted field galaxies. Therefore, their IR LFs would not be very different from that of field galaxies and they would show similar evolution. However, this explanation is not favored by our following analysis (see §4.3). More likely, the similarity in the evolution trend suggests that the cosmic SFR decline is caused by some general mechanism existing both in cluster and field environments, probably the consumption of the gas fuel for SF. Nevertheless, due to the intrinsic variation of cluster properties and with only two clusters in this comparison, these results are far from conclusive. More clusters need to be studied to confirm the evolution trend further.

3.4.3 Comparison with Field IR LF

The IR LFs we deduced for the cluster are all projected LFs. If we assume the cluster has a radius of about $5R_{200}$ ($R_{200}$ is the radius within which the mean cluster density is 200 times the critical density of the universe at that redshift $^2$), we can calculate the IR LF per volume and compare it with the field IR LF from Le Floc’h et al. (2005) at similar redshift. $5R_{200}$ is near the turnaround radius of the cluster, and there will be few infalling galaxies beyond it. Although the spectroscopic sample is almost free of contamination from field galaxies, the redshift selection ($0.81 < z < 0.85$) still could include a few foreground and background field galaxies whose redshifts fall within the cluster velocity dispersion. To exclude this field contamination, before we convert the projected cluster IR LF to LF per volume, we calculate the projected field IR LF in a cylinder with a length corresponding to $z = 0.81$ to $z = 0.85$ and subtract it from the projected IR LF of the cluster. In Fig. 3.6, the filled circles are the incompleteness-corrected IR LF per volume after the field subtraction. If we integrate the cluster LF in

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$^2$ $R_{200}$ is widely used as an approximation to $R_{\text{virial}}$. Strictly speaking, $R_{\text{virial}}$ is closer to $R_{100}$. The ratio of $R_{200}/R_{\text{virial}}$ depends on the mass distribution of a cluster. For a NFW profile (Navarro et al., 1997) with $R_{200}/r_s = 6$, $R_{200}/R_{\text{virial}} \sim 0.75$. 
the range of $10^{10.8} < L_{IR} < 10^{12} L_\odot$, it shows an overdensity of about 21 compared with the IR LF from the CDF-S field from Le Floc’h et al. (2005). The overdensity calculated here can be affected by the cosmic variance from field to field, especially the CDF-S field, in which a lower galaxy density up to a factor of two is found compared with other fields (Wolf et al., 2003). However, as a first-order correction, Le Floc’h et al. (2005) already normalized their IR LFs by the ratio between the B-band luminosity densities in the CDF-S and over the three fields of COMBO-17 (Classifying Objects by Medium-Band Observations in 17 filters; Wolf et al., 2003, 2004; Bell et al., 2004).

Although the estimate of the actual value of the overdensity has some uncertainties, it is clear that there is an excess of IR galaxies in the cluster compared with the field. Such an excess of MIR sources is also found in RXJ0152 (Marcillac et al., 2007), as well as in two intermediate redshift clusters Cl 0024+16 and MS 0451-03 (with a smaller significance) (Geach et al., 2006). Although the cluster shows a clear overdensity of the IR galaxies compared with the field, it is still smaller than the overdensity of the cluster in the optical bands. A fairer test to examine the star formation level in different environments is to compare the fraction of IR galaxies in the cluster and in the field. Among the 144 spectroscopically confirmed cluster members, 19 have 24 μm emission brighter than 50 μJy and 6 of them have $L_{IR} > 10^{11} L_\odot$. There are two AGNs also with 24 μm emission, but we already excluded them from the sample. Therefore, the fraction of star-forming galaxies with $f_{24} > 50$ μJy in the cluster is about 13 ± 3% and the fraction for LIRGs is 4 ± 2%. These fractions are barely affected by the incompleteness of the spectroscopic survey. There are 211 cluster member candidates selected by the photometric redshifts with $K_{s,AB} < 22$ (approximately the detection limit of the spectroscopic survey of $I_{814} = 23$) and 15 ± 3% of them are IR bright and 5 ± 2% are LIRGs. The results are therefore consistent with the fractions based only on the spectroscopically selected cluster members. For the CDF-S field, we select the galaxies with $0.81 < z_{ph} < 0.85$ and $R < 22.6$ mag using the photometric redshifts given by the COMBO-17 survey (Wolf et al., 2004). The cut in $R$ magnitude approximates the detection limit of
Figure 3.6 The IR luminosity function of MS 1054-03 compared with the field IR luminosity function at $z \sim 0.8$. The filled symbols are from the spectroscopic data after incompleteness correction. The solid curve is the best fitting Schechter function. The dotted curve is the field IR LF at the cluster redshift. The shaded area presents its one sigma uncertainties. The vertical dashed line is the IR luminosity corresponding to the 80% detection limit at 24 $\mu$m.
the spectroscopic survey in the cluster, \( I_{814} = 23 \). Altogether, we select 62 galaxies in an area of 775 arcmin\(^2\) (\( \sim 20 \) times larger than the cluster field) and 39 of them have \( f_{24} > 50 \) \( \mu \)Jy. Two of those field IR galaxies are classified as QSOs. So, the fraction of the star forming galaxies in the field sample at the same 24 \( \mu \)m threshold and of a similar redshift range is about 60 \( \pm \) 12\%, much higher than the fraction we found in the cluster. Although the photometric redshifts we used to select the field sample are less accurate than spectroscopic redshifts, the fraction of the star forming galaxies in the field does not change significantly in a large redshift range \((0.7 < z_{ph} < 0.95)\) and therefore redshift uncertainties will have little effect on the comparison. The smaller fraction of IR bright galaxies in the cluster compared with the field is consistent with the results given by studying the galaxy emission lines (Lewis et al., 2002; Gómez et al., 2003) and suggest that galaxies in the cluster have a lower level of star formation on average.

Even though the cluster galaxies have a lower level of SF on average compared with the field, a fraction of 13\( \pm \)3\% of star forming galaxies is still very substantial considering the short IR bright phase, especially for the 6 LIRGs which constitute 4\( \pm \)2\% of all the spectroscopically selected cluster members. Marcillac et al. (2006a) analyzed Balmer absorption lines and the 4000Å break of a sample of LIRGs at \( z \sim 0.7 \) and found that the duration of the LIRG phase is most likely \( \sim 0.1^{+0.16}_{-0.06} \) Gyr. The timescale of star formation in local IR bright galaxies is even smaller, \( \sim 10^7 \) yr (Gao & Solomon, 2004). If these active galaxies are due solely to infall from the field, such a short timescale would mean the cluster would have to accrete about 60\(^{+90}_{-37} \) LIRGs from the field per Gyr to sustain the observed SF level. This is about half of the current spectroscopically selected cluster sample. Even if we consider that about 30\% of LIRGs are experiencing their second star bursts in 1 Gyr (Marcillac et al., 2006a), it would still mean more than half of the cluster members are the LIRGs accreted from the field in the last Gyr. Such a large accretion rate is very unlikely. The average smooth growth of the cluster masses from the simulation of Rowley et al. (2004) in the one Gyr period \((z \approx 1.1 - 0.83)\) ranges from 10\% to 40\%. 
However, it is possible that we are seeing a large fraction of star forming galaxies in this cluster due to a temporary rise of the accretion rate caused by a major merger/infall event. The quadrupole-like temperature structure and the lack of shock-heated regions between the two X-ray peaks of this cluster suggest that the major clumps (the central and western clumps) are probably at a postmerger stage and the lack of an X-ray peak in the eastern clump may also suggest a recent infalling/passing-by (Jee et al., 2005a). These merger and infalling events might have introduced a large number of field galaxies into the cluster in a short time and boosted the accretion rate temporarily. However, the spatial distribution of the IR galaxies does not seem to support this scenario. Although MS 1054-03 has several subclumps and one of them has relatively enhanced SF, most of the IR galaxies do not concentrate in subclumps; instead, they tend to scatter around the cluster and avoid the two major clumps (see § 4.4). Similarly, the cluster members with 15 μm emissions in Cl 0024, a mid-redshift cluster with high star formation level, also do not show spatial concentrations (Coia et al., 2005a). Such a spatial distribution does not support a major merger/infalling event. In addition, RXJ0152 also has a similar fraction of IR bright galaxies, and they show no sign of concentration into a subclump (Marcillac et al., 2007). This evidence suggests that such high fractions of IR galaxies in high redshift clusters might be quite common, and it is unlikely that they are all due to major infall events. More likely, these IR galaxies have been in the cluster for quite a while. However, they probably have never been close to the high density region before and still retain a large amount of gas. The recent SF in these galaxies may be triggered either by interaction with the cluster intergalactic medium (IGM), with other galaxies, or by tides. In support of this hypothesis, evidence has been found previously for star forming bursts in infalling galaxies into clusters by, e.g., Gavazzi et al. (2003), Cortese et al. (2006) and Mercurio et al. (2004).

An alternative possibility is that the LIRGs in the cluster have lasted much longer than the time scale estimated by Marcillac et al. (2006a). If the timescale is an order of magnitude longer (∼ 1 Gyr), then the accretion rate would be 10
times smaller and would not raise the problem of too rapid growth. However, such a long timescale would indicate the accreted galaxies could retain their gas for a long period and keep their star formation untouched by the cluster environment. This alternative view is again inconsistent with the passive scenario that the star formation of field galaxies is quenched quickly after they are accreted into a cluster.

3.4.4 Spatial Distribution of the IR Galaxies

The spatial distribution of the IR galaxies in the cluster may help us understand the effect of the cluster environment on the galaxy SFR. As indicated by the X-ray and optical light distributions, the morphology of MS 1054-03 is quite complex. Jee et al. (2005a) reconstruct a high-resolution mass map of the cluster through ACS weak-lensing analysis. They confirm the three dominant mass clumps in the cluster previously reported by a WFPC2-based weak-lensing analysis (Hoekstra et al., 2000) and find some detailed substructures for the first time. In Fig. 3.7, we overplot the IR galaxies on this mass contour map. The mass map is constructed in units of the dimensionless mass density $\kappa$, and $\kappa > 0.1$ corresponds to a significance of $> 3$ sigma. The squares are from the spectroscopic sample, and the triangles are those additional members selected by photometric redshifts. The sizes of the symbols are proportional to the IR luminosities. For clarity, the LIRGs are also indicated by black dots. The three major clumps, eastern, central and western (E, C & W), as well as the four minor clumps (M1-M4), are labeled on the plot following Jee et al. (2005a). One distinct feature of Fig. 3.7 is that many IR galaxies are distributed in the outskirt region of the cluster. Two thirds of the IR galaxies are located in the low density region with $\kappa < 0.1$, and this ratio could be higher if we take into account projection effects.

Another interesting feature of the distribution is the lack of IR galaxies in the western clump and the southern extension compared to the rest of the major structure. We divide the major body of the cluster into two approximately equal parts by the dashed line in Fig. 3.7, the northeastern (NE) and southwestern (SW) regions. The NE region includes both the eastern and central clumps and the SW region
Figure 3.7 The spatial distribution of the IR galaxies in MS 1054-03. Open squares are the IR galaxies from the spectroscopic sample, and open triangles are the additional IR members selected by the photometric redshifts. The sizes of the symbols are proportional to their IR luminosities. LIRGs are also indicated by filled circles. Small open circles are the cluster members selected by the photometric redshifts. E+A Galaxies selected by Tran et al. (2003) are indicated as open stars. The contours are the mass contours from Jee et al. (2005a). The eastern, central, western and four minor mass clumps are labeled as E, C, W, and M1-M4. The solid circle is the region with effective gas-stripping. The rectangle is defined as the interface region of the two major clumps.
includes the western clump and its south extension. The SW region only contains 2 or 3 IR galaxies, while the NE region contains at least 9 IR galaxies. The ratio of the IR galaxies to the number of cluster candidates selected by photo-z in the SW and NE region is $2 \pm 1\%$ (3 vs. 125) and $7 \pm 2\%$ (9 vs. 130) respectively, compared to $10 \pm 2\%$ (22 vs. 213) in the outskirt region (900' away from the cluster center). Although it may arise partly from projection effects, the difference between these two regions is statistically significant. In addition, four out of the five brightest IR galaxies of the whole cluster correlate to the NE region. These observations probably suggest a recent star-forming episode in the NE region.

The X-ray study of the cluster may provide some support to this scenario. Unlike the other two major clumps, the eastern clump is absent from the X-ray map (Clowe et al., 2000; Jeltema et al., 2001; Jee et al., 2005a). Based on this fact and the anomalous X-ray profile of the central peak, as well as the temperature map of the region, Jee et al. (2005a) proposed that the eastern clump has passed through the dense region of the central clump recently as an off-center collision, during which the intracluster gas was stripped. It is possible that this recent off-center collision between the eastern and central clumps triggered SF in some of the IR galaxies.

By comparison, the merging between the western and central clumps is probably at a very late stage, suggested by the lack of a shock-heated region between them (Jee et al., 2005a). We define a central $9'' \times 25''$ rectangle as the interface of these two major clumps (solid box in Fig. 3.7); we found two out of 21 photometrically selected cluster candidates with detectable IR emission in this region, a fraction of $10\pm 7\%$, comparable to the fraction in the outskirt region of the cluster. However, we found no spectroscopically confirmed IR member in this region. The uncertainties of the photometric cluster candidates and the projection effects further weaken the evidence for activity at this interface. As a comparison, Marcillac et al. (2007) found no evidence of merging triggered SF activities in the interface of the two main merging clumps in the cluster RXJ0152 at a similar redshift. Combining the two results, clump interfaces do not appear in general to be sites of strongly enhanced star-forming activity.
Tran et al. (2003) studied E+A galaxies, characterized by strong Balmer absorption and little or no [O II] λ3727 emission, in this cluster. The strong Balmer absorption is evidence of recent substantial star forming activities (≤ 2 Gyr) and the lack of [O II] emission indicates that those galaxies probably have no current SF, and therefore they are usually classified as post-starburst galaxies (Dressler & Gunn, 1983). There are 19 E+A cluster members in the region covered by IR observations and they are shown as the open stars in Fig. 3.7. Most of these galaxies have no IR emission and they are real post-starburst galaxies in which SF has ceased at least a few Myr ago (Poggianti & Wu, 2000). One third of the post-starburst galaxies are concentrated in the NE region of the cluster, three or four are related to the SW region, and the rest are scattered outside of the main body of the cluster. For the few post-starburst galaxies related with the SW region, only one is located in the very inner region, and the rest are distributed along the boundary region. This result suggests the NE region of the cluster has been active in SF for many hundreds of Myr, and the SW region, on the contrary, has been quiescent for a long time. It is consistent with the scenario suggested by X-ray analysis, that the central and eastern clumps experienced a recent collision, while the merging between western and central clumps is at a late stage.

There are three E+A galaxies with IR emission, indicating ongoing SF. They are not post-starburst but rather dust-enshrouded starburst galaxies in which young stars are heavily obscured and their emission lines are extingued. The strong Balmer absorption suggests there are also a large number of A type stars, that have probably already moved out of the dusty star-forming regions, which indicates the SF in these galaxies started at least a few Myr ago (Poggianti & Wu, 2000). The dusty star-forming galaxies are all distributed outside of the main body of the cluster where gas stripping is not effective and the gas fuel for SF in the galaxies is not strongly depleted. This distribution helps explain why the SF in these galaxies continues for so long.
3.4.5 Mergers and Morphologically Irregular Members

One remarkable feature of MS 1054-03 is its high fraction of merging galaxies. Van Dokkum et al. (1999, 2000) reported 13 ongoing mergers in this cluster, comprising 17% of the cluster population with \( L > L_* \). They also classified one more galaxy (H1532) as a merging candidate but did not include it in their merger list due to the lack of spectroscopic data for its companion. The photometric redshift suggests its companion is also a cluster member, and therefore we include it as a merger; this brings us to a total of 14 merging systems. In addition, Tran et al. (2005) found 10 bound red galaxy pairs (5 of them already in van Dokkum’s sample) with projected distance smaller than 30 \( h^{-1} \) kpc and relative velocity \( \delta v \leq 300 \) km s\(^{-1}\). Most of the mergers between field galaxies are accompanied by triggered SF (e.g., Liu & Kennicutt, 1995; Patton et al., 2005). However, Tran et al. (2005) found that most of the merging galaxies in MS 1054-03 have no detectable [O II] emission lines and have probably lost their gas long ago.

As pointed out in the previous section, [O II] emission may underestimate the SFR in galaxies due to dust extinction and is a less robust indicator of SFR than the IR luminosity. Therefore, we discuss the IR properties of these merging galaxies. Among 14 merging systems, 4 have 24 \( \mu \)m emission \( f_{24} > 50 \mu \)Jy, H4683.4741, H6567, H2710 and H1532 (the last merger is the one confirmed by the photometric redshift). The brightest one is a double nucleus, highly disturbed disk system. The other three are interacting pairs. One galaxy (H4822) common to two red pairs found by Tran et al. (2005) has \( f_{24} > 50 \mu \)Jy. There is another galaxy in those red pairs having weak 24 \( \mu \)m emission \( f_{24} \approx 40 \mu \)Jy, not included in our spectroscopic sample. Altogether, about 29 ± 16\% of the merging systems show detectable IR emission. For red pairs, this fraction is even lower, only about 10-20\%.

Postman et al. (2005) classified the morphological types of spectroscopically confirmed cluster members of MS 1054-03. We correlate the IR galaxies in the spectroscopic sample with their classification. Fig. 3.8 shows the ACS images of these galaxies. Without distinguishing if galaxies are in merging systems, we found
21 ± 12% (4), 63±23% (12) and 16±10% (3) of the IR galaxies are early, late and irregular type galaxies, respectively. These fractions are very similar to what Marcillac et al. (2007) found for the IR galaxies in RXJ0152. If we consider all the members of MS 1054-03 with morphological classification, 4±2%, 52±19% and 50±35% of early, late and irregular type cluster galaxies have detectable IR emission ($f_{24} > 50 \mu$Jy). Again, these results agree with those of Marcillac et al. (2007) within the statistical errors. Therefore, only a very small fraction of early type galaxies in the spectroscopic sample have strong SF, but half of late type and irregular galaxies have SFRs > $10 M_\odot$ yr$^{-1}$.

In addition to those galaxies in merging systems, galaxies with irregular morphologies may also be considered as experiencing interactions. Therefore, if we count the irregular galaxy (H4389) as a merger too, 6 IR galaxies out of 19 (32±15%) are related to galaxy merging/interaction. Furthermore, two IR galaxies (H6065 and H6372) classified as normal late type galaxies also show some irregular features. If their irregular features are also related to galaxy merging/interaction, then 42±18% of the IR galaxies may have galaxy merging/interaction triggered SFs.
3.5 DISCUSSION

3.5.1 Comparison with RXJ0152.7-1357

From §4.2, we found that the IR LF of MS 1054-03 evolves as strongly as the field IR LF and has an over abundance of IR galaxies down to log$L_{IR} = 44.6$, comparable to the field IR LF at the same redshift. This result is quite surprising given studies showing decreased SF in rich clusters. However, with only one cluster, it is not clear if the result is typical of rich clusters at $z \approx 0.8$ or peculiar to MS 1054-03.

The study of IR galaxies in RXJ0152 by Marcillac et al. (2007) provides a good comparison. The 24 $\mu$m data for these two clusters have similar sensitivities and the optical data cover both central $5' \times 5'$ regions of the clusters. X-ray data show that RXJ0152 also has two regions with peak emission (e.g., Huo et al., 2004), and the dynamical analysis of the cluster suggests an ongoing merger in the system (Girardi et al., 2005). In addition, photometric and spectroscopic surveys by Kodama et al. (2005) and Tanaka et al. (2006) discovered two large-scale filament-like structures hosting the central main cluster. Marcillac et al. (2007) found 22 IR galaxies in RXJ0152 confirmed by spectroscopic data as cluster members. We plot the IR LF deduced from their data as the open stars in Fig. 3.5. We did not make any incompleteness correction for the IR LF of RXJ0152 because their sample only includes galaxies with $f_{24}$ above the 80% completeness limit and the spectroscopic data in this cluster are quite deep, complete down to $R = 24$ (Demarco et al., 2005). Therefore, the IR LF of RXJ0152 without any correction is comparable to that of MS 1054-03 with incompleteness corrections above the 80% completeness limit at 24 $\mu$m.

As stated in §3.5, Marcillac et al. (2007) use a different set of SEDs to deduce a total IR luminosity from the 24 $\mu$m flux. Although it does not result in a significant difference, it is better if we compare the IR LF of RXJ0152 with that of MS 1054-03 deduced from the same method (open and filled triangles in Fig. 3.5). There is a large difference in the faintest data points of the IR LF of RXJ0152 and MS 1054-03, due to the different cutoffs of 24 $\mu$m flux density in the two samples: the
RXJ0152 sample is only determined down to the 80% limit \((f_{24} > 83 \, \mu\text{Jy})\) while the MS 1054-03 sample, after incompleteness correction, is derived down to the 50% limit \((f_{24} > 50 \, \mu\text{Jy})\). The dashed vertical line in Fig. 3.5 shows the IR luminosity corresponding to the 80% limit. The lowest bin is partly below this limit. For both of the two brighter data points, RXJ0152 has a higher value than MS 1054. However, the differences are still within one sigma Poisson errors. The brightest data point for RXJ0152 includes 5 IR galaxies, while the data point for MS 1054-03 only includes 2 IR galaxies from the spectroscopic sample. The photometric selection adds two more galaxies in MS 1054-03 within this luminosity range, but as discussed before, those two are probably background sources. The IR LF of RXJ0152 confirms the strong evolution trend and the over abundance of bright IR galaxies we found in MS 1054-03 and it shows an even larger number of the brightest IR galaxies as pointed out by Marcillac et al. (2007).

Marcillac et al. (2007) find that most of the IR galaxies of RXJ0152 are distributed outside of the two major clumps indicated by X-ray emission. They also find a larger median redshift for these galaxies compared to the cluster redshift, which is identical to the larger median redshift of the infalling late-type cluster members found by Blakeslee et al. (2006). Based on these facts, they suggest that infall of galaxies is probably responsible for much of the star formation activity we see in the cluster. In MS 1054-03, we did not find a difference in the redshifts of the IR galaxies compared with the rest of the cluster members. However, about 60% of the IR galaxies are located outside of the main body of the cluster (major clumps E, C and W). The projection effect may make the fraction even larger. Some of these galaxies probably correspond to the infalling galaxies found by Marcillac et al. (2007). As discussed in §4.3 and §4.4, it is unlikely that the cluster only passively accretes star forming galaxies from the surrounding field and those galaxies have a high level of SF simply due to their recent origination from the field. On the contrary, it is very possible that we are seeing an increased SFR in infalling galaxies triggered by the galaxy-IGM interaction as shown by previous theoretical and observational evidence (Fujita & Nagashima, 1999; Gavazzi et al., 1995, 2001).
However, we can not rule out other mechanisms being responsible for the SF in these galaxies. In MS 1054-03, about one third of the outside IR galaxies are associated with some minor clumps of the cluster. Their SF may arise from processes more common in the group environment, e.g., galaxy interactions (Lewis et al., 2002). For the 40% of the IR galaxies correlated with the main body of the cluster, the majority are associated with the NE region of the cluster where a collision of subclumps might have occurred recently. This result indicates the interaction of the subclumps and the processes accompanied with it, e.g., the tidal gravitational field, may also play a role in triggering SF and cause the concentration of IR galaxies (Bekki, 1999).

The difference in the mass of the two clusters can complicate the comparison. Using the same weak-lensing technique and data of similar quality, Jee et al. (2005a,b) produced enclosed mass profiles for both of them. The profiles show that MS 1054-03 is much richer and more massive than RXJ0152. The enclosed mass within 1 Mpc of MS 1054-03 is about two times as large as that in RXJ0152. Therefore, with the similar $5' \times 5'$ IR and spectroscopic/photometric coverage of the clusters, we actually only observe the inner part of MS 1054-03 but reach the outside region in RXJ0152, where most of its LIRGs reside. It is possible that we would find more infalling IR galaxies if our IR and spectroscopic/photometric data extended further to the outer regions of MS 1054-03. The many IR galaxies distributed at the very edge of the survey region (see Fig. 3.7) seem to support this argument. This would also explain the slightly higher IR LF of RXJ0152 compared with MS 1054-03.

Although both MS 1054-03 and RXJ0152 have two X-ray peaks and two corresponding major clumps indicating a merger, MS 1054-03 lacks shock-heated regions between the two X-ray peaks (Jee et al., 2005a), but RXJ0152 has excess X-ray emission between the two clumps suggestive of a shock front (Maughan et al., 2003). The differences may indicate the different merger stage the two clusters are in: MS 1054-03 is probably at a post-merger stage while RXJ0152 is at a pre-merger stage. This difference may contribute to the slightly larger star formation rate in RXJ0152 than in MS 1054-03.
3.5.2 Evolution of the Integrated SFR in Clusters

We have already compared the IR LF of MS 1054-03 to the Coma cluster and found a strong evolution in both $\phi^*$ and $L_{IR}^*$. Another way to compare the SFR in clusters is to compare their integrated SFRs within a certain radius. Using the SFR measured from emission lines, Finn et al. (2004, 2005), Kodama et al. (2004), and Homeier et al. (2005) compared the integrated SFRs of several clusters within $0.5R_{200}$. They also compared the integrated SFRs normalized by the cluster masses. The mass-normalized integrated SFRs are comparable to the fractions of star-forming galaxies in the clusters, which are widely used in many systematic studies of cluster SF. Some suggestive correlations between the integrated SFRs and redshifts/masses of the clusters were found. However, the results are very uncertain.

There are concerns about the usual methods for estimating the cluster masses. Finn et al. (2005) used velocity dispersion, while Homeier et al. (2005) suggest X-ray temperature may be a better indicator of the mass. However, velocity dispersion and X-ray temperature are valid mass estimators only in relaxed clusters under the assumption of hydrodynamic equilibrium, which is often questionable, especially for clusters at high redshift. To clarify the results found in those studies, we add more data points by including the integrated SFRs of three clusters observed by MIPS (Coma, MS 1054-03, RXJ0152), and four clusters observed by ISOCAM (A2218, A1689, A2219, Cl 0024). The seven clusters with the SFRs measured from $H\alpha$ emission are also added (A1367, AC114, A2390, Cl 0023, Cl 1040, Cl 1054 and Cl 1216). Despite the systematic difference between the SFR measured from the emission line strengths and from the IR luminosity, there is general agreement after extinction correction. We also add an average value for clusters at $0.3 < z < 0.5$ deduced from IRAS data. For the cluster mass, we take the mass measured from lensing analysis whenever it is available because it is free from any assumptions about the dynamical state of the clusters. We limit our calculation to within the $0.5R_{200}$ region and set the cutoff in the SFR as $2 M_\odot \text{yr}^{-1}$. The references and details about the integrated SFR and the masses of these clusters are provided in
Appendix A.

In panels a and b of Fig. 3.9, we plot the integrated SFRs as a function of redshift and cluster mass. In panels c and d, we plot the mass-normalized values. The integrated SFRs show a weak evolution with redshift. The evolution is more pronounced in the mass-normalized SFRs, approximately $\propto (1 + z)^5$. The nonparametric Spearman tests show that the significances of the correlations are 97% and 99% for the integrated SFRs and the mass-normalized integrated SFRs. However, this evolution trend is complicated by the anticorrelation between the mass-normalized integrated SFRs and the cluster masses. Although the integrated SFR does not show an apparent correlation with mass, the mass-normalized one has an anticorrelation with mass, $\propto M^{-0.9}$, with a Spearman significance of 97%. This anticorrelation agrees with the results found in previous comparisons (Homeier et al., 2005; Finn et al., 2005). It also agrees with the anticorrelation found by Poggianti et al. (2006) between the fraction of star-forming galaxies and the cluster velocity dispersion, in the sense that the fraction of star-forming galaxies is comparable to the mass-normalized integrated SFR. Given this anticorrelation, the evolution we found in the mass-normalized integrated SFR is probably due to the different masses of the low-redshift and high-redshift clusters in our sample.

As shown in panel e of Fig. 3.9, the clusters with $z < 0.5$ in our sample are on average more massive than those with $z > 0.5$. Therefore, the increased mass-normalized integrated SFRs at higher redshifts found in the sample could merely be a selection effect. To disentangle the mass factor from the evolution trend, we select a subsample of clusters with a mass range of $3 \times 10^{14} M_\odot < M < 12 \times 10^{14} M_\odot$, in which both low-redshift and high-redshift clusters have good sampling, and plot their mass-normalized SFRs vs. redshift in panel f. The evolution trend of the subsample becomes much weaker, but it still has a significance of about 89%. In addition, even if the evolution of the mass-normalized integrated SFR can be largely caused by the anticorrelation between the mass-normalized integrated SFR and the cluster mass, the evolution of the integrated SFR without mass normalization is still significant and can not be easily explained by the mass selection effect.
Figure 3.9 (a) and (b), the integrated SFRs vs. redshifts and cluster masses; (c) and (d), the mass-normalized SFRs vs. redshifts and cluster masses; (e), the cluster masses vs. redshifts; (f), the mass-normalized SFRs vs. redshifts for clusters with $3 \times 10^{14} M_\odot < M < 12 \times 10^{14} M_\odot$. The mass selection limits are indicated as the two dashed horizontal lines in (e). The filled stars are three clusters observed with MIPS: Coma, MS 1054-03, and RXJ0152. The open star is the eastern clump of MS 1054-03. Filled circles are the clusters observed with ISOCAM, and open circles are from Hα emission line measurements. The dotted curves in (c) and (f) are the fitted correlation between mass-normalized SFRs and redshifts for all the clusters (not including the eastern clump of MS 1054-03). The dotted curve in (d) is the fitted correlation between mass-normalized SFRs and masses (not including the eastern clump of MS 1054-03).
Among all the clusters in our sample, Cl 0024 has the largest integrated SFR with an intermediate redshift and cluster mass. Its integrated SFR is at least five times larger than those clusters with similar masses. Using MIPS 24 μm data, Geach et al. (2006) also found a very significant excess of mid-infrared sources up to $r < 5$ Mpc in Cl 0024 compared to another cluster MS 0451-03 at $z = 0.55$. These results suggest that Cl 0024 is quite unusual compared to other clusters in the sample.

Another unusual aspect of Cl 0024 is its relatively faint X-ray emission compared to its large mass. It has a mass a little larger than RXJ0152, but its X-ray luminosity is only about a fifth of RXJ0152.

The eastern clump of MS 1054-03 also has significant star formation activities but is absent in X-ray emission, contradicting the expected $L_X$ from its mass (Jee et al., 2005a). For a comparison, we calculate the integrated SFRs for the eastern clump of MS 1054-03 separately and plot it as an open star in Fig. 3.9. This result has the interesting implication that clusters or cluster subclumps with unusually low X-ray emission may have very active SF. A recent work by Popesso et al. (2007) seems to support this conclusion. Popesso et al. (2007) studied 137 Abell clusters and found that clusters with lower X-ray luminosity than expected from the $L_X - M$ relation, the so-called X-ray-Underluminous Abell clusters (AXU), show a velocity distribution characteristic of accretion and have a higher fraction of blue galaxies in their outer regions. They suggest the low X-ray luminosities of these clusters are due to the ongoing accretion or merging process. Although Cl 0024 is not exactly X-ray underluminous according to their definition, the exceptionally high SFRs in it and in the eastern clump of MS 1054-03 generally agree with the scenario they propose. They also found that about 40% of the clusters they studied are AXU, indicating that AXU clusters are not a small minority, at least at $z < 0.4$, and suggesting they probably host more SF in total than the X-ray-luminous clusters. Since most of the clusters in our sample are X-ray luminous ones, the SFRs have probably been biased towards the lower value and have an evolution reflecting only conditions in well relaxed systems with substantial amounts of hot, X-ray emitting plasma.
As pointed out previously, the star-forming galaxies tend to be located in the outer regions beyond $0.5R_{200}$. Thus, the integrated SFRs within $0.5R_{200}$ only present a portion of the total star forming activities in the cluster. This cutoff effect is especially significant for RXJ0152 due to its irregular morphology. The integrated SFR within $0.5R_{200}$ of RXJ0152 only accounts for about $13\pm3\%$ of its total SFR in the survey region, much smaller than the 50% expected from a singular isothermal (SIS) distribution of the star-forming galaxies. For MS 1054-03, this fraction is higher, 70%, comparable with 66% expected from a SIS distribution.

3.5.3 Ram Pressure Stripping

In the preceding section, we showed that the mass-normalized integrated SFRs of clusters have an anticorrelation with the masses. This result indicates that massive clusters are probably more effective in suppressing SF than the low mass ones (see also, Poggianti et al., 2006). We also found that very few IR galaxies in MS 1054-03 are distributed in the region of high mass density, especially in the southwestern part. On the other hand, gas stripping by ram pressure in clusters (Gunn & Gott, 1972) is also found to be more pronounced in the massive clusters and more effective in the high density regions (e.g., Giovanelli & Haynes, 1985). The coincidence may suggest SFR suppression in the clusters due to gas stripping by the ram pressure of the intracluster medium (ICM).

To investigate the effect of the ram pressure gas stripping, following Homeier et al. (2005), we calculate the effective radius for this process. Jee et al. (2005a) found the X-ray surface brightness profile of the cluster is best fitted by an isothermal $\beta$ gas model with $\beta = 0.78 \pm 0.08$ and $r_c = 16'' \pm 15''$. Due to the complex morphology of the cluster, this isothermal form does not fit the surface brightness profile of the inner $r < 45''$ region, but it fits the outer region very well and predicts a projected mass profile consistent with the result from the weak-lensing analysis. The virial radius of the cluster is $1.7 \pm 0.2$ Mpc and the corresponding virial mass is $1.2 \pm 0.2 \times 10^{15}$ M$_{\odot}$ (Jee et al., 2005a). If we assume the gas mass is about 10% of the total mass, as suggested in Neumann & Arnaud (2000), we can deduce a central gas density
$\rho_{0,\text{gas}} = 8 \times 10^{14} \, \text{M}_\odot \, \text{Mpc}^{-3}$. According to the ram pressure stripping criterion for the gas in a disk (Fujita & Nagashima, 1999) and the gas profile of MS 1054-03, we obtain a ram pressure stripping effective radius of $r_{rp} = 63'' \sim 0.5 \, \text{Mpc}$ for a Milky Way-type galaxy with a velocity of 1000 km s$^{-1}$.

We show the $r_{rp}$ in Fig. 3.7. For RXJ0152, $r_{rp} \sim 0.3 \, \text{Mpc}$ (Homeier et al., 2005) and none of its star-forming galaxies lies within this radius (also see the discussion in Marcillac et al., 2007). In MS 1054-03, the majority (80%) of the IR cluster galaxies are distributed outside of $r_{rp}$, providing strong evidence of SF suppression due to ram pressure stripping. For the six IR galaxies within $r_{rp}$, only two of them are brighter than $f_{24} = 80 \, \mu\text{Jy}$. The fraction of IR galaxies (4 ± 2%) in this region is about half of that in the outskirt region but still larger than the fraction in the southwestern part, which supports the suppression effect of ram pressure stripping, but also suggests it is less effective for some galaxies and $r_{rp}$ is only an approximate measurement of its effectiveness. There may be a number of explanations. First, this could just be a projection effect, that is at least some of the six galaxies lie in front of or behind the ram stripping region. Second, the isothermal density profile is only an approximate description of the gas distribution, so $r_{rp}$ is only a rough indicator of the effectiveness of ram pressure stripping. Third, the ram pressure stripping criterion we used to deduce $r_{rp}$ is only for the gas in the disk of a galaxy. The gas in the inner disk of a galaxy is harder to strip and therefore any SF occurring there, e.g., circumnuclear SF, is more difficult to suppress.

Another interesting fact is that about half of the E+A galaxies are distributed along the effective radius. This behavior suggests gas stripping as the reason that the star forming activity stopped in these galaxies.

3.5.4 Galaxy Interaction

Many studies find that most of the star-forming galaxies in both the field and clusters are morphologically not strongly disturbed at $z \sim 0.8$ (e.g., Bell et al., 2005; Marcillac et al., 2007) and argue that mechanisms that would dramatically disturb the morphology of a galaxy, e.g. strong galaxy interactions, can not be the major
factor causing the change of SFRs with epoch and environment. However, in MS 1054-03, we found 5 out of 19 IR galaxies of our spectroscopic sample are in interacting systems, one isolated galaxy is irregular, and two more have some irregular features. Therefore, more than 30% of the star-forming galaxies in the spectroscopic sample may be related to galaxy interactions. Among 5 IR galaxies in interacting systems, only two have disturbed morphology, and the other three look regular. If we only count the irregular galaxies as mergers, no matter if they are in merging systems or not, only 16% (3 out 19) of the IR galaxies are related to galaxy interaction, consistent with the result from Bell et al. (2005), who found less than 30% of field IR galaxies are strongly interacting at $z \sim 0.7$.

For the regular IR galaxies in interacting systems, it seems that the galaxy interactions may have triggered their star formation activity but do not change their morphology sufficiently to be obvious. This could be due to the different time scales on which SF and morphological change occur during a galaxy interaction. It is also possible that those interactions are only strong enough to trigger the instability of the galaxies and cause star formation activity, but not to cause observable morphology distortions. Interaction triggered SF is not always accompanied by disturbed morphology and the study of galaxy morphology at the redshift of MS 1054-03 is probably only sensitive to the strongly interacting systems.

On the other hand, the majority of the bright interacting systems ($\sim 70\%$) in the cluster do not have detectable IR emission. Some of them have strong interacting features, e.g., double nuclei, distorted morphologies, but these characteristics are not accompanied by strong SF. This is probably because most of the interacting galaxies have already lost their gas (dry merger) while falling into the cluster due to, e.g., ram pressure stripping, and cannot support a high level of SF. An example of a dry merger with little star formation increase has also been found among local galaxies (e.g., Boselli et al., 2005).
3.6 CONCLUSIONS

Using the MIPS 24 μm data for the rich cluster MS 1054-03 at $z = 0.83$, we found 19 IR emitting cluster members selected by spectroscopic data and 15 additional IR cluster member candidates selected by photometric data.

We constructed the IR luminosity function of the cluster and find a strong evolution when compared with the IR LF of the Coma cluster with a similar mass at $z = 0.02$. The characteristic IR luminosity ($L_{IR}^*$) of MS 1054-03 is about one order of magnitude larger than that of the Coma cluster. The SFR density integrated from the IR LF is about 16 times larger than that in the Coma cluster. The evolutionary trend of the IR LFs from Coma to MS 1054-03 is similar to the evolution of the IR LFs in the field. The comparison of the mass normalized integrated SFR of MS 1054-03 with several other clusters seems to agree with the evolution suggested by the IR LFs, but it is less conclusive because of the combined mass and redshift dependence of the SFR. The similar SFR evolution in the clusters and in the field favors some internal mechanism, e.g., the consumption of the gas fuel in galaxies, as being responsible for the decline of SFR in different environments.

A substantial fraction (13±3%) of cluster galaxies are forming stars actively. Although the fraction is lower than that in the field (52%), the overdensity of the IR galaxies in the cluster is still quite high, ~20. Such a high level of SF is evidence against the scenario that the cluster is only accreting star-forming galaxies from the surrounding field passively, after which their star formation is quenched. Instead, it appears that many cluster galaxies continue to form stars at a high rate. A number of cluster galaxies still have large amounts of gas and their SF can be triggered by the interactions with the intergalactic medium, with other galaxies, or, by tides. However, there are few IR galaxies distributed in the high density regions of the cluster, indicating the suppression effect of ram pressure stripping on the SFR in those regions. Both the IR galaxies and the E+A galaxies of the cluster show a concentration in the NE region of the cluster, supporting the scenario that an interaction between subclumps occurred recently and enhanced the SFR.
About half of the bright late type and irregular cluster galaxies have detectable IR emission, but for early type galaxies this fraction is only about 4%. Only 29% of the mergers in the cluster have detectable IR emission. The majority of the mergers probably have lost their gas fuel long ago and can not support a high level of SF. More than 30% of IR galaxies show evidence of galaxy interaction, and only half of them have irregular morphologies, suggesting the interaction-triggered morphological change and star formation activities of galaxies have different time scales and intensities.
4.1 INTRODUCTION

In the last chapter, by comparing Coma and two other high redshift clusters, we found a strong evolution of the IR LFs in both density and luminosity ($L_{IR}$) from $z \sim 0$ to $z \sim 0.8$. However, since the comparison is based on only one low redshift cluster, Coma, there are possible systematic uncertainties in the evolution we found.

It has become clear that the Coma Cluster, once thought to be the archetype of a well relaxed cluster, has many small substructures (Mellier et al., 1988; White et al., 1993; Neumann et al., 2003). Although we did not found any apparent difference of the IR LF in an infalling group in Coma, it is still not clear how these substructures may affect the overall IR LF. Furthermore, the two high redshift clusters we studied, MS 1054-03 and RXJ0152, both show signs of recent merger events. The merger may affect their IR LFs and might skew the comparison with the more relaxed Coma Cluster. To study how different dynamical states may affect the IR LF and to investigate the cluster-to-cluster variations, we need to study more low redshift clusters.

For this purpose, we study the IR LF of A3266 in this chapter. A3266 is a nearby rich cluster ($z = 0.06$) with mass similar to Coma and MS1054-03. It has a large sample of spectroscopically confirmed cluster members (more than 300), making it possible to obtain a complete IR LF down to a faint limit. It is very bright in the X-ray ($L_X \approx 10^{45}$ ergs s$^{-1}$) and its X-ray morphology and the temperature map, as well as the statistical analysis of the velocity dispersion, all suggest a recent major merger (Quintana et al., 1996; Henriksen et al., 2000). The special dynamical status of A3266 makes it more comparable to the two high redshift clusters and provides a comparison to the more relaxed Coma Cluster too.
The organization of this Chapter is as follows. In §4.2 and 4.3, we present the data analysis; in §4.4, we deduce the IR LF and compare it with the LFs of high-z clusters. We also study the distribution of the IR bright galaxies in clusters and compare it with the distribution of all the cluster members. In §4.5, we summarize the main results.

4.2 OBSERVATION AND DATA REDUCTION

4.2.1 MIPS Observations and Source Extraction

The A3266 cluster was observed by MIPS in medium scan map mode on Jun 28, 2005 at 24, 70, 160 μm simultaneously. A rectangular region of size 45′ × 60′ was mapped. Due to the array arrangement, the coverages at the three wavelengths do not totally overlap. The data were processed with the MIPS Data Analysis Tool (DAT version 3.02; Gordon et al., 2005) and array-averaged background subtraction was applied to improve the images. The final mosaics have exposure times of ~80, ~40 and ~8 s pixel$^{-1}$ at 24, 70 and 160 μm, respectively. The cluster resides in a region with low IR background and for the given exposure time, the 3 σ point source sensitivities at 24, 70 and 160 μm bands are 0.25, 15 and 150 mJy respectively.

We use SExtractor to extract sources and measure photometry. Before source detection, the images are background subtracted and filtered with Gaussian functions with the full width at half maximum (FWHM) matching the FWHM of the images to help improve the measurements of faint sources. The flux of each source is computed in an adaptive Kron aperture.

4.2.2 Spectroscopic Data

To derive a spectroscopically confirmed cluster member list, we retrieved all the galaxies with 0.047 < z < 0.072 in the cluster region from the NASA/IPAC Extragalactic Database (NED). The redshift range corresponds to a 3σ line-of-sight velocity dispersion (Christlein & Zabludoff, 2003). We retrieved 297 cluster members in the region covered by 24 μm observations. Among them, 255 are also covered
by 70 μm observation and 272 are covered at 160 μm.

The spectroscopic data in NED come from several different surveys and are not homogeneous. Therefore, we made use of the $R$-band photometric catalog in the cluster field (Christlein & Zabludoff, 2003) to define the completeness of the spectroscopic data. We obtained all the galaxies with redshifts in the same region from NED and compared their number with the total number of galaxies in the photometric catalog. In Fig. 4.1, we show these ratios as a function of $R$ magnitude. As can be seen in the plot, the spectroscopic data have a high degree of completeness at $R < 17$ mag, but the completeness drops rapidly to less than 50% at $R > 17.5$ mag.

This completeness function does not change much across the whole survey region, but the data are slightly more complete at the cluster center region. When we
calculate the IR luminosity of the cluster in the following section, we will use the inverse of these ratios as the weighting factors to correct for the incompleteness of the spectroscopic survey.

4.3 ANALYSIS

4.3.1 Correlating the IR emission with Optically Selected Cluster Members

We correlated the spectroscopically confirmed cluster members with the nearest 24, 70 and 160 μm sources within 6", 10" and 15" radii respectively. The matching radii take into consideration the large FWHM of the images, 6", 18" and 40" at 24, 70 and 160 μm, respectively. At 24 μm, the rather large matching radius relative to the small astrometric uncertainties (< 1") also accounts for the possible physical displacement between the optical and 24 μm brightness centroids. Altogether, we found 108 cluster members with $f_{24} > 0.25$ mJy, 48 with $f_{70} > 15$ mJy and 15 with $f_{160} > 150$ mJy.

4.3.2 Deducing Total IR Luminosity from 24 μm Emission

The total IR luminosity ($L_{IR}$, 8 – 1000μm) of a star-forming galaxy is directly proportional to the star formation Rate (SFR) and can be used as a robust SFR indicator (e.g., Kennicutt, 1998a). However, since the direct measurement of the total IR luminosity is possible only for a limited number of galaxies, many SFR studies based their calculation on the total IR luminosity extrapolated from a single band IR emission. The mid-IR continuum emission, e.g., in Infrared Astronomical Satellite (IRAS) 12 μm and Spitzer 24 μm bands, has been shown to correlate with the total IR luminosity very well (Takeuchi et al., 2005; Alonso-Herrero et al., 2006; Calzetti et al., 2007).

Because there are only a small number of cluster members in A3266 that have been detected at 70 and 160 μm, we will rely on the 24 μm emission to deduce the total IR luminosity. We based our estimates on the sample of star-forming galaxy SEDs developed by Dale & Helou (2002). These SEDs are based on IRAS and
Infrared Space Observatory (ISO) observations of 69 normal galaxies and have been well calibrated at the far-infrared and submillimeter bands. They are luminosity-dependent and their total IR luminosities are linearly correlated with the 24 μm luminosity in logarithm space. The deduced total IR luminosities of the cluster members with $f_{24} > 0.25$ mJy range from $3 \times 10^{42}$ to $6 \times 10^{44}$ ergs s$^{-1}$. Only one galaxy has IR luminosity $\sim 10^{11}$ L$_\odot$ and falls into the Luminous IR Galaxies (LIRGs) category.

4.3.3 Comparison of SFRs Deduced from Different Methods

Once we have the total IR luminosities of galaxies, we can deduce SFRs using the formula in Kennicutt (1998a). However, due to the uncertainties involved in deducing the total IR luminosity, recent studies have also determined a direct correlation between the 24 μm luminosity and the SFR. Alonso-Herrero et al. (2006) studied a sample of luminous infrared galaxies and give a relation $\text{SFR}(M_\odotyr^{-1}) = 8.45 \times 10^{-38}[L_{24\mu m}]^{0.871}$. Based mostly on a sample of H II regions in nearby galaxies, Calzetti et al. (2007) give a very similar formula with slightly smaller normalization. Here, we compare SFRs of cluster members given by these different methods (Fig. 4.2).

The SFR deduced with the formula of Alonso-Herrero et al. (2006) shows a better consistency with the SFR we deduced, with a systematic difference of 0.1 dex. The formula given by Calzetti et al. (2007) shows a much larger systematic difference, $\sim 0.4$ dex. This is probably caused by the fact that their calibration is based on individual HII regions rather than galaxies. To keep the continuity with our previous works, we will use the SFR deduced from the total IR luminosity in this paper. There may be systematic errors of $\sim 0.1$ dex in the results, but since our goal is to compare the behavior of different clusters, this error is not important.
Figure 4.2 SFRs deduced from the total IR luminosity compared to SFRs deduced directly from 24 μm luminosity.
4.4 RESULTS

4.4.1 IR Luminosity Function of A3266

We calculate the IR luminosity function (LF) over the 16 Mpc$^2$ surveyed area in A3266. The results are shown as the open squares in Fig. 4.3; the vertical dotted line is the 24 $\mu$m detection limit. To account for the incompleteness of the spectroscopic data, we use the inverse of the completeness function (shown in Fig. 4.1) as the weighting factors when we calculate the number counts in each luminosity bin.

The filled squares are the results of the incompleteness-corrected IR LF. The correction raises the LF slightly at the faint end, but there is still a drop of galaxy number density at the smallest luminosity bin. This behavior suggests that the simple incompleteness correction we made is probably not adequate. To test this possibility, we calculate the median $f_R/f_{24}$ ratio of the cluster members with $17 < R < 17.75$ mag, and use this ratio to calculate the corresponding 24 $\mu$m detection limit corresponding to $R = 17.75$, where the spectroscopic survey drops below 50% completeness. The vertical dashed line is the total IR luminosity ($\sim 10^{43}$ ergs s$^{-1}$) corresponding to this limit and it matches the point where the LF starts to drop. The test supports the hypothesis of an inadequate incompleteness correction and suggests the IR LF of A3266 is complete above $10^{43}$ ergs s$^{-1}$.

Along with the IR LFs of A3266, we plot the IR LF of the Coma cluster and its best-fitted Schechter function (Bai et al., 2006) in Fig. 4.3. The Coma IR LF is obtained with a similar data set as in A3266. However, Bai et al. (2006) use slightly different SEDs to deduce the total IR luminosity from the 24 $\mu$m flux. We updated the total IR luminosities of the Coma galaxies using the same SEDs we use in this paper. The resulting IR LF is only slightly changed.

From the plot, we can see the IR LF of A3266 is very similar to that of the Coma cluster in the luminosity region above the completeness limit. For further comparison, we fit the incompleteness-corrected IR LF of A3266 with a Schechter function (Schechter, 1976). We adopt a chi-square minimization method used in Bai et al. (2006, 2007) to find the best fitted parameters. The method incorporates the
Figure 4.3 The IF LF of A3266 (open squares). The filled squares are the IR LF after being corrected for the incompleteness of the spectroscopic data and the solid curve is its best fitting Schechter function. The open circles are the IR LF of the Coma cluster (Bai et al., 2006) and the dash-dotted curve is its best fitting Schechter function. The dotted vertical line is the luminosity corresponding to the detection limit of the 24 μm data. The dashed vertical line is the luminosity corresponding to the spectroscopic completeness limit.
non-detection of the brighter galaxies beyond the brightest bin into the chi-square calculation. Because we do not have many data points at the faint end to constrain the faint end slope, we have fixed it at \( \alpha = -1.41 \), the value given by the Coma IR LF. We only fit the data points above the detection limit \( (L_{IR} > 10^{43} \text{ ergs s}^{-1}) \) and we find the best fitted parameters

\[
\alpha = 1.41 \ (\text{fixed}), \ \log(L^*_IR/L_\odot) = 10.41^{+0.18}_{-0.19}.
\]

The \( L^*_IR \) value is only slightly smaller than that in the Coma cluster \( (\log(L^*_IR/L_\odot) = 10.49^{+0.27}_{-0.49}, \text{ Bai et al., 2006}) \).

### 4.4.2 Composite IR Luminosity Function

The similarity of the IR LFs of the Coma cluster and A3266 indicates the universality of the IR LF in local rich clusters and we can therefore obtain a composite LF for these two clusters. For this purpose, we only include the IR cluster members with \( L_{IR} > 10^{43} \text{ ergs s}^{-1} \). Above this limit, the spectroscopic and IR surveys in these two clusters are both complete. We added up the number counts of the galaxies in each luminosity bin and divided them by the total survey area of the two clusters. The composite IR LF is shown in Fig. 4.4. The best fitted parameters of the Schechter function are:

\[
\alpha = 1.41 \ (\text{fixed}), \ \log(L^*_IR/L_\odot) = 10.49^{+0.09}_{-0.10}.
\]

The \( L^*_IR \) of the composite LF is almost identical to the best fitted Schechter function of the IR LF in the Coma cluster.

Bai et al. (2007) found the IR LF of a high redshift cluster, MS 1054-03 \( (z = 0.83) \), shows a strong evolution compared with the IR LF of the Coma cluster. The best fitting Schechter function of MS 1054-03 IR LF has a \( L^*_IR \) about an order of magnitude larger than that found in the Coma cluster. To confirm this trend, here we combined the data from MS 1054-03 with the data from another high redshift cluster RXJ0152 (Marcillac et al., 2007) and obtained a composite IR LF for them. The total IR luminosities are deduced in the same way to minimize the difference caused by systematic errors. The composite IR LF of the high-z clusters has a
Figure 4.4 The composite IR LF of A3266 and Coma (filled stars). The best fitted Schechter function is shown as the solid curve. The dashed vertical line is the luminosity corresponding to the spectroscopic completeness limit. The filled circles are the composite IR LFs of MS 1054-03 ($z = 0.83$) and RXJ0152 ($z = 0.84$). The dash-dotted line is its best fitted Schechter function. The dotted line is the IR LF of A3266 and Coma evolved to $z = 0.83$ using $L_{IR}^* \propto (1 + z)^{3.15}$, $\phi^* \propto (1 + z)^{1.02}$. 

$\phi^* [\text{Mpc}^{-2}/\log L_{IR}]$ vs. $\log L_{IR} [\text{ergs s}^{-1}]$
logL^*_IR/L_{sun} = 11.45^{+0.21}_{-0.22}, very close to the value obtained by the IR LF of MS 1054-03 alone. Its normalization is slightly smaller than the IR LF of MS 1054-03, but is still much higher than the composite LF of the low-z clusters. This result confirms the strong evolution trend of IR LFs we found before.

4.4.3 Composite IR LFs in Different Regions

Bai et al. (2006) studied the IR LFs in different regions of the Coma cluster and found a flatter faint end slope and lack of very bright galaxies in the core region. Although the data in A3266 are not deep enough to constrain the faint end slope of the LFs, the composite LFs combining the similar regions of these two clusters will have better statistics at the bright end and provide information about the general variation of the LF across the clusters. For this purpose, we define three regions in each cluster: the core region (r < 0.3 Mpc), the intermediate region (0.3 < r < 0.6 Mpc) and the outer region (0.6 < r < 1.2 Mpc). The three regions in A3266 are shown in Fig. 4.6. We combine the IR galaxy number counts above the completeness limit (logL^*_IR > 43) of the two clusters in these three regions. Altogether, there are 7, 14 and 32 IR galaxies with logL^*_IR > 43 found in the core, intermediate and outer region, respectively.

The resulting IR LFs are shown in Fig. 4.5. In the core region, there is no galaxy in the brightest bin and the rest of the LF is almost flat. Combining with the very flat faint end slope found in the IR LF of the Coma core region (logL^*_IR < 43, \alpha = 0.99), the behavior suggests that the IR LFs in the cluster core regions are probably quite flat over a large luminosity range (42 < logL^*_IR < 44) and they lack very bright IR galaxies. However, since we only have 7 galaxies to construct this LF, the result has a large uncertainty. We fixed the faint end slope and L^*_IR of the Schechter function to the value given by the overall composite LF and found the best fitted normalization with the data. A chi-squared test shows that there is no reason to reject the null hypothesis of the core IR LF being consistent with the overall IR LF. The normalization of the IR LF in the core region is slightly higher than the average. But, as shown in the following section, the fraction of cluster members
Figure 4.5 The composite IR LFs in the different regions of the clusters. The solid curves are the best fitted Schechter function of the total composite IR LF of these two clusters. The dotted curves are the best fitted Schechter function in different regions. The vertical dashed line indicates the completeness limit.
with IR emission is actually lower in the core regions compared to the average value in the clusters.

In the intermediate and outer regions, the IR LFs are similar to the composite LF of the whole clusters. We fitted them with a Schechter function with fixed faint end slope as before. The LF in the intermediate region has a slightly higher normalization compared to the LF in the whole region, which again is due to the higher galaxy density in this region. It also has a larger $L^*_{IR}$ ($\log L^*_{IR} = 44.26^{+0.58}_{-0.50}$), but the difference is within the 1σ error. The LF in the outer region is very close to the LF in the whole region, with $\log L^*_{IR} = 43.96^{+0.18}_{-0.18}$.

Overall, we found the normalizations of the IR LFs decrease from the cluster core to the outer region due to a decreasing galaxy density. Despite a smaller fraction of cluster members with detectable IR emission (as shown in the following section), clusters still show higher IR galaxy concentration in the inner region. In the core region of the clusters ($r < 0.3$ Mpc), the IR LF has a "flat" shape over a large luminosity range and lacks very bright IR galaxies. However, this result has a large uncertainty due to the small number statistics.

4.4.4 Distribution of the IR Galaxies in the Cluster

Many previous studies show that the star forming galaxies are less common in clusters compared with the field and there is a general trend of less star forming activity with increasing galaxy density (Balogh et al., 1997; Lewis et al., 2002; Gómez et al., 2003). The infrared galaxies scatter around the whole region, but appear to be more frequent at the outer region. This is basically consistent with the general trend between star formation and density.

To further study this trend, we plot the fraction of the IR bright galaxies at different radii. We calculate this fraction for all the galaxies above the spectroscopic detection limit $M_R = -20.15$ mag. We set the lower luminosity limit of IR bright galaxies to $\log L_{IR} = 42.7$, which corresponds to a SFR~$0.2 \ M_\odot \ yr^{-1}$ and is above the completeness limit of 24 μm detection. As can be seen in Fig. 4.7, the fraction of IR bright galaxies in both clusters increases with radius. There is good agreement
Figure 4.6 The sky map of A3266. East is to the left and north is at the top. The IR cluster members are shown as filled circles. The symbol sizes are proportional to the 24 μm flux. The open circles are spectroscopically confirmed cluster members. The three big circles indicate the three regions in which we extracted IR LFs (r = 0.3, 0.6, 1.2 Mpc).
Figure 4.7 The fraction of the IR bright galaxies ($\log L_{IR} > 42.7$, $\sim SFR > 0.2 \ M_\odot \ yr^{-1}$) as a function of distance from the cluster centers. The horizontal lines are the average value within $r < 1.5 \ Mpc$ for each cluster.

In the fraction in the inner region of the two clusters ($r < 1.0 \ Mpc$). About 25% to 30% of the galaxies are IR bright up to $r \approx 0.8 \ Mpc$. Further away ($r > 1.5 \ Mpc$), the fraction increases to 46% in A3266 and 36% in Coma. The general trend of a decreasing fraction of IR bright galaxies with increasing galaxy density confirms the suppression effect of the cluster environment on star formation. The higher fraction of IR bright galaxies in the outer region of A3266 is probably due to its less relaxed dynamic state compared to the Coma Cluster.

In Fig. 4.8, we show the cumulative distribution of the projected distances of IR bright galaxies against the distribution of all the spectroscopically confirmed members. Again, we set the luminosity limit for IR bright galaxies to $\log L_{IR} = 42.7$, which corresponds to a $SFR \sim 0.2 \ M_\odot \ yr^{-1}$. In the Coma Cluster, the cumulative
Figure 4.8 The cumulative distribution of the projected distances of galaxies in A3266 and Coma. The solid lines are for the IR bright galaxies, and the dotted lines are for all the spectroscopically confirmed members.
distribution of the IR bright galaxies is very similar to the distribution of the whole cluster sample. A Kolmogorov-Smirnov (K-S) test shows the two distributions are consistent at the 92% level. In A3266, the distribution of the IR bright galaxies is very different from the distribution of the whole sample. The K-S test shows there is only 13% probability of consistency. However, the discrepancy is mostly due to a higher fraction of IR bright galaxies in the outer region of A3266. A K-S test conducted only on galaxies within $r < 1.2$ Mpc of A3266 shows a much higher consistency, $\sim 85\%$. This implies a change of star forming properties of cluster galaxies at a distance larger than $\sim 1$ Mpc. This distance is about $0.5R_{200}$ of the cluster ($R_{200}$ is the radius within which the mean cluster density is 200 times the critical density of the universe at that redshift). The change of the properties of IR bright galaxies at $r > 0.5R_{200}$ is also indicated by the increase of the fraction of IR bright galaxies as shown in Fig. 4.7.

4.5 DISCUSSION

4.5.1 The Evolution of the Integrated SFRs

In last chapter, we studied the integrated SFRs in clusters and found some tentative correlations with redshifts/masses. To further confirm those results, here we add the data from A3266 to the study. Following the last chapter, we integrated the SFRs of the cluster members within the $0.5R_{200}$ ($\sim 1.2$ Mpc) down to a SFR limit of $2 \, M_\odot \, yr^{-1}$. This gives a value of $24 \, M_\odot \, yr^{-1}$. The spectroscopic incompleteness correction slightly increases this value to $27 \, M_\odot \, yr^{-1}$. Therefore, the SFR density within $0.5R_{200}$ is about $6.0 \, M_\odot \, yr^{-1} \, Mpc^{-2}$. In the region $> 0.5R_{200}$, the integrated SFR is $52 \, M_\odot \, yr^{-1}$, and the SFR density is smaller, $\sim 4.5 \, M_\odot \, yr^{-1} \, Mpc^{-2}$. We also calculated the mass normalized integrated SFR, for which we use a cluster mass of $3.3 \pm 0.1 \times 10^{15} \, M_\odot$. The cluster mass is deduced using a velocity dispersion of 1255 km s$^{-1}$ (Christlein & Zabludoff, 2003) and utilizing the formula given by Finn et al. (2004). The error on the mass takes into consideration the enhanced velocity dispersion caused by a possible merger.
Figure 4.9 (a) and (b), the integrated SFRs vs. redshifts and cluster masses; (c) and (d), the mass-normalized SFRs vs. redshifts and cluster masses; (e), the cluster masses vs. redshifts. The filled stars are four clusters observed with MIPS: Coma, A3266, MS 1054-03, and RXJ0152. The open star is the eastern clump of MS 1054-03. Filled circles are the clusters observed with ISOCAM, and open circles are from Hα emission line measurements. The dotted curve in (c) is the fitted correlation between mass-normalized SFRs and redshifts for all the clusters (not including the eastern clump of MS 1054-03). The dotted curve in (d) is the fitted correlation between mass-normalized SFRs and masses (not including the eastern clump of MS 1054-03).
As can be seen in Fig. 4.9, the integrated SFR and the mass normalized integrated SFR in A3266 are both consistent with the evolution trend we found before, which increase with redshift. With the added new data point, the mass-normalized SFR evolution trend becomes slightly steeper, \( \propto (1 + z)^{5.4} \). On the other hand, the relations between the mass-normalized integrated SFRs and cluster masses is less conclusive compared to the evolution trend. Especially for the clusters with mass < \( 10^{15} M_{\odot} \), there is large scatter in both the integrated SFR and the mass-normalized integrated SFR.

4.5.2 Ram Pressure Stripping

In the luminosity range of \( \log L_{IR} > 43 \), the IR LF in the core region (\( r < 300 \) kpc) of the two clusters shows a flat shape and lacks very bright galaxies, which may suggest different star forming properties in the core region. But this difference is not significant due to the small number statistics and more cluster data will be needed to constrain the shape of the LF at this luminosity range. However, at the lower luminosity range (\( 42 < \log L_{IR} < 43 \)), the IR LF in the Coma core region clearly shows a flatter faint end slope compared to the overall IR LF. The flattening of the IR LF in the lower luminosity range suggests an enhanced SF suppression in this high density region which works more effectively for galaxies with smaller IR luminosities and generally less mass. The suppression must relate particularly to the region because the projection effect and dynamic segregation would both work against a flatter faint end.

The enhanced suppression effect in the cluster core region could be caused by galaxy harassment and/or ram pressure stripping. Although the stellar and gas content of the low surface brightness galaxies are strongly affected by galaxy harassment, the galaxies in the mass range of our study are relatively resistant to the tidal stripping (Moore et al., 1996, 1999). The ram pressure stripping is therefore most likely to be responsible for the flattening of the IR LF. The time scale of this process can be very short, \( \sim 10^7 \) yr (Abadi et al., 1999), which is only a fraction of the typical crossing time of cluster galaxies. This helps to explain why we only find
the flattening of the IR LF in the core regions.

Although the flatter faint end slope of the IR LF indicates the effect of ram pressure stripping, the very existence of a large number of star forming galaxies with $42 < \log L_{IR} < 43$ in the Coma core suggests that ram pressure stripping may not be as effective as many previous theoretical works suggest (see discussion in Chapter 2). Some recent numerical simulations on the galaxy evolution in clusters support the ram pressure stripping as the primary mechanism for galactic gas loss, but the stripping strength each galaxy experiences can vary greatly due to different orbital histories (Jáchym et al., 2007) and the ICM inhomogeneities (Tonnesen et al., 2007). Tonnesen et al. (2007) also find that the time scale of the ram pressure stripping can be much longer ($\sim$ Gyr) and the stripping significantly affects the gas content of the galaxies out to larger radii in clusters ($r < 0.5R_{200}$). The longer time scale of the ram pressure stripping is consistent with the substantial fraction of strong star-forming galaxies found in MS1054-03, which goes against the scenario that the star formation in galaxies get quenched quickly after they fall into the cluster. The larger region that ram pressure affects is also supported by the change of star forming properties at $r \sim 0.5R_{200}$ found in the Coma and A3266 clusters. Altogether, our results support a ram pressure stripping mechanism that is more complicated than the popular Gunn & Gott (1972) prescription. Therefore, additional studies will be required to understand this behavior (e.g., the study of X-ray underluminous clusters proposed in Chapter 6).

4.6 CONCLUSIONS

Despite the very puzzling merging history and the complicated dynamical state (Sauvageot et al., 2005; Finoguenov et al., 2006), we found the IR LF in A3266 is very similar to that in the much more relaxed Coma Cluster, suggesting a universal form of the IR LF in the local rich clusters. When compared to the IR LFs of two rich clusters at $z \sim 0.8$, the local LF has a $L_{IR}^*$ about an order of magnitude smaller, consistent with the evolution found in the field IR LFs. This behavior suggests that
the evolution of the IR LF in rich clusters is largely determined by the universal
decline of the star forming activities, rather than the environmental effects directly
related to the high density region in the clusters.

The integrated SFR within $0.5R_{200}$ of A3266 is also similar to that in Coma and
agrees well with the evolution trend found in Bai et al. (2007). The mass-normalized
SFRs of clusters show a good correlation with redshift, increasing as $(1 + z)^{5.4}$. On
the other hand, the correlation between the integrated SFRs and cluster masses is
less conclusive and has large uncertainties.

In the cluster core region ($r < 0.3$ Mpc), the composite IR LF of A3266 and
Coma appears to be flat and lacks very bright IR galaxies, indicating an enhanced
SFR suppression effect in this region. However, more cluster data are needed to
confirm this result. The fraction of the IR bright galaxies (SFR $> 0.2M_\odot$ yr$^{-1}$) in
A3266 and Coma remains almost constant ($\approx 25\%$) within $r < 1$ Mpc ($\approx 0.5R_{200}$),
but increases to 46% and 36%, respectively, at larger radii. This implies a change of
the star formation properties of cluster galaxies at $\approx 0.5R_{200}$, which is also suggested
by the cumulative distribution of the IR bright galaxies. These results support the
varied effects of ram pressure stripping in cluster galaxies.
CHAPTER 5

IR Emission from Intracluster Dust in A2029

5.1 INTRODUCTION

Other than the X-rays themselves, there are few measures of the conditions in the X-ray-emitting plasmas in massive clusters. An important constituent of this gas is thought to be material lost from cluster galaxies. Such gas would be well processed and would contain a significant component of heavy elements, indicated by the absorption lines in the X-ray spectra. This galactic-originated gas would also introduce dust grains into the intracluster (IC) gas, which can survive sputtering by ambient gas for a typical time scale of $\sim 10^8$ yr. However, in contrast to the heavy elements, solid evidence of the presence of dust grains in IC gas is still lacking. The indirect measurement of ICD, suggested by enhanced visual extinction towards clusters deduced from high-redshift objects, is still very controversial (e.g., Maoz, 1995).

A direct measurement of ICD can be provided by its IR emission. Dust grains present in the IC medium can be collisionally heated by hot X-ray emitting gas. Dwek et al. (1990) modeled this process and predict flux levels of about 0.2 MJy sr$^{-1}$ at 100 $\mu$m in the Coma cluster. Their calculations, and the upper limit constraints provided by IRAS suggest a deficiency of dust in the central region by a factor of 100 compared with the interstellar dust-to-gas ratio. Using ISO data, Stickel et al. (1998) report the detection of a flux excess of $\sim 0.1$ MJy sr$^{-1}$ at 120 $\mu$m in the central region of the Coma cluster and attribute this excess to the ICD emission. Stickel et al. (2002) confirmed this excess in the $I_{120} \mu$m/$I_{180} \mu$m color profile across the Coma core region, but they did not find the same signal in the other 5 clusters they studied. Quillen et al. (1999) estimated the flux in Coma that might arise from faint infrared-excess galaxies and concluded that it could be a significant fraction.
of the apparent extended component. Bai et al. (2006) have studied the Coma cluster and found the projected number density of infrared-emitting galaxies is the highest in the core region. Such an excess of IR galaxies could cause an excess of IR emission in the cluster core region, raising more questions about the origin of the excess emission reported by Stickel et al. (1998, 2002).

The observational situation is therefore muddled. The difficulties are mostly associated with the sensitivity and detector stability in previous missions, but also with their limited angular resolution which has made it difficult to distinguish the composite of the emission from individual cluster galaxies from that of ICD. The low resolution also causes confusion limitations due to extragalactic sources. But with the much-improved sensitivity and spatial resolution of current and future IR telescopes, e.g., Spitzer, AKARI and Herschel, we may marginally reach the detection thresholds predicted by theoretical calculations (Yamada & Kitayama, 2005).

In this chapter, we present an attempt to measure the extended IR emission from ICD in the galaxy cluster A2029 at \( z = 0.077 \). It is one of the brightest X-ray clusters nearby, with a X-ray luminosity \( L_X(2 - 10\text{keV}) = 1.1 \times 10^{45}h_{70}^{-2}\text{ergs s}^{-1} \) (David et al., 1993) and an intracluster gas metallicity about a third of the solar metallicity (White, 2000). The cluster is in a region of relatively low IR cirrus, which makes it a perfect target for searching for the ICD emission. The size of its X-ray emitting gas (\( \sim 2' \)), which limits the size of the ICD emission, is well suited to sensitive measurements with Spitzer. Hansen et al. (2000) attempted to assess the IR emission from ICD in this cluster with ISO data, but with no success. Using MIPS observations, we can disentangle the IR emission of the galaxies from that of the ICD in A2029. We are able to set upper limits to the ICD emission at 24 and 70 \( \mu \text{m} \) and compare them to the theoretical expectations.
5.2 DATA

5.2.1 Observations and Data Reduction

The cluster was first observed in Feb. 2004 with MIPS in a medium rate scan mode. The 24 μm, 70 μm and 160 μm data were acquired simultaneously for the central 40′ × 60′ region. The integration time was about 80, 40, and 8 seconds at 24, 70 and 160 μm. To further confirm the weak extended emission detected in the cluster core region, a second observation was obtained in Jan, 2005. It followed the same observation strategy as the first one, but tripled the observation time.

The data were processed with the MIPS Data Analysis Tool (DAT version 2.9; Gordon et al., 2005). At 24 μm, extra steps were carried out to remove scattered light, which appears as a low-level background modulation synchronous with scan mirror position. We generated average backgrounds for each scan mirror position and subtracted them from the images. The final mosaic combining old and new observations has an exposure time of ~ 340 s pixel⁻¹ on average. For 70 μm, we only use the data from the second observation because the first observation was taken before the bias was changed on the 70 μm array and has quite noticeable stim latents. The total exposure time for the 70 μm image is ~ 120 s pixel⁻¹ and is ~ 30 s pixel⁻¹ for the 160 μm image. At the 70 and 160 μm bands, we took extra processing steps to improve the images. The pixel-dependent backgrounds were subtracted from the images, which were obtained by fitting the images outside of the central 6′ region of the cluster. This process tends to de-emphasize the extended emission outside the source region, but it keeps the signal we are interested in. The mosaics have point-spread functions (PSF) with FWHMs of ~ 6′′, 18′′, 40′′ at 24, 70 and 160 μm.

5.2.2 IR Source Extraction

To avoid contamination from individual galaxies, we extract all the IR sources from the images using SExtractor. For the 24 μm image, we exclude all the pixels contributing to IR sources down to the 1 σ detection limit, which is about 45 μJy for a
field with medium level background. After the source extraction, 74% of the pixels remain in the 24 μm image. For the 70 and 160 μm data, due to the lower uniformity of the mosaic image, we only exclude the IR sources down to the 2 σ (∼7 mJy and ∼50 mJy, respectively) sensitivity level, after which, 76% and 85% of the pixels remain at each band.

If the IR source density in the cluster core region were greatly enhanced by the cluster galaxies, this source extraction process might cause a bias when we try to measure the extended emission from the remaining pixels. However, this is not the case. The fractions of the remaining pixels in the central r < 2′ region of the cluster are 70%, 80% and 90% at 24, 70 and 160 μm, respectively, which do not differ significantly from the average values for the whole images.

5.3 RESULTS

After excluding the IR sources, we smooth the 24 μm, 70 μm and 160 μm images using a median filter with a box size of ∼2′5. The filter matches roughly the size of the X-ray emitting region (to ∼10% of the central gas density, Lewis et al., 2003).

All IR images show significant brightness fluctuations across the map, and the patterns of the fluctuations are roughly consistent at the three wavelengths. The fluctuations are probably due to the foreground cirrus emission, but they could also be caused by the fluctuation of the number density of unresolved faint sources, especially at 70 μm, where the observations have not reached the confusion limit due to extragalactic sources (Dole et al., 2004) and the cirrus emission is still relatively weak. In Fig. 5.1, we show the smoothed images with the X-ray contours overlaid.

The X-ray data were retrieved from the Chandra Data Archive (CDA). The observation (ObsID 4977) has an exposure time of 79 ks. We obtained the full resolution ACIS image of the cluster and adaptively smoothed it before extracting contours. The 24 μm smoothed image shows a weak enhancement corresponding to the X-ray emitting region, but it is indistinguishable from the foreground cirrus structure and its morphology has no apparent similarity with the X-ray image. At
Figure 5.1 24 μm, 70 μm and 160 μm images smoothed with a median filter of size \(~2\)'. The overlaid X-ray contours are logarithmic, and spaced by 0.48. The image sizes are 20' x 20'. East is to the left and north is at the top. The low-level grid patterns are artifacts of the boxcar smoothing.

70 μm, the enhancement is even harder to recognize due to a large cloud of faint emission crossing the cluster. The core region is also slightly fainter than the outer region of the X-ray emitting region. The enhancement, if any, is likely just to be the extended emission from the Galactic cirrus. At 160 μm, the X-ray emitting region is totally indistinguishable from the background.

Using ISO observations, Stickel et al. (1998, 2002) found a peak in the \(I_{120} \mu m/I_{180} \mu m\) surface brightness ratio towards the Coma cluster center and they use this color difference to discriminate the ICD emission from the foreground cirrus. They believe the emission in the cluster has a slightly higher dust temperature compared to the foreground cirrus and therefore it is the true emission from the ICD. To see if a similar enhancement of the brightness ratio occurs in A2029, we derived a color map by dividing the 24 μm image by the 70 μm image. Since the backgrounds have already been subtracted from both images and we are mostly interested in comparing the color of the cluster emission with that of the interstellar cirrus, we add the average brightness of the interstellar cirrus estimated by SPOT \(^1\) before we calculate the brightness ratio. In Fig. 5.2, the X-ray emission region shows a warmer color than the faint cloud shown in the 70 μm map. However, again,

\(^1\)SPOT, the Spitzer tool for planning observations and submitting proposals, http://ssc.spitzer.caltech.edu/propkit/spot/
this enhancement is not significant compared to the fluctuations in the color map, and there are some other patches in the image also showing similar color to the X-ray emission region. We do not show the $I_{70} \mu m/I_{160} \mu m$ color map here because the color is dominated by the fluctuations at 70 $\mu m$ due to the much larger cirrus emission at 160 $\mu m$ than at 70 $\mu m$.

Although the extended IR emission of the cluster is indistinguishable from the foreground cirrus in the images, we can obtain an upper limit to the extended emission in the cluster. In Fig. 5.3, we plot the radial profile of the average surface brightness as a function of distance from the cluster center, derived from the point sources-removed, non-smoothed image. The error bars are the standard error of the mean for each data point. The 24 $\mu m$ radial profile shows a clear peak at radius < 1′, which is coincident with the peak of the X-ray brightness profile. The enhancement within $r < 1′$ relative to the average of the whole image sets a 2σ upper limit of $5 \times 10^3$ Jy sr$^{-1}$ for the extended emission from the ICD. However, the apparent significance of the peak in the radial profile is mostly due to the fact
Figure 5.3 Top: the radial profiles of brightness at 24 and 70 $\mu$m as a function of distance from the center of the cluster. The error bars are the errors of the mean in each region. The dashed lines are the average values for each image. The X-ray brightness profiles are plotted as the dotted lines. Bottom: the histograms of the smoothed images. The 24 $\mu$m image is smoothed with a median box of size 80$''$ and the 70 $\mu$m image is smoothed with a median box of size 160$''$. The vertical lines are the values at the center of the cluster.

that at large radii, the surface brightness is the average of pixels in a larger area, in which the small scale flux density fluctuations have already been canceled out. To show the fluctuation of the brightness at a smaller scale, we plot the histogram of the pixels in the IR sources masked-out, smoothed 24 $\mu$m image. The smoothing uses a median box of size 80$''$; it retains the fluctuations at spatial scales larger than the box size. The surface brightness at the center of the cluster, although also showing an enhancement ($\sim 4 \times 10^3$ Jy sr$^{-1}$), is only 1$\sigma$ higher than the average of the smoothed image.

At 70 $\mu$m, the enhancement in the cluster is less obvious due to the foreground cloud it lies in. The peak of the emission is not at the center of the cluster, but about 2$'$ away. Therefore we estimate the enhancement in the central $r < 2'$ region, and obtain a 2$\sigma$ upper limit of $1 \times 10^5$ Jy sr$^{-1}$. However, if we exclude the emission in the cluster coming from this foreground cloud and compare the enhancement of the
cluster relative to the local average brightness in the \( r < 15' \) region (approximately the scale of the cloud), we have a smaller upper limit, \( 5 \times 10^4 \) Jy sr\(^{-1} \). The cloud also causes the histogram of the smoothed image (with a median box of size 160") to peak slightly off the mean. Although the surface brightness at the cluster center shows an enhancement at about 0.9\( \sigma \) relative to the average, the enhancement is less significant compared to the peak of the distribution. We can also compare our results with the average brightness fluctuation of cirrus emission given by Miville-Deschênes et al. (2007), which is about \( 2 \times 10^4 \) Jy sr\(^{-1} \) at this scale for a low brightness region. The upper limit we measured is only a few times larger than the average cirrus fluctuation, which again proves the insignificance of the enhancement compared to cirrus noise.

At 160 \( \mu m \), the cluster region shows a lower than average surface density compared to the whole image. The 2\( \sigma \) error of this non-detection is \( 6 \times 10^4 \) Jy sr\(^{-1} \). The non-detection confirms that the brightness fluctuation at 160 \( \mu m \) is dominated by the cirrus emission and the confusion caused by extragalactic sources (Yamada & Kitayama, 2005).

5.4 DISCUSSION AND CONCLUSIONS

We detected weak signals of extended emission in both the 24 and 70 \( \mu m \) images in the cluster A2029 and estimated the upper limits of IR emission from ICD. We now compare our upper limits to the expected values given by theoretical calculations. Dwek et al. (1990) calculated the infrared emission of the ICD collisionally heated by X-ray-emitting hot gas in the Coma cluster. The hot gas in the Coma cluster has a similar temperature and metallicity as in A2029, but with a higher density (White, 2000). Therefore the expected dust emission in the Coma cluster should be larger than that in A2029 and can provide an upper limit to the theoretical expectation of the dust emission in A2029. In Coma, at a distance of about 100 kpc from the cluster center, the expected dust emission is about \( 5 \times 10^2 \) Jy sr\(^{-1} \) at 25 \( \mu m \) and \( 3 \times 10^4 \) Jy sr\(^{-1} \) at 60 \( \mu m \). The upper limit we obtained at 24 \( \mu m \), \( 5 \times 10^3 \) Jy sr\(^{-1} \)
within \( \sim 90 \) kpc of A2029, is 10 times larger than the expected intensity. At 70 \( \mu \text{m} \), the upper limit excluding emission from the foreground cloud, \( 5 \times 10^4 \) Jy sr\(^{-1} \), which does not change much from \( r < 90 \) kpc to \( r < 180 \) kpc, is very close to the expected intensity. According to Dwek et al. (1990), their calculation suggests the dust in the central region of a cluster is deficient by a factor of 100 relative to the standard value for the ISM. The agreement between our upper limit measurements and their calculation confirms that the dust, if any, should be at least deficient by that amount.

Yamada & Kitayama (2005) performed a comprehensive study of the emission of ICD in a sample of clusters with \( z \sim 0.01 - 0.8 \). They present the expected 70 \( \mu \text{m} \) intensities at the projected distance of 20 kpc from the center of the clusters as a function of Galactic latitude (Fig. 7 of their paper). In order to compare their results with the upper limits we obtained for A2029, we scale the intensities at 20 kpc with a factor of 0.28 to deduce the average intensities in the central 175 kpc region, the same region in which we measured the upper limits for A2029. The factor is obtained by assuming the clusters have a similar intensity radial profile as illustrated by the Perseus Cluster in their paper. The results are shown in Fig. 5.4. The two upper limits we obtained are plotted as the downward arrows. They are very close to the predicted intensities of the clusters at similar redshift (the large circles and triangles). In particular, there is one cluster, A3112 (shown as the filled triangle), with very similar properties to A2029. They both are regular, X-ray bright clusters with redshift \( z \sim 0.07 \) and at similar Galactic latitudes. According to the X-ray analysis by White (2000), on which Yamada & Kitayama (2005) base their calculation, A2029 has very similar metallicity, gas temperature and density compared to A3112, which would indicate an IR ICD emission at the same level as that in A3112. The expected intensity in A3112 is very close to the conservative upper limit we measured but is higher than the upper limit that excludes the emission from the foreground cirrus. The discrepancy suggests that the theoretical calculation by Yamada & Kitayama (2005) may overestimate the observed ICD emission.

Another way to detect the weak IR emission from ICD is by stacking many
Figure 5.4 Expected 70 $\mu$m intensities of ICD in the central 175 kpc of a sample of clusters from Yamada & Kitayama (2005) compared with the upper limits measured in A2029 in the same region. The triangles are for the five clusters with highest 70 $\mu$m intensity. The filled triangle is A3112, which we expect to have a similar level of emission as A2029. The large circles are clusters at redshift $0.01 < z < 0.1$, medium circles are at $0.1 < z < 0.3$ and small circles are at $0.3 < z < 0.8$. The top downward arrow is the 2$\sigma$ upper limit for A2029 measured relative to the whole 70 $\mu$m image; the lower downward arrow is the upper limit obtained by subtracting the local foreground emission ($r < 15'$).
galaxy clusters. Montier & Giard (2005) stacked a large sample (11,507) of IRAS cluster maps together and found a statistical detection of $2.1 \pm 0.7 \times 10^3$ Jy sr$^{-1}$ at 25 $\mu$m and $1.6 \pm 0.7 \times 10^4$ Jy sr$^{-1}$ at 60 $\mu$m, both several times smaller than the upper limits we obtained in A2029. This is consistent with the fact that A2029 is one of the brightest X-ray clusters and we would expect the ICD emission in this cluster to be higher than the average value of a large sample of clusters.

The faint average value from stacking plus our failure to detect significant signals in a cluster expected to be relatively bright together indicate that the IR emission of ICD gas must be generally very faint. Even with the much improved sensitivities of the current generation of IR telescopes, this faint ICD emission will be very hard to be distinguished from cirrus fluctuations.
6.1 CONCLUSIONS

6.1.1 IR Properties of Galaxies in Rich Clusters

In the two local rich clusters, Coma and A3266, we found very similar IR LFs despite their quite different dynamical status. Their composite IR LF can be fitted well with a single Schechter function with $\log(L_{IR}^*) = 10.49^{+0.09}_{-0.10}$ and a faint end slope $\alpha = 1.41$. The shape of this LF is very similar to the IR LF in the field at the same redshift.

The IR LF obtained in MS 1054-03, and RXJ0152 (Marcillac et al., 2007) at $z \sim 0.8$, shows a strong evolution compared to IR LF in Coma and A3266. The $L_{IR}^*$ is an order of magnitude larger. The evolution rates in both luminosity and density are similar to the evolution rates found in the field IR LFs. The similar pattern of evolution found in very different environments favors some internal mechanism, e.g., the gradual consumption of the gas fuel in galaxies, as being responsible for much of the star formation evolution. The mass-normalized integrated SFRs within an $0.5R_{200}$ region of these clusters also shows an evolution trend, $\propto (1 + z)^5$. However, the evolution has large scatter and may be affected by the mass selection effect of the sample.

In the core region ($r < 0.3$ Mpc), the IR LF of the Coma cluster has a flatter faint end slope compared to the overall IR LF. It also has a lower fraction of star forming galaxies (25%) compared to the outer region. In MS 1054-03, similar to the two local clusters, there are few IR bright galaxies in the cluster core region. This may be evidence of enhanced effect of the ram pressure stripping in the very high density region. We also find a change of star forming properties occurring at $r \sim 0.5R_{200}$ in the Coma and A3266. A substantial fraction (13%) of cluster
members in MS 1054-03 are still forming stars actively (> 10 $M_\odot$ yr$^{-1}$). Although the fraction is lower than that in the field (52%), the overdensity of the IR galaxies in the cluster is still quite high, $\sim$20. Such a high level of SF is evidence against the scenario that the cluster is only passively accreting star-forming galaxies from the surrounding field, after which their star formation is quenched quickly. These results cannot be explained by the simple ram pressure stripping model, but support varied effects of stripping due to inhomogeneities in the ICM and different orbital histories of cluster galaxies.

6.1.2 Extended IR Emission from ICD

We have searched for IR emission from the ICD in the galaxy cluster A2029. Weak signals of enhanced extended emission in the cluster are detected at 24 and 70 $\mu$m. However, the signals are indistinguishable from the foreground fluctuations. The 24 versus 70 $\mu$m color map does not discriminate the dust emission in the cluster from the cirrus emission. After excluding the contamination from the point sources, we obtain upper limits for the extended ICD emission in A2029, $5 \times 10^3$ Jy sr$^{-1}$ at 24 $\mu$m and $5 \times 10^4$ Jy sr$^{-1}$ at 70 $\mu$m. The upper limits are generally consistent with the expectation from theoretical calculations and support a dust deficiency in the cluster compared to the ISM in our galaxy. Our results suggest that even with the much improved sensitivity of current IR telescopes, a clear detection of the IR emission from ICD may be difficult due to cirrus noise.

6.2 FUTURE WORK

6.2.1 A More Complete Evolution Study in Rich Clusters

This dissertation only studied the star formation in two local clusters and two $z \sim 0.8$ clusters. The evolution trend we found in their IR LFs are not conclusive considering the big cluster-cluster variance. Many other properties of the clusters, such as masses, ICM properties, and substructures, could affect the star formation and cause large scatter in the evolution we studied. The lack of data for clusters at
intermediate redshifts ($z \sim 0.4$) also weakens our conclusions.

To clarify the situation, we will conduct similar analysis on more clusters and expand our statistical sample. The GTO program data we are currently using includes dozens of clusters in a large redshift range, making it an ideal data set for this purpose. We will focus on clusters with intermediate redshifts in this sample to complete the evolutionary trend.

More clusters in this systematic study will also help us understand cluster properties that may affect the star formation and to distinguish the importance of the different physical mechanisms that may be responsible for the star formation suppression in the dense environments. Since the efficiency of these mechanism vary with the physical properties of clusters, with more clusters in our study, we will be able to shed more light on this question.

6.2.2 Star Formation in X-ray Underluminous Galaxy Clusters

Although the current cluster sample with MIPS observations promises to reveal a more coherent picture of star formation evolution, it comprises mostly massive, X-ray luminous systems. Our IR cluster sample, and most of the current cluster SFR studies, are focused on X-ray luminous clusters because selecting clusters by the X-ray emission of the hot intracluster gas is more robust against contamination compared to selecting by optical overdensity, especially at high redshifts. The selection effects associated with high X-ray luminosity may pose a serious bias in the current systematic study of cluster star formation, because there is growing evidence suggesting an intrinsic difference between X-ray luminous and X-ray faint clusters.

Most recently, Popesso et al. (2007) studied the X-ray properties of a large sample of Abell clusters and found about 40% of these clusters are X-ray underluminous, which means that their X-ray luminosities are much too faint compared to expectations from the scaling relation between X-ray luminosity and virial mass traced by the X-ray-selected cluster sample. Further comparison of the velocity dispersion distribution and blue galaxy fraction between X-ray underluminous and luminous clusters seems to suggest the X-ray underluminous clusters are clusters in the pro-
cess of formation, undergoing large mass accretion or mergers. Their low X-ray luminosities are probably a result of the intracluster gas still being in the process of infalling.

If these X-ray underluminous clusters are really nascent clusters and star formation suppression in clusters is primarily due to mechanisms caused by the interactions with the ICM, e.g., ram pressure stripping and hot gas starvation, we would expect a higher level of star formation when compared to the X-ray luminous clusters, due to the fact that a large fraction of galaxies just began falling into the clusters and the suppression may just have begun to take effect.

Coincidently, some results from our work have shown some tentative evidence supporting this expectation. In §3.5.2, we compared the integrated SFR in more than a dozen clusters with different redshifts and masses. Cl0024+1654, a cluster with exceptionally low X-ray luminosity compared with other clusters of similar mass, shows an exceptionally high integrated SFR. In addition, we found enhanced star formation in an X-ray underluminous subclump in cluster MS 1054-03. If the star formation suppression of clusters is mostly the result of preprocessing in the group environment (Lewis et al., 2002), we may not see much difference in the star formation of the X-ray luminous and underluminous clusters since the gas fuel in galaxies will have been exhausted by the star formation triggered by galaxy-galaxy interactions. Either way, since the X-ray underluminous clusters compose a large fraction of all the clusters, it is very important to examine the star formation in these clusters and compare it with the X-ray luminous ones before we can have an unbiased assessment of the star formation in clusters.

To investigate this problem, we obtained MIPS observation of a small sample of X-ray underluminous clusters in the last Spitzer cycle and we are going to propose more observations in this cycle. We also proposed a follow-up spectroscopic survey of these clusters with the MMT and the data for one cluster have already been taken. With both spectroscopic data and MIPS observations, we will be able to assess the star formation in the X-ray underluminous clusters and compare it to the X-ray luminous sample we studied for this thesis.
Appendix

**Integrated SFRs and Masses** The integrated SFR of MS 1054-03, RXJ0152 and Coma, are 372, 134 and 35 $M_\odot$ yr$^{-1}$, respectively. Since the MIPS IR data are only complete down to $\sim 10$ $M_\odot$ yr$^{-1}$ for MS 1054-03 and RXJ0152, we have applied a correction factor of 1.5 estimated from their best fitted IR LFs to the observed integrated SFRs. We adopt weak-lensing masses of $1.1 \pm 0.1 \times 10^{15} M_\odot$ (Jee et al., 2005a) and $4.5 \pm 2.7 \times 10^{14} M_\odot$ (Jee et al., 2005b) for MS 1054-03 and RXJ0152. For the Coma cluster, we use a mass of $1.4 \pm 0.4 \times 10^{15} M_\odot$ from the dynamical analysis (Lokas & Mamon, 2003).

The four clusters observed by ISOCAM are A2218 (Biviano et al., 2004), A1689 (Duc et al., 2002), A2219 (Coia et al., 2005b) and Cl 0024 (Coia et al., 2005a). We adopt their masses as $4.8 \pm 1.4 \times 10^{14} M_\odot$ (Pratt et al., 2005), $1.93 \pm 0.2 \times 10^{15} M_\odot$ (Broadhurst et al., 2005), $1.0 \pm 0.7 \times 10^{15} M_\odot$ (Dahle, 2006) and $5.7 \pm 1.1 \times 10^{14} M_\odot$ (Kneib et al., 2003). These are all lensing masses, except for A2218, which is measured by fitting the X-ray temperature profile. The ISOCAM surveys of A2218, A1689 and A2219 only covered the central $\sim 0.2R_{200}$ regions. Following Finn et al. (2004), we correct for the small coverage by assuming the star-forming galaxy distribution has a singular isothermal (SIS) profile. This correction will give a lower limit to the integrated SFR if the star-forming galaxies are more likely to reside in the outskirts of the cluster as suggested by MS 1054-03 and RXJ0152. For A2219 and Cl 0024, we also need to correct for the incompleteness of the detection limits, which are both $\sim 10$ $M_\odot$ yr$^{-1}$. Since we do not have IR LFs for these two clusters, we use the IR LFs of field galaxies at similar redshifts to estimate the correction to extend the detection limit down to $2 M_\odot$ yr$^{-1}$. This correction is made on the assumption that the shape of the IR LF of the rich cluster does not differ significantly from that of field galaxies at the same redshift, which is probably true...
given Coma and MS 1054-03 as examples. After these corrections, the integrated SFRs for A2218, A1689, A2219 and Cl 0024 are: 14, 64 ± 17, 307 and 753 \( M_\odot \) yr\(^{-1}\).

For the SFRs deduced from the IR luminosity, we assume a 50% error if it has not been given, considering the typical uncertainties of the IR flux measurement.

We include seven clusters with SFRs measured from \(H\alpha\) emission in the comparisons, A1367 (Iglesias-Paramo et al., 2002), AC114 (Couch et al., 2001), A2390 (Balogh & Morris, 2000), Cl 0023 (Finn et al., 2004) and three clusters from Finn et al. (2005): Cl 1040, Cl 1054, Cl 1216. The SFRs of these clusters are measured from \(H\alpha\) narrowband imaging, except AC114 which is measured from \(H\alpha\) spectroscopy. The mass of A1367 is estimated using the dynamical analysis, 7.1 ± 1.5 \( \times 10^{14} \) \( M_\odot \) (Girardi et al., 1998). We use the lensing mass of 7.3\(^{+1.4}_{-1.9}\) \( \times 10^{14} \) \( M_\odot \) (Natarajan et al., 1998) for AC114. For A2390, we adopt a mass of 13.6 ± 0.7 \( \times 10^{14} \) \( M_\odot \) from X-ray analysis (Allen et al., 2001), which gives a consistent result with the lensing analysis in the inner region where it is available (Squires et al., 1996). Following Kodama et al. (2004), we use a dynamical mass of 2.3 ± 1.2 \( \times 10^{14} \) \( M_\odot \) for Cl 0023 (Postman et al., 1998). For Cl 1040, Cl 1054, and Cl 1216, we use the lensing masses of 0.55\(^{+0.75}_{-0.48}\) \( \times 10^{14} \) \( M_\odot \), 4.8\(^{+1.5}_{-1.4}\) \( \times 10^{14} \) \( M_\odot \) and 9.5\(^{+1.8}_{-1.8}\) \( \times 10^{14} \) \( M_\odot \) (Clowe et al., 2006), respectively. For A1367, we correct for the incomplete coverage both in space and velocity range by a factor of 1.7 (Iglesias-Paramo et al., 2002) and obtain an integrated SFR of 29.1 ± 3.1 \( M_\odot \) yr\(^{-1}\). For AC114, we also include a correction factor of 2.8 for the sampling fraction and aperture bias of the spectroscopic survey following Kodama et al. (2004). All of these \(H\alpha\) surveys are complete down to 2 \( M_\odot \) yr\(^{-1}\) and we make a correction for incomplete survey coverage for Cl 1216. The integrated SFRs for AC114, A2390 and Cl 0023 are 21.6 ± 19.5, 80 ± 28 and 71 ± 23 \( M_\odot \) yr\(^{-1}\). These values are slightly smaller than those given by Homeier et al. (2005) because we limit the integration to galaxies with SFR > 2 \( M_\odot \) yr\(^{-1}\). For Cl 1040, Cl 1054 and Cl 1216, we obtain integrated SFRs of 63 ± 12, 90 ± 19 and 369 ± 55 \( M_\odot \) yr\(^{-1}\). The results for Cl 1040 and Cl 1216 are similar to those found by Finn et al. (2005). However, because the lensing mass of Cl1054 is about three times larger than the mass estimated from the velocity dispersion by Finn et al. (2005), the integrated
SFR is also about three times larger than that given by Finn et al. (2005) due to the larger $R_{200}$.

In addition, the SFRs of these seven clusters are deduced by assuming a H$\alpha$ extinction of 1 mag, which corresponds to $A_V \sim 1.2$ mag. However, as mentioned in section 4.3, most of the star-forming galaxies have extinctions larger than this value. For example, all the IR galaxies in MS 1054-03 have $A_V^{IR}$ larger than 1.5 mag. To account for the underestimate of the extinction for the H$\alpha$ deduced SFRs, we need to know the average $A_V$ of galaxies in each cluster. Since we do not have the $A_V$ measured for these galaxies, we have to assume the shapes of the IR LFs of clusters are not very different from those of field galaxies at the same redshifts and estimate the average IR luminosities for those galaxies with SFR $> 2 \ M_\odot \ yr^{-1}$. This assumption may be inaccurate, but both Coma and MS 1054-03 IR LFs seem to support it. From the average IR luminosities, we can estimate the $A_V^{IR}$ with the IR-luminosity-dependent extinction formula given by Choi et al. (2006). Comparing those $A_V^{IR}$ with the assumed 1 mag extinction at H$\alpha$, we deduce correction factors for the integrated SFRs in these clusters, which range from 1.2 to 1.5. We apply the corrections for all the H$\alpha$ deduced integrated SFRs when comparing them with those deduced from IR luminosities.

Using IRAS 60 $\mu$m data, Kelly & Rieke (1990) find the average flux of a sample of clusters by stacking and folding their addscan signals. There are 58 clusters in their sample with $0.3 < z < 0.5$, and their average flux is about 29.1 mJy. (They also calculated a value for a sample of local clusters with $z \sim 0.05$, but due to the uncertainties caused by the different techniques used to deduce the average flux, we do not consider those clusters here.) Each scan of the $z > 0.3$ clusters is about 20$'$ long and 5$'$ wide and the signal is recorded as the one dimensional flux along the scan. The width of the scan is approximately equal to $R_{200}$ of a cluster with $7 \times 10^{14} \ M_\odot$ at this redshift and the PSF fitting of the scan signal along the length includes the flux approximately from the central 5$'$ region. So the average flux they obtained comes from a similar region as our integrated SFR for a cluster with $7 \times 10^{14} \ M_\odot$. For the clusters with larger/smaller mass than $7 \times 10^{14} \ M_\odot$, the flux
is an underestimate/overestimate of the total flux within $0.5 R_{200}$ regions due to the limitation of the scan region. Because the evolved Coma IR LF suggests that about one third of the total IR luminosity is coming from LIRGs at this redshift, we deduce a composite $L_{IR}/L_{60}$ ratio for the clusters by averaging the ratio given by LIRG and late type SEDs weighted by this factor. Using this composite $L_{IR}/L_{60}$ ratio, we can correlate the 60 $\mu$m flux of the cluster to the total IR luminosity and therefore the total SFR. The error of this total SFR is dominated by the uncertainties caused by the composite $L_{IR}/L_{60}$ ratio. Since the average 60 $\mu$m flux of these clusters is obtained by stacking, it is not limited by the detection limit of the observations and the total SFR deduced from it also includes the contribution from the galaxies with SFR $< 2 M_\odot$ yr$^{-1}$. Those galaxies contribute 30% of the total SFR, estimated from the IR LF. Using this factor, we convert the average total SFR to the average integrated SFR. Assuming a typical mass of $7 \times 10^{14} M_\odot$ for these clusters, we obtain the mass-normalized integrated SFR. The assumption of the typical mass here will cause some uncertainty on this data point, but it will partly offset the effect caused by the limitation of the scan region.
REFERENCES
REFERENCES

Beijersbergen, M. & van der Hulst, J. M. 2003, thesis: The galaxy population in the Coma cluster, Chap. 4


Kennicutt, R. C., Jr. 1998a, ARA&A, 36, 189


Yamada, K., & Kitayama, T. 2005, PASJ, 57, 611