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Resolved (KPC-Scale) Properties of Emission-Line Galaxies at Intermediate Redshifts

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Physics

by

Shoubaneh Hemmati

December 2015

Dissertation Committee:

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ABSTRACT OF THE DISSERTATION

Resolved (KPC-Scale) Properties of Emission-Line Galaxies at Intermediate Redshifts

by

Shoubaneh Hemmati

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, December 2015
Dr. Bahram Mobasher, Chairperson

The focus of this dissertation is to study resolved substructures in galaxies at kpc-scale and their relation with the global properties of the host galaxies. I use combined high resolution photometric data from the Hubble Space Telescope and very deep long exposure spectroscopic observations with the Keck telescopes. Using the optical and near-infrared data taken as part of the CANDELS project, I perform pixel-by-pixel analysis of 120 galaxies at intermediate redshifts. I produce resolved rest-frame (U-V) color, stellar mass surface density, star formation rate surface density, stellar age and extinction maps and profiles along the galaxies rotation axes. I developed a method to identify clumps and use them to investigate their distribution and covering fraction. Investigating the evolution of covering fraction and average radial distance with respect to both redshift and stellar mass of the host galaxy, I explore if the bulge growth is due to migration of star-forming clumps, it is likely to have happened at higher redshifts. I find that there exists a tight correlation between the stellar mass and star formation rate surface densities of pixels inside individual galaxies as well as among red and blue clumps over different galaxies. The tightness of the blue clumps main sequence regardless of the large redshift range of the hosts, suggests no evolution in the nature of blue clumps with time. I estimate small-scale distribution of stellar dust extinction from pixel-by-pixel SED fitting and

used $H\alpha/H\beta$ nebular emission line ratios from Keck/DEIMOS spectra at each spatial resolution element to measure attenuation faced by ionized gas at different radii from the center of galaxies. A good agreement is found between the integrated and median of resolved color excess measurements in galaxies. I find that inclination plays an important role in the variation of the nebular to stellar color excess ratio. The increase in the nebular color excess with stellar mass surface density found here, explains the absence of strong radial trend in the nebular color excess in lower mass galaxies. I also demonstrate the usefulness of resolved optical line ratio plots in identifying otherwise hidden AGNs.

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Chapter 1

Introduction

Study of galaxy formation and evolution is very challenging and different from other fields of physics due to the main fact that life is too short compared to the shortest time scales involved in galaxy evolution. While the evolution of individual galaxies can not be observed in isolation, galaxies with their diverse properties over cosmic time are used in a statistical sense to infer their evolution. Galaxies are defined by and observed through their stellar content. The electromagnetic spectrum observed of galaxies spanning a wide wavelength range is the only accessible data to explore their physical properties. Individual stars can not be resolved in most observations except for nearby galaxies. Therefore, to extract information about galaxies, cumulative light of stars is analyzed using stellar population models. A further complication here is the presence of gas and dust in the Inter-Stellar Medium (ISM) of galaxies which affects their observed spectrum by absorption and re-emission of star light as well as nebular emission. Nebular emission lines offer additional vital diagnostics about galaxies. Combination of stellar population models with information from the nebular emission-line strengths and ratios offers a wealth of information about galaxy properties and evolution. This dissertation is an effort to extend this methodology to small-scales ($\sim$ kpc) in galaxies to study how internal properties of galaxies govern their global properties and to constrain the role of internal processes on the observed (global) evolution of galaxies.

1.1 Measurement of the Physical Properties of Galaxies: Stellar Population models

The most widely used technique for measuring physical properties of galaxies is to fit their observed Spectral Energy Distribution (SED) with stellar population synthesis models (e.g. Faber 1972, Walcher et al. 2011 Reddy et al. 2012). This is also the standard method for measuring the photometric redshifts of galaxies. There is a wealth of useful physical information buried in the far-ultraviolet to the far-infrared SEDs of galaxies, such as the amount of their stellar mass, star formation history, metal content, dust distribution and radiation from the ISM. Observed SEDs of galaxies, constructed from multi band photometric observations or higher spectral resolutions spectroscopic data, are fitted against Composite Stellar Population models (CSPs) specifically developed to produce these observations.

Building CSPs needs certain ingredients as presented in Figure 1.1 (adopted from the review on SED modeling by Conroy (2013)). First, Simple Stellar Population models (SSPs) (e.g. Bruzual & Charlot 2003, Maraston et al. 2006) are constructed from library of stellar spectra and their evolutionary tracks in the form of isochrones (e.g. Bressan et al. 1993, Bertelli et al. 2009), and with assumption about an Initial Mass Function (IMF), which is an empirical relation describing the distribution of initial masses for a population of stars (e.g. Salpeter 1955, Kroupa 2001, Chabrier 2003). The CSPs are then built using these SSPs combined with a recipe for dust absorption and emission (e.g. Witt & Gordon 2000, Calzetti et al. 2000, Charlot & Fall 2000 Popescu et al. 2011) and an assumption about the star formation history and chemical evolution.

Different fitting techniques are suggested in the literature for finding the best fit from the model library, with the most widely used method being the grid-based minimum χ^2 fitting method. A critical and maybe limiting portion of uncertainties in the SED fitting results are inherited from uncertainties in various steps of building the SPS models (discussed in detail in the review by Conroy (2013)). There is however an interplay between the quality of available data, the quality of available models and the best fitting techniques to obtain realistic measure-

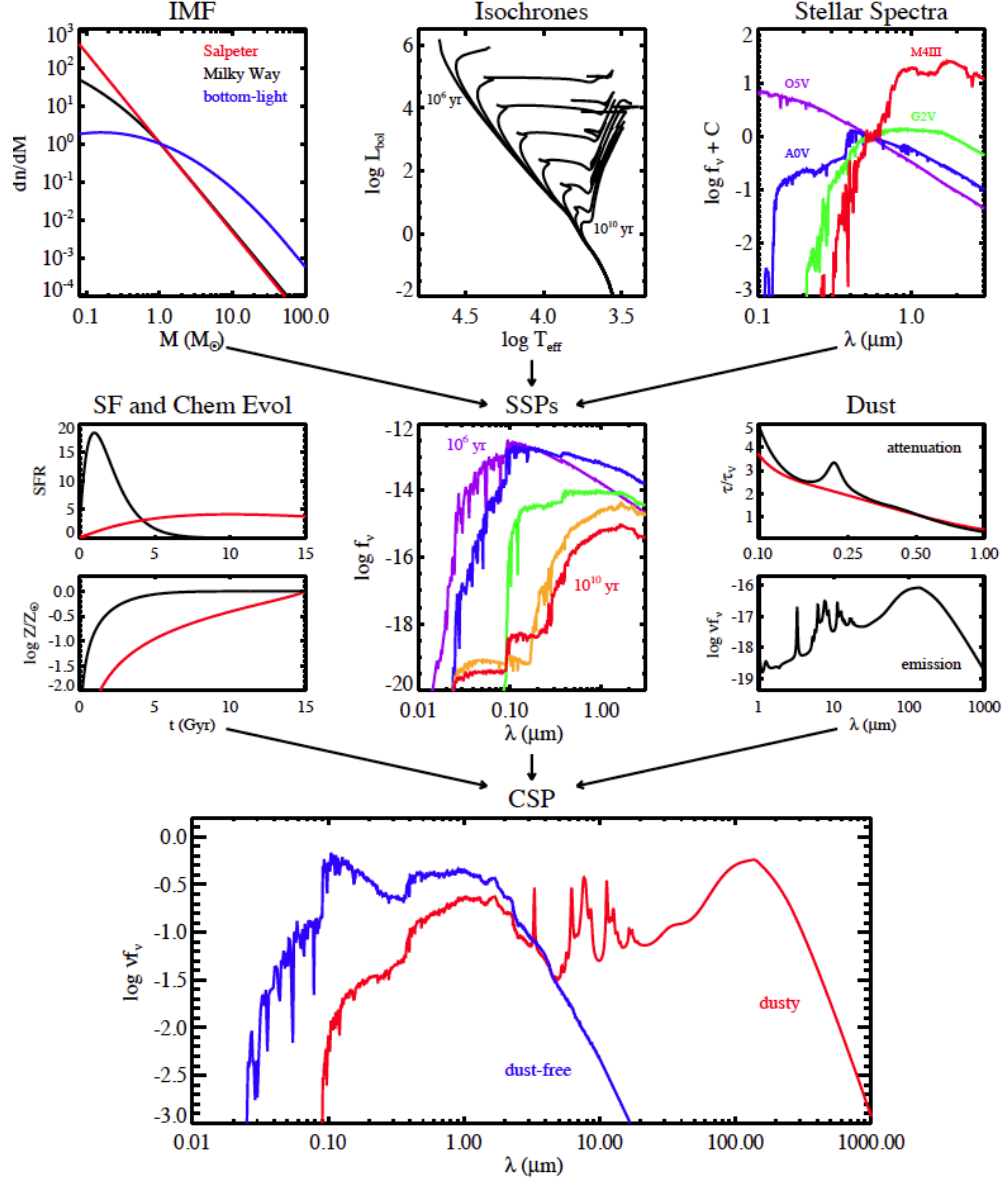


Figure 1.1: Overview of the stellar population synthesis technique as presented in Conroy 2013. The upper panels highlight the ingredients necessary for constructing simple stellar populations (SSPs): an IMF, isochrones for a range of ages and metallicities, and stellar spectra spanning a range of T_{eff} , L_{bol} , and metallicity. The medium panels highlight the ingredients necessary for constructing composite stellar populations (CSPs): star formation histories and chemical evolution, SSPs, and a model for dust attenuation and emission. The bottom row shows the final CSPs both before and after a dust model is applied.

ments and uncertainties (Walcher et al. 2011, Mobasher et al. 2015). To test the accuracy of physical parameters estimated through the SED fitting process, the outputs such as redshift, stellar mass, star formation rate, etc. can be compared with some independent measurements, ideally derived from spectroscopic observations.

1.2 Measurement of the Physical Properties of Galaxies: Nebular Emission Lines

Radiation from stars within or near emission nebulae ionizes the gas in the nebula through the photoionization process that leads to radiation from the nebula. This radiation can be from the decay of electrons (captured to excited states during recombination) to lower energy levels, producing the recombination lines such as all the Balmer and Paschen series. Ionized gas will also emit forbidden-line spectrum from the collisionally excited ions, such as [NII],[OII] or [OIII]. Figure 1.2 shows the ultraviolet, optical and near-infrared spectrum of a gaseous nebula with the strong emission lines identified.

Aside from accurate redshift measurements, strength and ratio of nebular emission lines are a major source of direct and indirect information for estimating various physical properties of galaxies such as temperature, electron density, star formation, and nebular dust attenuation.

The nebular dust attenuation is measured from the ratio of first two Balmer transitions ($H\alpha$ and $H\beta$) or the so-called Balmer decrement. Ratio of the luminosities of Balmer transitions arising from HII regions around very massive stars is known to be the most practical indicator measuring attenuation by dust in these regions. In the absence of dust, the intrinsic theoretical $H\alpha$ to $H\beta$ line ratio, assuming Case B recombination, a temperature of $T = 10^4 K$, and an electron density of $n_e = 10^2 cm^{-3}$ is known ($F(H\alpha)/F(H\beta) = 2.86$; Osterbrock 1989). Any deviation from this amount is indicative of the amount of dust attenuation.

While stars are a major source of photoionization in the diffuse gaseous nebula in galaxies, the so-called “HII” regions, emission lines from extragalactic objects can be produced due to different excitation mechanisms, such as photoionization by a power-law continuum source,

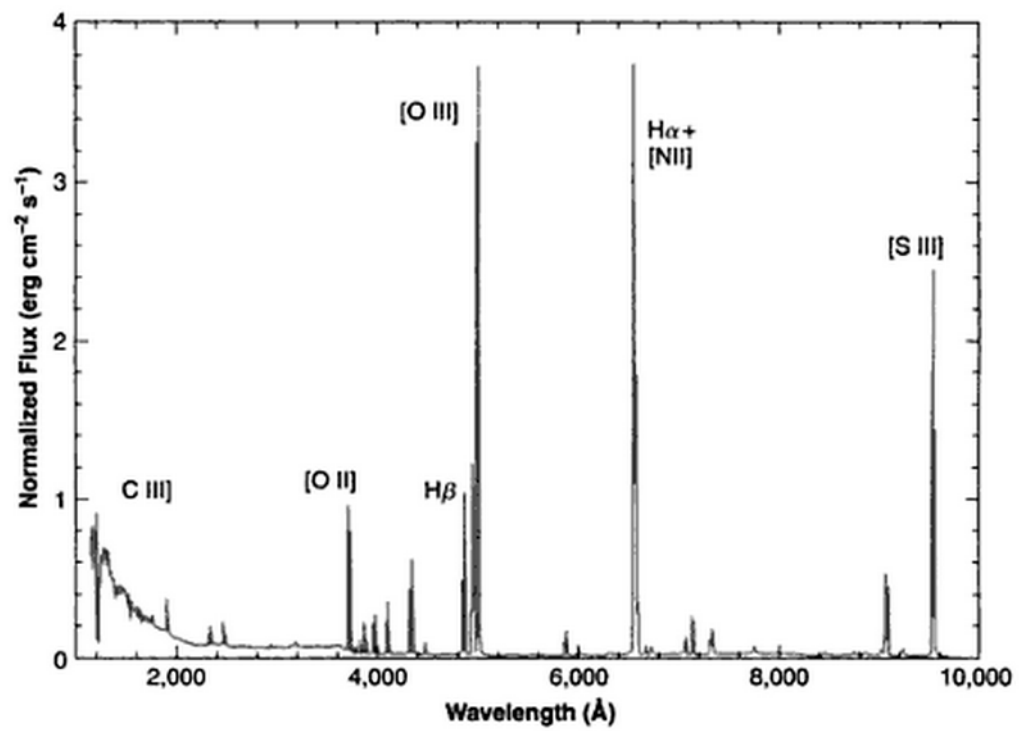


Figure 1.2: Spectra of a gaseous nebula (inner regions of the Orion Nebula) in the ultraviolet, optical, and near infrared with strong recombination and forbidden emission-lines identified on the (Courtesy of Osterbrock 1989).

or shock-wave heating. The relative strengths of emission lines therefore offers a very good diagnostic tool to distinguish between these sources. One such diagnostic diagrams which has been used extensively over the past decades is the so called “BPT” diagram (e.g. Baldwin et al. 1981, Ho et al. 1997), distinguishing between starbursts, AGNs and composite systems.

1.3 This Dissertation

As discussed in the previous sections, physical properties of galaxies can be estimated through SED fitting as well as from diagnostic nebular line measurements. Recent photometric and spectroscopic studies of galaxies show various trends in the evolution of their physical properties with redshift, leading to the populations of galaxies we see today. In particular, at intermediate redshifts, there is evidence for the formation and development of the Hubble sequence (e.g. Wuyts et al. 2011; the growth of central bulges (e.g. Elmegreen et al. 2008; Daddi et al. 2007; Hopkins et al. 2010; Lang et al. 2014) Bell et al. 2012), disk growth (Miller et al., 2011), potential “disk settling” (Kassin et al., 2012), and quenching of star formation (e.g. Bell et al. 2004; Faber et al. 2007), all affecting observed global properties of galaxies.

However, despite extensive observational studies and theoretical simulations over the last decade, the specific details behind many of these processes are not well understood. For example, we do not yet know which parameters govern the star formation activity in galaxies and their dependence on look-back time (e.g., Lilly et al. 1996; Madau et al. 1998; Bell et al. 2005, Mobasher et al. 2009). Processes potentially responsible for this are a drop in the galaxy major merger rate (e.g., Patton et al. 2002; Lin et al. 2004; Bell et al. 2006; Lotz et al. 2011), exhaustion of the cold molecular gas (e.g., Tacconi et al. 2013; Daddi et al. 2010) or the occurrence of disk instabilities that cause the migration of gas clumps into galaxy centers, creating bulges that stabilize the disk against further clump formation (e.g., Elmegreen et al. 2008; Dekel et al. 2009; Genzel et al. 2011; Wuyts et al. 2012, Guo et al. 2012).

While a number of studies have been performed to address these questions, they are largely based on the integrated properties of galaxies, without considering the details of the individ-

ual components and processes internal to galaxies. A physical understanding of the relations between various global properties of galaxies would not be complete without knowledge of the processes involved at kpc scales or smaller. Furthermore, one could achieve fundamental insights to the formation and evolution of galaxies by studying the relations between the integrated and internal (i.e. resolved) properties of galaxies over time. This requires deep multi-waveband images with high spatial resolution for representative samples of galaxies with available measurements of their global properties (i.e. stellar mass, star formation rate). With the advent of high resolution imaging detectors on the Hubble Space Telescope (HST), one can resolve kpc-scale structures in galaxies along with their photometrically derived properties.

Over the last decade, extensive multi-waveband photometric surveys of galaxies have become available. The Cosmic Assembly Near-infrared Deep Evolution Legacy Survey (CANDELS; PI. S. Faber and H. Ferguson; see Grogin et al. 2011 and Koekemoer et al. 2011) have provided high-resolution and deep images of galaxies in different pass bands spanning the optical and near-IR wavelengths. Using the imaging data in the GOODS-S field, Wuyts et al. (2012) studied resolved colors and stellar populations of a complete sample of star-forming galaxies at $0.5 < z < 2.5$. The galaxies were selected to be massive ($> 10^{10} M_{\odot}$) with high specific star formation rates. The Spectral Energy Distributions (SEDs) were constructed per bins of pixels of constant signal-to-noise and analyzed to study variations in rest-frame colors, stellar surface mass density, age and extinction as a function of global properties of galaxies. They identified off-center clumps in galaxies and studied their contribution to the integrated star formation rate and integrated stellar mass. However, to fully understand the nature of these structures, one needs resolved spectroscopy.

Förster Schreiber et al. (2009) studied the properties of these stellar “clumps” for a sample of six star-forming galaxies at $z \sim 2$ using near-infrared integral field spectroscopy from SINFONI at the Very Large Telescope (VLT). This allowed measurement of the dynamical mass of the clumps and their spectral line emission diagnostic of star formation activity. Furthermore, they identified the “clumps” based on their emission lines (i.e. $H\alpha$ emitting clouds) and used this information to study the nature of these structures. While this provides a superior

technique for studying kpc-scale structure of galaxies, it is technically challenging. One could acquire such data with adequate S/N ratios for only a handful of galaxies, making it difficult to generate a statistically large sample.

In this thesis, I combine high spatial and spectral resolution photometric and spectroscopic observations of star forming galaxies at intermediate redshifts to study how small scale properties of galaxies correlate with their global properties and to constrain the role of internal processes on the evolution of global properties of galaxies such as their stellar mass and star formation and metal enrichment. A summary of the following chapters is given below.

In *Chapter 2*, I explain the methodology developed to construct kpc-maps of physical properties of galaxies using pixel-by-pixel SED fitting procedure. I study different sources of uncertainty as well as the effect of including emission-lines in the fitting procedure.

I develop clump identification scheme in *Chapter 3* where I present the clump identification technique, study the properties of red and blue clumps and compare them to the properties of underlying disk of galaxies. The evolution of red and blue clumps covering fractions as well as radial distance from the center as a function of host galaxy stellar mass and redshift is also investigated in detail in this chapter.

Chapter 4 is an investigation of the relation between the stellar mass and star formation surface density (the “resolved main sequence of star formation”) among pixels in individual galaxies as well as clumps over a larger sample. I demonstrate the importance of sample selection in studying the global main sequence of star formation.

Spectroscopic data will be used in *Chapter 5* to construct resolved nebular optical line ratio diagnostics along the major axis of galaxies. Resolved nebular and stellar dust distribution in galaxies will be studied and compared against global dust attenuations. Using the optical line ratios, I will construct the resolved BPT diagram to distinguish AGN from star forming galaxies.

I conclude by a summary in *Chapter 6* and discuss some of the main ongoing projects which use the same methodology developed in this dissertation. Throughout this work I assume a standard cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ and all magnitudes are expressed in AB system (Oke & Gunn 1983).

Chapter 2

KPC-Scale Maps of Emission-line Galaxies

2.1 Introduction

In this chapter, I explain the step-by-step method I develop to make resolved rest-frame optical color, stellar mass surface density, star formation rate surface density, age, and extinction maps by performing spectral synthesis fitting per resolution element for each galaxy.

As discussed in detail in the previous chapter, one of the most-widely used methods to study physical properties of galaxies (e.g. stellar masses, star formation histories and rates, metallicities, ages) at different redshifts is to fit their observed spectral energy distributions with stellar population synthesis models. While there still exists many sources of uncertainties in the models and fitting methods, there has been huge progress in studying statistical properties of galaxies at all redshifts (e.g. Mobasher et al. 2009, Reddy et al. 2012, Conroy 2013).

Here, we apply this technique to the SEDs per resolution element in each galaxy instead of its integrated light (e.g. Zibetti et al. 2009, Welikala et al. 2011, Wuyts et al. 2012, Lanyon-Foster et al. 2007). At the most basic level, resolved SED fitting allows the analysis of sub-structures in any given galaxy and reduces the uncertainties caused by using an “average” dust attenuation law and star formation history for the whole galaxy.

The structure of this chapter is as follows, in §2.2 I present the criteria used for selecting the sample and describe the properties of the galaxies selected. While the results in the following chapters of this dissertation are derived mainly using this sample of emission-line galaxies located in the GOODS fields, the techniques described in this chapter for producing the resolved (kpc-scale) maps of physical parameters can be used on any galaxy for which high resolution HST data exist. In §2.3 I discuss the preprocessing of images and pixel-based multi-waveband photometry catalog building. I explain the parameters characterizing the model SEDs in the library, in §2.4. The resolved SED-fitting process and the 2D map products are presented in §2.5. Integrated and resolved measurements are compared in §2.6 followed by a summary of main points in §2.7.

2.2 Sample

Results derived in this dissertation except for parts of Chapter 4 (which will be described there in detail) are based on the sample used in Hemmati et al. (2014). This sample is selected in GOODS-S and GOODS-N fields (Giavalisco et al., 2004), with available ground-based spectroscopy from DEIMOS (DEep Imaging Multi-Object Spectrograph; Faber et al. 2003) on Keck II.

The galaxies in this sample are selected to be brighter than 22.5 magnitude in the ACS F850lp filter and lie within the spectroscopic redshift range $0.2 < z < 1.3$. They have resolved, disk-like structures, including not only well-formed spirals but also disturbed and morphologically irregular and abnormal systems. Early-type spheroids and unresolved objects were excluded from the sample. Finally, a magnitude limit of $K_s \leq 22.2$ is imposed to ensure a high fraction of reliable stellar masses.

Keck DEIMOS spectra were obtained for 236 galaxies that were selected using the above criteria (Miller et al., 2011). A total integration time of 6-8 hours were acquired with the 1200 lmm^{-1} grating and $1''$ slits and a central wavelength of $7500 \text{ \AA}$, achieving a spectral resolution of $\sim 1.7 \text{ \AA}$. Of the 236 targets, 129 of the galaxies (about 55% of the original sample) that

were observed spectroscopically, revealed resolved emission lines for which accurate rotation curves are measured (the emission extends beyond the seeing-dispersion PSF in the spectrum). Figure 2.1 shows that the distribution of sizes or masses of our selected targets is not biased with redshift or magnitude compared to galaxies with the same redshift and magnitude cut.

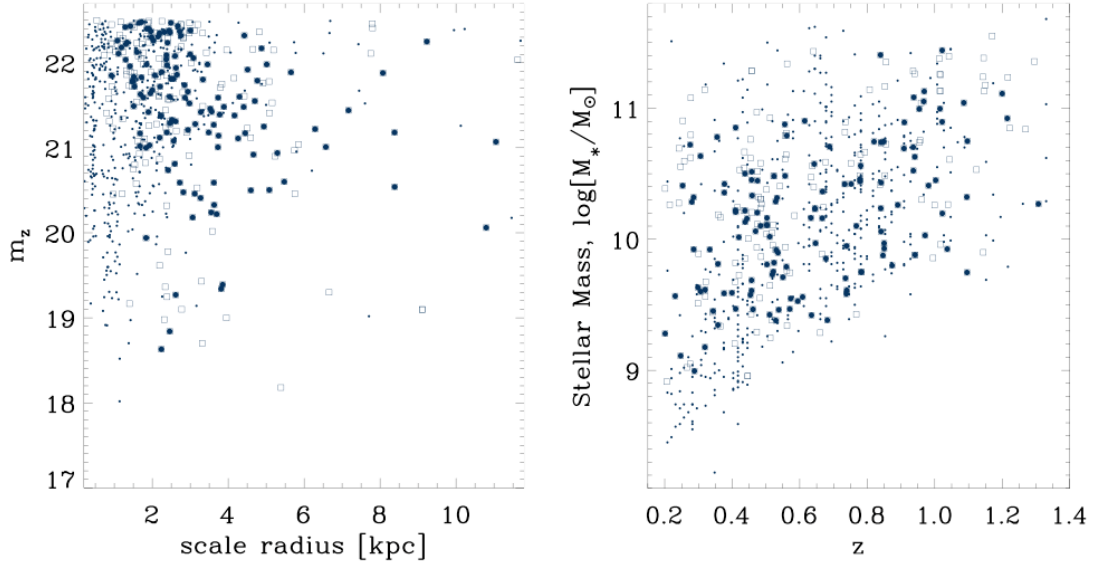


Figure 2.1: Apparent magnitude (z_{F850lp}) vs. disk scale radii (in kpc) and stellar mass vs. redshift for galaxies selected for the present study, consisting of 129 resolved emissions (large filled squares). There are 107 galaxies which also satisfy the selection criteria here, with available spectroscopic data but unresolved or undetected emission (empty squares). These are not included in the analysis in this study. A control sample is also shown with similar photometric redshift and magnitude cuts (small dots).

This sample is most desirable for studying resolved properties of galaxies for the following reasons:

1. Availability of seven high resolution Hubble Space Telescope (HST) optical and infrared images taken by ACS and WFC3 from the CANDELS. It has been shown that using optical + NIR filters reduces the uncertainties in studying resolved properties in galaxies compared to using optical filters only (Welikala et al., 2011). In this study we use HST/ACS observations in the F435W, F606W, F775W and F850LP (hereafter B_{F435W} , V_{F606W} , I_{F775W} and Z_{F850lp}) and HST/WFC3 observations in the F105W, F125W and F160W (hereafter

Y_{F105W} , J_{F125W} and H_{F160W}) filters. The ACS images have been multi-drizzled to the WFC3 pixel scale of $0''.06$ (Koekemoer et al., 2011).

2. The availability of spectroscopic redshifts for all the galaxies. One of the major sources of uncertainty in measuring galaxy properties through fitting their spectral energy distribution is the uncertainty in their photometric redshift. By knowing the precise spectroscopic redshift of the galaxy we overcome this issue.
3. Kinematic information are available with high spectral and spatial resolution for rotation curves and dynamical models of all the galaxies in this sample. This allows direct comparison between high resolution photometric maps (of stellar mass, SFR, etc.) and dynamical information at kpc-scales.
4. All galaxies have high spatial and spectral resolution extended emission lines which allows radial gradient measurement of ratios of diagnostic nebular lines across the disk at small scales.

2.3 Preprocessing

Before performing the SED fitting per resolution element some necessary steps need to be taken. The very first step in making resolved maps of galaxies is to make sure that we are combining the same resolution and pixel scale in different images. To bring the images to the same resolution one needs to match their Point Spread Functions (PSF match). I make cutouts of 200×200 pixels centered on the galaxy coordinates from the seven band HST/ACS and WFC3 CANDELS images (which are all set to have $0''.06$ pixel scale) and their corresponding RMS error maps. 200 pixels is big enough to contain the galaxy itself as well as some neighboring objects and will ensure that there would not be any edge problems close to the galaxy. I construct the PSFs of each waveband using an interactive IDL routine `PSFGEN.PRO`. This routine uses a list of stars distributed in the field and stacks the PSFs of the user specified stars that user specifies to produce an average PSF for each image. To PSF-match the cutout images

across the range of the filters used, I take all lower resolution images to the resolution of F160W (which has the longest wavelength available from HST) using the IRAF PSFMATCH task. This routine computes the convolution kernel from the input and reference PSFs using the convolution theorem. This gives a spatial resolution of $\sim 0''.17$. After matching the resolutions I make the smaller cutouts of 80×80 pixels which at the redshift range of our sample corresponds to a box size of $\approx 15 - 40$ kpc (see Figure 2.2).

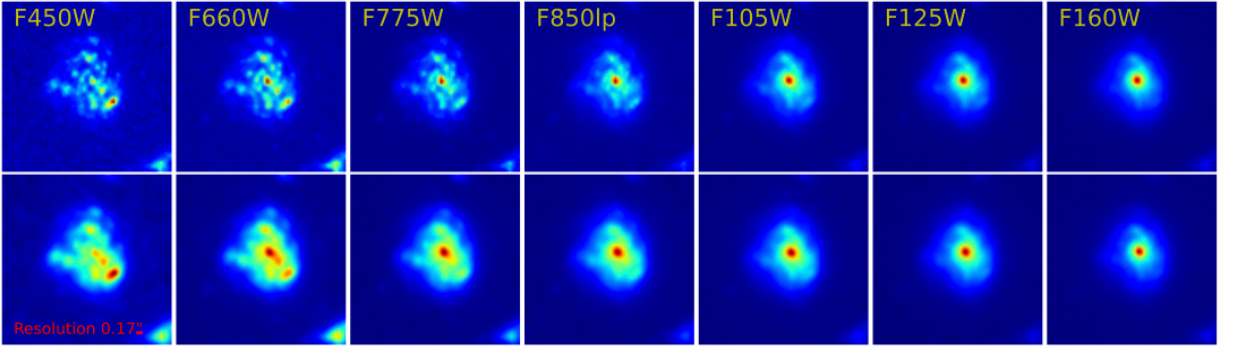


Figure 2.2: 7-band HST 80×80 pixel cutouts of a typical emission-line disk galaxy at $z=1.1$ (80 pixel = 39.7 kpc) before and after PSF-matching in top and bottom rows respectively.

I removed 10 galaxies located at the edge of the fields because the constructed PSF is not a good representation of the true PSF at these locations, due to distortion, lower exposures, and signal-to-noise level. The final results are sensitive to this as a wrong PSF kernel would lead to ripples in the final maps. Fitting Gaussians to the PSFs before performing the PSF-matching would clear this issue, however for the sake of consistency, we discard these 10 galaxies. This leaves us with 119 galaxies.

To define the boundary of the galaxy, we run the Source Extractor code (Bertin & Arnouts, 1996) on the z band cutouts (as seen in Figure 2.2, of all the ACS bands, the z band reveals the deepest, smoothest, most extended light. This feature is seen in most of the galaxies in our sample). The parameters in the SExtractor configuration file are optimized to find the galaxy at the center of the cutout without dividing it into its subcomponents. Table 2.1 summarizes the main parameters in the SExtractor configuration file. We flagged and masked out any neighboring object in the segmentation maps produced by SExtractor. The very low surface brightness out-

Table 2.1: Main Parameters in SExtractor Configuration File

DETECT_MINAREA	5	minimum number of pixels above threshold
DETECT_THRESH	3.5	<sigmas> or <threshold>,<ZP> in mag.arcsec-2
ANALYSIS_THRESH	2.0	<sigmas> or <threshold>,<ZP> in mag.arcsec-2
FILTER	“Y”	apply filter for detection (“Y” or “N”)?
FILTER_NAME	“gauss_5.0_9x9.conv”	name of the file containing the filter
DEBLEND_NTHRESH	32	Number of deblending sub-thresholds
DEBLEND_MINCONT	0.001	Minimum contrast parameter for deblending

Table 2.2: HST/ACS and WFC3 Zeropoints

B_{F435W}	V_{F606W}	I_{F775W}	Z_{F850lp}	Y_{F105W}	J_{F125W}	H_{F160W}
25.673	26.486	25.654	24.862	26.2687	26.2303	25.9463

skirts of galaxies are also masked by multiplying this segmentation map to individual cutouts in all bands. Instead of using SExtractor segmentation maps, other thresholding and segmentation algorithms from different existing image processing packages can be applied to cutout images.

To build the multi-wavelength catalog for each galaxy, I converted the flux at each pixel to an AB magnitude using the Zeropoints listed in table 2.2. Each row in the catalog corresponds to a resolution element inside the galaxy with four band ACS, three band WFC3, their corresponding RMS errors and spectroscopic redshift of the galaxy. A more detailed description of the catalog is provided in table 2.3.

Table 2.3: Multi-waveband Photometry Catalog of Resolution Elements for each Galaxy

1	Pixel ID	corresponds to the position of the pixel in the 80*80 pixel galaxy cutout
2, 3	U, Error	AB magnitude and Error (-99.0,-99.0), needed for rest-frame U measurement
4, 5	B_{F435W} , Error	AB magnitude and Error
6, 7	V_{F606W} , Error	AB magnitude and Error
8, 9	I_{F775W} , Error	AB magnitude and Error
10, 11	Z_{F850lp} , Error	AB magnitude and Error
12, 13	Y_{F105W} , Error	AB magnitude and Error
14, 15	J_{F125W} , Error	AB magnitude and Error
16, 17	H_{F160W} , Error	AB magnitude and Error
18	context	an integer value which specify the filter combination to be used
19	Spec z	redshift of the host galaxy from Keck/DEIMOS

2.4 Library of Model SEDs

The first phase of the SED-fitting process is to generate an inclusive library of model SEDs which span a wide range in parameter space. At the same time increasing the library size by too much could result in more degenerate solutions or no solution at all. Therefore finding an optimum size library with physically motivated range of values for different parameters is crucial. I use the PICKLES library for stars (Pickles, 1998), different synthetic and composite quasar libraries available in the LePhare package (Arnouts et al. 1999; Ilbert et al. 2006) and BC03 models (Bruzual & Charlot, 2003) for the galaxy library. While the relative contribution of thermally pulsating asymptotic giant branch (TP-AGB) stars is still uncertain, it has been shown in previous studies that the Maraston (Maraston et al., 2006) models over predict the near-infrared luminosity (Kriek et al., 2010) compared to BC03.

The Initial Mass Function (IMF) assumed here is adapted from the Chabrier (2003). IMF is an empirical relation that dictates the initial distribution of masses for a population of stars. As is the case in most galaxy evolution studies, there is an inherent uncertainty due to assuming a fixed IMF as there are some indications of non-universality of the IMF (e.g. Cappellari et al. 2012) over different galaxy populations, and maybe different parts of a galaxy. Extinction values range from zero to one using the Calzetti Starburst attenuation curve (Calzetti et al. 2000) and 57 different ages ranging from zero to the age of the universe at the spectroscopic redshift of the galaxy. I adopt single burst, constant and exponentially declining star formation histories. I fix the metallicity to 40% solar to mitigate the fitting degeneracies by shrinking the library size. I explore the effects of choosing this particular grid by comparing it to models with different metallicities, star formation histories and different resolutions in extinction and age. Parameters used for the synthetic libraries are summarized in table 2.4.

Table 2.4: Parameters for BC03 Models		
Parameters	steps	Range
Age (Gyr)	57	0.01 – 13.5
Extinction E(B-V)	15	0.0 – 1.0
τ (Gyr)	21	0.001 – 10.0
metallicity		40% $Z_{\odot}$

2.5 KPC-Scale Maps of Physical Properties

2.5.1 SED Fitting per Resolution Element

After finalizing the library and making the multi-waveband catalog for each pixel in galaxies, I fit the observed flux per resolution element to the model SEDs. For this I use the LePhare code, an SED fitting code based on χ^2 minimization. The code compares the observed flux (F_{obs}) and its corresponding uncertainties (σ) with the flux from templates (F_{Temp}) defined as:

$$\chi^2 = \sum_i \left[\frac{F_{obs,i} - sF_{temp,i}}{\sigma_i} \right]^2 \quad (2.1)$$

where the sum is over different bands (i) and s is the scaling factor chosen to minimize the χ^2 values (see the LePhare documentation for more detail). In the χ^2 method it is important to provide reliable uncertainties. If the error bars are too small, the χ^2 becomes extremely large and the method breaks down. To mitigate this effect, I add errors of 0.1 mag in quadrature to fluxes in all bands enabling the code to find a more accurate median of the probability distribution function. While the biggest uncertainty in relative fluxes is just a few percent due to PSF matching, 0.1 mag would account for uncertainties from our model library. After fixing the redshifts to their spectroscopic values, we fit the SEDs to find the closest match from the model library created for that specific redshift and measure the physical information associated to the galaxy (absolute magnitudes, stellar mass, star formation rate, age and extinction). The Physical parameters from the SED fitting output in this work correspond to the median of the probability distribution function marginalized over all other parameters.

The LePhare code uses different techniques to compute absolute magnitudes. The direct

methods in which the observed magnitude in a filter will be used to measure the absolute magnitude in the same filter is not appropriate for our purpose both because we do not have high resolution U band observations of our galaxy as well as the method being too sensitive to k-correction and to systematics in the apparent magnitude measurements. I use the best-fit template to estimate the absolute magnitudes which is more model dependent compared to previous methods which use the observed magnitudes. The $(U - V)_{rest-frame}$ colors per resolution element is then measured using U and V band absolute magnitudes. The U-band response function here corresponds to Johnson filter. I choose this rest-frame optical color in order to straddle the Balmer/4000Å break. It has been shown that the Balmer/4000Å break feature is not only very sensitive to the stellar age (e.g., Kauffmann et al. (2003), Nayyeri et al. (2014)), but that the strength of this break strongly correlates with the width of H α and the best-fit specific star formation rate (Kriek et al., 2011). Therefore, using passbands straddling the Balmer break is optimized for our purpose, and provides great insight on the star formation histories of substructures in galaxies.

The high resolution maps measured through the SED fits per resolution element, are presented in Figures 2.3-2.6 for a subsample of galaxies ¹. These show the $(U - V)_{rest-frame}$ color, stellar mass surface density, stellar mass surface density 1σ error, star formation surface density, extinction, and age maps for example galaxies from the sample. Unlike the more normal Hubble-type galaxy morphologies in figures 2.3-2.5, figure 2.6 shows an example of a galaxy with an abnormal feature (i.e. blue nuclei).

In $(U - V)_{rest-frame}$ maps, there is a general tendency towards a central red bulge and some blue regions in the overall green disk. There are three clear exceptions in our sample with the nuclear region in the galaxy significantly bluer than its surroundings (e.g., see figure 2.6). These are examples of “blue-nucleated galaxies” (Schade et al., 1995; Abraham et al., 1999). These three galaxies have Chandra X-ray detections (matched with a $1''$ radius), which suggest the presence of an AGN at their centers. Interestingly, even though I include quasar libraries while performing the SED fitting, none of the central elements in these galaxies were

¹ Maps of all galaxies in the sample are at: <http://www.shouby.com/research/disk-galaxies/>

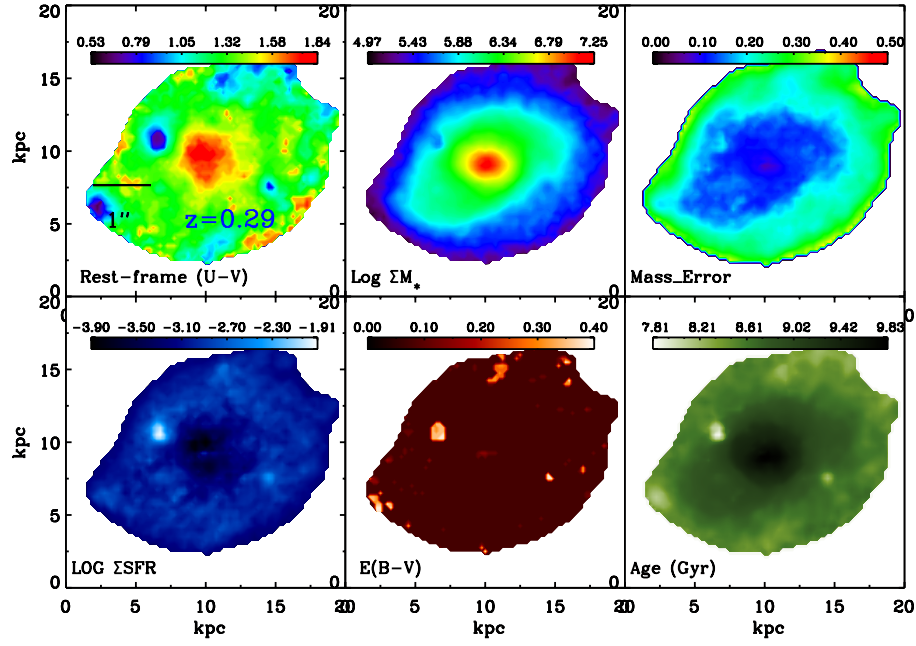


Figure 2.3: Resolved (kpc-scale) 2D Maps of $(U-V)_{\text{rest_frame}}$, stellar mass surface density, stellar mass surface density error, SFR surface density, extinction, and age for a sample galaxy at $z = 0.29$ from top left to bottom right respectively.

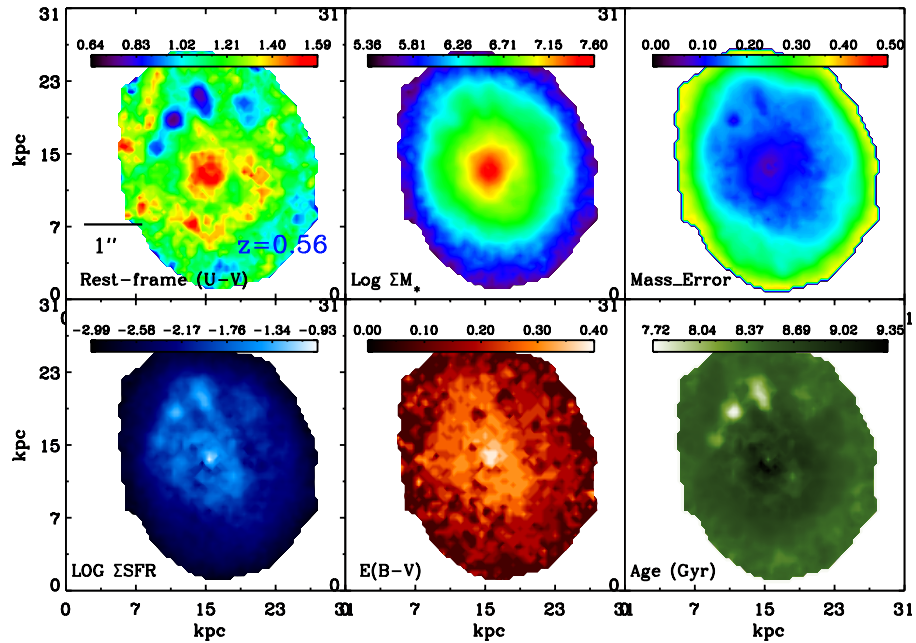


Figure 2.4: 2D resolved maps similar to figure 2.3, of a normal disk galaxy at $z = 0.56$.

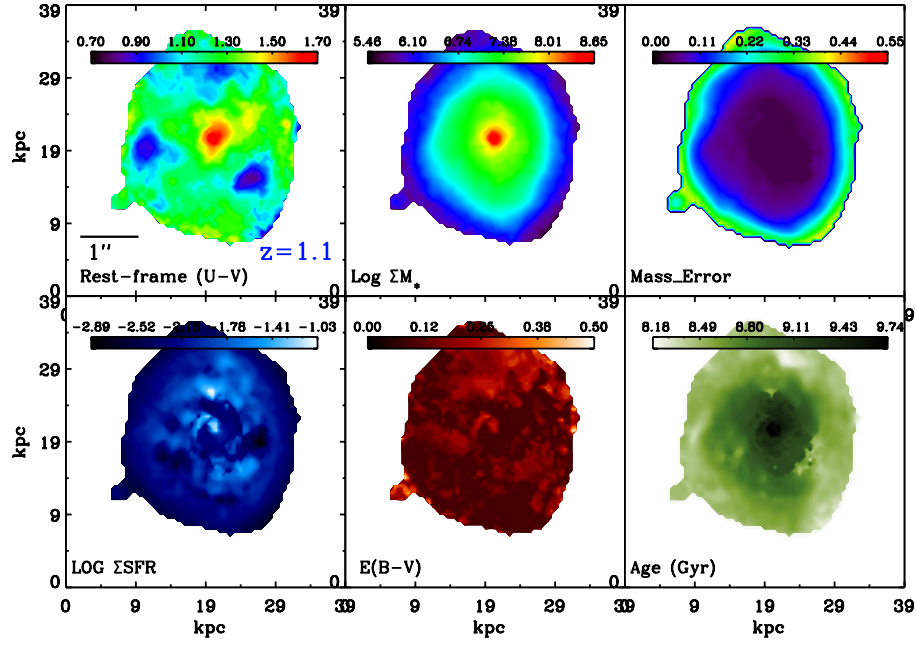


Figure 2.5: 2D resolved maps similar to figure 2.3, of a normal disk galaxy at $z = 1.1$.

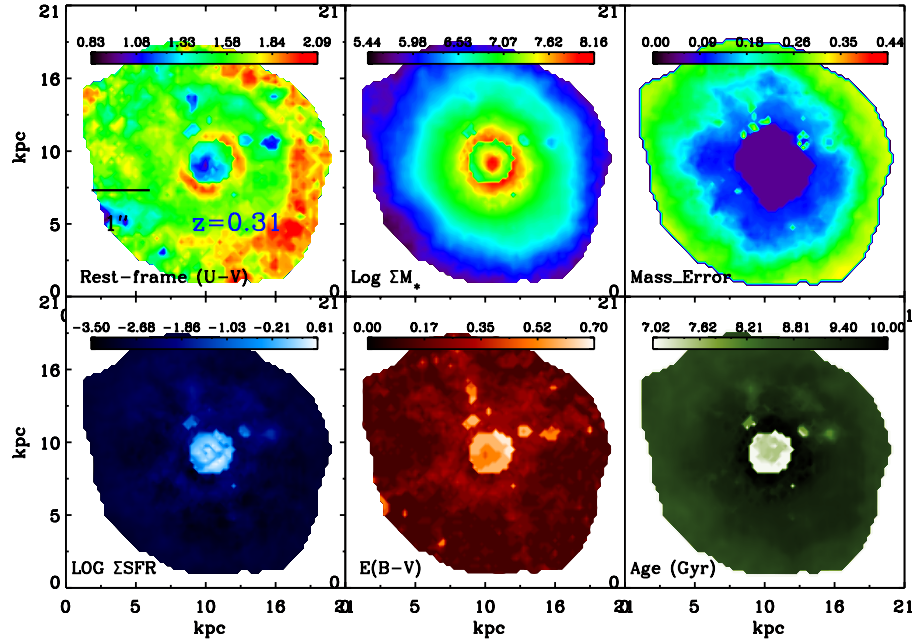


Figure 2.6: 2D resolved maps same as figure 2.3, of a disk galaxy at $z = 0.31$ with an abnormally blue nucleus.

“best” fitted to these templates. In future works I will investigate whether adding dust to the quasar models alter the fitting/color of the central resolution elements in these galaxies.

Contrary to the UV-optical color maps which often show “clumpy” structures, the stellar mass surface density maps are mostly smooth with most of the mass concentrated in the bulge. The same trend was also reported in Wuyts et al. (2012) for galaxies at somewhat higher redshift from $1 < z < 2$. Lanyon-Foster et al. (2012) however claims that, the smoothness of the stellar mass maps neither holds true for all galaxies nor for all features seen. This difference might be explained by Lanyon-Foster et al. (2012) not probing the infrared part of the SED and using optical colors only.

To further examine the absence of structure in the stellar mass maps, I smooth them with a Gaussian of width σ (where σ is the dispersion of stellar mass surface density over all resolution elements) and subtract them from their respective unsmoothed stellar mass maps. Weighting the residual by the stellar mass error, the structure residuals in all galaxies account for less than 1.2% of their total stellar mass surface density. Wuyts et al. (2012) find a similar 2-3% of the total stellar surface density in the clumps as defined by either rest-frame U- or V-band maps of Voronoi-binned pixels for galaxies from $0.5 < z < 1.5$.

The star formation rate surface densities are directly derived from the SED fitting. Estimating the SFRs from the SED is very challenging due to both the age-dust-metallicity degeneracy and the choice of SFH prior, especially at high-redshifts (Conroy, 2013). However, it has been shown that at $z < 1$ this is less of an issue and SFRs derived by fitting the SED agree very well with the other indicators of SFR with less than 0.23 dex scatter (Salim et al., 2009).

2.5.2 Error Estimates and Sources of Uncertainty

Error estimates in each of the physical parameters are measured from the Maximum Likelihood analysis and the error maps correspond to the 1σ (16% lower and higher) values. Examples of stellar mass error maps are presented in the third panel of figures 2.3-2.6. However, the physical parameters measured by fitting the SED of the integrated light of galaxies or individual pixels are drawn from a library of model SEDs. This means that choices in the discrete nature

Table 2.5: Parameters of different SED fitting test runs

Run	SFH	τ (Gyr)	E(B-V)	Age(Gyr)	metallicity (Z_{solar})
1	declining	21: 0.01-10.0	15: 0-1.0	57: 0.01-13.5	40%
2	declining	21: 0.01-10.0	21: 0-1.0	57: 0.01-13.5	40%
3	declining	21: 0.01-10.0	15: 0-1.0	40: 0.01-13.5	40%
4	declining	21: 0.01-10.0	15: 0-1.0	57: 0.01-13.5	100%
5	declining	21: 0.01-10.0	15: 0-1.0	57: 0.01-13.5	20%

of model libraries affects the estimated output parameters. Many studies look at the effect of these choices, including their uncertainties, on the integrated (see e.g. Conroy 2013, Ilbert et al. 2010) or resolved (see e.g. Welikala et al. 2011) SED fitting results. Here, I analyze the effect of some of my assumptions regarding the model library on the output parameters.

To inspect how choosing a particular grid of input parameters for the library affects the output from SED fits and therefore the maps, I select 9 representative galaxies from the sample spanning the whole redshift range studied in this work ($0.2 < z < 1.2$). I fit the SED per resolution element following the methods described in previous sections, using different libraries. I change one parameter in the library at a time while keeping all the other library parameters the same (See table 2.5). I then compare the measurements at resolution elements. The first run (Run1) is performed using the library described in §2.3 and all the other measurements will be compared to this one. The next two runs (Run2 and Run3) are generated by changing the resolution in extinction and age. Ideally, one would expect the highest resolution grids to produce smoother maps, but in reality increasing the library size arbitrarily could lead to more degeneracies (e.g. Walcher et al. 2011), in the χ^2 fitting of the SEDs, let alone the high computational cost. And finally in the last two runs (Run4 and Run5) I examine the outcome by changing stellar metallicity to solar (m62) and then to 20% solar (m42).

I compare the E(B-V) maps from the first two runs, in which I increase the number of steps in extinction by 25%. Subtracting the two maps I find a median offset of 0.0 and a scatter in the range of 0.0 – 0.02. The small median difference and scatter should not be a surprise as I have only changed the resolution and not the range. In Figure 2.7, I plot the extinction maps for one of the galaxies using the two libraries and their difference. This Figure demonstrates the point

that extinction maps produced from the two runs are visually indistinguishable. The same has been seen for all the test galaxies. Even though at some individual resolution elements there are small differences, the overall structure and patterns remain intact.

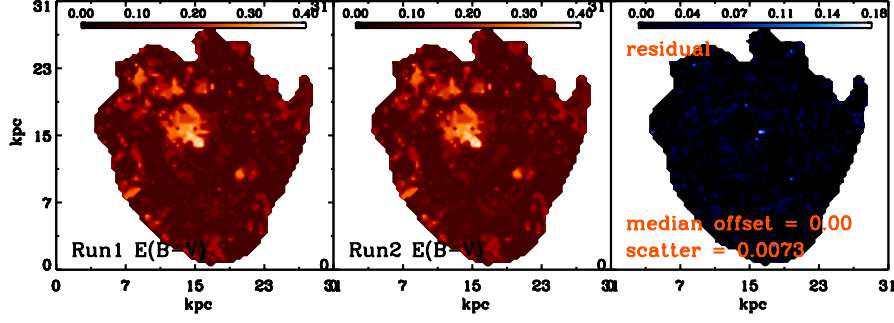


Figure 2.7: Comparing E(B-V) maps from Run1 and Run2 for a galaxy in our sample. Run 2 has a higher resolution in extinction levels compared to Run1.

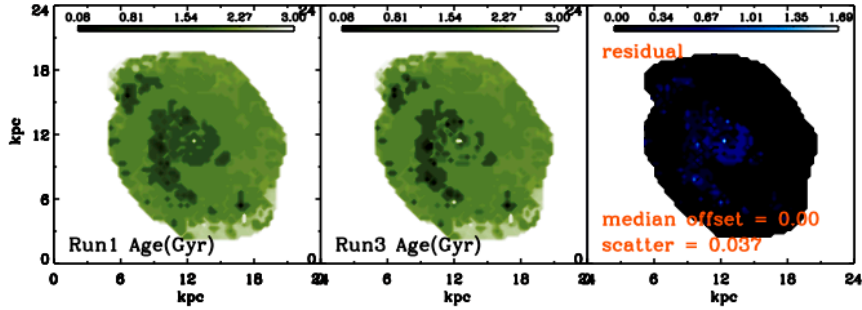


Figure 2.8: Comparing Age maps from Run1 and Run3 for a galaxy in our sample. Run 3 has less resolution in age levels compared to Run1.

The same situation holds, comparing the age maps from third run to the first, with the overall trends not changing but slightly larger offsets resolution element by resolution element (Figure 2.8). The median offset is 0.0 for all the test galaxies, but there is a larger scatter in the range 0.01 – 0.1. The difference in each resolution element is always well below its 1σ uncertainty of that resolution element in both runs. This does not necessarily mean that the difference is small for all resolution elements, but rather it shows that for resolution elements with less constrained Probability Distribution Function (PDF) can play an important role.

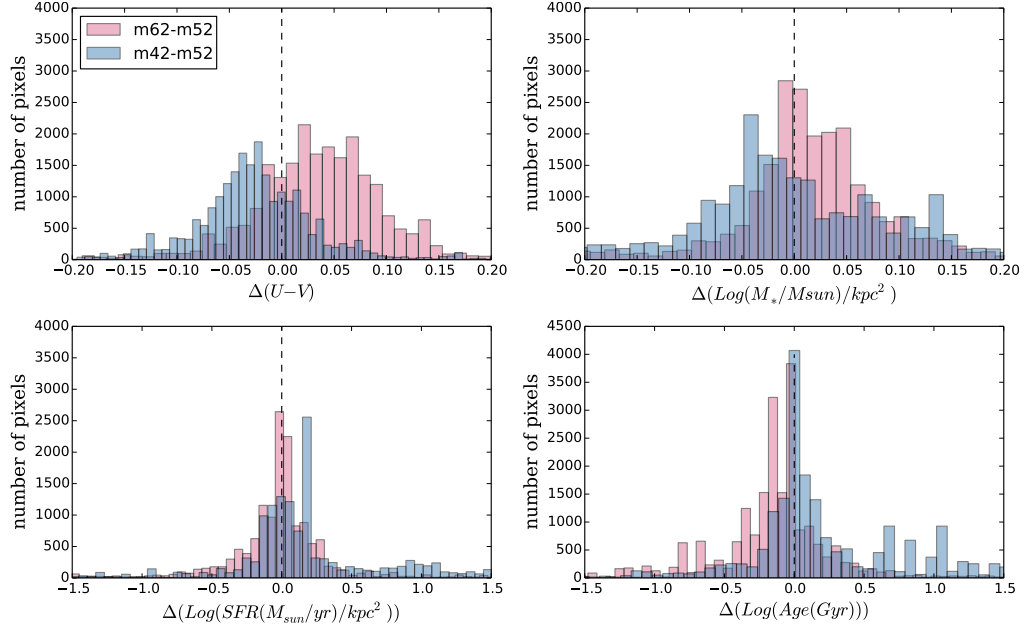


Figure 2.9: Effect of metallicity on rest-frame (U-V), stellar mass surface density, SFR surface density and stellar age. Red and blue colors correspond to $\Delta(m62 - m52)$ (Run4-Run1) and $\Delta(m42 - m52)$ (Run5-Run1), respectively.

Table 2.6: Offset and scatter by changing library parameters

	(U-V) (rest-frame)	$\text{Log}(\Sigma M_*)$ ($M_{\text{sun}}/\text{kpc}^2$)	$\text{Log}(\Sigma \text{SFR})$ ($M_{\text{sun}} \text{yr}^{-1}/\text{kpc}^2$)	$\text{Log}(\text{Age})$ (Gyr)
Run4 - Run1 median offset	0.04	0.01	-0.01	-0.12
Run4 - Run1 dispersion	0.06	0.09	0.53	1.14
Run5 - Run1 median offset	-0.03	-0.01	0.14	0.11
Run5 - Run1 dispersion	0.06	0.14	0.77	1.6

In the last two runs I study the dependence of the parameters on variations in metallicity. I change the metallicity once to solar (m62) and once to 20% solar (m42) and compare the physical parameters with the first run which has metallicity fixed to 40% solar (m52). This is shown in Figure (2.9), where red and blue histograms correspond to $\Delta(m62 - m52)$ (Run4-Run1) and $\Delta(m42 - m52)$ (Run5-Run1), respectively. The median offset and dispersion in rest-frame (U-V) color, stellar mass, SFR and stellar age over all resolution elements in the test galaxies are listed in table (2.6).

In this dissertation, I fixed the metallicity to 40% solar and produced maps of physical

properties of galaxies. I selected clumps based on (U-V) rest-frame color (Chapter 3). Fixing the metallicity to higher or lower values, the same clumps would be identified, with slightly different properties as quantified in Table 2.6. This is because the clump selection is based on the color distribution in each galaxy and does not assume a predefined cut. This is of course different from having the metallicity as a free parameter, which will worsen the degeneracies, especially with age. I find that assuming stellar metallicity leads to redder (U-V) rest-frame colors, slightly larger masses, no significant change in median SFR (although significant scatter) and younger ages. Further work is needed to fully uncover the effects of all different grid parameter choices (from IMF and SSPs to star formation histories) on resolved SED fitting results.

2.5.3 Effect of Nebular Emission-lines in the Library

In fitting the SED to stellar population synthesis models lies the assumption that all the light of the galaxy is produced from the stars. However, we know that a substantial fraction of the galaxy light comes from the interstellar medium due to nebular emission and continuum, which needs to be taken into account. Different studies have included emission-lines in their SED fitting procedure and investigated the difference (e.g. Zackrisson et al. 2008, Schaerer & de Barros 2009, Nayyeri et al. 2014). Including emission lines in the fitting procedure is most essential if emission-line galaxies are the targets of SED fitting. LePhare code accounts for the contribution from emission lines with a simple recipe based on the Kennicutt relations (Kennicutt 1998). The following lines are included in this treatment: $\text{Ly}\alpha$, $\text{H}\alpha$, $\text{H}\beta$, $[\text{OII}]$, $[\text{OIII}]4959$ and $[\text{OIII}]5007$ with different ratio with respect to $[\text{OII}]$ line as described in Ilbert et al. 2008. The intensity of the lines are scaled according to the intrinsic UV luminosity of the galaxy.

I investigate the effect of adding emission lines to the SED fitting procedure by comparing the fits with and without emission lines included. In figure 2.10, I show three examples of the $(U - V)_{\text{rest-frame}}$ 2D color maps with and without emission line in the SED fitting and the residual of the two. While for some galaxies (e.g. first row of figure 2.10) the residual is

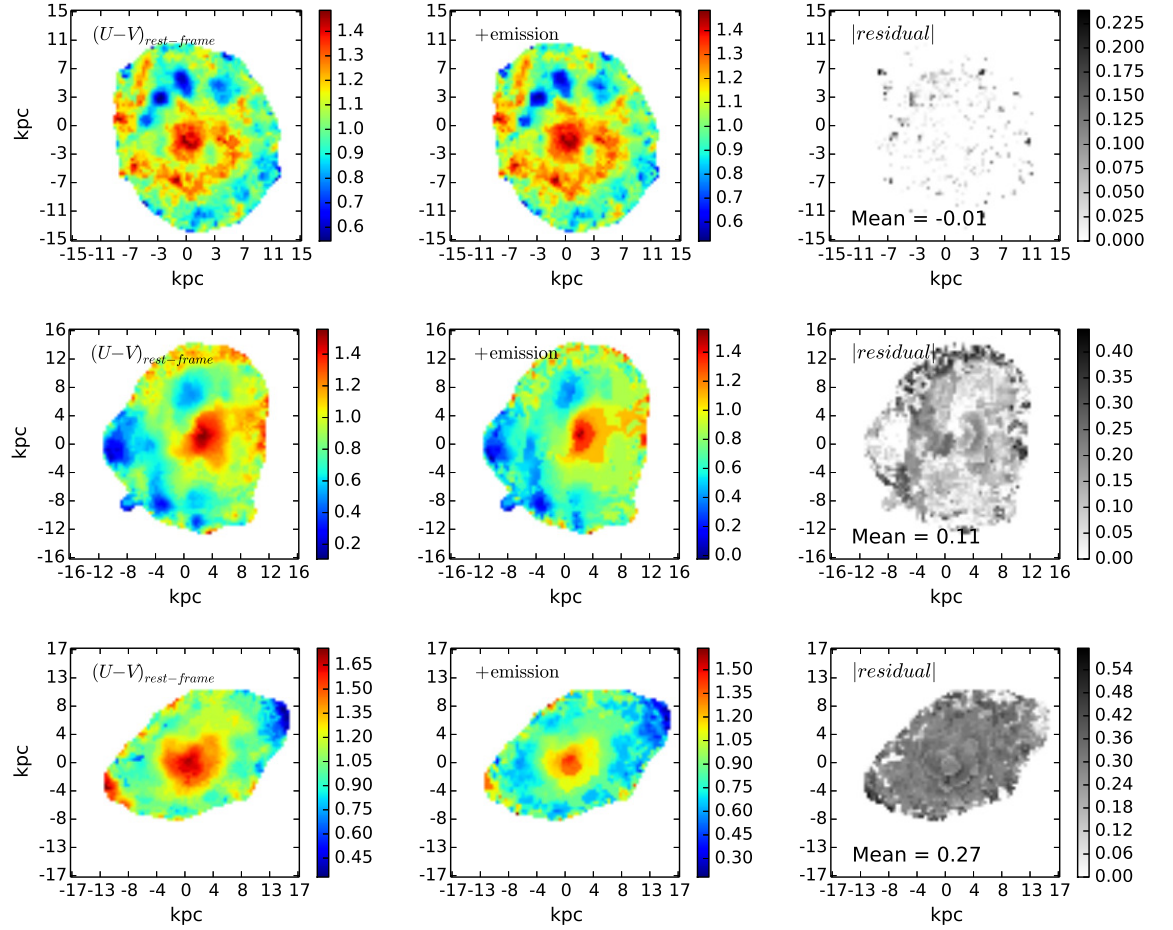


Figure 2.10: Comparison of $(U-V)_{\text{rest-frame}}$ color maps with and without emission-line in the SED fitting process. From Left to right the 2D map w/o emission lines, with emission and the absolute value of their difference.

negligible and well within the uncertainty of the parameters, for some (e.g. third row of figure 2.10) the difference can be larger compared to the uncertainties. Interestingly, this difference does not vary as a function of position inside galaxies, meaning if the emission line is changing the fits for a galaxy by a large factor, it does so for most of the pixels (and the other way around).

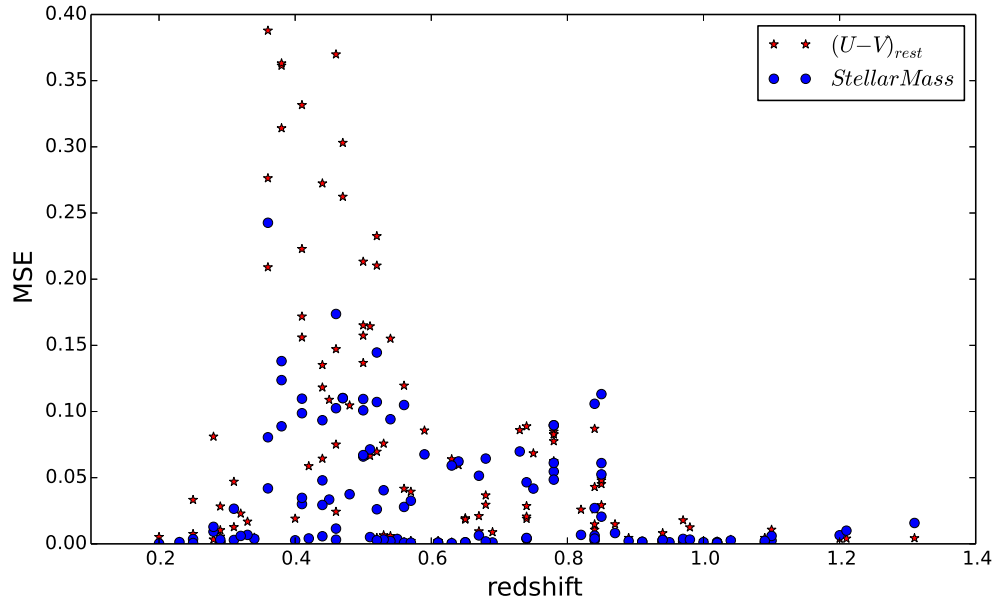


Figure 2.11: Mean Square Error of $(U - V)_{rest-frame}$ color (red stars) and stellar mass surface density (blue circles) maps with and without emission line in the SED fitting process as a function of redshift.

To compare how different the measurements with and without emission lines in their fit are and where the discrepancy comes from, I use the mean squared errors (MSE) which is a measure of how different two maps are, and is defined as:

$$MSE = \frac{1}{n} \sum_{p=1}^n (F_p^1 - F_p^2)^2 \quad (2.2)$$

where F_p^1 and F_p^2 are the value (color or stellar mass surface density) of the pixel “p” in a map with and without emission lines in their SED fit respectively, and “n” is the number of pixels in the map. I plot the MSE of $(U - V)_{rest-frame}$ and stellar mass surface density as a

function of redshift of the galaxy (figure 2.11). It is clear from figure 2.11 that the galaxies in which including emission lines in the fit has a larger effect are not distributed evenly at all redshifts. Instead they are located at $z \approx 0.3 - 0.8$. In figure 2.12, I investigate this trend by checking where the strong nebular emission lines lie compared to the filters used in performing the SED fits. The redshift range where the large discrepancies between the fits occur, is exactly where H α line (the strongest line in this redshift range) shifts and contaminates more than one of the filters. While this correlation seems to be a plausible explanation, it might not necessarily be causal.

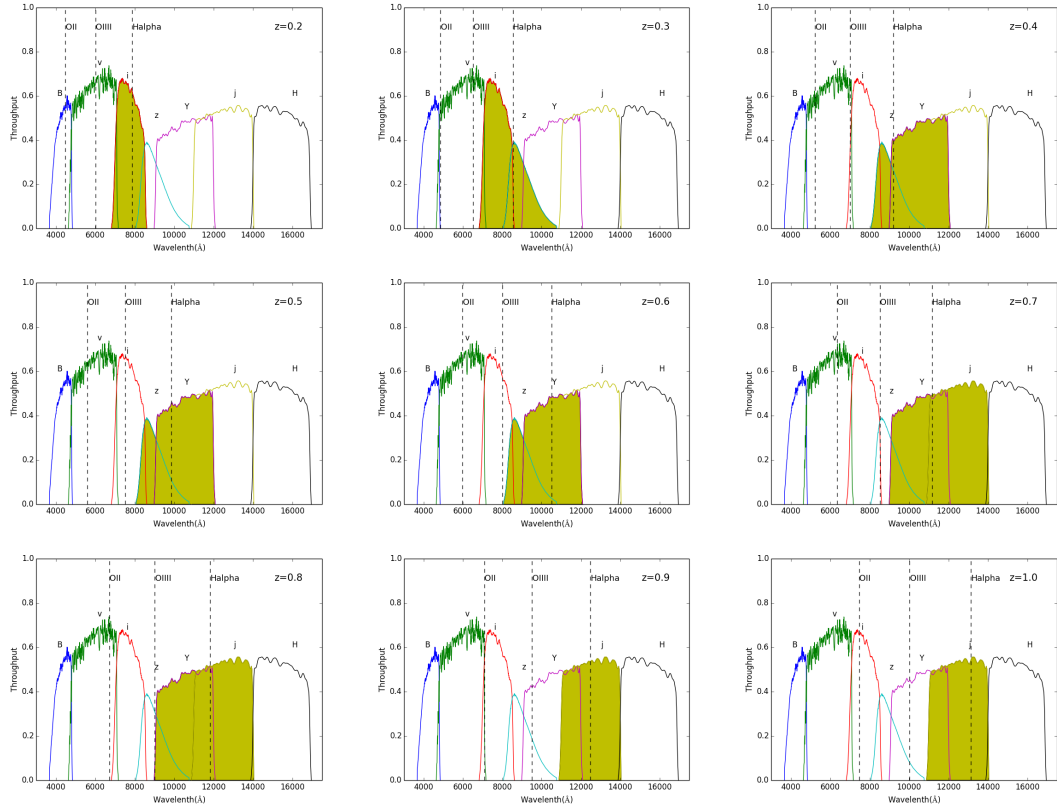


Figure 2.12: Filters contaminated by strong nebular emission lines at $z = 0.2$ (top left) to $z = 1.0$ (bottom right). Notice where more than one filter is contaminated by the H α emission line is where probability of a large MSE is higher (figure 2.11).

Including the emission lines to the SED fitting procedure is also beneficial as it enables the SED fitting code to predict the amount of nebular emission. With this technique I have produced kpc-scale H α maps of galaxies in the sample which can be potentially compared to

observed $H\alpha$ maps to constrain the assumptions made in including the emission lines to SED fitting codes, such as a fixed ratio between different lines and the Kennicutt relation. Figure 2.13 shows an example $H\alpha$ map for a galaxy from our sample. Similar to a new study (Nelson et al. (2015)) looking at 2656 kpc-scale radial profiles of $H\alpha$ from HST grism observations of $z \sim 1$ galaxies, most of our predicted $H\alpha$ maps are centrally peaked but unlike what was found from the stacks in that study our predicted maps do not show very extended emission to outer parts of the disk.

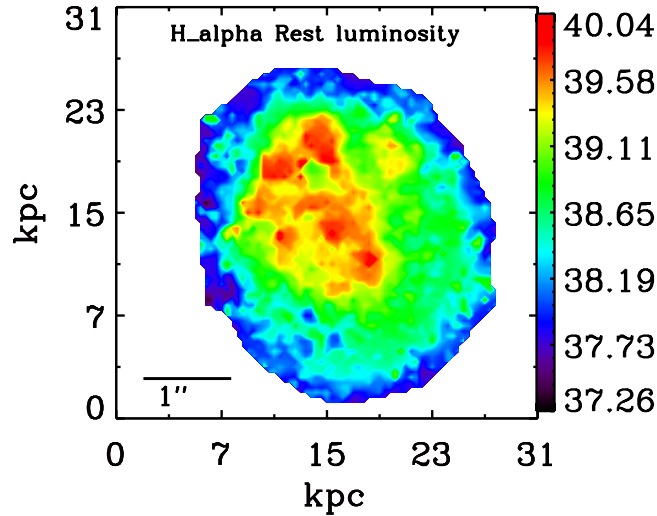


Figure 2.13: An example of kpc-scale $H\alpha$ map for a galaxy at $z = 0.56$. Color bar shows logarithm of $H\alpha$ rest frame luminosity.

2.6 Integrated vs. Resolved Properties

In this section I examine the consistency between resolved measurements and those derived for the entire galaxy. I measure the photometry of galaxies in the same seven HST bands by adding up the fluxes within the boundary of the galaxy defined by the segmentation map of the galaxy. The “global” stellar mass, star formation rate and mean stellar age for each galaxy are estimated by fitting the integrated fluxes with the same model library used in the previous sections.

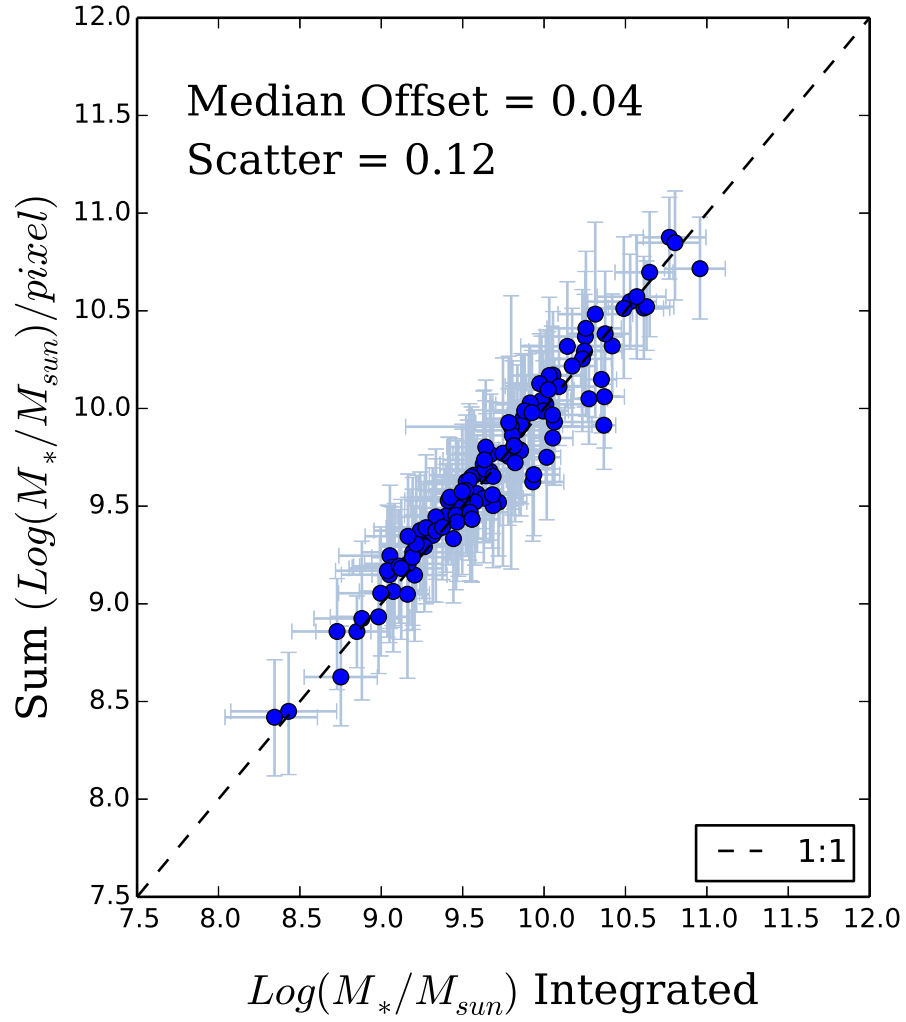


Figure 2.14: Comparison between resolved and the integrated properties: integral of stellar mass surface density per resolution element vs. integrated stellar mass.

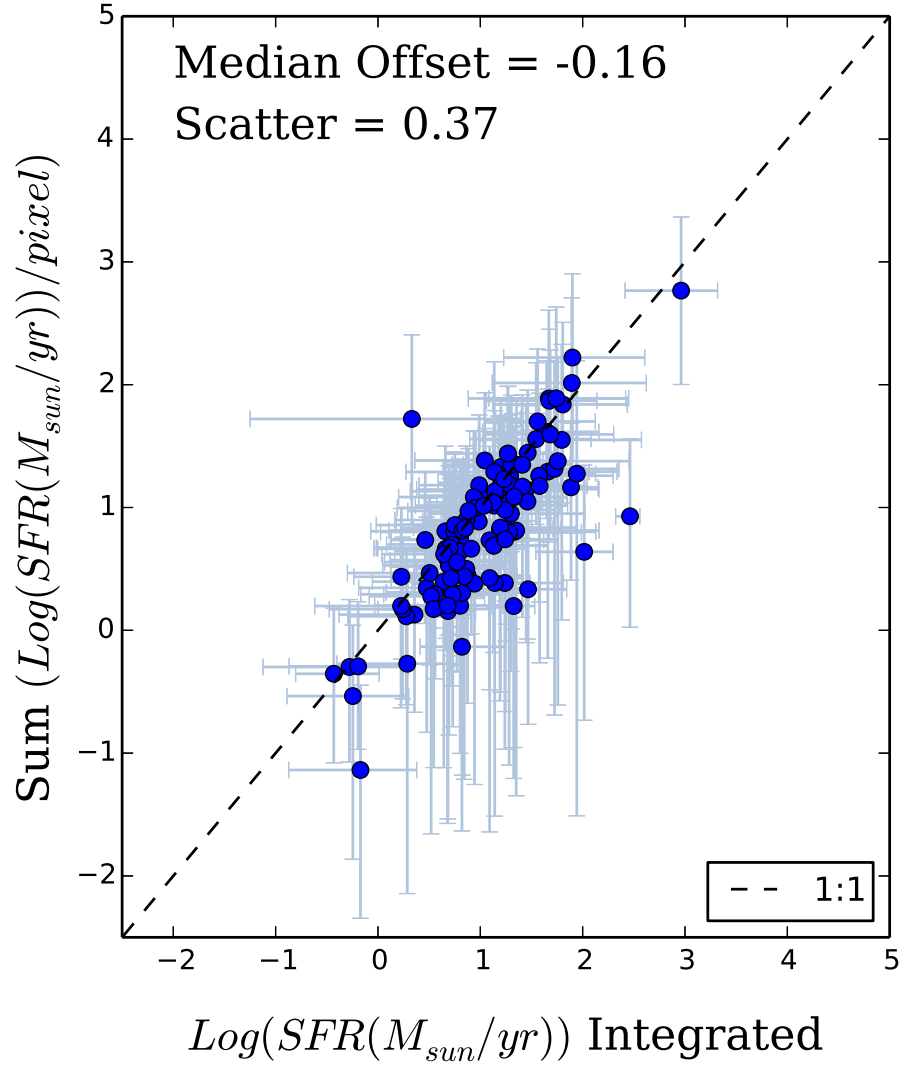


Figure 2.15: Comparison between resolved and the integrated properties: integral of SFR surface density per resolution element vs. integrated SFR.

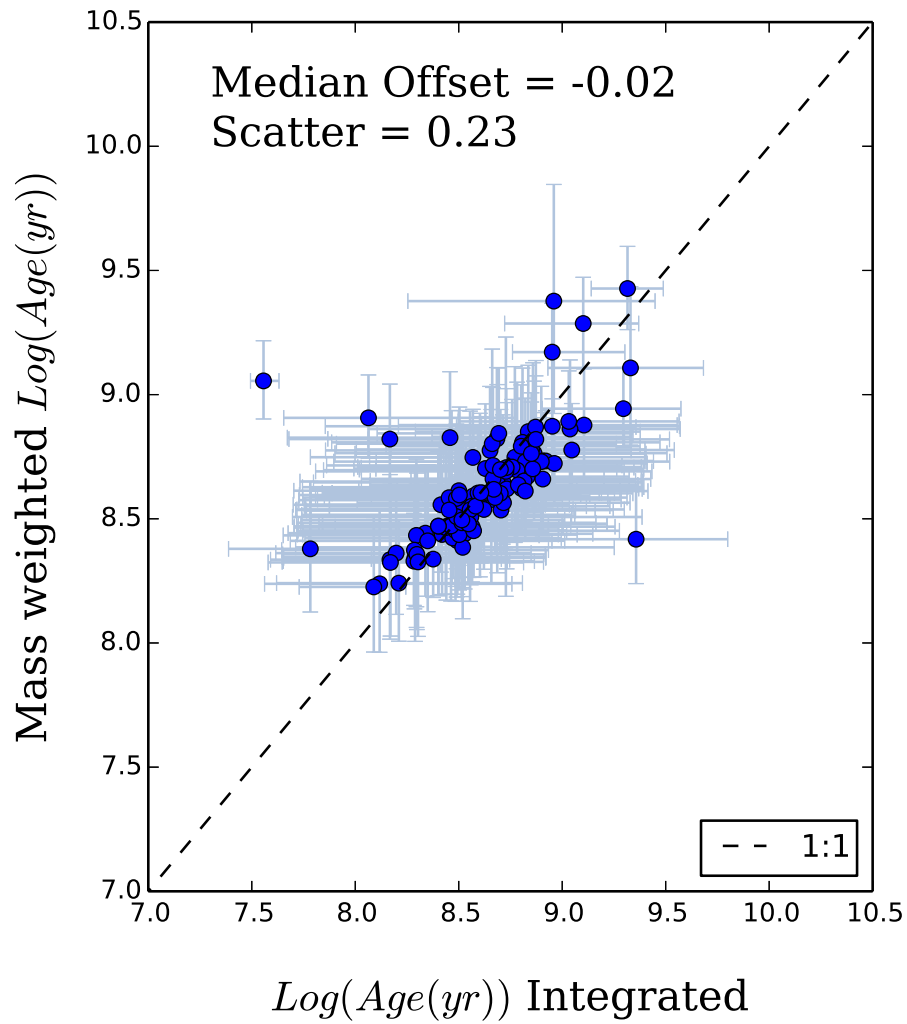


Figure 2.16: Comparison between resolved and the integrated properties: mass weighted stellar age vs. integrated age of the galaxies.

In figure 2.14 I compare the integrated stellar masses with the sum of stellar masses measured per resolution element. I find a median offset of 0.04 dex and a scatter of 0.12 dex for stellar masses. Wuyts et al. (2012) reported no median offset using Voronoi-binned pixels rather than individual pixels. This is contrary to some of the previous works which found larger disagreement, with the global mass being lower than the integral of masses over resolution elements up to 40% for a sample of nearby galaxies (Zibetti et al., 2009). The small offset can be explained by lower estimates of M/L from the integrated fluxes due to more luminous young stars in the disk (e.g., Papovich et al. 2001; Shapley et al. 2001).

Comparing the resolved and the integrated SFRs, a median offset of 0.16 dex is found with a scatter of 0.37 dex (figure 2.15). In a similar study (Wuyts et al., 2012), a larger offset of 0.27 dex in the opposite direction was found. The SFR estimates from the SED-fitting have different sources of uncertainty. This makes explaining the offset difficult. One possible source of the offset is due to overcorrection for dust extinction and hence slightly larger SFRs (in 90% of the galaxies in the sample the average $E(B-V)$ over resolution elements is less or equal to the $E(B-V)$ estimate for the galaxy).

For stellar age comparison, I calculate the stellar mass weighted age from the resolved SED fits. Figure 2.16 shows the comparison of resolved and integrated stellar ages. A very small offset of 0.02 dex with a scatter of 0.23dex is observed. This median offset is 10 times smaller than that of Wuyts et al. (2012). The plausible explanation for this small offset is that using the stellar mass weighted age rather than light weighted age would make outshining of older more massive stars by younger less massive stars (e.g., Papovich et al. 2001; Maraston et al. 2010) less of an issue.

2.7 Discussion and Summary

In this chapter I explained and tested the methodology developed to produce resolved kpc-scale maps of physical parameter of galaxies. Much uncertainty in galaxy evolution arises because galaxies are often divided into two broad populations of passive and actively star form-

ing systems. Ability to resolve galaxies to small scales and to know the distribution of physical parameters in galaxies has the potential to overcome some of this uncertainty.

I produced resolved 2D maps of physical parameters (stellar mass and star formation surface density as well as age, extinction and rest frame optical color) for galaxies with the highest resolution possible with the HST ($\sim kpc$). This resolution is dictated by the longest wavelength covered by the WFC3 instrument used in this work (F_{160W} band) and all the other images were PSF-matched to this resolution, which is higher than what previous works using similar data have achieved due to different techniques (e.g. Voronoi binning). I found that the stellar mass distribution in the disks are very smooth and 30-90% of the total stellar mass comes from the central 2.5 kpc of the galaxies of our sample.

The impact of nebular emission lines in the SED fitting procedure was studied before but here for the first time I investigated the effect in resolved SED fitting, by comparing the 2D maps produced with and without including emission lines in the fits. I find small variation in residual maps inside each galaxy, suggesting that including the emission line would not have much spatial effect in galaxies. This means that qualitatively the 2D maps look the same, even for the galaxies with large residuals. I found the largest residuals to coincide with the redshifts where more than two broadband filters are contaminated with $H\alpha$, while the correlation is strong further investigation and simulations are needed to certify the causality of this correlation.

Including the emission-lines in the fit also has the advantage of enabling the recovery of line luminosities as outputs from the fit. Using the best fit SED models including nebular emission line, I made $H\alpha$ maps for galaxies in the sample. The $H\alpha$ luminosities can be compared against resolved spectroscopic observations (such as OSIRIS) to test for the widely used assumptions regarding line ratios and gas-star formation relations that also affect measurement through the SED fits.

Compared the stellar mass surface density, SFR surface density and stellar ages measured by resolved SED fitting to the integrated stellar masses, SFRs and ages I found good agreements with offsets of 0.04 dex, 0.16 dex and 0.02 dex for stellar mass, SFR and age respectively. The overall agreement certifies the resolved SED fitting technique. The small offset in stellar mass

can be explained by lower estimates of M/L from the integrated fluxes due to more luminous young stars in the disk (e.g., Papovich et al. 2001; Shapley et al. 2001). The slightly larger offset found in the SFR comparisons is mostly due to dust attenuation compared to the average of resolved color excesses at individual resolution elements. The very tight agreement between the age comparison is a result of weighting the stellar age by the stellar mass which helps avoiding the outshining problem.

An uncertainty map is also produced for each physical parameter map by marginalizing over the PDF of other parameters. Here, I studied different sources of uncertainty arising from the model library such as fixing the stellar metallicity or the choice of the specific grids of age and extinction used in this work and quantified the difference they would have on the final map products. However, there still exists other uncertainties that need better modeling of resolved SEDs such as the choice for the star formation histories or the IMF.

Chapter 3

Clump identification and Properties

3.1 Introduction

It is well known that the star formation rate density of the Universe peaks at $z \sim 2$ and decreases exponentially towards the present day (see review by Madau & Dickinson 2014) and that there is a “bimodality” in galaxy population out to $z \sim 3$ (e.g. Kauffmann et al. 2003, Whitaker et al. 2011). While the number density of blue galaxies decreases with lookback time from $z \sim 1$ to today, the number density of red galaxies is increasing in the same epoch by a factor of $\sim 2 - 4$ (Faber et al. 2007). This implies that while some new star forming galaxies were created some have become passive. Exactly how star formation shuts down or “quenches” in galaxies and the details of the transition from blue star forming to red and passively evolving systems is unclear.

Simulations of $z \sim 2$ galaxies have reproduced the clumpy structure in marginally unstable disks as seen in observations. Theoretically, giant clumps (kpc size, $\log(M_*/M_\odot) \sim 8 - 10$) are formed in the unstable thick disk that is constantly fed by gas through cold streams. In this framework, when the disk becomes stable against fragmentation, star formation decreases and the galaxy quenches what is dubbed as morphological quenching (e.g. Martig et al. 2009). Ceverino et al. (2010) showed that clump migration and angular momentum transfer due to dynamical friction in the disk on an orbital timescale help the galaxy bulge to grow. Observations of age gradients in the disk and the bulge have also been interpreted as migration of

massive clumps towards the center (e.g. Elmegreen et al. 2008, Förster Schreiber et al. 2011). However, an “inside-out” formation of the galaxy could produce the same age gradients seen or inferred (from color gradients) in observations. Also, Genel et al. (2012) using strong stellar feedbacks in his simulations of $z \sim 2$ galaxies argues that giant clumps are short-lived and are disrupted by wind-driven mass loss, and therefore will not make it to the center of the galaxy as suggested before.

While in many simulations disks of galaxies is already stabilized by $z \sim 1$ (e.g. Dekel et al. 2009, Ceverino et al. 2010) observations of galaxies at $z \sim 1$ have found clumps with comparable properties to the higher redshift galaxies (e.g. Guo et al. 2012, Elmegreen et al. 2008). Also, observationally the spatial resolution needed to study kpc-sized clumps is not accessible at $z \sim 2 - 3$. Therefore, to allow the study of substructures in galaxies at kpc scales and to address the above mentioned challenges (at lower redshifts), I identify clumps based on the resolved photometric maps i.e. the $(U - V)_{rest-frame}$ color maps. Most of these regions are kpc size with comparable characteristics to what are called “clumps” in previous simulations and observational studies (e.g., Guo et al. 2012, Elmegreen et al. 2008, Förster Schreiber et al. 2009). While, I remain agnostic regarding the nature of these regions, I also use the term “clump,” even though it connotes a distinct entity within the galaxy, potentially even a distinct self-gravitational mass, which may not be accurate. Using the available deep spectra and kinematic information, I aim in future work to more precisely evaluate which regions are gravitationally-bound “clumps” and which regions are simply differentiated by their relative star-formation or dust properties with respect to the surrounding parts of the galaxy.

The structure of this chapter is as follows: I first describe my method of clump identification in §3.2. In §3.3 I test the method against redshift evolution biases. I study the physical properties of “blue” and “red” clumps and compare it to the underlying “green” disk in §3.4. In §3.5 The evolution of clumps with both redshift and stellar mass of the host galaxies is investigated. And the main points from this chapter are summarized in §3.6.

3.2 Clump Identification

I select red and blue clumps inside galaxies by fitting weighted rest-frame color distributions in each galaxy to Gaussian functions. To avoid selecting insignificant clumps at the very edges of galaxies with very low surface brightness, I weight pixels in the color maps before the clump identification. The (U-V) weight maps (see figure 3.1) are calculated from the square root of the sum of squares of fluxes in U and V bands and normalized to the maximum value. I plot the distribution of weighted rest-frame color for each galaxy. I choose the bin size following Scott's rule ($\text{binsize} = \frac{3.5\sigma}{n^{1/3}}$, where σ is the sample standard deviation and n is the number of data points), which is optimal for normally distributed data (Scott, 1979). I then fit the color distribution in four ways: 1) with a single Gaussian, 2) with a single skewed Gaussian, 3) with three Gaussians, and 4) with three skewed Gaussians (figure 3.2). As expected, method 4 gives the least χ^2 (because it has larger degrees of freedom) and is visually a better fit to the distributions, at the same time it is a more physically motivated fit with one Gaussian for fitting the median color of the galaxy and the other two allowing for the bluer or redder regions with centers constrained at two sides of the central peak.

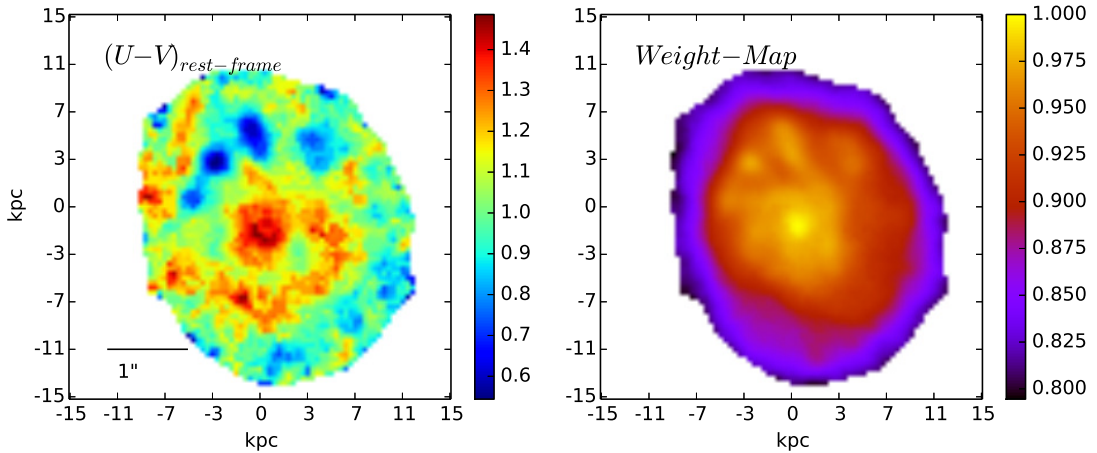


Figure 3.1: (U-V) color and weight map for a sample galaxy. These two maps will be used for clump identification purposes.

Fits to the color distributions are done to build high-pass (red) and low-pass (blue) filters

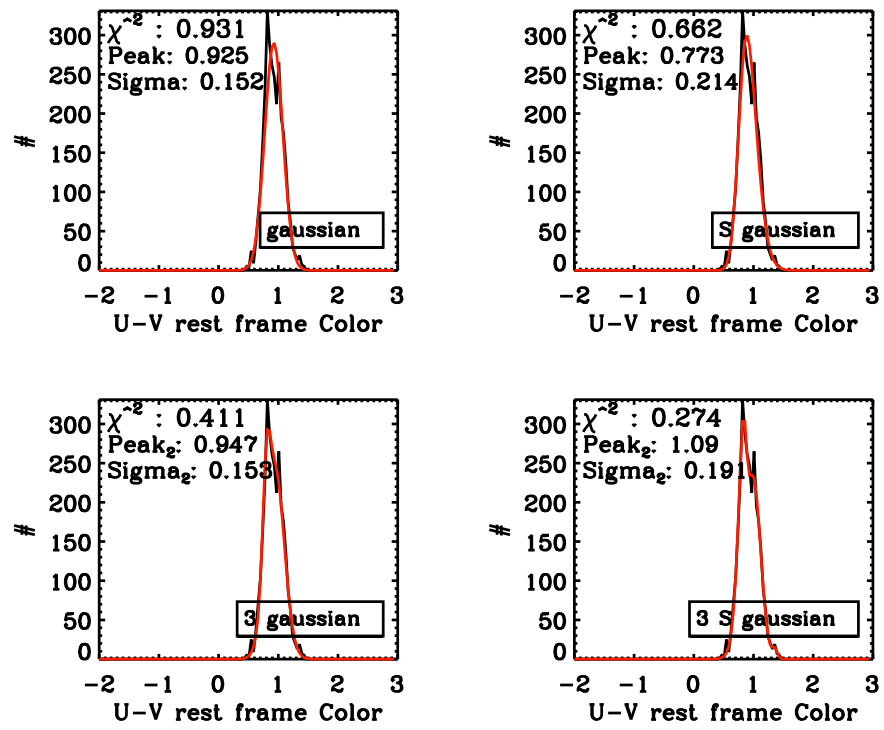


Figure 3.2: Weighted (U-V) color distribution and Gaussian fits for the same galaxy as in figure 3.1. From top-left to bottom-right the fits are 1) a single Gaussian, 2) a skewed Gaussian, 3) three Gaussians, and 4) three skewed Gaussians.

Table 3.1: Main Parameters in SExtractor Configuration File for Clump Identification

DETECT_MINAREA	7	minimum number of pixels above threshold
DETECT_THRESH	0.01	<sigmas> or <threshold>,<ZP> in mag.arcsec-2
ANALYSIS_THRESH	5	<sigmas> or <threshold>,<ZP> in mag.arcsec-2
FILTER	“N”	apply filter for detection (“Y” or “N”)?
DEBLEND_NTHRESH	2	Number of deblending sub-thresholds
DEBLEND_MINCONT	0.001	Minimum contrast parameter for deblending

based on the relative color distribution for each galaxy. Specifically, I do this by taking the $middlepeak + 1.5\sigma$ for the red clumps and $middlepeak - 1.5\sigma$ for the blue clumps. I examine different filtering sigma thresholds for identifying the clumps. Setting higher sigma values would only select clumps with the most contrast while choosing a smaller sigma factor would be sensitive to lower levels of “unsmoothness” closer to the noise level. Another advantage of this method is that the middle Gaussian identifies the “green” or intermediate color properties of the distribution. For our purposes in this chapter, I find that 1.5σ clumps most closely match our visual intuition for red and blue regions of color (See figure 3.3, first row). For future work, I will use adaptive thresholds and study its advantages over a fixed σ value.

I then run SExtractor on the high and low pass filtered color images with the SExtractor configuration file carefully optimized by visual inspection of all selected regions. The same configuration file for blue and red regions was used. The configuration parameters are listed in table 3. I did not use any filter (e.g. Gaussian, Top-Hat) to avoid introducing any resolution elements from outside of the region area identified by the filters. SExtractor will provide us with two segmentation maps per galaxy, for the red and blue filtered images, which I use to build the clump map for each galaxy (see figure 3.3, second row).

Here I take advantage of the dual mode features of SExtractor to estimate properties of the clumps. In dual mode the sources are detected in the first image and the photometry is then performed on the second image based on those detections. I use the filtered color maps as our detection image and use the stellar mass and SFR surface density maps as our second images. This way I not only know the area and position of each identified clump based on the segmentation maps, I also know their corresponding stellar masses. I measure this by

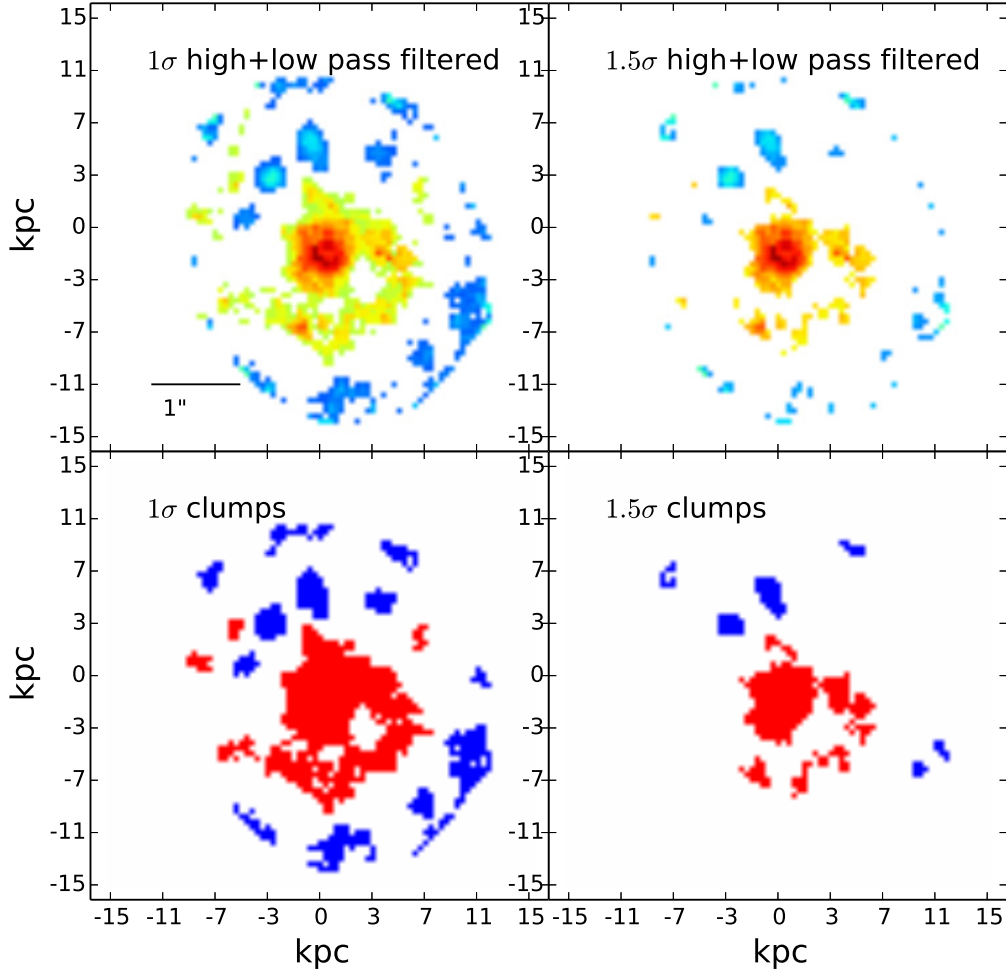


Figure 3.3: High-pass + low-pass filtered $(U-V)_{\text{restframe}}$ color maps(top) and Red + Blue Clump maps (bottom) using a 1σ and 1.5σ threshold in left and right columns respectively.

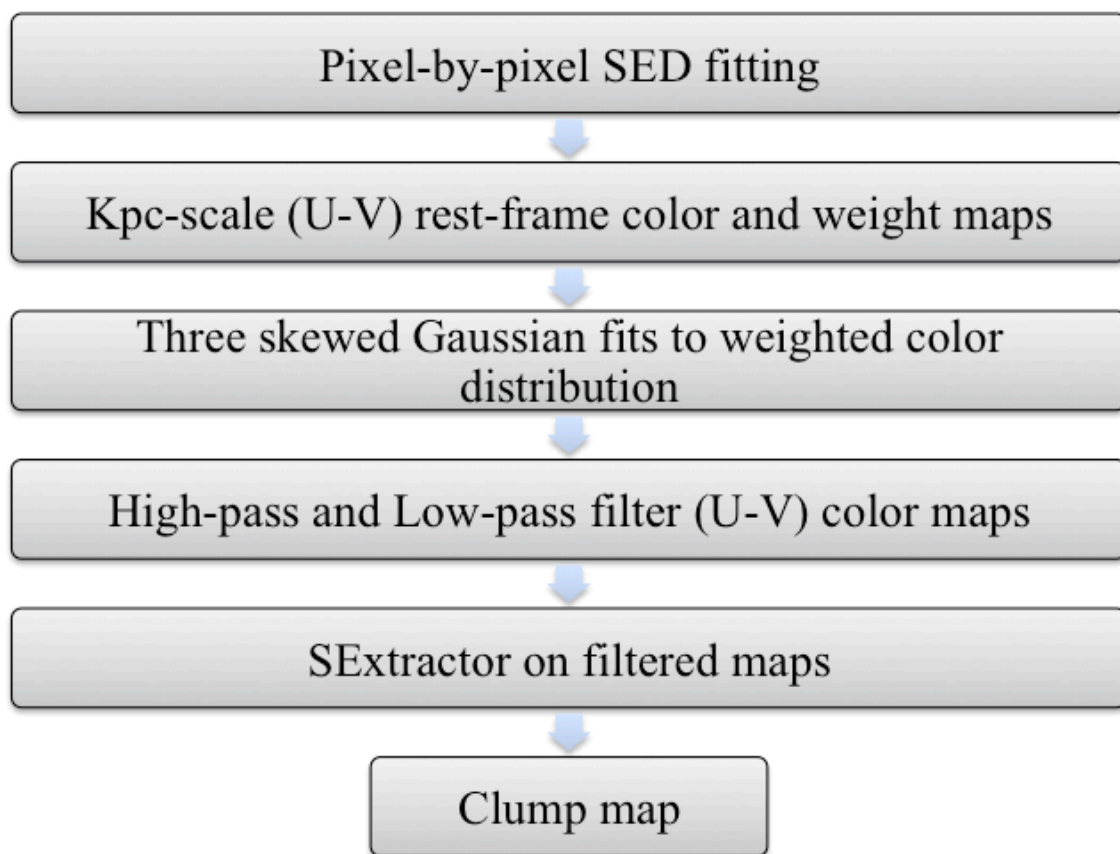


Figure 3.4: Schematic representation of clump identification process

converting our stellar mass and star formation rate surface density maps, from logarithmic to linear scale, measuring the isophotal flux output from SExtractor for each galaxy (this is the best choice for our purpose with no assumption depending on the shape). In Hemmati et al. (2014) I do not a priori decompose the bulge from the disk, to minimize assumptions on clump definitions however, there are GALFIT bulge-to-disk decompositions for all galaxies in the sample (Miller et al. 2011), and I confirm that bulges are consistently identified as red clumps between the two methods with the exception of the three galaxies with blue nuclei mentioned above. Schematic summary of the steps in clump identification process are presented in figure 3.4.

3.3 Redshift-dependent Bias Test

Since the pixel size is fixed for all the images, the apparent change due to redshift in the angular size of galaxies is likely to introduce a bias in the way the clumps are identified and in their estimated size. Here I examine the presence of such biases by simulating the images of galaxies. I artificially redshift galaxies from $0.3 < z < 0.5$ to $z = 1.0$ and re-identify their clumps using the same technique.

By identifying regions based on color maps rather than a parameter sensitive to surface brightness dimming, any redshift dependent bias could be better revealed. The dimming factor is redshift dependent (not wavelength dependent) and thus, the primary redshifting effect I need to account for is the relative change in observed angular size, a , with redshift. Assuming a_0 and a_i to be the angular sizes of the same galaxy at redshifts z_0 and z_i respectively, and d_0 and d_i being the luminosity distances corresponding to these redshifts (Barden et al., 2008), we have $\frac{a_o}{a_i} = \frac{d_i/(1+z_i)^2}{d_o/(1+z_o)^2}$.

I shift galaxies within the observed redshift range $0.3 < z < 0.5$ to $z_{rest-frame} = 1$, and for each galaxy identify the blue and red clumps at the two redshifts (the observed redshift and at $z=1$). I then estimate the covering fractions of these clumps and compare them in Figure 3.5. I define covering fractions by normalizing the area within blue and red clumps to the total area

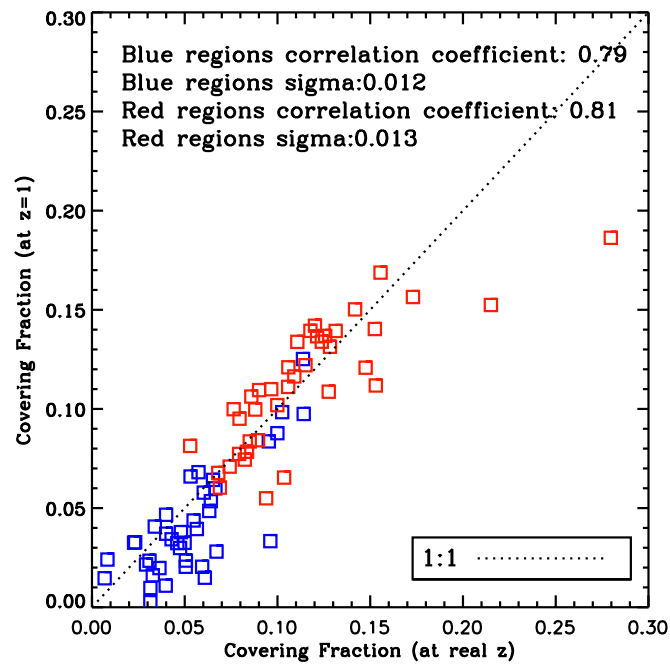


Figure 3.5: The covering fraction of red and blue regions inside galaxies redshifted to $z=1$ versus the covering fraction at their real, observed redshift. Blue/Red squares represent covering fraction of Blue/Red regions respectively.

of a galaxy, defined based on the number of resolution elements in the segmentation maps of both the clumps and galaxies. The linearity of the relation and small scatter ($\sigma \simeq 0.01$) around the 1:1 line in Figure 3.5 confirms that there is no significant bias due to cosmological angular size evolution for our clump selection method at higher redshifts ($z \simeq 1$) as compared to lower redshifts in our sample.

3.4 Physical Properties of Clumps

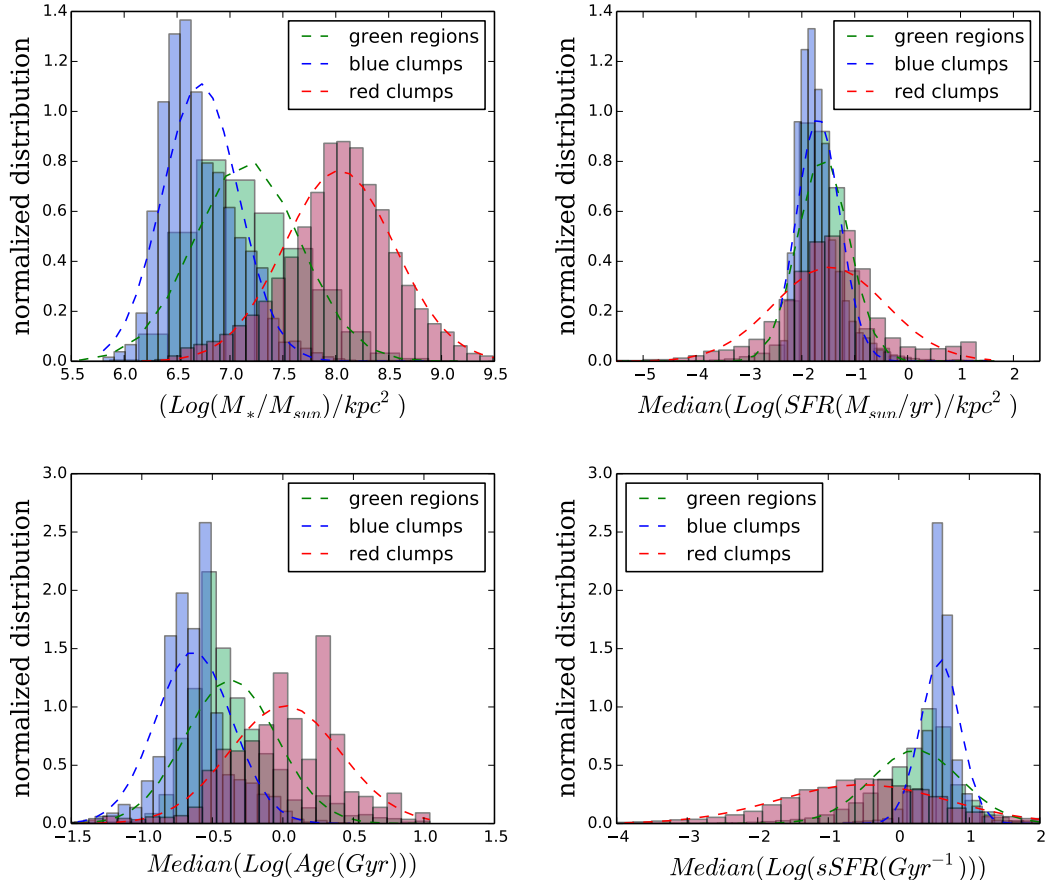


Figure 3.6: Physical properties of the blue and red clumps compared to underlying green regions in the disk of galaxies. Histogram of stellar mass surface density, star formation rate surface density, stellar age and sSFR of all pixels are plotted from top left to bottom right respectively. Dashed curves are Gaussian functions fitted to each histogram.

In order to study the physical nature of the red and blue clumps, I compare the distributions of stellar mass surface density, SFR surface density, age and sSFR for the clumps associated with each galaxy as well as the underlying green regions inside disks (figure 3.6). To account for the effect of redshift (a resolution element at low redshift corresponds to a smaller area than at higher redshifts), I normalized each measured parameter by the physical area of a resolution element at the spectroscopic redshift of the galaxy. While red and blue clumps are identified solely based on rest-frame (U-V) colors, there is a clear distinction between their stellar mass surface density, age and sSFR distribution. However, they have similar SFR surface densities. As in most of our galaxies, especially as mass increases, the bulge, central pseudo-bulge, or central disk contributes to a significant portion of the red clumps. It is in the red clumps where the highest concentration of stellar mass exists. It is also clear that the distribution of stellar ages in blue clumps peaks at younger ages, even though the overall distribution of star formation rates are similar as that in red clumps.

In figure 3.7 and 3.8, I plot the stellar mass of each identified clump as a function of total stellar mass, color-coded by redshift. There is an overall trend of more massive clumps being in more massive hosts and an interesting bimodal behavior seen in the distribution of red clumps. To explore the extent to which the tight sequence of high-fraction red clumps are bulges or central spheroidal components, I divide the clumps into two groups based on their distance from the center of galaxy (Figure 3.7 & 3.8). Circles show clumps closer than 2.5 kpc to the center and triangles represent clumps further than 2.5 kpc from the center (where clump centers are calculated using SExtractor). More than 98% of blue clumps are further than 2.5 kpc from the center. 45% of the red clumps are located within the 2.5 kpc of the center, 90% of which contribute around 30–90% to the total stellar mass of the host galaxy. It is worth noting that 2.5 kpc is an arbitrary cut chosen for simplicity rather than binning in distance. The red clumps that are further than 2.5 kpc from the center (red triangles) are likely to be dustier regions in the disk. This will be explored further in future work by cross correlating the mass and extinction maps. It is possible many central components could be dusty star forming regions as well, rather than relatively passive spheroidal components like classical bulges.

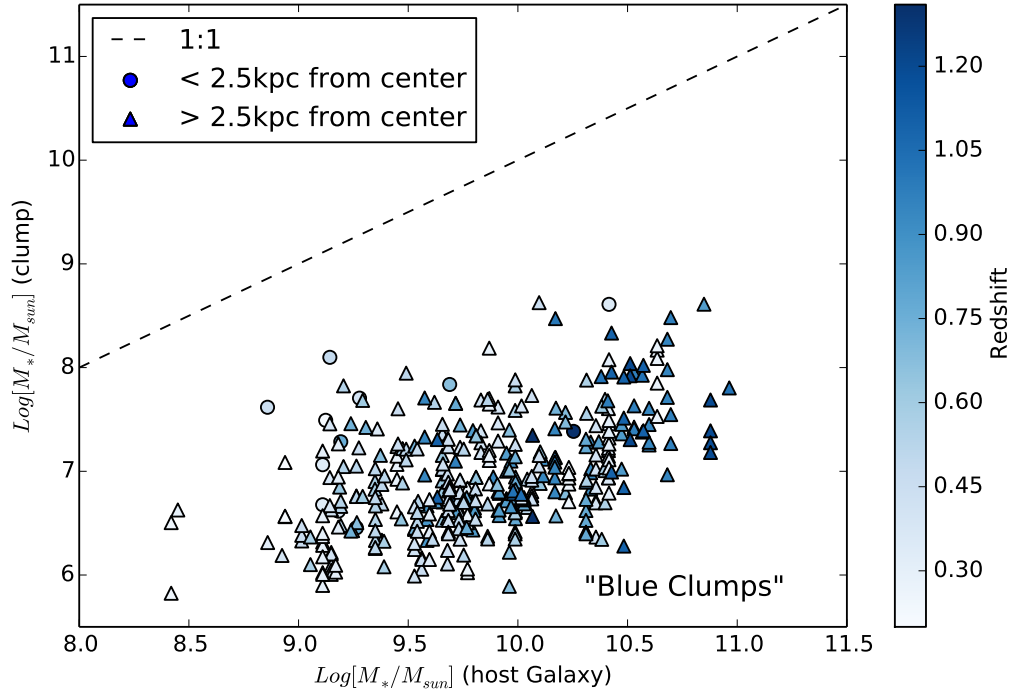


Figure 3.7: Stellar mass of blue clumps versus stellar mass of the host galaxy. Filled circles (triangles) represent regions with distances less (more) than 2.5. Lighter color corresponds to lower redshift.

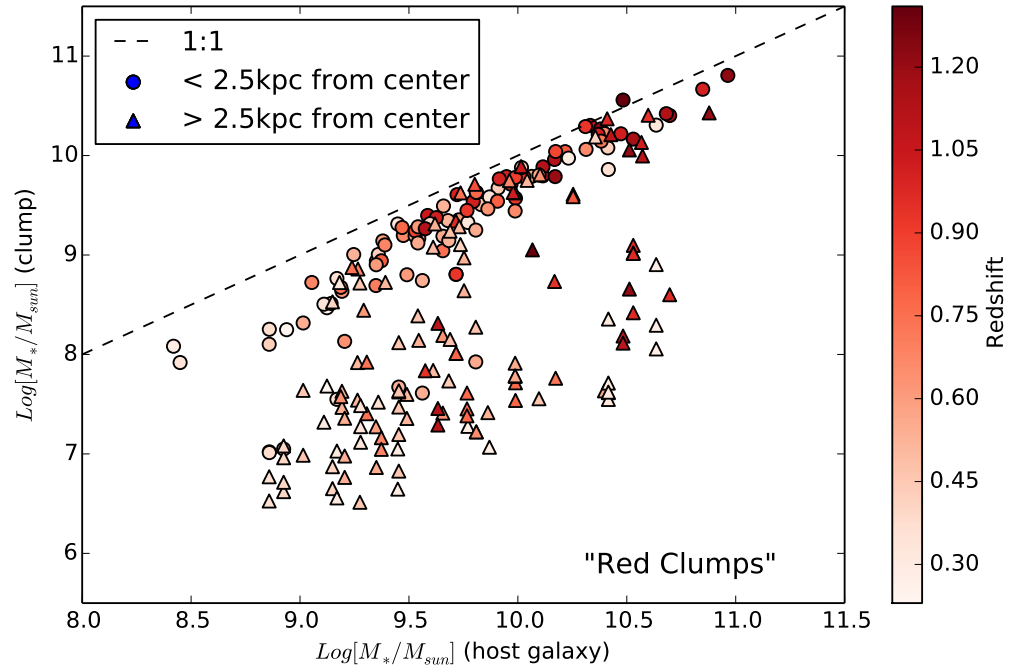


Figure 3.8: Stellar mass of Red clumps versus stellar mass of the host galaxy. Filled circles (triangles) represent regions with distances less (more) than 2.5. Lighter color corresponds to lower redshift.

3.5 Clump Evolution

As described before, some simulations suggest blue clumps spiraling towards the center of the galaxy causing the central bulge growth and maybe the morphological quenching. To test this using our sample, I studied the evolution of the relative area covered by blue and red clumps as well as the average distance of clumps from the center, with respect to both redshift and the total stellar mass in Hemmati et al. (2014). Figure 3.9 shows the covering fraction of blue and red clumps as a function of redshift and stellar mass. Clearly, the covering fractions of red clumps were always larger than blue clumps. Also, the dispersion in the distribution of the covering fractions for red clumps was consistently larger than that for the blue. Furthermore, I found no significant evolution with either redshift or stellar mass in the covering fraction of blue or red regions. Our findings supported the paradigm that small-scale properties of galaxies on average are not evolving much over intermediate redshifts.

I measured distances of red and blue clumps from each of their associated resolution elements to the center of their respective galaxy as defined by the rotation curve. I then normalized to the scale radius of the galaxy to avoid biases due to the evolution of galaxy size across redshift. Figure 3.10 shows the median and dispersion of distances from the center of the galaxy for both blue and red clumps vs. redshift and total stellar mass respectively. Blue clumps were almost always further away from the center of the galaxy than red regions with a larger dispersion in the distribution of distances. Since the red clumps are often found to be synonymous with the bulge, the increase of the weight and strength of this red, bulge region (manifested by the decrease in scatter) with the stellar mass can be seen in figure 3.10. I found no significant evolution in the median distance (scaled by the scale radii of the galaxy) of red or blue clumps from the center with time in the redshift range covered in this study. However, there was a slight increase in the median distance between blue and red clumps in more massive galaxies compared to the least massive galaxies.

However, studying properties of the sample on which I performed the analysis in Hemmati et al. (2014) more precisely, one would see a clear bias in the selection. Figure 3.11 shows

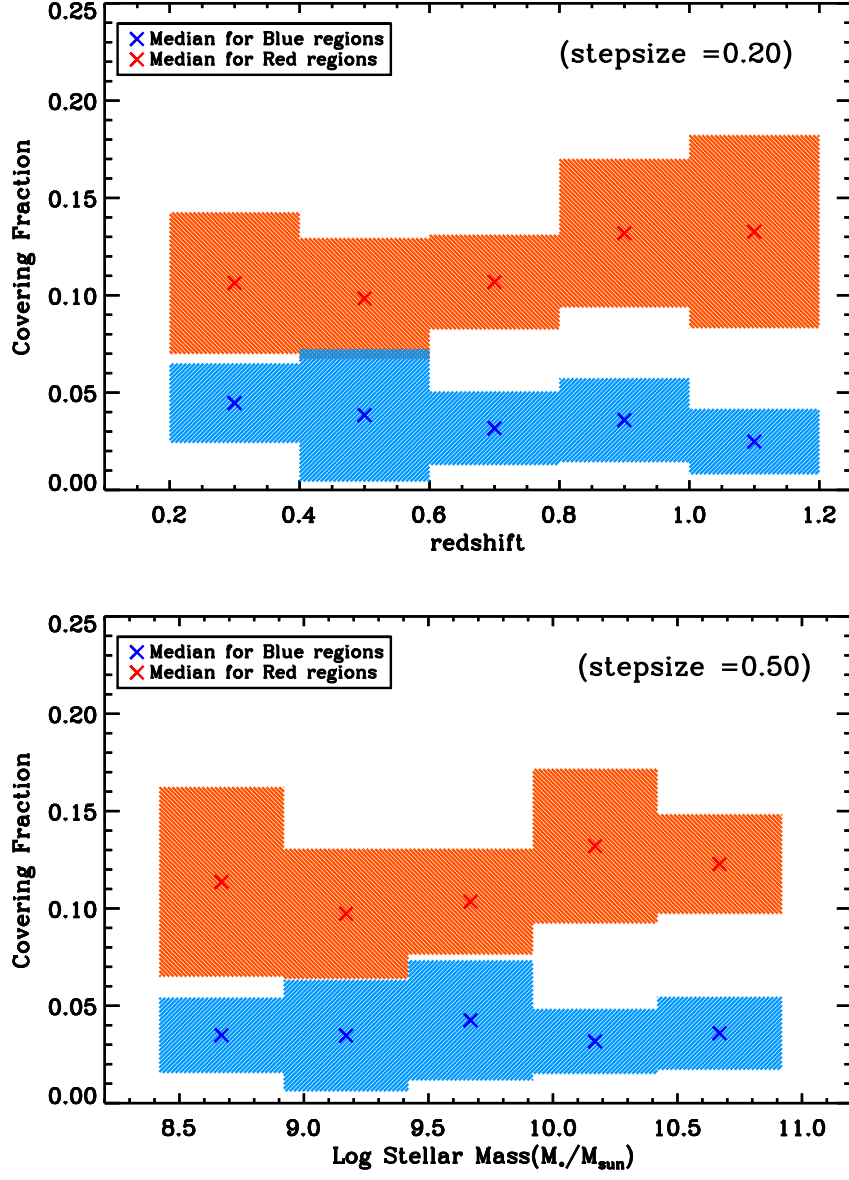


Figure 3.9: Covering fraction of red and blue regions inside galaxies (area of identified red or blue regions divided by the area of the galaxy) as a function of redshift and stellar mass in top and bottom panels, respectively. Crosses show the median in each bin and the shaded area show the 1σ dispersion.

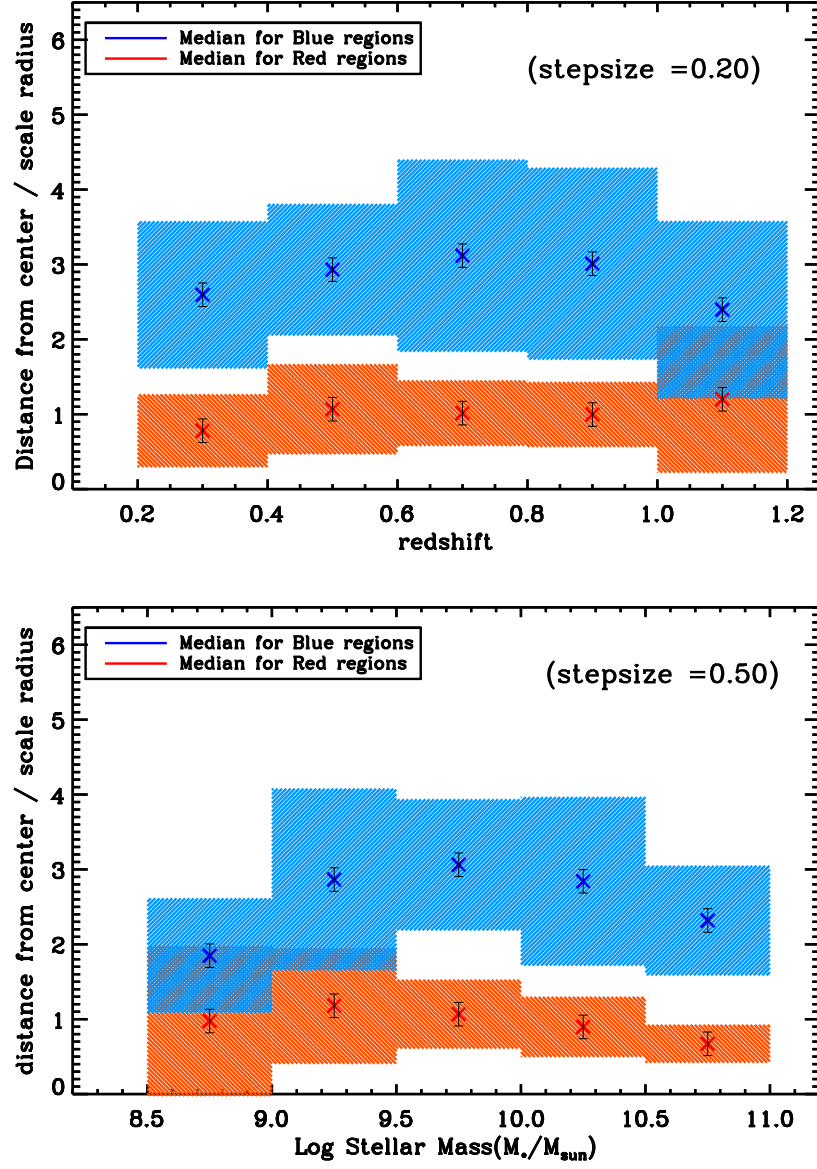


Figure 3.10: Spatial distribution of red and blue regions in their host galaxies. The figure shows the distance of blue and red regions from the dynamical center of galaxy as a function of redshift and stellar mass of the host galaxy. Cross symbols represent the median in each bin, error bars are measurement errors and shaded region shows the dispersion of distances of resolution elements in the identified regions for galaxies at each bin. Blue regions are always at larger distances from the center of galaxy compared to red regions.

the stellar mass of the host galaxies as a function of their redshift and I was sampling more massive galaxies at higher redshifts therefore any evolutionary trend with mass and redshift or lack thereof would not be correct without taking this fact into account. To avoid this issue, I have selected a subsample of galaxies to cover a whole mass range ($9.0 < \log(M_*/M_\odot) < 10.5$) in the redshift range ($0.4 < z < 0.9$) selected and vice versa (plotted as dashed lines in figure 3.11).

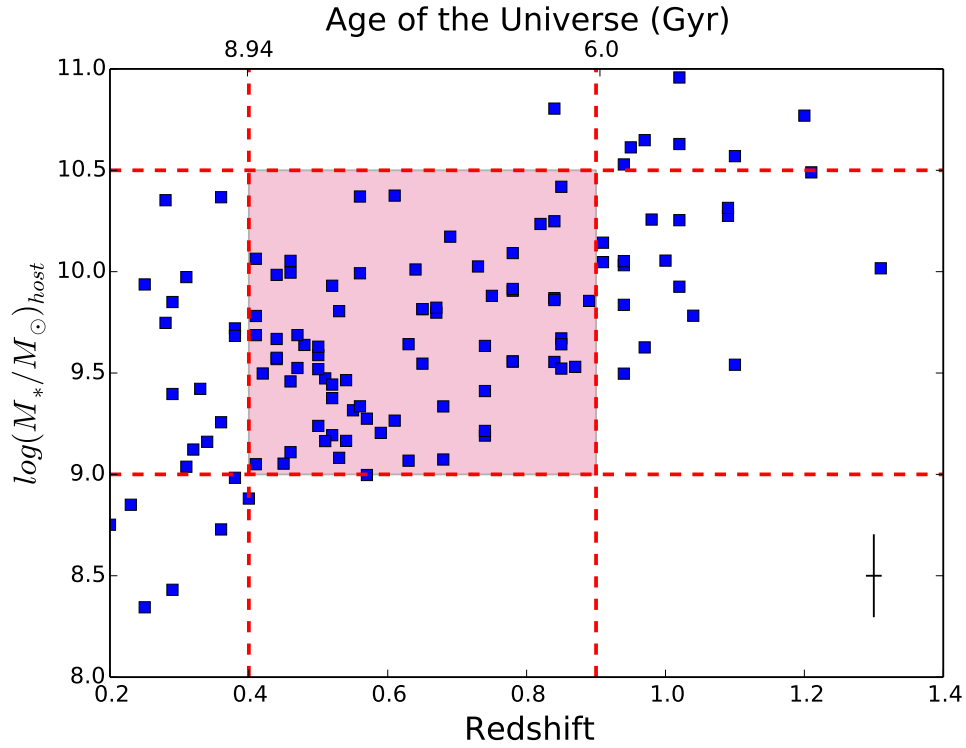


Figure 3.11: Unbiased subsample selected from the original sample of galaxies. Red dashed lines show the criteria in mass and redshift to construct an unbiased sample, with selected galaxies located in the shaded region.

The subsample not being complete down to the lower limit of mass at all redshifts is no longer a concern as we are sampling similar number of galaxies with similar properties at each redshift or stellar mass bin. Using this subsample I study again the evolution of covering fraction and spatial position of red and blue clumps with both redshift and stellar mass. Separating the red regions which are closer to the center (bulges) I found that the trends observed for bulges

Table 3.2: Significance of Red and Blue Clumps Evolution with Redshift and Stellar Mass

	$r_{red-clumps}$	$P_{red-clumps}$	$r_{blue-clumps}$	$P_{blue-clumps}$
Covering fraction with redshift	0.30	0.0	-0.18	0.1
Covering fraction with mass	0.31	0.0	-0.11	0.35
Distance from Center with redshift	0.03	0.78	0.24	0.03
Distance from Center with mass	-0.14	0.21	0.42	0.0

are similar to those seen for all the red clumps but with smaller scatter. This was expected as bulges fabricate a large portion of the red clumps. By selecting the sample as here, we have a small dynamical range in both redshift and mass and therefore any trends may disappear. Also, in studying evolution with redshift (mass) dividing the subsample into smaller mass(redshift) bins does not change the overall trends that I discuss below.

Plotted in figure 3.12 is the covering fraction of blue and red clumps as function of redshift (top) and stellar mass (bottom) for galaxies in the subsample. As was found in Hemmati et al. (2014), covering fraction of red regions is almost always larger than blue regions, with blue and red clumps covering about 5% & 12% of the area of the galaxy. These numbers are of course dependent on the threshold defined for selecting the clumps. I have previously found no evolution in the covering fraction of red and blue clumps including the whole sample. Here focusing only on the unbiased subsample and by looking at the median values at each bin, I find that the covering fraction of red clumps is increasing with both stellar mass and redshift of the galaxy while the covering fraction of blue clumps stays almost unchanged. In figure 3.13 average distance of clumps from the center of galaxy is plotted as a function of redshift (top) and stellar mass (bottom). The median red clump's distances is always less than that of blue clumps as expected and does not evolve with either redshift or stellar mass. The median distance of blue clumps, however, evolves significantly with stellar mass and also there is an slight increase in the distance with increasing redshift. To test for the significance of these trends, I ran a Pearson correlation test and the corresponding two-tailed "p-value" (listed in table 3.2). The correlation coefficient "r" is a value between (-1 and 1) where positive (negative) correlations imply as x increases y increases (decreases) and 0 implying no correlation. The "p-value" is a number between 0 and 1, representing the probability of the null-hypothesis being true.

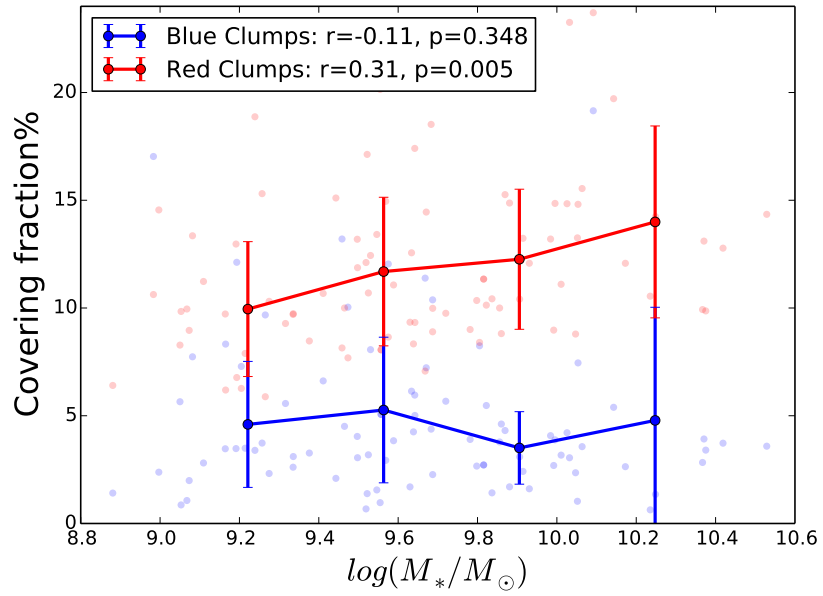
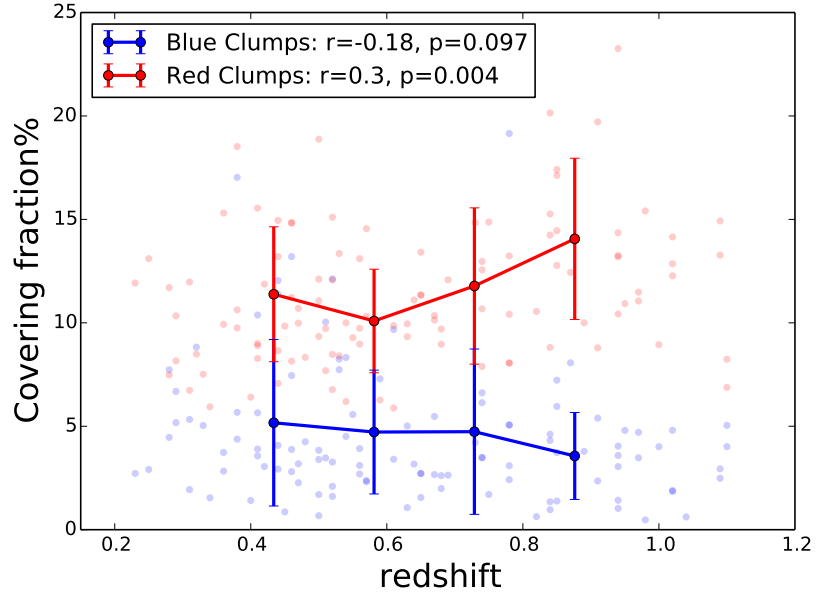


Figure 3.12: Covering fraction of red and blue clumps as a function of redshift (top) and stellar mass(bottom).

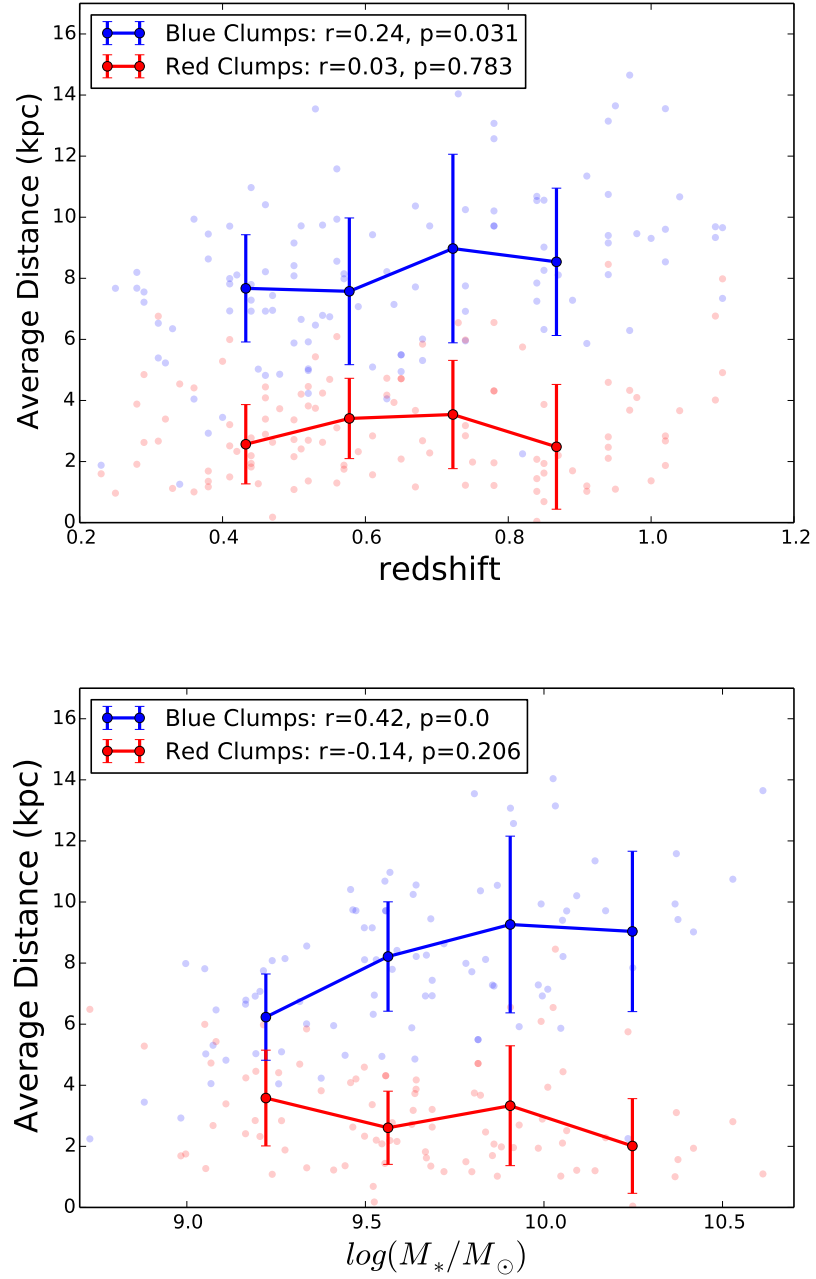


Figure 3.13: Average distance of red and blue clumps from the center of galaxies as a function of redshift (top) and stellar mass(bottom).

These tests confirm our interpretation based on median binned values.

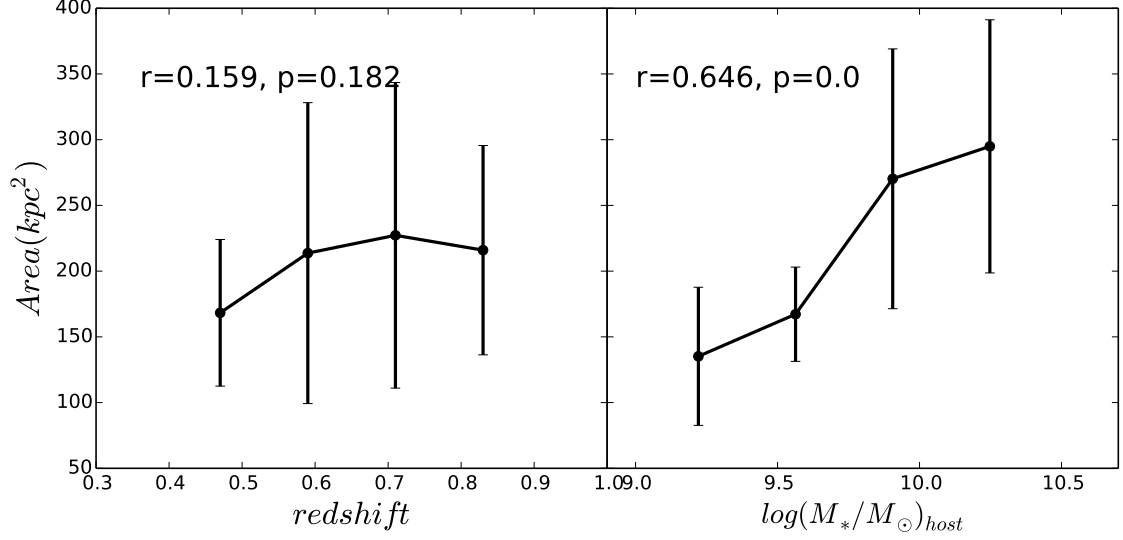


Figure 3.14: Galaxy size evolution as a function of redshift (right) and stellar mass(left).

To understand the physics behind these trends, we also need to have in mind the change in the physical sizes of galaxies as a function of redshift and stellar mass (figure 3.14). Median physical sizes of galaxies in this subsample are not evolving with redshift. And the more massive the galaxy the larger its physical size (the well-studied mass-size relation). The covering fraction plots (figure 3.12) already take into account the change in the area of the galaxy contrary to the average distance plots (figure 3.13).

A non-correlation in the blue clumps covering fraction with time suggests that either these clumps are not spiraling into the bulge or disrupted by strong winds or that new clumps are forming while the older ones are destroyed having the total covering fraction fixed with redshift. It is then expected to have the average distance of the blue clumps scaled by the size of the galaxy to not evolve with redshift as was shown here. There is however a slight decrease in the covering fraction of red clumps with time inconsistent with the picture of bulge growth (at least in size).

A non-correlation in the blue clumps covering fraction with stellar mass does not suggest

that there are the same amount of clumps in galaxies with different masses but rather suggests that as the galaxy becomes more massive and at the same time larger, the contribution of the blue clumps to the area also increases in a way to have the same covering fraction. In this picture it makes sense to expect larger average distance of blue clumps in more massive galaxies as was found here. Increase in the red clumps covering fraction with stellar mass means that in more massive systems bulges grow larger compared to the overall growth of the galaxy size.

3.6 Discussion and Summary

In this chapter I identified red and blue clumps in galaxies using the photometric maps produced through resolved SED fitting as opposed to the routines of selecting clumps base on observed images in single bands. The clumps are selected from high-pass and low-pass filtered $(U - V)_{rest-frame}$ color maps using SExtractor. The clump identification routine is visually inspected and also tested against redshift biases by artificially redshifting lower redshift galaxies to $z \sim 1$ and reidentifying their clumps. While the threshold for making the high-pass and low-pass filtered maps are set by visually optimizing the selected clumps, in future works this technique can be improved by using an adaptive threshold rather than a fixed one.

I studied the physical properties of pixels belonging to red and blue clumps in galaxies as well as the properties of the pixels in the underlying green disk. I found that blue clumps on average are not regions of high star formation surface density in the disk and rather regions of higher specific star formation. This finding suggests that studies of clumps based on $H\alpha$ observations should do the identification based on the EW of the line rather than the luminosity. The median ages of blue clumps, green pixels and the bulge are respectively $\sim 0.15, 0.3, \text{ and } 1 \text{ Gyr}$ which are of the order of several to tens of orbital times ($\sim 50 \text{ Myr}$ measured from rotation curves for galaxies in this sample). This age gradient is consistent both with the migration of clumps inward and an inside-out growth of the galaxy.

Stellar mass and star formation rate surface density of individual clumps inside galaxies are measured using the dual nature of the SExtractor program. I found more massive galaxies

to have on average more massive clumps. I have also found a bimodal distribution in the red clumps consisting of bulges (very massive and close to the center of the galaxy) and dustier less massive regions (in the outer disk). However, the average properties of red clumps is mostly dictated by the larger contributor which is the bulge and separating the two classes did not change the results.

I studied the effect of sample selection in the trends found in the present study, due to incompleteness. To explore the effect of the bias on the results, I cut the sample into a smaller range of host galaxy stellar mass ($9.0 < \log(M_*/M_\odot) < 10.5$) and redshift ($0.4 < z < 0.9$). In this subsample, the covering fraction of blue clumps is about 5% , smaller compared to higher redshift studies and about half the contribution of the red clumps. Blue clumps are found to always be at further distances from the center compared to red clumps with average distance of 6 – 8 kpc. Average distances of red clumps do not evolve with either time or stellar mass but I found an increase in the average distance of blue clumps with increasing stellar mass of the galaxy and no significant evolution with time. I found no significant evolution in the covering fraction of blue clumps with either redshift or stellar mass, while the covering fraction of red clumps increases with increasing stellar mass and decreases with look-back time. No significant evolution in the blue clumps covering fraction with look-back time implies that either these clumps are not spiraling into the bulge or disrupted by strong winds or that new clumps are forming while the older ones are destroyed having the total covering fraction fixed with redshift. Combining this with the decrease in the covering fraction of red clumps with look-back time, suggests that we are not witnessing the bulge growth (at least in physical size) scenario here and if this is the mechanism for the central bulge formation and growth as some theories and simulations suggest, then it must have happened at earlier epochs.

Chapter 4

The Main Sequence of Star Formation

4.1 Introduction

There is a strong correlation between the SFR and stellar mass “*main sequence*” in star-forming galaxies out to high redshifts (e.g. Lilly et al. (2013), Salmon et al. (2015)), with the bulk of star formation occurring in massive galaxies than in less massive systems (e.g. Noeske et al. (2007), Bell et al. (2005), Reddy et al. (2006), Elbaz et al. (2007)). A population of passive galaxies also exists, located below the main sequence, whereas starbursts lie above. The slope of the main sequence, or the sSFR (SFR/mass), is almost constant along the main sequence at each epoch but the zero point evolves significantly with time. The cause of the evolution in the main sequence is not very well understood. There is also discrepancy among slopes and scatters around the relation reported in different studies using different SFR diagnostics and various sample selections.

In this chapter I study the relation between stellar mass and SFR surface density pixel by pixel and also in individual clumps, to investigate whether the main sequence exists among substructures in galaxies. If so, how does the slope and scatter compare with the host galaxy and whether there is an evolution with redshift.

Table 4.1: Properties of Galaxies in figures 4.1-4.5

Figure	redshift	$\log(M_*/M_\odot)_{Mlow}^{Mup}$	$\log(M_\odot/yr)_{SFRlow}^{SFRup}$	feature
4.1	0.56	$9.99_{9.81}^{10.13}$	$1.20_{0.64}^{1.65}$	blue clumps
4.2	0.97	$10.65_{10.43}^{10.79}$	$1.80_{1.12}^{2.43}$	blue clumps
4.3	0.78	$9.91_{9.68}^{10.01}$	$1.32_{0.70}^{1.85}$	Quenching
4.4	0.82	$10.23_{10.02}^{10.41}$	$1.67_{1.06}^{2.14}$	Double Nucei
4.5	0.31	$9.97_{9.89}^{10.03}$	$2.46_{2.32}^{2.55}$	AGN

4.2 Resolved Main Sequence in Individual Galaxies

Main sequence of star formation evolves with redshift, with higher redshift galaxies having higher SFR at fixed stellar mass. While the reason behind this evolution is not very well understood, studies suggest that this could either be due to a larger reservoir of gas and/or higher rate of cold gas accretion from the halos at higher redshifts or due to higher efficiency of turning gas into stars. On the other hand, we have clear observational evidence of change in the structure of star forming galaxies with redshift, where disks of galaxies become more stable and less clumpy with time. To understand the connection between the two, I study the relation between the star formation surface density and stellar mass surface density at resolution elements (“the resolved main sequence”) in galaxies and its variance as a function of position in the galaxy as well as other physical properties.

In figures 4.1-4.5, I present the resolved main sequence for five individual galaxies spanning redshifts of $\sim 0.3 - 1.0$. The four panels in each plot from top-left to bottom-right are color coded based on $(U - V)_{rest}$ color, $\log(\text{age}(\text{yr}))$, $E(B - V)$, and radial distance from the center (kpc), respectively. It is worth noting that because star formation and stellar mass surface densities are both measured through SED fitting process they are not independent.

The trends seen inside galaxies are worth a careful exploration because, the fitting at each resolution element is completely independent of the rest of the resolution elements. In figures

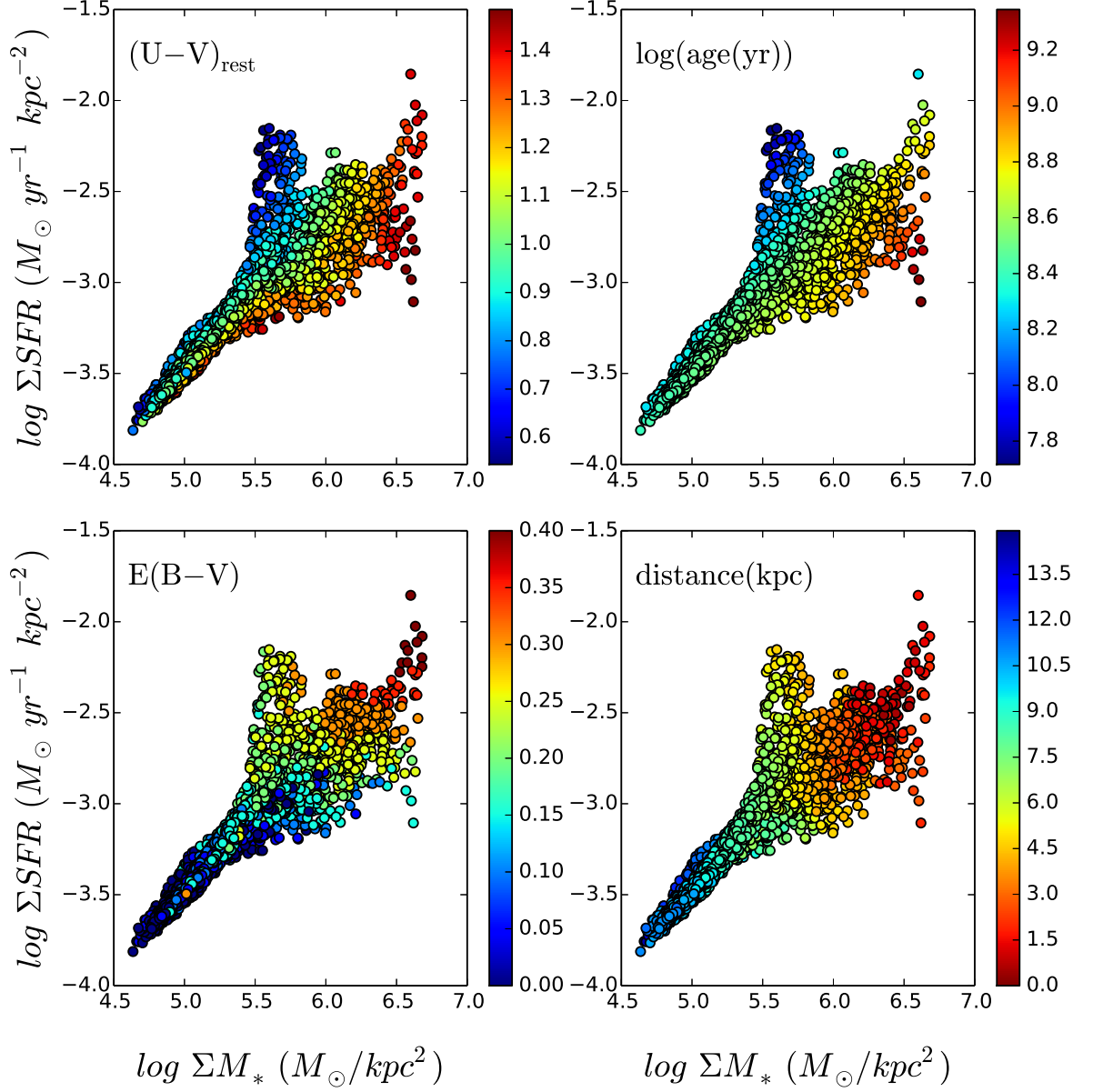


Figure 4.1: SFR vs. stellar mass surface density or the resolved Main Sequence of star formation at resolution elements color-coded by rest-frame $(U-V)$, $\log(\text{age}(\text{yr}))$, $E(B-V)$, and distance from the center respectively from top-left to bottom-right, for a galaxy at $z = 0.56$.

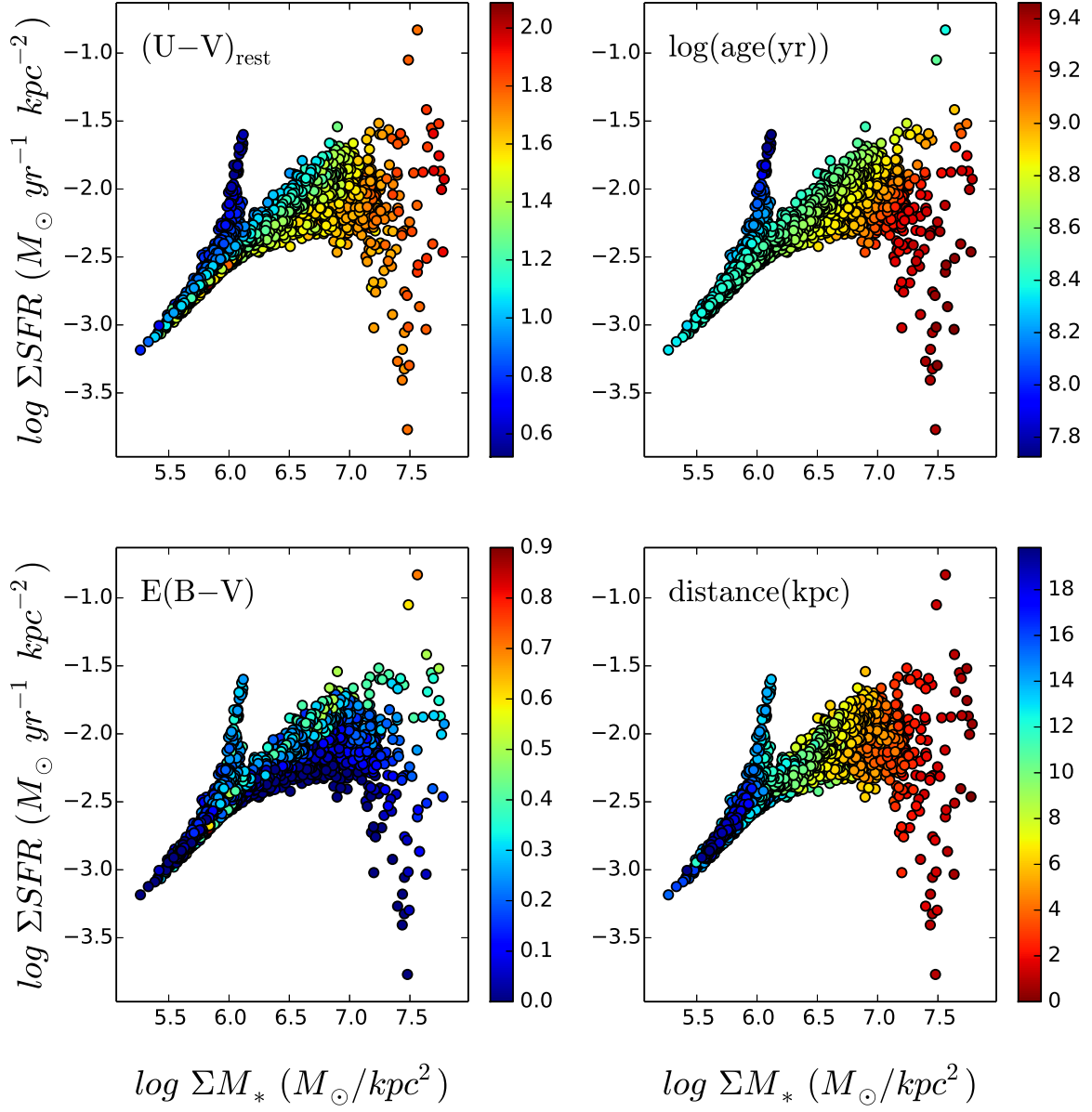


Figure 4.2: Same as figure 4.1 for a galaxy at $z = 0.97$ with obvious blue clump in the disk.

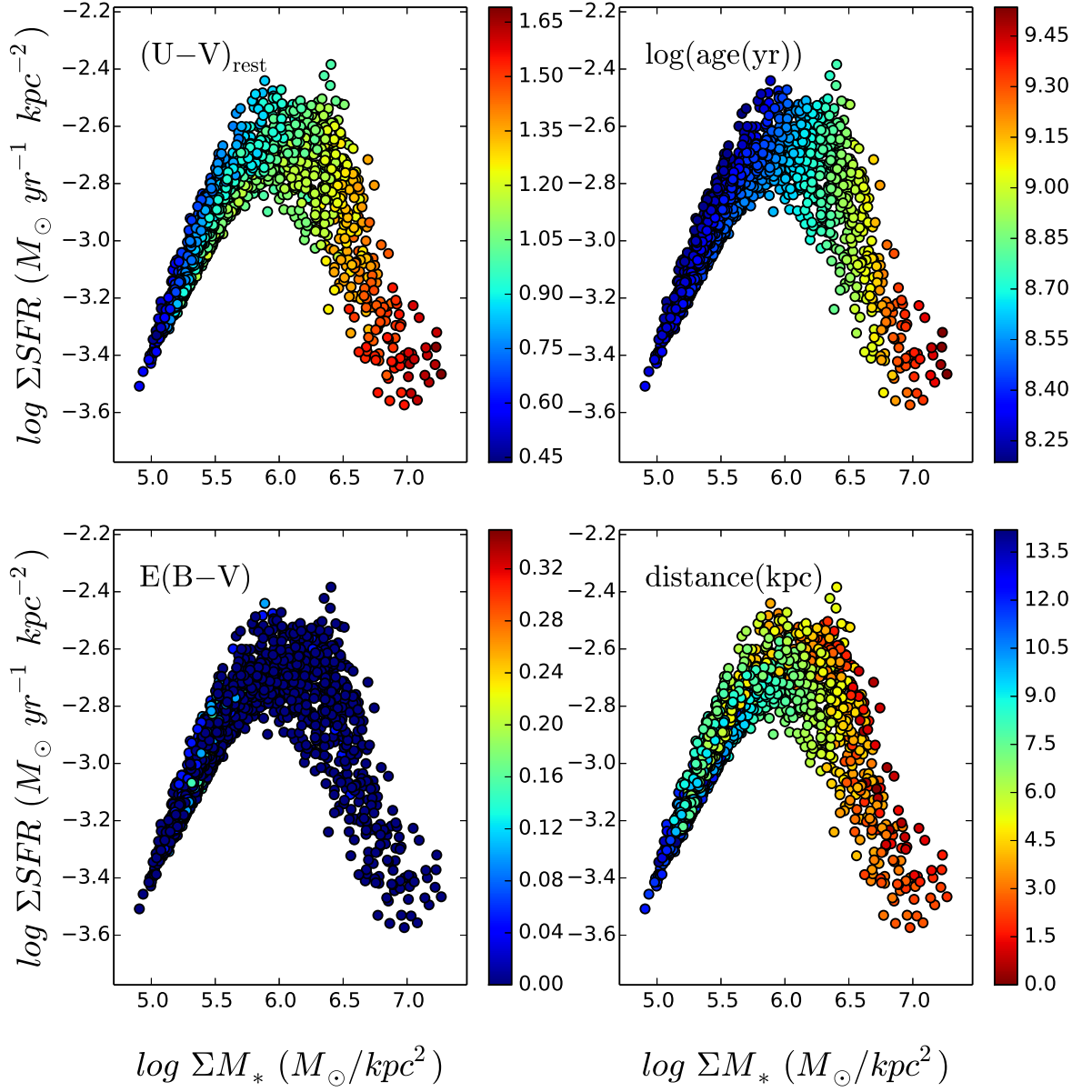


Figure 4.3: Same as figure 4.1 for a galaxy at $z = 0.78$ with star formation quenched at central parts.

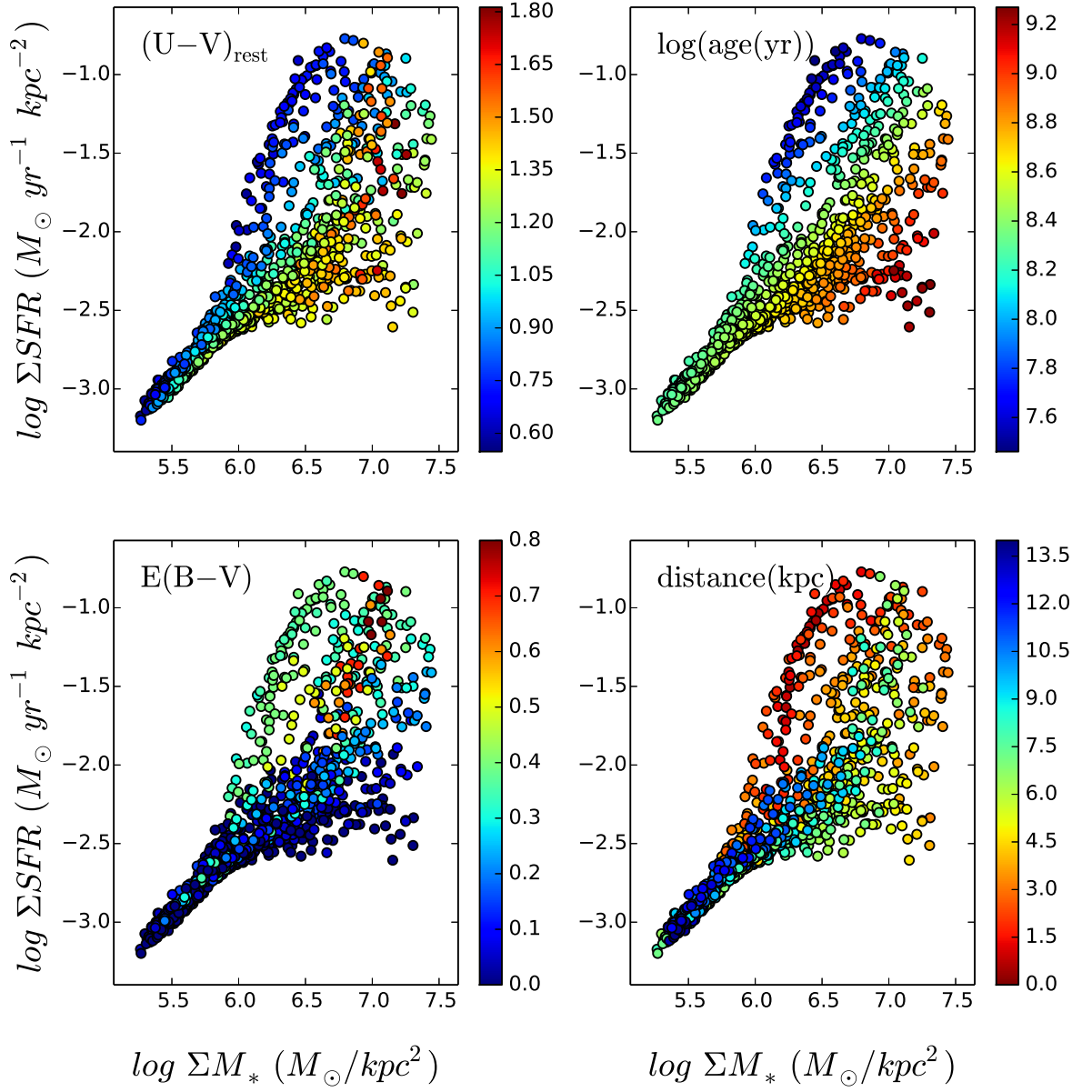


Figure 4.4: Same as figure 4.1 for a galaxy at $z = 0.82$ with double nuclei, possibly a post merger.

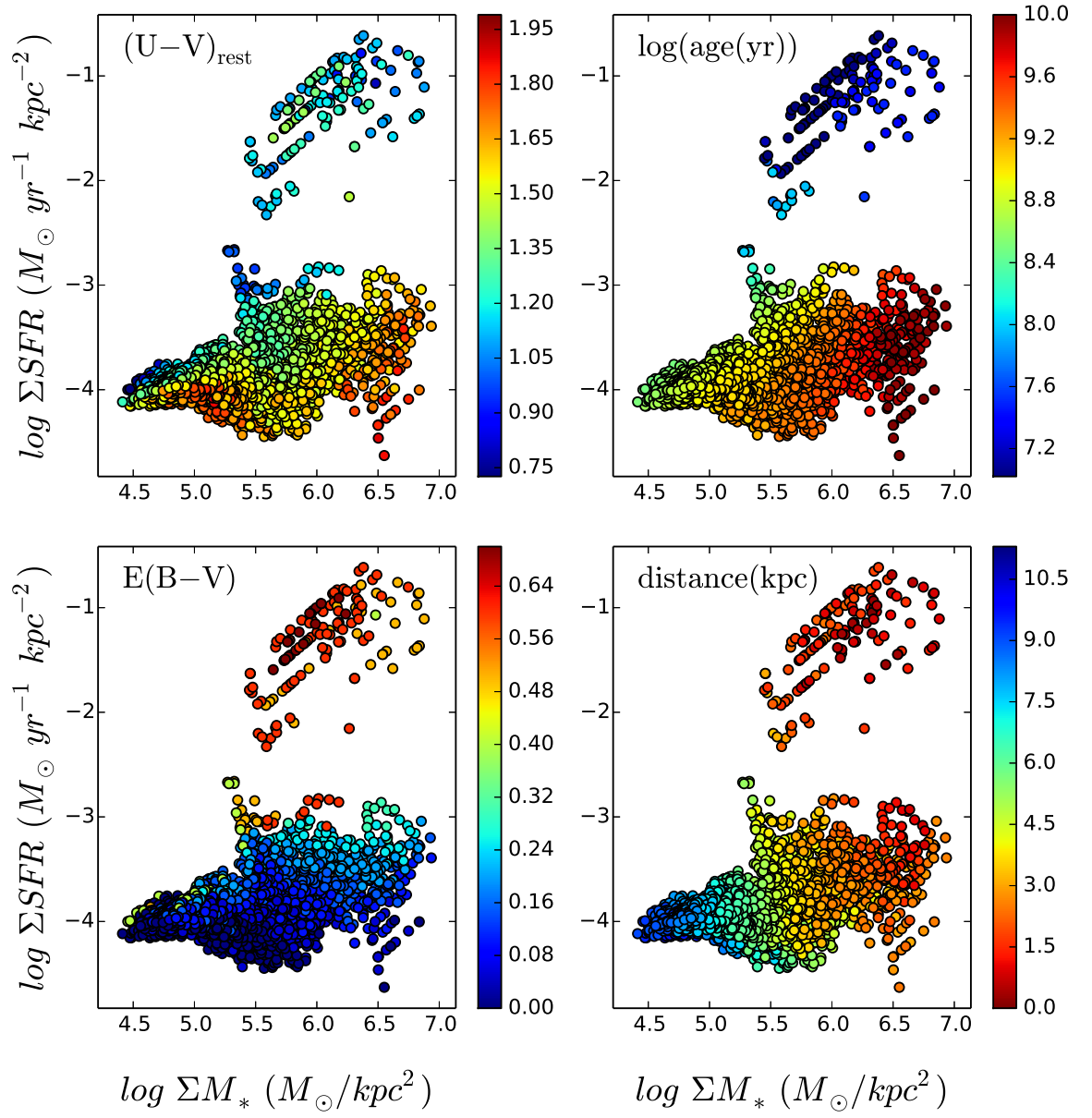


Figure 4.5: Same as figure 4.1 for a galaxy at $z = 0.31$ with possibly an AGN at the center.

4.1 and 4.2, two disk galaxies at $z = 0.56$ and $z = 0.97$ show the clear trend of increase in the SFR surface density with increase in the stellar mass surface density, but more interesting is the branch that goes up with a steeper slope compared to the rest of the pixels, corresponding to the blue clumps in the disk. I also find larger scatter at the massive end due to a larger age and extinction gradients. The trends seen in these two galaxies are not always the case, as can be seen in figure 4.3, the resolved main sequence for a galaxy at $z = 0.78$ shows a clear knee in the relation, suggestive of a quenched central regions in this galaxy. In figure 4.4, I plot the resolved main sequence for a galaxy at $z = 0.82$ with double nuclei, indicative of a possible post-merger system. The large scatter could then be explained by the merger. It can be seen from this figure, that at high masses and high SFR surface density, there are points with very young ages but high stellar mass. And the last example of an individual resolved main sequence is plotted in 4.5 for a galaxy at $z = 0.31$, the trend is quite different from the previous resolved main sequences. This galaxy is detected in x-ray and is possibly hosting an AGN at the very center, causing the blue pixels with very young ages with elevated star formations at the center. Properties of the host galaxies in these five examples are listed in table 4.1. Aside from the points made from individual plots, these plots also give an overall idea of how sample selection is key in determining the slope or scatter of the main sequence. These galaxies for instance are all selected with extended emission lines, and will be classified as star forming galaxies, however, some show quite different trends and therefore could cause a large scatter in the main sequence of star formation.

Dividing galaxies based on host stellar mass into three intervals of $\log(M_*/M_\odot)_{host} = [9 - 9.5]$, $[9.5 - 10]$ and $[10 - 10.5]$ I plot the resolved main sequence in figure 4.6, color-coded with the spectroscopic redshift of the host galaxy. This figure demonstrates to some extent the evolution seen in the “global” main sequence where at fixed stellar masses galaxies at higher redshifts have higher SFR, this can be seen from this figure as the change in the trends from higher redshifts to lower redshifts. Comparison of the three panels also shows how the trends get more complete towards building the bulge component as the host galaxy becomes more massive. I also find an increase in the overall average mass surface density with increase in the

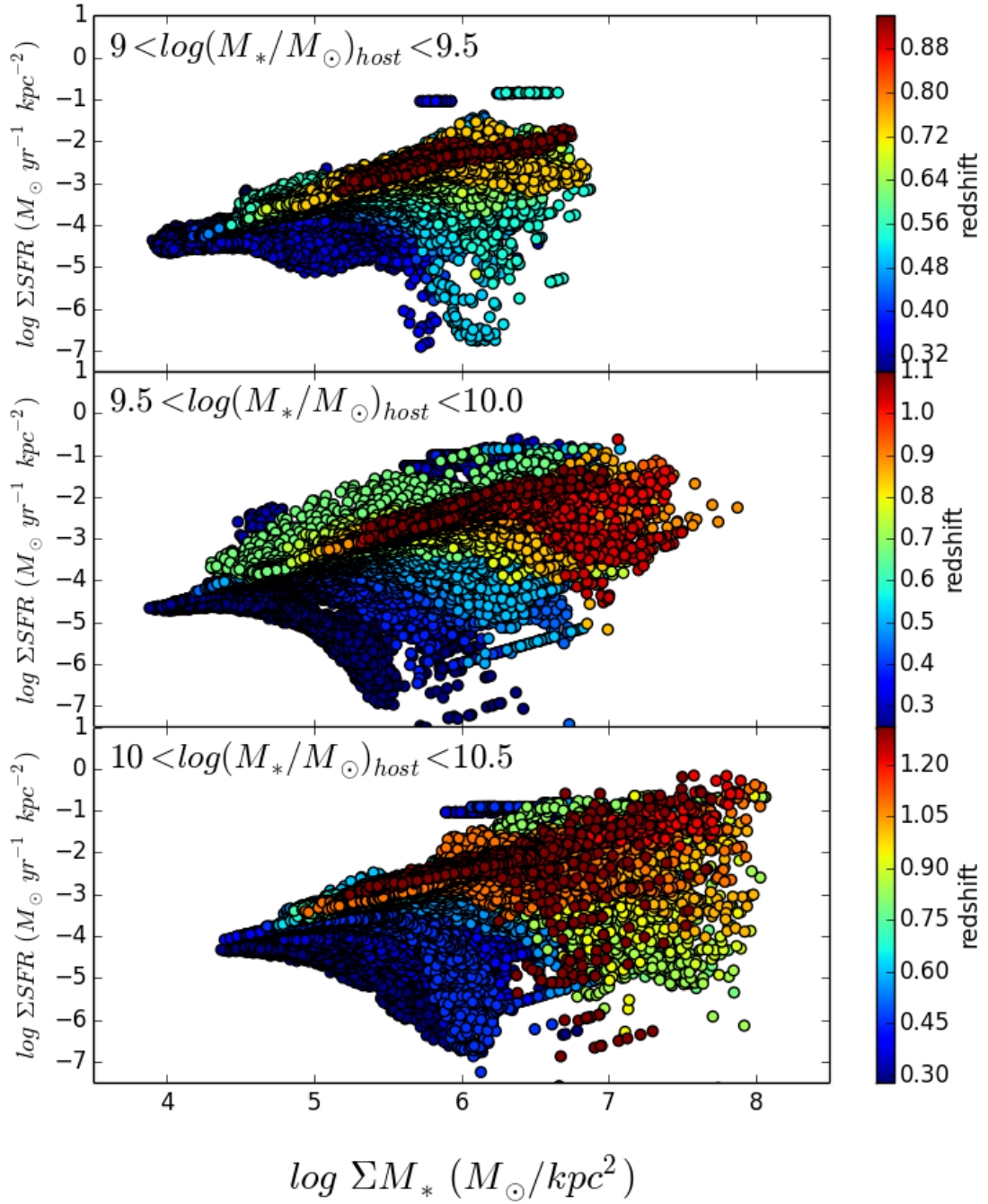


Figure 4.6: Resolved main sequence over pixels in galaxies with masses in the range $\log(M_*/M_{\odot})_{\text{host}} = [9 - 9.5]$ (top), $[9.5 - 10]$ (middle), and $[10 - 10.5]$ (bottom) color coded based on redshift.

host stellar mass.

4.3 The Main Sequence Among Clumps

In chapter three of this thesis, I explained in detail the methodology in identifying red and blue clumps as well as their physical properties. Here, I study the resolved main sequence of star formation in pixels belonging to the red and blue clumps. Figure 4.7 demonstrates the difference between resolution elements in red and blue clumps as well as the underlying green disk on a resolved main sequence plot. This plot further confirms the validity of our clump identification scheme.

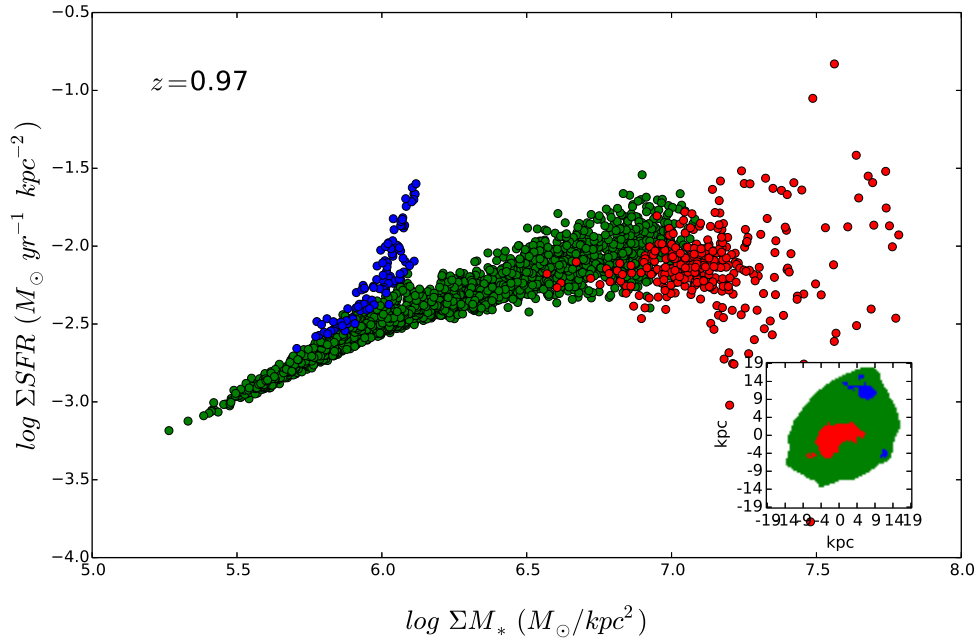


Figure 4.7: Pixels selected as blue and red clumps on a resolved main sequence for a sample galaxy at $z = 0.97$.

In Hemmati et al. (2014), we studied the resolved main sequence among blue and red clumps (plotted in figure 4.8) in which each data point is the average of red or blue clump property in a single galaxy. There is a clear bimodality between the red and blue clumps, with red regions having a higher stellar mass surface density compared to blue clumps at a fixed

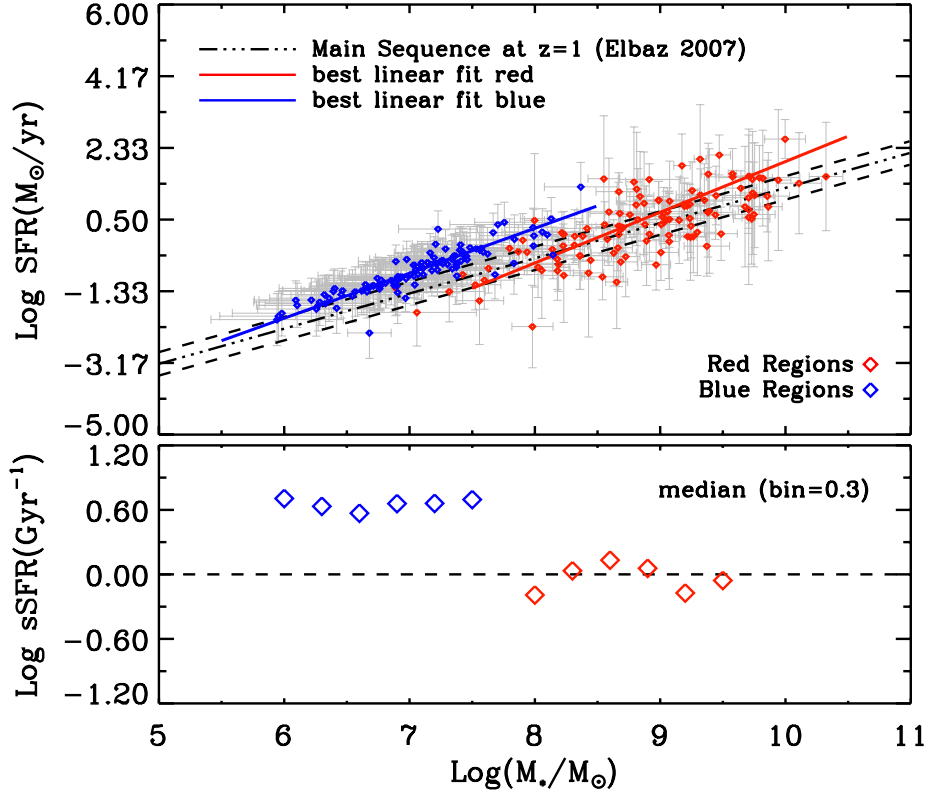


Figure 4.8: The top panel is the median star formation rate as a function of median stellar mass for red (red diamonds) and blue (blue diamonds) clumps in galaxies (1 red and 1 blue point for each galaxy in our sample). Linear fits to blue and red clumps are plotted as solid lines. The dashed-dotted lines represent the extrapolation of the main sequence at $z \sim 1$ (Elbaz et al., 2007) (best fit and 1σ). In the bottom panel the median sSFR in blue and red regions are plotted in stellar mass bins of 0.3 dex.

star formation rate. The blue clumps form a tight relation with a scatter of ~ 0.2 dex which is three times less than that seen in the red regions (~ 0.6 dex). This agrees with the spread in the SFR for red regions shown in the previous chapter. The best linear fit to the blue and red clumps, shown with solid lines, have slopes of 1.1 ± 0.1 and 1.3 ± 0.1 respectively. This is steeper compared to the relation seen for integrated main-sequence galaxies (Elbaz et al., 2007) extrapolated to lower stellar masses. However, this is consistent with a recent work by Whitaker et al. (2014), studying lower mass systems ($\log(M_*/M_{sun}) < 10$) and finding a slope of ~ 1.0 roughly constant over the redshift range $0.5 < z < 2.5$. I also show the relation between the sSFR and median stellar mass, where blue clumps have higher sSFR compared to red regions, a trend which does not appear to depend on median stellar mass of the region in this projection, however this changes as I account for stellar mass of the sample as a function of redshift.

The specific star formation rate is known to evolve over intermediate to low redshifts with both redshift and stellar mass of the galaxies (e.g. Feulner et al. (2005)). In figure 4.9, I present a 3D plot of the sSFR vs. redshift vs. stellar mass surface density for individual resolution elements belonging to red (left) or blue (right) clumps. The sSFR of red regions decreases as the stellar mass increases for all redshifts. The same overall trend can be seen among resolution elements in blue clumps. Binning by stellar mass, I fit a function of the form $sSFR \propto (1+z)^b$ to the sSFR per resolution element in red and blue regions. This is plotted in Figure 4.10 where I find an increase in the b value with increasing stellar mass. It is known that at any given redshift, the mean sSFR is smaller for high mass galaxies (Damen et al., 2009). In the context of “downsizing” more massive galaxies formed their stars before less massive systems (Cowie et al., 1996). The trend that I see here for substructures in galaxies is very similar with bluer less massive clumps having higher sSFRs compared to red regions. This implies that the more massive regions have assembled more of their mass at earlier times.

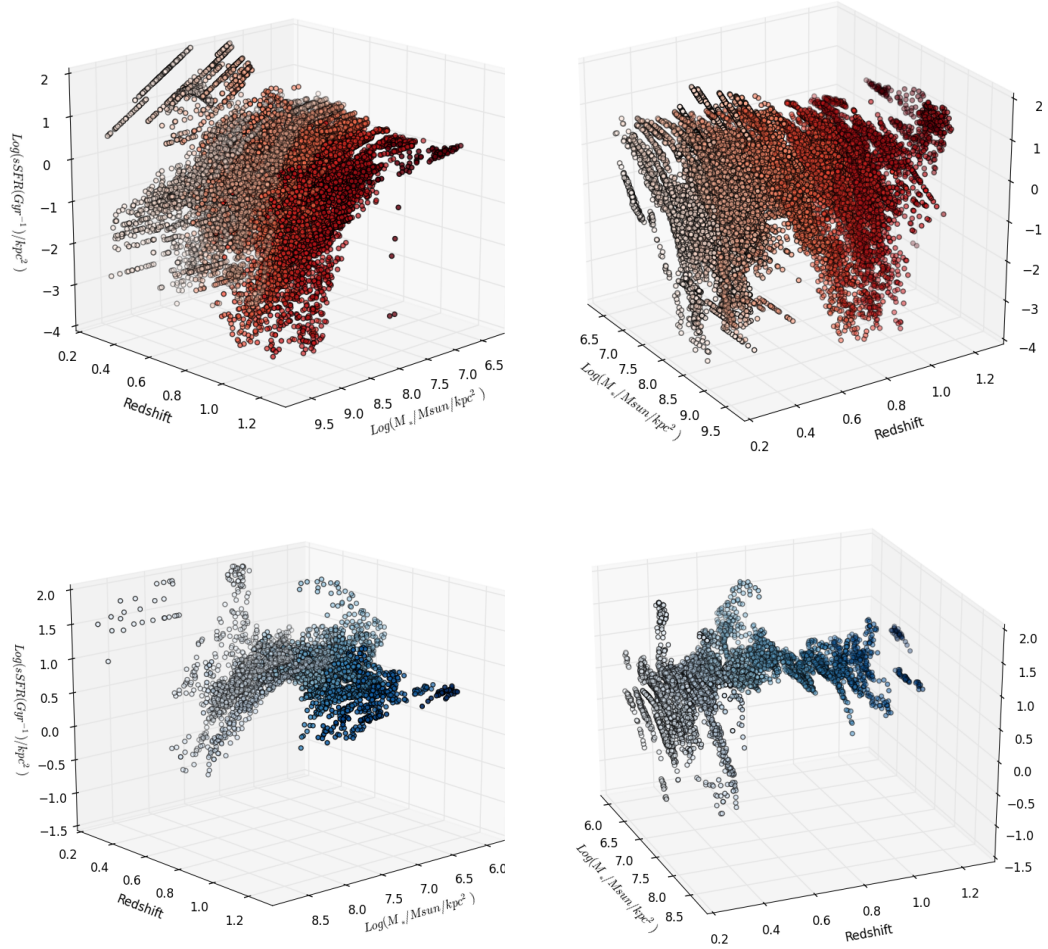


Figure 4.9: sSFR plotted as a function of stellar mass and redshift for resolution elements associated with red(top) and blue(bottom) regions at two different projections (right/left). Each point is color coded based on redshift.

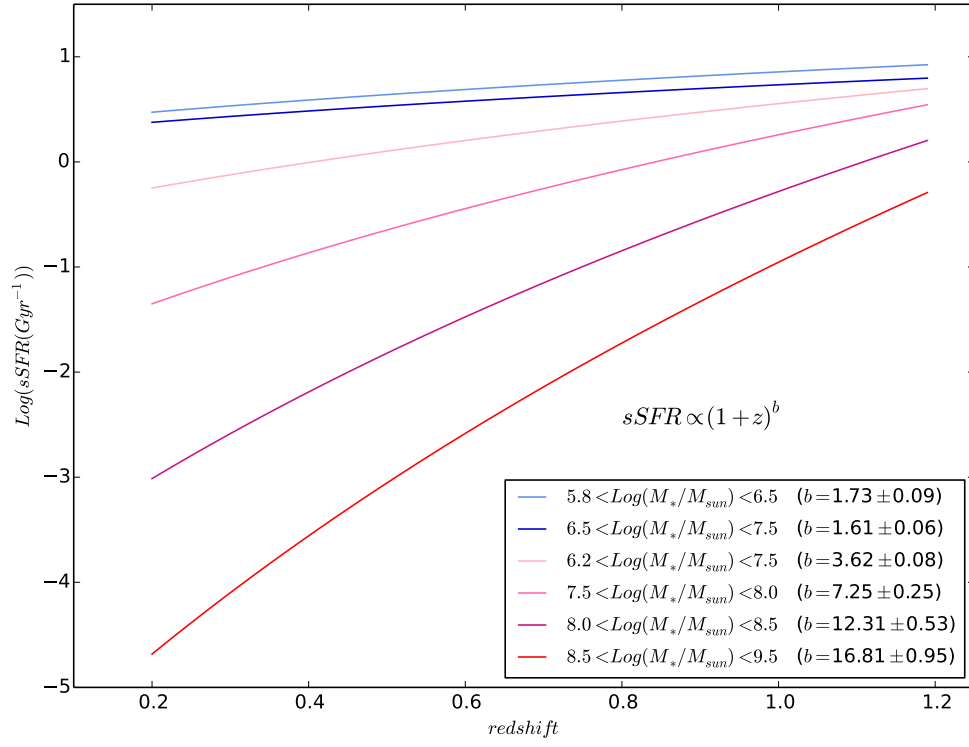


Figure 4.10: Redshift evolution of specific SFR: red and blue lines represent the best fit to the resolution elements in red and blue regions binned by stellar mass surface density, respectively.

4.4 The Effect of Sample Selection

Most galaxy evolution studies divide galaxies into different classes based on various selection criteria, for instance the Lyman Break Galaxies (LBGs), the Dust Obscured Galaxies (DOGs), the Luminous IR Galaxies (LIRGs), emission line galaxies and so forth. While these classifications help in simplifying the big picture to some extent, the overlaps between different groups as well as small differences in selection of the same population adapted in different studies (for instance many different criteria for selecting star forming galaxies) can cause huge problems in interpreting the results.

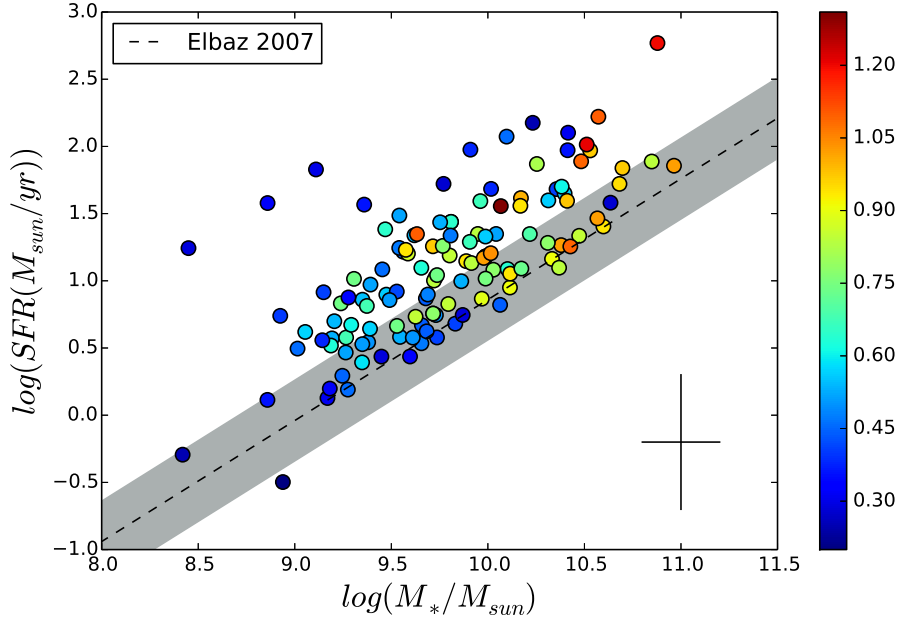


Figure 4.11: Main sequence of star formation for galaxies in the original sample color-coded by redshift. Dashed black line and grey shaded region are from Elbaz et al. (2007) for the main sequence at $z = 0.7$ and its 1σ uncertainty.

In previous sections I studied the resolved main sequence over resolution elements in individual galaxies as well as over clumps in a sample described in detail in Chapter 2 of this thesis. Figure 4.11 shows the position of galaxies in this sample on the “global” SFR vs. stellar mass plain compared to a main sequence at $z \sim 1$ from Elbaz et al. (2007). A larger spread

compared to this previous study is both a result of a different selection as well as a larger redshift range covered among galaxies in the sample. This sample was selected to have extended emission-lines and visual disk morphologies.

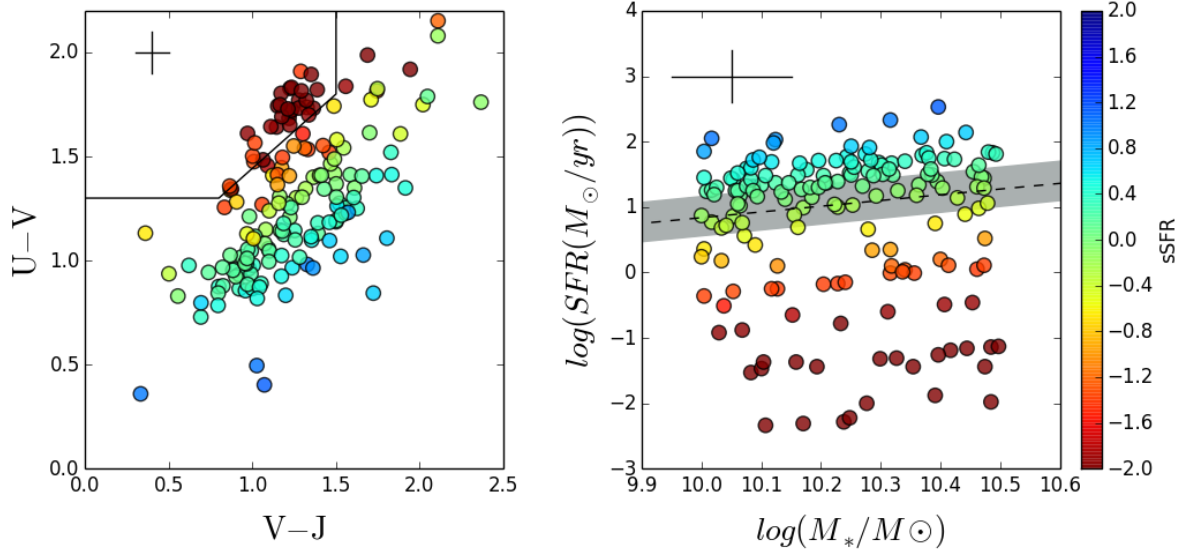


Figure 4.12: The UVJ and main sequence plots for a sample of galaxies in the GOODS-S field at $z \sim 1$ and $\log(M_{*}/M_{\odot}) \sim 10 - 10.5$. Dashed black line and shaded grey region shows the extrapolation of Elbaz et al. 2007 main sequence and 1σ uncertainty.

However, to uncover the evolution of galaxies in terms of stellar mass build up and star formation, one should select galaxies spanning the whole SFR-stellar mass plain rather than focusing on the star forming galaxies or the strong emission-line galaxies. These kind of studies are now possible thanks to large surveys such as CANDELS. In practice, in making the resolved kpc-scale maps of galaxies (described in Chapter 2) no selection criteria is necessary other than coverage in optical and NIR at high spatial resolution. Spectroscopic redshifts reduce the uncertainties in the fitting process and fortunately at low redshifts there is not a large bias in the spectroscopic samples towards the most luminous star forming systems (as is the case at high redshifts). We have an ongoing project to study the resolved main sequence of star formation for galaxies with different mass ranges to $z \sim 3$ over all five CANDELS fields. In this thesis, however, I only explore this by focusing on massive galaxies at $z \sim 1$ in the GOODS-S field without any further selection criteria based on star formation or color. Figure 4.12 represents

this subsample on a UVJ color-color plot (left) and a SFR-stellar mass plot (right) color-coded based on sSFR. The UVJ color selection is one of the methods used most frequently to divide galaxies into star forming and passive systems (e.g. Williams et al. 2009, Brammer et al. 2011). I fit the SED at each resolution element of these galaxies which span more than four orders of magnitude in SFR, and identify the blue clumps as well as the central bulges with the same techniques described in previous chapters.

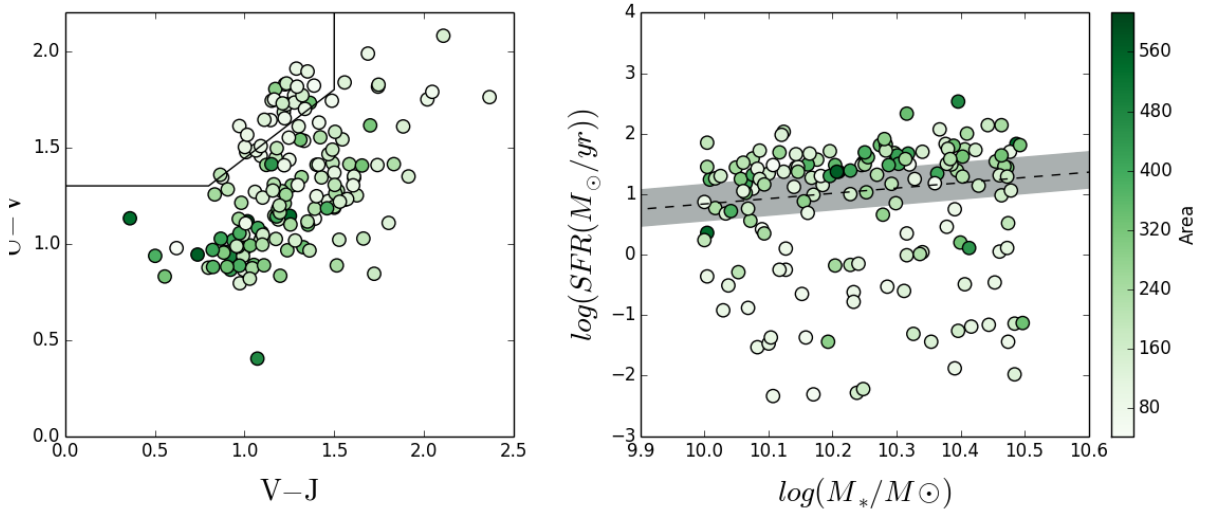


Figure 4.13: The UVJ and main sequence plots for a sample of galaxies in the GOODS-S field at $z \sim 1$ and $\log(M_*/M_\odot) \sim 10 - 10.5$, color-coded based on the area of galaxies in kpc^2

In figure 4.13, I plot again the UVJ and SFR-Stellar Mass plots but this time color coded as a function of area of the galaxy. This figure shows that while smaller galaxies ($< 300 \text{kpc}^2$) can be found over a wide range of properties from star forming to passive, most of the large galaxies are more likely classified as star forming than passive, meaning on or above the main sequence of star formation and in the star forming part of the UVJ plot. I also study the covering fraction of blue clumps and bulges as a function of where they reside in the SFR-Stellar mass plane (figures 4.14 and 4.15). Covering fraction of blue clumps in galaxies does not correlate with its position relative to the main sequence or UVJ diagram and so does the covering fraction of bulges. However, we find that galaxies with very small contribution from the bulge (less than $\sim 5\%$ of the area) will be more likely to be selected as star forming than passive, meaning on

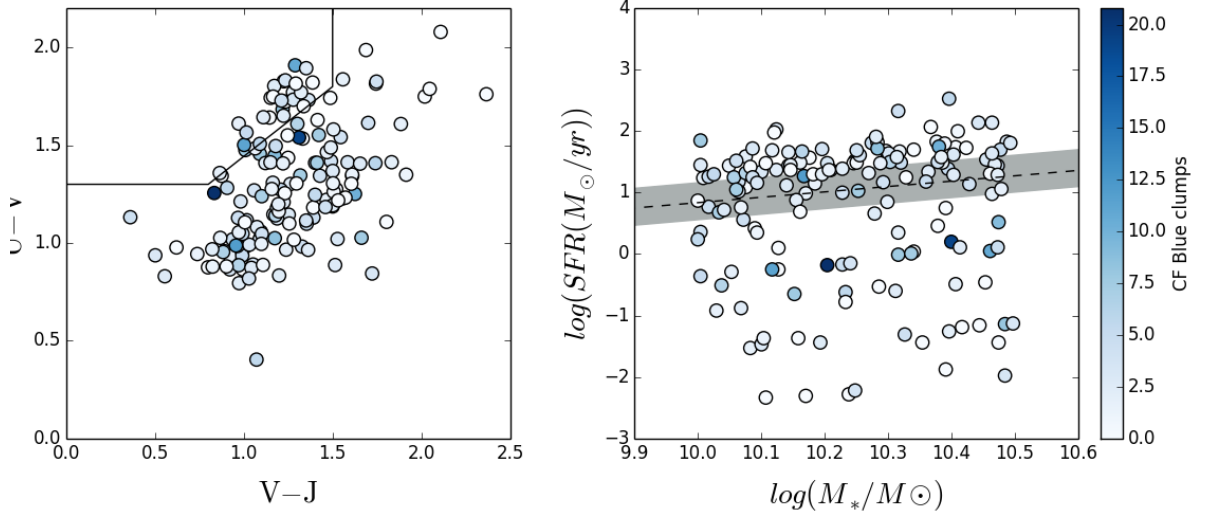


Figure 4.14: The UVJ and main sequence plots for a sample of galaxies in the GOODS-S field at $z \sim 1$ and $\log(M_{*}/M_{\odot}) \sim 10 - 10.5$, color coded based on the Covering fraction of Blue clumps.

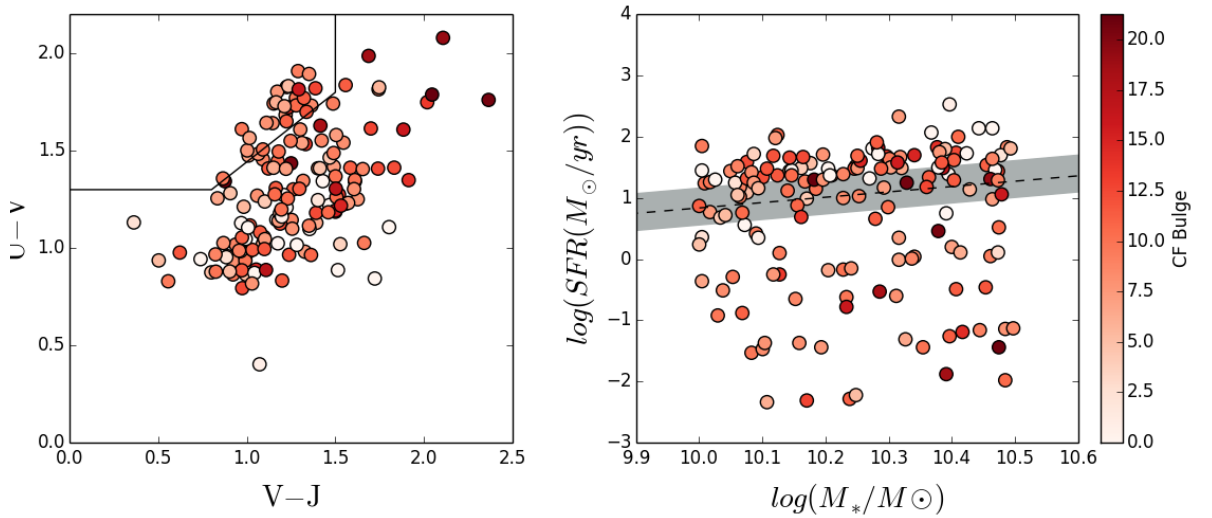


Figure 4.15: The UVJ and main sequence plots for a sample of galaxies in the GOODS-S field at $z \sim 1$ and $\log(M_{*}/M_{\odot}) \sim 10 - 10.5$, color coded based on covering fraction of central bulges.

or above the main sequence of star formation and in the star forming part of the UVJ diagram. This work will be extended to other redshifts and stellar masses to study evolution with as less bias as possible.

4.5 Discussion and Summary

While the relation between the global star formation rate and stellar mass of galaxies is studied extensively, the exact physics behind the evolution of the relation with redshift and the scatter around the relation is not yet fully understood. In this chapter I studied the relation between star formation rate and stellar mass surface density at resolution elements inside individual galaxies as well as among clumps in the larger sample of galaxies.

Since both star formation rate and stellar masses are measured through the SED fitting process and are therefore dependent on one another, a smaller scatter is found as expected compared to studies that use other star formation diagnostics such as $H\alpha$ or IR luminosities. We found very interesting trends in individual galaxies, which can explain parts of the scatter around the global main sequence relation. That is, even though the galaxies are selected through emission-line strengths and therefore would be selected as star forming in similar studies, the resolved maps reveal features such as double nuclei, a very blue center (AGN in this case) or a quenched center which will have different star formation rate- stellar mass surface density gradients and scatter as shown in this chapter.

The very tight relation between the blue clumps regardless of the redshift of the galaxies is fundamental in understanding the physics of the global main sequence evolution with redshift. If the evolution is caused due to a higher efficiency of converting gas into stars then the same would have been seen inside blue clumps. On the other hand if the evolution is due to change in the amount of gas and therefore overall disk morphology and clumpiness then we would not expect to see this evolution inside individual clumps.

In this chapter, I demonstrate the importance of sample selection specifically in investigating the main sequence relation slope and scatter. I used a larger sample of galaxies from the

CANDELS at specific stellar mass and redshift without any further selection criteria on the morphology or star formation and constructed the maps and the main sequence for these galaxies. I plan to extend this study to higher redshifts and other stellar masses to study galaxies closer to the peak of the cosmic star formation density.

Chapter 5

Resolved Emission-line Ratios Along the Disk of Galaxies

5.1 Introduction

High spatial resolution observations of galaxies in the local Universe enabled the derivation of well calibrated relations among the physical properties of galaxies (such as stellar mass, dust mass, SFR, gas phase metallicity, etc.) at $z \sim 0$ (e.g. Calzetti et al. 2000, Kennicutt et al. 2007, Kreckel et al. 2013, Boquien et al. 2011). However until recently, at intermediate and high redshifts, studies of resolved (kpc-scale) properties of galaxies was not possible. High resolution multi-waveband surveys using the Hubble Space Telescope such as Cosmic Assembly Near-infrared Deep Legacy Survey (CANDELS; Grogin et al. 2011, Koekemoer et al. 2011) have enabled such studies through optical and near-infrared photometric observations out to ($z \sim 2$) (e.g. Wuyts et al. 2012, Hemmati et al. 2014, Guo et al. 2015). In these studies, resolved physical properties of galaxies were assessed by fitting the observed Spectral Energy Distribution (SED) at each pixel to the theoretical stellar synthesis models. Therefore the uncertainties inherent to SED fitting will be inevitable using only photometric data. Spectroscopic data from grism observations by surveys such as 3D-HST have improved measurements of resolved physical properties (such as SFR surface densities). Wuyts et al. (2013) using a sample

of massive CANDELS and 3D-HST galaxies at $z \sim 1$ showed that for the integrated $H\alpha$ SFR to agree with the SED inferred SFR an extra amount of attenuation is needed for nebular gas. One caveat to such studies is however the poor spectral resolution of grism observations, which can not resolve the NII and $H\alpha$ emission lines. The advent of Adaptive Optics (AO) aided Integral Field Spectrographs (IFS), enabled spatially resolved spectroscopic observations of intermediate redshift galaxies (e.g. Förster Schreiber et al. 2009, Genzel et al. 2010). However, obtaining statistical sample of galaxies with AO aided IFS is expensive in terms of observing time.

In this Chapter, I combine photometric data from CANDELS with spectroscopic data from Keck/DEIMOS observations in §5.2. In §5.3, I study dust distribution in a subsample of emission-line galaxies. I demonstrate the usefulness of the technique on a small sample and will expand this to a larger sample of emission-line galaxies in future works. I also briefly investigate the resolved BPT diagram in small scales in galaxies §5.4. A conclusion and summary of this chapter is presented in §5.5.

5.2 Methodology

5.2.1 Photometric Measurements

Using the photometric data, I have made 2D maps of physical parameters of galaxies (such as stellar mass and star formation rate surface density, age and extinction) in the sample by measuring the observed SED for individual pixels and fitting them to template SEDs. The method and the uncertainties in the estimated parameters are discussed in detail in Chapter 2 of this thesis. Here I briefly explain the method for producing 2D maps. I then use the 2D maps to produce 1D profiles along the disk of the galaxy. These profiles will then be used to directly combine/compare with spectroscopic data from DEIMOS.

I first make 80×80 pixel cutouts of galaxies in seven bands HST science and rms error images. I PSF-match them to the resolution of the H_{F160W} band. By multiplying the segmentation maps from SExtractor (Bertin & Arnouts 1996) to the psf-matched cutouts I define the boundary of galaxy and remove any surrounding object. Using the LePhare code (Arnouts et al. 1999;

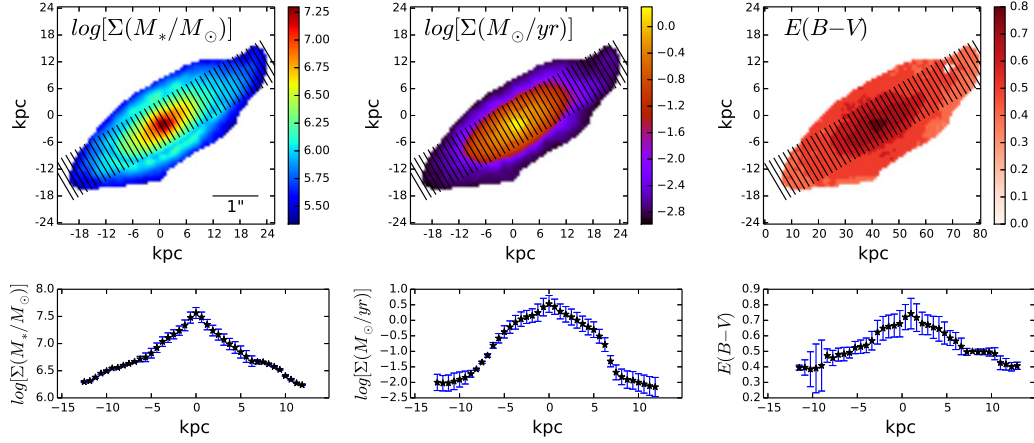


Figure 5.1: An example of deriving the photometric properties of a galaxy to be comparable to its spectroscopic properties. 2D maps from pixel-by-pixel SED fitting are on the first and 1D profiles along the major axis of the galaxy on the second row. Left to right, stellar mass surface density, SFR surface density and $E(B-V)_{star}$ distribution of an example galaxy. The black solid lines on top of 2D maps, represent the coverage and spatial resolution of DEIMOS observation on this galaxy.

Ilbert et al. 2006), I then fit the SED of each pixel with spectral synthesis models to obtain the physical properties at that pixel (redshift is fixed to the spectroscopic redshift of the galaxy).

The model library is built using BC03 (Bruzual & Charlot 2003) models, Chabrier (Chabrier 2003) Initial Mass Function (IMF), solar metallicity, declining star formation histories with a range of τ (including constant and bursts) and ages less than the age of the Universe at the redshift of the galaxy in question. I use the Calzetti starburst (Calzetti et al. 2000) attenuation curve with a range of $E(B-V)$ from zero to one. I also include nebular emission lines in the fitting procedure. LePhare code accounts for the contribution of emission lines with a simple recipe based on the Kennicutt relations (Kennicutt 1998). The following lines are included in this treatment: $\text{Ly}\alpha$, $\text{H}\alpha$, $\text{H}\beta$, $[\text{OII}]$, $\text{OIII}[4959]$ and $\text{OIII}[5007]$ with different ratio with respect to $[\text{OII}]$ line as described in Ilbert et al. 2008. The intensity of the lines will be scaled according to the intrinsic UV luminosity of the galaxy. The 2D maps of physical parameters from the SED fitting output correspond to the median of the probability distribution function marginalized over all other parameters. I use 16% lower and 16% higher values from the

Maximum Likelihood analysis to measure the 1σ error for each parameter. Using the same library and code, I also measure integrated properties of galaxies by fitting the integrated light of all the pixels in the defined boundary of the galaxy in the same seven ACS and WFC3 bands.

To be able to compare these measurements with their spectroscopic counterparts from Keck/DEIMOS, I need to convert 2D maps to 1D profiles. I combine measurements of all pixels which correspond to one spatial resolution in the DEIMOS spectra. In making the profiles, I only include pixels that are covered by the DEIMOS slit. This is to avoid uncertain slit loss corrections in the spectral measurements. Therefore in the direction perpendicular to major axis of the galaxy I bin all pixels in the slit and bin again in the direction of major axis of the galaxy to match the spatial pixel scale of DEIMOS (0.12" per pixel). Figure 5.1 shows the 2D maps and 1D profile of stellar mass, SFR and E(B-V) for one of the galaxies in the sample.

5.2.2 Spectral Measurements

I measure diagnostic nebular line ratios along the disk of the galaxies using the ratio of emission lines, these measurements will be used to measure the amount of nebular dust attenuation along the disk as well as constructing the BPT diagram and the resolved stellar mass surface density-gas phase metallicity relation. Here, I describe in detail the methodology to measure the resolved nebular dust attenuation, however the same methodology is applied in other line measurements as well.

The nebular dust attenuation is measured from the ratio of first two Balmer transitions ($H\alpha$ and $H\beta$) or the so-called Balmer decrement. Ratio of the luminosities of Balmer transitions arising from HII regions around very massive stars is known to be the most practical indicator measuring attenuation by dust in these regions. In the absence of dust, the intrinsic theoretical $H\alpha$ to $H\beta$ line ratio, assuming Case B recombination, a temperature of $T = 10^4 K$, and an electron density of $n_e = 10^2 cm^{-3}$ is known ($F(H\alpha)/F(H\beta) = 2.86$; Osterbrock 1989). Any deviation from this amount is indicative of the amount of dust attenuation. I model the line emission at each spatial resolution element of continuum subtracted DEIMOS spectra. I convert the $H\alpha$ to $H\beta$ line ratio at each spatial resolution to an extinction measure using:

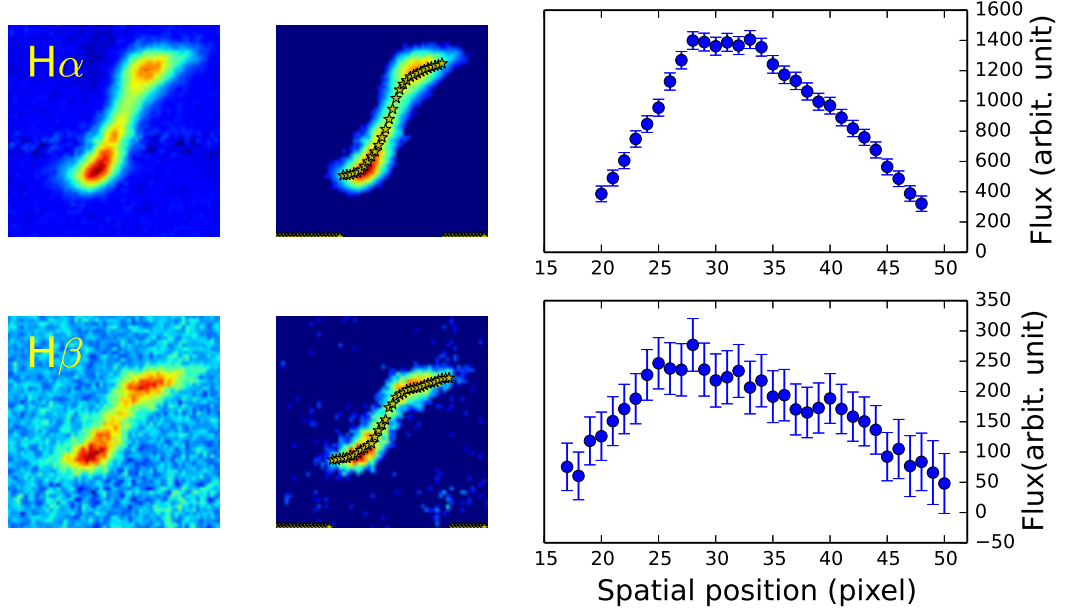


Figure 5.2: Left to right, emission line cutout, thresholded emission and total flux as a function of spatial position for $H\alpha$ (top) and $H\beta$ (bottom) of an example galaxy. Yellow star symbols over plotted on thresholded emission show peaks of Gaussians at each spatial position.

$$E(B - V)_{gas} = \frac{-2.5}{k(H\beta) - k(H\alpha)} \log_{10} \left(\frac{2.86}{H\alpha/H\beta} \right) \quad (5.1)$$

I use the Cardelli Galactic extinction curve (Cardelli et al. 1989) for measuring $k(H\beta)$ and $k(H\alpha)$. A line-of-sight attenuation curve such as Cardelli, is more appropriate for recombination emission of compact HII regions compared to more extended stellar continuum attenuation curves such as Calzetti et al. (2000). The latter would cause smaller $E(B - V)_{gas}$ values by a factor of 0.9 (see Reddy et al. 2015 for a more detailed discussion).

I model and subtract the continuum by first making cutouts of $\sim 100\text{\AA}$ around the emission line ($H\alpha$ or $H\beta$ in this case). I mask the wavelength range ($\sim 15 - 20\text{\AA}$) where I have the emission in the cutout and bin the rest of the spectra in the wavelength direction with bins of $\sim 5\text{\AA}$. The median values in each wavelength bin are then fitted with a Gaussian function in the spatial direction. I measure the continuum under emission by interpolating these values over

the masked wavelength range and subtract this continuum from the cutout spectra to have the continuum free emission line.

To model the line emission at each spatial resolution in the galaxy, I make small cutouts covering only the emission from the continuum subtracted spectra. To be able to trace the emission to furthest points from the center and to avoid tracing and fitting the noise in the background, I use the Otsu method (Otsu 1979). Otsu method is an unsupervised automatic thresholding algorithm, which reduces a gray level image to a binary image by finding an optimum threshold to maximize the separability of the two classes. Here, using this method I separate the emission from the noise in the background, by multiplying the binary image to the continuum subtracted cutout. I fitted Gaussian functions to the emission at each spatial resolution (in the wavelength/velocity direction) to measure the total flux from that spatial resolution. In figure 5.2 I show cutouts of $H\alpha$ and $H\beta$, as well as the thresholded cutout and traced emission for one example galaxy. I have centered emission lines by the spectroscopic redshift, which comes from visually aligning all the emissions lines, however in order to measure the ratio of two lines I need to be more precise in centering the emissions. I center each emission line by fitting the peak of modeled Gaussians with an arctangent function (in the spatial direction). I measure the Balmer decrement along the major axis of galaxies by setting a minimum signal-to-noise ratio (S/N) of 5 and 3 at each spatial resolution for $H\alpha$ and $H\beta$ lines respectively and then dividing the two. Nebular color excess $(E(B - V))_{gas}$ along the disk is then calculated by the conversion in equation 5.1. The uncertainty in this ratio is calculated by the standard error propagation method using the $H\alpha$ and $H\beta$ flux uncertainties at each spatial position. Extinction uncertainties range from 0.03-0.2 magnitude and its variation is larger between galaxies compared to that of one single galaxy.

I also measure the integrated or “global” Balmer decrement and nebular color excess values for the whole galaxy by extracting the 1D spectra and measuring line fluxes. I correct our measurements for the underlying Balmer absorption using the stellar population model fits. The corrections to the $H\alpha$ to $H\beta$ ratio are $\lesssim 4\%$. In the resolved line measurement, I did not correct for the Balmer absorption because the corrections are very small and well within the

uncertainty of the line measurements. As the sample size is small, the global properties will be used to study where the sample galaxies sit compared to larger samples of galaxies. For simplicity, I refer to our dust measurements at each spatial distance from the center as resolved dust measurement.

5.3 Resolved Nebular and Stellar Dust Attenuation

The existence of interstellar dust was suggested about a century ago, even before the great debate about the nature of galaxies (Curtis 1918). The presence of dust in galaxies was later established firmly not only from dimming and reddening of light but also from dust scattering and Far Infrared (FIR) continuum emission. Dust absorbs more than half of the Ultra Violet (UV) and optical radiation budget of the Universe (e.g. Calzetti 2001). Most of the radiation from the star formation in galaxies is emitted in the UV and optical, the wavelength range most susceptible to dust extinction and where most of the observations are taken. Therefore, without a thorough understanding of the attenuation of light of galaxies (coming from both stars and nebulae) by dust, interpretation of their physical properties (e.g. star formation rate, stellar age and stellar mass to light ratio) will not be accurate.

A lot of progress has been made in our understanding of the attenuation of light by dust. It is now well established that the amount of extinction in galaxies is wavelength dependent. Variation of dust extinction as a function of wavelength, or the so called extinction curve, is studied from observations of nearby galaxies and the Milky Way (e.g. Prevot et al. 1984, Cardelli et al. 1989, Calzetti et al. 1994, Gordon et al. 2003). In the extinction curve there is information about chemical composition and sizes of dust grains. The smoothness of the FIR part of the extinction curve suggests that a variety of grain sizes exist. While the overall shape of the extinction curves measured from these local galaxies agrees, especially towards the infrared, there are some differences in the slopes, the normalizations, and the presence of the 2175 Å bump (e.g. Stecher 1965, Calzetti 2001, Reddy et al. 2015, Scoville et al. 2015). These differences are attributed to different metallicities and dust-to-gas ratios as well as differences

in the composition of the dust grains (e.g. Calzetti et al. 1994, Reddy et al. 2015).

Local extinction and attenuation curves are often used to correct for dust attenuation at intermediate and high redshifts. Recently, study of dust attenuation at higher redshifts has become accessible by infrared surveys. Studies at $z \sim 1 - 2$ (e.g. Scoville et al. 2015, Reddy et al. 2015) have found attenuation curves very similar to the usually assumed Calzetti et al. (2000) attenuation curve derived from nearby galaxies. However, other studies reported poor fits from nearby curves to high redshift galaxies and found strong spectral dependence in the attenuation curve in their sample (e.g. Kriek & Conroy 2013), suggesting different star-dust geometry, dust grain properties or both.

Comparison of attenuation towards nebular star forming regions inside galaxies with that of the stellar continuum hints about the geometry of dust relative to stars. Local studies have found higher attenuation towards the nebular regions compared to the integrated dust from stellar continuum (e.g. Calzetti et al. 2000, Wild et al. 2011). This is consistent with the picture from radiative transfer model by Charlot & Fall (2000) in which recombination lines generated in the HII regions, the birth clouds of most massive O stars, face an extra amount of attenuation by dust. However, at higher redshifts the picture is not as clear. By comparing star formation rates from different diagnostics, some studies (e.g. Erb et al. 2006; Reddy et al. 2010; Shivaee et al. 2015) found that the best agreement between the SFRs is met with no extra color excess towards the nebular regions. Other studies have found quite the opposite, with higher attenuation needed towards the nebular regions (e.g. Förster Schreiber et al. 2009; Wuyts et al. 2011; Price et al. 2014). Using a large sample of emission line galaxies from MOSDEF survey (Kriek et al. 2015), Reddy et al. (2015) demonstrated that the ratio of nebular to stellar attenuation is a function of the star formation and specific star formation rates of galaxies. However, there is a huge scatter in the relation. A detailed analysis of spatially resolved colors is needed to understand the source of this scatter.

The amount of nebular attenuation by dust is also shown to correlate with galaxies physical properties, such as luminosity, Star Formation Rate (SFR), Mass and Metallicity (e.g. Wang & Heckman 1996, Sullivan et al. 2001, Pannella et al. 2009, Asari et al. 2007). Garn & Best

(2010) investigated these different dependencies and found mass to be the best parameter predicting the amount of dust extinction for $z \sim 0.1$ galaxies from the Sloan Digital Sky Survey, Data Release 7 (SDSS DR7; Abazajian et al. 2009). This result was later confirmed by studies at high redshift (e.g. Sobral et al. 2012, Domínguez et al. 2013). It is however not clear whether these relations hold at smaller scales inside galaxies.

In this section, I combine photometric data from CANDELS with spectroscopic data from Keck/DEIMOS observations to study dust distribution in a sample of emission-line galaxies. I measure the stellar continuum and ionized gas dust extinction along the major axis of disk galaxies. Stellar Continuum and the ionized gas extinctions are measured from resolved SED-fitting per pixel (Hemmati et al. 2014) and the Balmer decrements from Keck/DEIMOS spectra, respectively. I investigate how integrated dust measurements in galaxies compare to the spatial variation of dust along the disks. I also study the ratio of nebular to stellar color excess as a function of radial distance from center of galaxies.

5.3.1 Sample

The sample for this section consists of eight disk galaxies at $z \sim 0.4$ with median stellar mass of $\log(M_*/M_\odot) = 9.6$ and median SFR of $SFR(M_\odot/\text{yr}) = 10.0$. These galaxies are selected from a parent sample described in detail in Bundy et al. (2005) and Miller et al. (2011) as well as chapter 2 of this thesis. Here, I present the selection criteria for this sample.

Galaxies in the parent sample were initially adapted from a $Z_{F850LP} < 22.5$ sample in the Great Observatories Origins Deep Survey (GOODS) North and South fields (Giavalisco et al. 2004) in the redshift (spectroscopic when available) range of $0.2 < z < 1.3$ and were visually inspected to have prominent disks. A further magnitude cut of $K_s < 22.2$ was applied to ensure reliable stellar mass measurements. I have then observed these galaxies with the DEIMOS (Faber et al. 2003) instrument on KECK with long (~ 6 -8 hours) exposures. The 1200 lmm^{-1} grating and $1''$ slits with a central wavelength of $7500 \text{ \AA}$ is used, achieving FWHM spectral resolution of $\sim 1.7 \text{ \AA}$. Out of the galaxies with extended line emission, eight which have both $H\alpha$ and $H\beta$ covered in their DEIMOS spectra are selected for this study. The PA of slits are

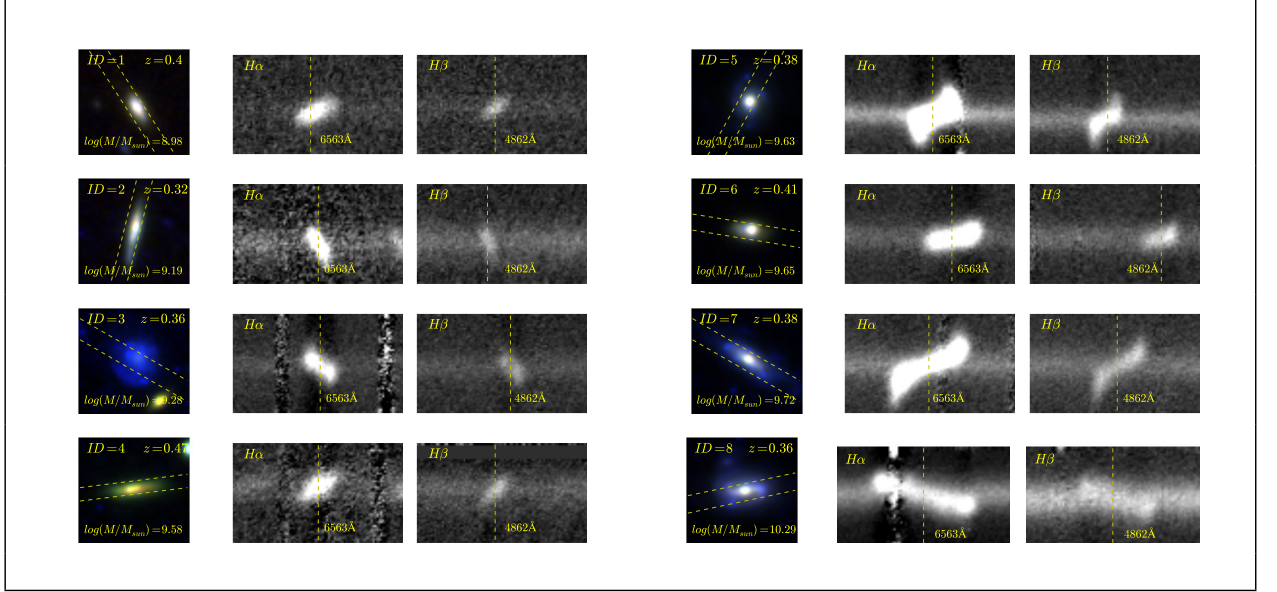


Figure 5.3: HST (B_{F435W} , Z_{F850lp} , H_{F160W}) stacked images of galaxies in the sample as well as their $H\alpha$ and $H\beta$ emission line cutouts from the DEIMOS 2D spectra, sorted based on stellar mass. BZH stacked images are 80 pixels in each side (~ 25 kpc at $z \sim 0.4$). Yellow dashed lines on images of galaxies show DEIMOS 1'' slit.

almost aligned with the galaxies major axis. I note that as the spectroscopic data are not flux calibrated, I only use the line ratios in this work. Figure 5.3 shows the stacked HST (B_{F435W} , Z_{F850lp} and H_{F160W}) images as well as cutouts of $H\alpha$ and $H\beta$ emission lines from the DEIMOS 2D spectra of all galaxies in the sample, and table 5.1 summarizes the properties of these galaxies measured through SED fitting and spectral measurements.

Table 5.1: Integrated Properties of Galaxies in the Sample

ID	spectroscopic redshift	$\text{Log}(M_*/M_\odot)^1$	$\text{SFR}(M_\odot \text{yr}^{-1})^1$	$E(B-V)_{\text{star}}^1$	$E(B-V)_{\text{gas}}^2$
1	0.40	8.98 ± 0.11	$1.74^{+4.60}_{-1.41}$	0.10	0.13 ± 0.26
2	0.32	9.19 ± 0.12	$1.68^{+5.07}_{-1.43}$	0.15	0.42 ± 0.32
3	0.36	9.28 ± 0.11	$3.31^{+7.69}_{-2.48}$	0.15	0.16 ± 0.27
4	0.47	9.58 ± 0.30	$17.53^{+40.34}_{-13.89}$	0.4	0.53 ± 0.18
5	0.38	9.63 ± 0.22	$13.83^{+16.74}_{-8.45}$	0.4	0.67 ± 0.06
6	0.41	9.65 ± 0.13	$6.36^{+9.13}_{-4.58}$	0.4	0.43 ± 0.13
7	0.38	9.72 ± 0.20	$29.28^{+40.50}_{-18.88}$	0.45	0.54 ± 0.15
8	0.36	10.29 ± 0.10	$21.17^{+12.86}_{-8.47}$	0.5	0.97 ± 0.21

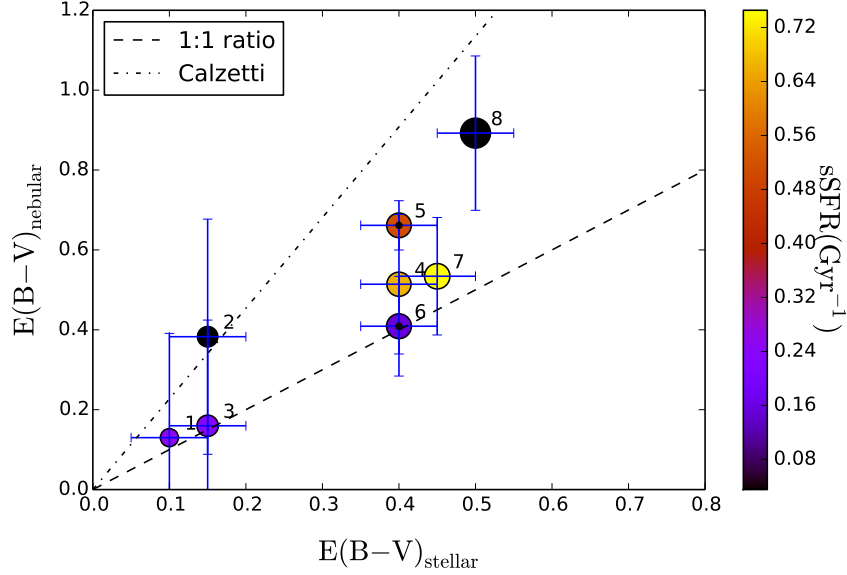


Figure 5.4: Integrated nebular color excess of galaxies in the sample measured through the Balmer decrement compared to their stellar color excess measured through SED fitting. Nebular to stellar color excess ratio of 1 and 2.27 (Calzetti et al. 2000) are shown with dashed and dotted-dashed lines respectively. Galaxies are color coded based on their sSFR and symbol size increases with stellar mass.

5.3.2 Color Excess, Stellar Continuum vs. Ionized Gas

The ratio of the nebular to stellar dust extinction has been studied extensively over the past decade. Studies of local star forming galaxies (e.g. Calzetti et al. 2000; Wild et al. 2011) have found larger attenuation towards the nebular regions compared to the stellar continuum. However, in almost all of these works there is a large scatter in the nebular vs. stellar color excess relation. Some of the recent works (Reddy et al. 2015) have attributed the scatter in this relation, seen in samples of higher redshift star-forming galaxies, to physical properties of galaxies, specifically their stellar mass or sSFR.

In Figure 5.4, I compare the integrated nebular and stellar color excesses of galaxies in our sample. I have color-coded our galaxies based on their sSFR and the symbol sizes increase with stellar mass. All the galaxies sit on or above the 1 : 1 (dashed line) nebular to stellar color

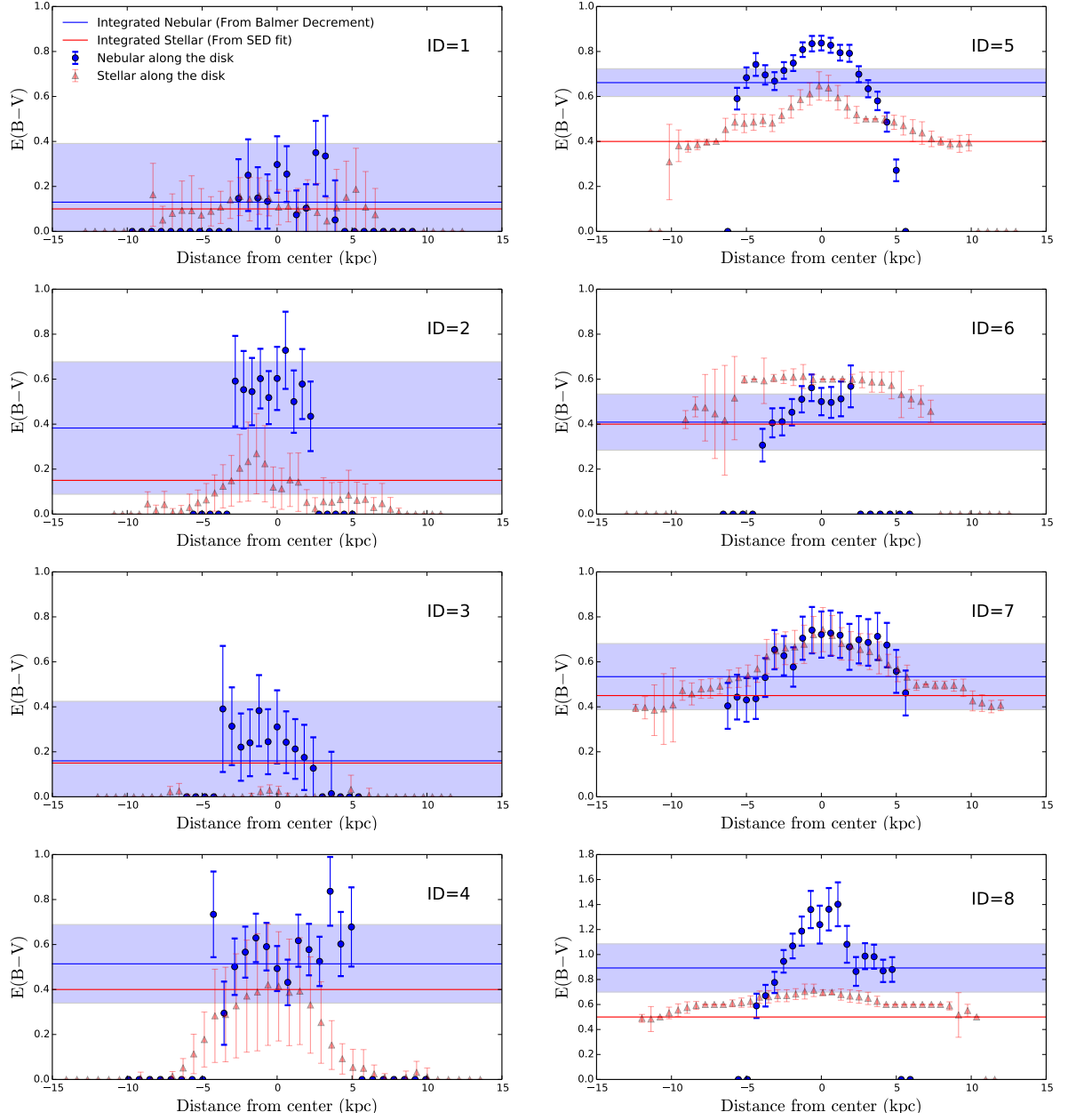


Figure 5.5: Nebular and stellar color excess along the major axis of galaxies in our sample shown with blue circles and red triangles respectively as a function of distance from the center of galaxies. Blue and red Solid lines show the nebular and stellar integrated color excess measured in each galaxy and the blue shaded region is the 1σ uncertainty in the integrated nebular color excess.

excess ratio. While I do not see any clear trend in this ratio with the sSFR or stellar mass, the sample size is too small to draw any strong conclusions.

I now compare resolved stellar and nebular attenuation measures along the disk of galaxies (as explained in the previous section). Plotted in Figure 5.5, are nebular (blue circles) and stellar (red triangles) color excess as a function of distance (in kpc) from the center of the galaxy, as well as the global measurement for each galaxy (solid lines). An agreement is seen amongst the nebular measurements at the resolution elements with the global measured value for that galaxy. The difference between the median of the measured points and the integrated value in each galaxy ranges from zero to maximum of 0.1 magnitude (well within the uncertainty of the integrated value of each galaxy). The small offset towards higher median values, might be due to the S/N criteria which affects the spectra of the outer parts of the disk more than the central parts. The uncertainties in the measured values become considerably smaller in galaxies with larger stellar masses (the right panels). Almost all eight galaxies show higher stellar continuum extinction in the central regions compared to the outer parts in the disk. This differs from the nebular color excess of the lower mass galaxies ($ID = 1 - 4$) which does not significantly vary as a function of their distance from the center. More massive galaxies ($ID = 5 - 8$) however, show higher nebular extinction towards the central parts of the galaxies more similar to the stellar continuum color excesses.

As was shown in Figure 5.4, the nebular to stellar color excess ratio, varies from galaxy to galaxy. Examining $ID = 5$ and $ID = 7$, two galaxies with the most extended emissions, highest S/N ratio, exact same redshift and comparable stellar masses, I find very different ionized to continuum color excess ratio. Between the two galaxies the one with the higher sSFR ($ID = 7$) has smaller color excess ratio, inconsistent with the findings from higher redshifts ($z \sim 1 - 2$) galaxies (e.g. Price et al. 2014, Reddy et al. 2015) and framework depicted by radiative transfer models (e.g. Charlot & Fall 2000).

An important factor that might be playing a role is the difference in the inclination of these two galaxies. The inclination affects observed physical properties of galaxies and in particular their surface brightness (e.g. Holmberg 1958). Many studies used inclination and surface

brightness to measure the amount of extinction in disk galaxies (e.g. Giovanelli et al. 1995, Peletier & Willner 1992), knowing that with the same surface brightness, the more inclined galaxy suffers more from dust extinction. More recent study by Yip et al. (2010), confirmed the result of higher stellar extinction in more inclined galaxies using a large sample of local SDSS disk galaxies. More interestingly, this study showed that the amount of the Balmer decrement stays constant with inclination. If true, this can explain some of the dispersion in the ionized vs. stellar dust extinction studies. In the case of this study, if the more inclined galaxy ($ID = 7$) were face-on, it would have had less stellar continuum color excess and therefore larger ratio of ionized to stellar color excess similar to the other galaxy ($ID = 5$).

I do not, however, find any significant correlation between the nebular to stellar color excess ratio and distance from the center of galaxies except for the most massive galaxy ($ID = 8$) in which this ratio decreases with distance from the center. This is because the resolution of boxes in which the color excess is measured is still a lot larger compared to the sizes of original clouds (sub-kpc) producing the recombination lines. However, future telescopes such as thirty meter telescope (TMT) equipped with integral field unit (IFU) technology and assisted by adaptive optics (AO) systems will be able to provide us with wealth of information on these clouds at these redshifts.

5.3.3 Variation of Color Excess with Stellar Mass Surface Density

The typical dust extinction of a galaxy has been shown to depend upon different properties of the galaxy, most fundamentally on its stellar mass (e.g. Garn & Best 2010, Sobral et al. 2012, Ibar et al. 2013). Here, I investigate the variation of color excess in galaxies as a function of the stellar mass surface density at each resolution element along the major axis of the disks.

Figure 5.6, shows the color excess of the ionized gas as a function of stellar mass surface density for the two galaxies top: $ID = 5$ and bottom: $ID = 7$. The data points are color-coded based on their distance from the center and the typical error bars are shown in the top-left corner of each panel. The stellar mass surface density maps from the resolved SED fitting are shown in the lower right part of each plot and over plotted with dashed black lines are the

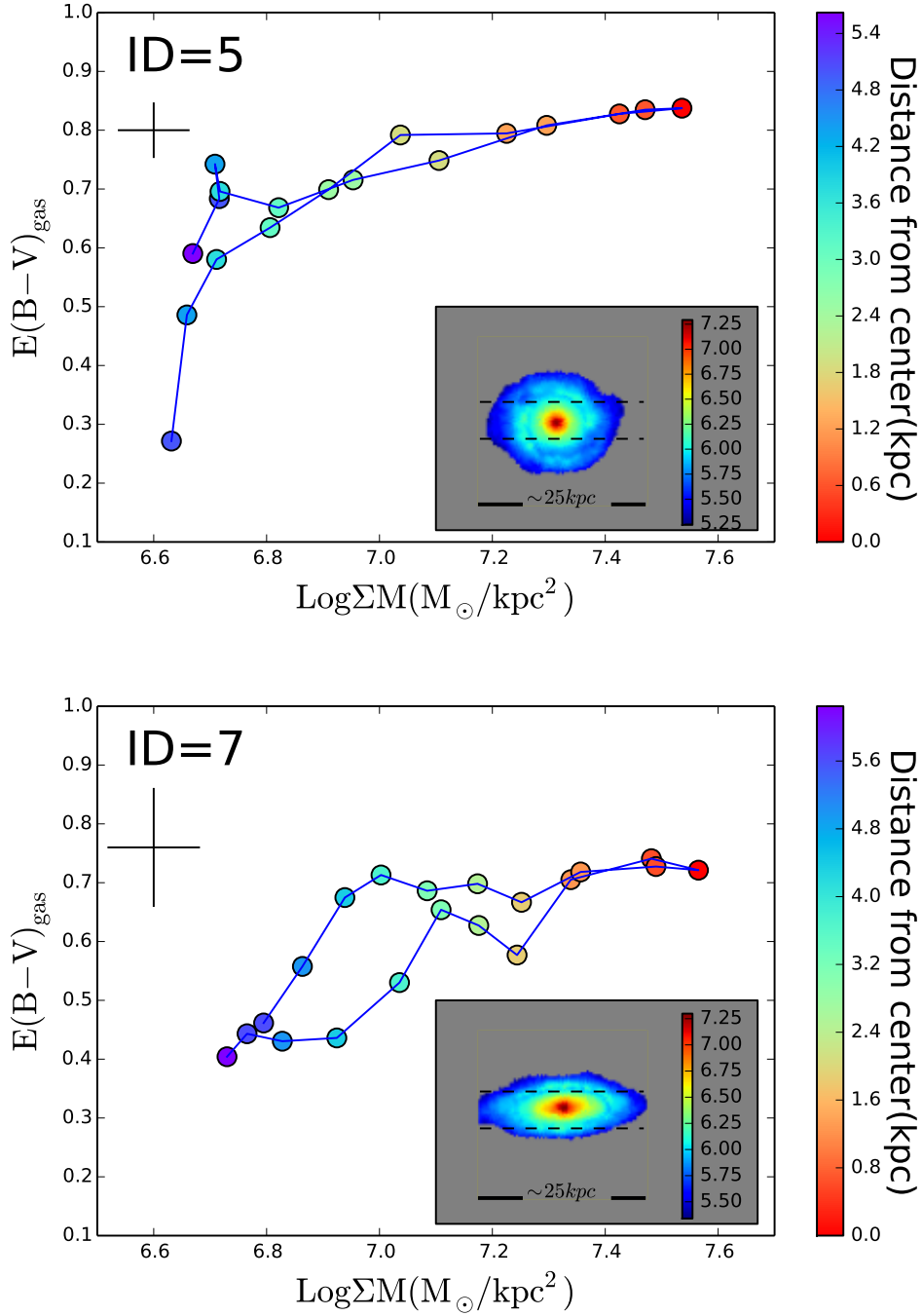


Figure 5.6: Variation of color excess as a function of stellar mass surface density in two of the galaxies. The stellar mass surface density maps are plotted in the corner right of each plot with the DEIMOS slit coverage over plotted. The measurements at each resolution element in the disk are color coded based on their distance from the center. Average uncertainty in measurements is shown in top left of each panel.

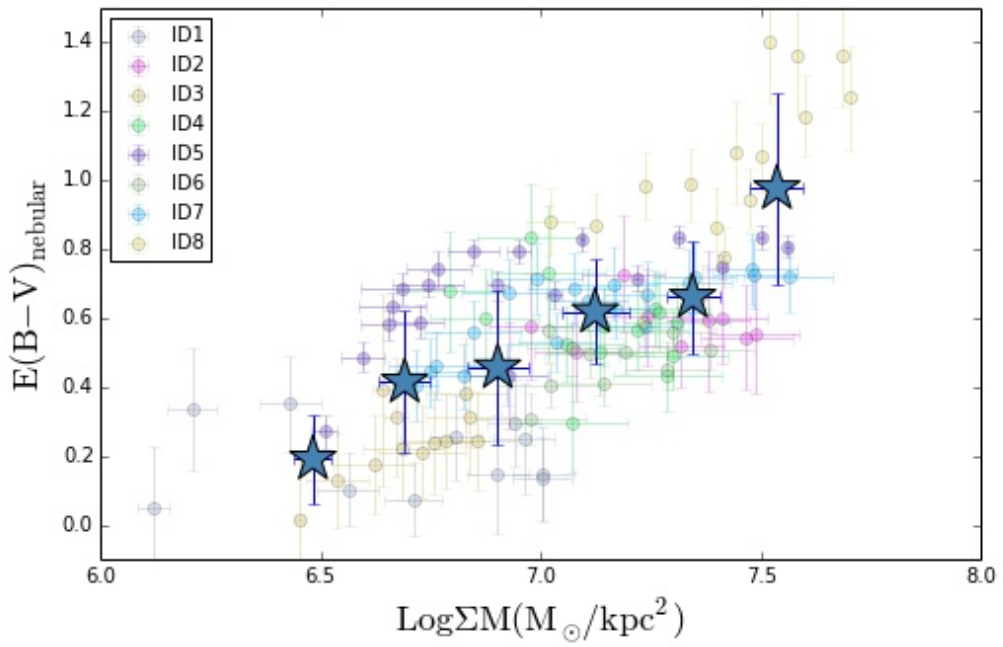


Figure 5.7: Variation of color excess as a function of stellar mass surface density in all resolution elements of the galaxies in the sample. Different colors correspond to different galaxies. There is an overall increasing trend of color excess with increasing stellar mass surface density clear from the median represented with blue stars.

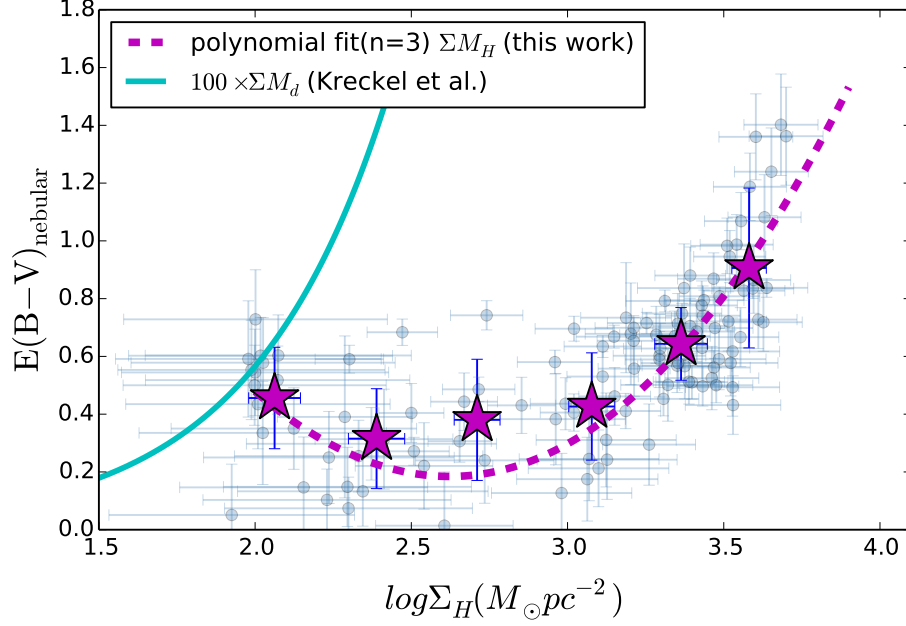


Figure 5.8: Variation of color excess as a function of gas surface density in all resolution elements of the galaxies in the sample. There is an overall increasing trend of color excess with increasing gas surface density. Magenta stars show the median in bins of gas surface density and the magenta dashed line is a third order polynomial fit to the data (blue circles).

DEIMOS slit position and coverage. It is important to note that while the size of the disk's major axis is about 20 kpc in these galaxies, the extent of the emission lines is only about 12 kpc. This can be either due to lack of strong emission at large distances in these galaxies, or due partly to the over subtraction of background in larger radii in the DEIMOS reduction pipeline.

The trend seen in the galaxies in figure 5.6 is very clear with color excess of ionized gas symmetrically increasing from the outer parts of the galaxy towards the bulge, a similar trend as for the stellar mass. This trend in the rest of the sample is not as clear and symmetric. However, putting all the resolution elements of all galaxies in the sample together on the color excess vs. stellar mass surface density plot in figure 5.7, I find the overall increase of the median of color excess in bins of stellar mass surface density.

5.3.4 Dust to Gas Ratio

A tight correlation between the mean surface density of cold gas and the average SFR per unit area (the so-called SFR law) is observed on global scales (e.g. Kennicutt 1998) as well as on resolved kpc-scales (Kennicutt et al. 2007). This relation is parametrized using a power-law introduced by Schmidt (1963). Here, I convert our SFR surface density (Σ_{SFR} ; in units of $M_{\odot}yr^{-1}kpc^{-2}$) measurements to gas surface density (Σ_H ; in units of $M_{\odot}pc^{-2}$), using:

$$\log \Sigma_{SFR} = (1.56 \pm 0.04) \log \Sigma_H - (4.32 \pm 0.09) \quad (5.2)$$

derived by Kennicutt et al. (2007) using observations of the nearby spiral galaxy M51a. Figure 5.8 shows the variation of color excess at resolution elements along the major axis of galaxies in our sample as a function of gas surface density. There is an increasing trend of color excess with gas surface density at ($\log \Sigma_H \gtrsim 2.5$). I formalize this relation by fitting a third order polynomial to $E(B - V)_{nebul\,ar}$ versus $x \equiv \log \Sigma_H$ (shown on Figure 5.8 with magenta dashed line).

$$E(B - V)_{nebul\,ar} = 0.03x^3 + 0.49x^2 - 3.32x + 4.87 \quad (5.3)$$

It is however important to note again that, the sample size is small and I might be missing population of galaxies which might alter this fit. In Figure 5.8, I over plot also the relation of nebular color excess as a function of dust mass surface density (multiplied by a factor of hundred) derived by Kreckel et al. (2013), from resolved FIR (Herschel and Spitzer) and optical integral field observations of a sample of eight nearby disk galaxies. The nebular color excess versus dust mass surface density relation formalized by Kreckel et al. (2013) (solid cyan line in Figure 5.8), is well bracketed by the two extremes of dust geometry discussed in Calzetti et al. (1994) (a uniform foreground dust screen model and a mixed media model), suggesting a combination of the two effects. The shape of the color excess versus dust mass surface density resembles the shape of color excess versus gas surface density (for higher gas surface densities). This implies that the change in the dust to gas ratio is insignificant in regions with different

amounts of extinction for high gas surface density regions in galaxies. Many previous studies have assumed a fixed dust to gas ratio in galaxies (e.g. Leroy et al. 2011, Sandstrom et al. 2013), this result further certifies the fairness of this assumption.

5.4 Resolved BPT Diagram and AGN Classification

Emission lines from extragalactic objects are produced due to different excitation mechanisms, such as photoionization by O and B stars, photoionization by a power-law continuum source, or shock-wave heating. The relative strengths of emission lines therefore offers a very good diagnostic tool to distinguish between these sources. One such diagnostic diagrams which has been used extensively over the past decades is the so called “BPT” diagram (e.g. Baldwin et al. 1981, Ho et al. 1997). One of the original three BPT diagrams is a plot of $\frac{[\text{OIII}]\lambda 5007}{\text{H}\beta\lambda 4861}$ versus $\frac{[\text{NII}]\lambda 6584}{\text{H}\alpha\lambda 6563}$ with AGNs including LINERS (Low Ionization Narrow Emission Line Regions) and seyferts separated cleanly from the star forming galaxies. Kauffmann et al. (2003) later defined a new “composite” region between the previous two classes where composite starburst-AGN objects lie on this diagram. The star forming sequence on the BPT is a tight sequence among star forming galaxies from low metallicities (low $\text{N[II]}/\text{H}\alpha$, high $[\text{OIII}]/\text{H}\beta$) to high metallicities (high $\text{N[II]}/\text{H}\alpha$, low $[\text{OIII}]/\text{H}\beta$) and galaxies in the composite region are likely to have metal-rich stellar population and an AGN (extending from high $\text{N[II]}/\text{H}\alpha$ of star forming sequence towards high $[\text{OIII}]/\text{H}\beta$) (Kewley et al. (2006)).

The BPT diagram studied at higher redshifts reveal an evolution in the separating lines with redshift (e.g. Masters et al. 2014, Coil et al. 2014, Steidel et al. 2014). However, while some of these studies attribute this evolution to Nitrogen enhancement at star forming high redshift galaxies, some other suggest a harder ionizing radiation field and ionization parameter is the main cause for this evolution. Some studies have suggested that composite galaxies have also different ionization conditions associated with their starbursty nature (e.g. Liu et al. 2008, Brinchmann et al. 2008). While others (e.g. Wright et al. 2010, Trump et al. 2013) instead argued that the line ratio gradients suggest both star forming and AGN. Some of these indicate

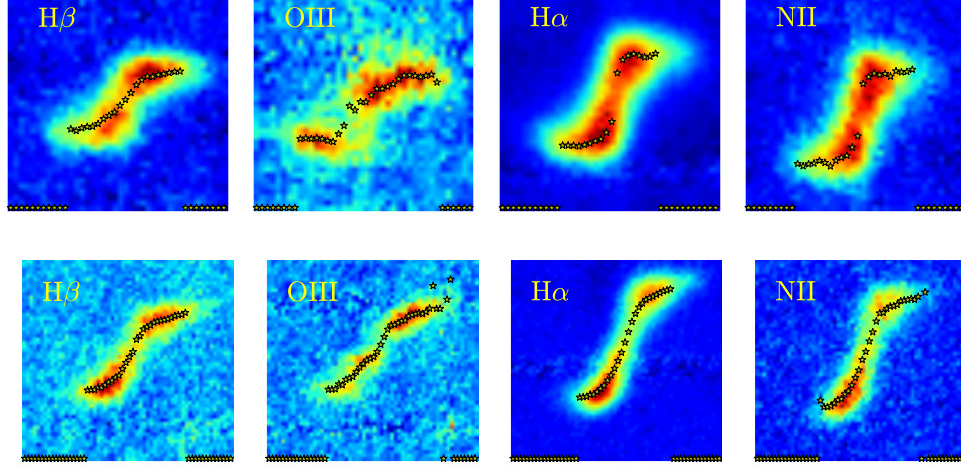


Figure 5.9: Cutouts of continuum subtracted $H\beta$, $[OIII]$, $H\alpha$, and $[NII]$ (from left to right) emission lines for two galaxies at $z = 0.38$ (top and bottom).

that there might be similar mechanisms between the composite galaxies at low redshifts and the higher redshift star forming galaxies. Resolving the line ratios to small scales can help in identifying the source of these discrepancies and shed light on the major source of the elevated star forming sequence.

Here, I model the optical BPT diagnostic lines along the major axis of the galaxy as explained in the previous sections. Figure 5.9 shows from left to right the continuum subtracted $H\beta$, $[OIII]$, $H\alpha$, and $[NII]$ emission line cutouts for two sample galaxies at $z = 0.38$. The resolved BPT diagram for these two galaxies along the disk is plotted in figure 5.10, where I have color coded each resolution element with distance from the center (the measurements extend to about 10 kpc in the disks). While the integrated line ratios of both these galaxies lie on the composite part of the BPT diagram, the resolved version clearly stretches towards the AGN part from outer parts of the disk inwards, suggestive of a harder ionizing source at the center. The two galaxies are at the same redshift and show very similar line ratios but among the two galaxies the one on top panel was previously identified as an AGN host from x-ray observations while the other was undetected in x-ray. Another interesting feature which can be seen from figure 5.10 is the increase in the $[NII]/H\alpha$ in the galaxy on top in one side of the disk. The

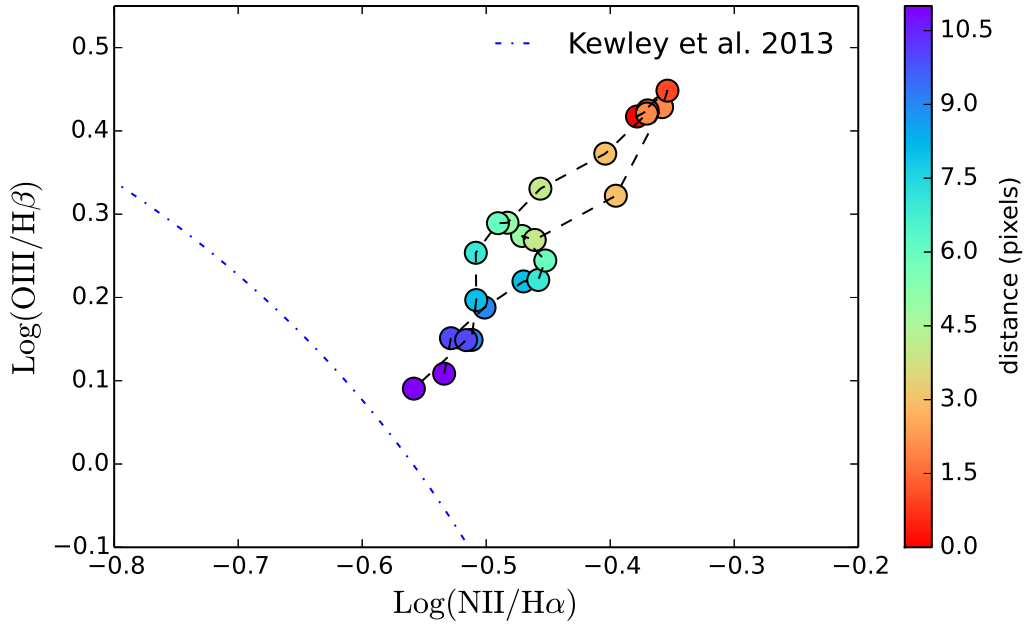
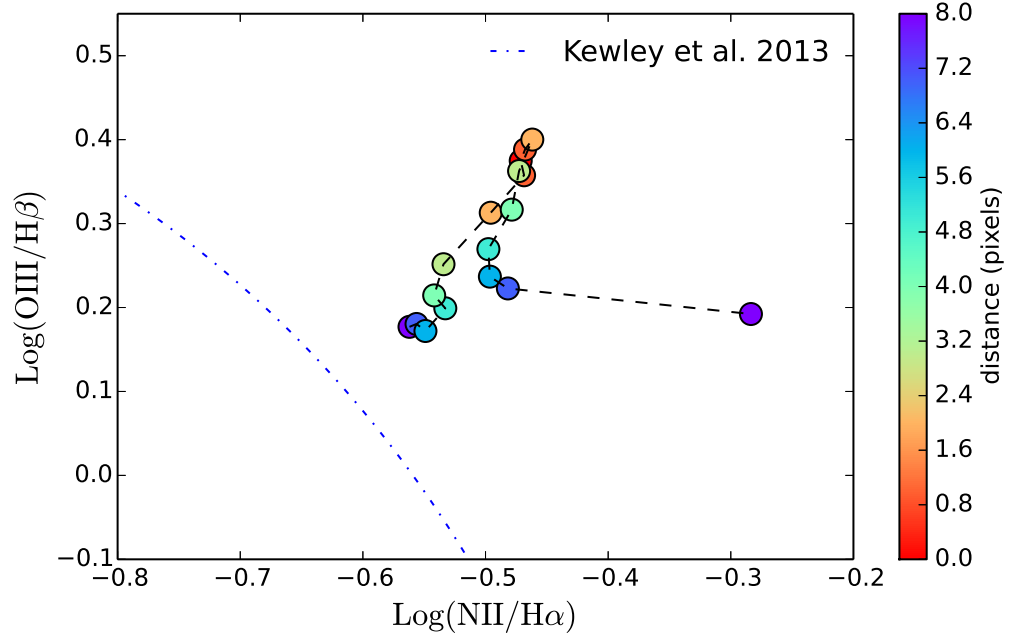


Figure 5.10: The resolved BPT diagram along the disk of two galaxies at $z = 0.38$. The dashed blue line is the separating line between AGNs and starbursts at the same redshift using Kewley et al. (2013) relation. Both $[NII]/H\alpha$ and $[OIII]/H\beta$ increase from the outer parts of the disk towards the central parts.

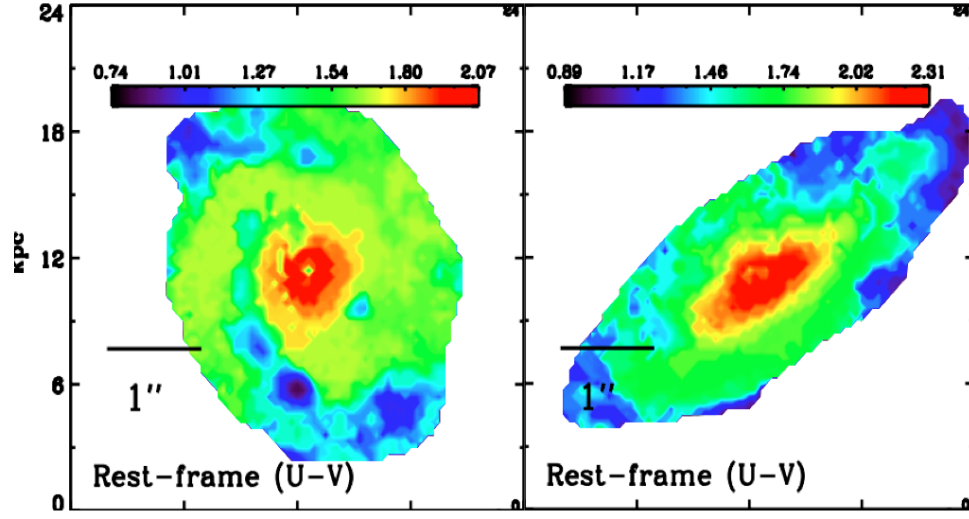


Figure 5.11: The $(U - V)_{\text{rest-frame}}$ color maps of the same two galaxies at $z = 0.38$ with resolved BPT in figure 5.10. The position of the blue clump in the left panel galaxy coincides with the excess in the $[NII]/H\alpha$.

$(U - V)_{\text{rest}}$ color map of the two galaxies can be seen in figure 5.11 and the increase in the $[NII]/H\alpha$ coincides with the position of the very blue clump in the disk.

The resolved BPT diagram therefore could be used to identify AGNs where other methods fail, due to X-ray obscuration or galaxy dilution of the integrated line ratios. Also using the technique on a larger sample of star forming and/or composite galaxies where individual clumps (similar to HII regions) can be resolved and cross-correlated with the resolved spectra as well as central kpc parts of the galaxies hosting AGNs can shed light on the discrepancies discussed above.

5.5 Discussion and Summary

In this work, I have measured dust extinction along the major axis of eight emission-line disk galaxies at $z \sim 0.4$. I have used pixel-by-pixel SED fitting and Keck/DEIMOS spectra to infer stellar and nebular dust extinction, respectively. While the sample size is small to draw robust statistical inferences about galaxy populations in general, I developed the methodology that

can be practically used on much larger samples to measure dust inside galaxies at different radii from the center, using optical spectra to $z \sim 0.5$ and infrared spectra at higher redshifts.

The integrated nebular to stellar color excess ratio for the galaxies in our sample span the range $1.0 - 2.5$ with median $(E(B - V)_{\text{nebular}}/E(B - V)_{\text{stellar}}) = 1.3$ and standard deviation 0.5. Due to the small sample size a clear trend of nebular to stellar color excess ratio was not seen with either stellar mass or the sSFR. However the nebular to stellar color excess ratio dependence can be investigated for individual galaxies. I specifically compared two of the galaxies in the sample (ID = 5&7) with the same redshift ($z = 0.38$) and comparable stellar mass ($\text{Log}(M_*/M_\odot) \sim 9.65$). Between the two, the one with higher SFR has smaller nebular to stellar color excess ratio. This is in agreement with the work of Price et al. (2014) but contrary to the overall trend seen in Reddy et al. 2015 with integrated measurements for larger samples of galaxies at higher redshifts. The difference here can be explained due to differences in the orientations (inclinations) between the two galaxies, a parameter that is often overlooked in many studies.

I also compared the integrated and resolved nebular color excess in galaxies and found a good agreement between the two, with the integrated value, being equal or slightly less than the median of resolved measurements (median $\Delta E(B - V)_{\text{median-integrated}} \sim 0.05$ mag). This small offset is mostly due to the signal to noise criteria applied to $\text{H}\alpha$ and $\text{H}\beta$ emission lines at resolution elements, which exclude the outer parts of the emission line (which also appear to have lower extinction) from the resolved measurements. I found that the resolved stellar continuum color excess profiles show higher extinction towards central regions of galaxies compared to outer parts of the disk. This is contrary to the nebular color excess profiles in the lower mass galaxies which show almost flat radial profiles.

The relation between the stellar mass and color excess has been studied at various redshifts (e.g. Garn & Best 2010, Sobral et al. 2012, Domínguez et al. 2013). Here, I extended this relation to substructures inside galaxies, by studying the variation of nebular color excess as a function of stellar mass surface density and found an increasing amount of nebular color excess in regions with higher stellar mass surface density. This also explains to some extent, the lack

of a correlation in the nebular attenuation as a function of distance from the center in lower mass galaxies in which the stellar mass surface density range covered is lower, when compared to higher mass galaxies.

I also examined the relation between the nebular color excess and the gas mass surface densities, converted from the SFR surface densities. The shape of the attenuation relation for high gas mass surface densities resembles the attenuation versus dust mass surface density relation found in Kreckel et al. (2013), implying that the dust to gas mass ratio is not changing significantly as a function of extinction at physical scale probed in this study. It is however important to note the assumptions made in deriving this result, such as the conversion from SFR surface density to gas surface density and the dust mass surface densities which are all measured from local observations and might not hold true at higher redshifts. Resolved FIR observations with the Atacama Large Millimeter/submillimeter Array (ALMA) will be essential to examine the validity of these assumptions.

Chapter 6

Conclusion

In this thesis, I have focused my studies on resolved properties of emission-line galaxies at intermediate redshifts by combining high resolution photometric and spectroscopic data. Galaxies in this work are selected from the GOODS South and North field where highest spatial resolution HST images in the optical and near infrared exist as part of the CANDELS project alongside a wealth of other ancillary data from other space or ground-based telescopes. We have observed these galaxies along their major axis with the DEIMOS instrument on the Keck telescope in long exposures to obtain high spatial and spectral rotation curves.

I developed and tested a method to generate spatially-resolved rest-frame color, stellar mass surface density, age, SFR surface density and extinction maps of galaxies with HST resolution, allowing for differences in PSFs from different instruments. I investigated the impact of nebular emission lines in the SED fitting procedure, by comparing the 2D maps produced with and without including emission lines in the fits. I found small variation in residual maps inside each galaxy, suggesting that including the emission line would not have much spatial effect in galaxies, even for the galaxies with large residuals. Large residuals happen in the redshifts where more than two broadband filters are contaminated with $H\alpha$.

$H\alpha$ maps for galaxies in the sample are made using the best fit SED models including nebular emission line. The $H\alpha$ luminosities predicted can be compared against resolved spectroscopic observations (e.g. with OSIRIS) to test for the assumptions that go into the SED fitting

when accounting for emission-line contamination such as the Kennicutt relation or a fixed ratio of emission lines.

Comparing the stellar mass surface density, SFR surface density and stellar ages measured by resolved SED fitting to the integrated stellar masses, SFRs and ages I found a good agreement with offsets of 0.04 dex, 0.16 dex and 0.02 dex for stellar mass, SFR and age respectively. This is a confirmation of the methodology developed and the consistency of the map products to results of global SED fitting in galaxies. I found that the stellar mass distribution in the disks are very smooth and 30-90% of the total stellar mass comes from the central 2.5 kpc of the galaxies of our sample.

I identified red and blue clumps in galaxies using the photometric maps produced through resolved SED fitting as opposed to the routines of selecting clumps based on observed images in single bands. The clumps are selected from high-pass and low-pass filtered $(U - V)_{rest-frame}$ color maps using SExtractor. I visually inspected the clump identification routine and also tested it against redshift biases by artificially redshifting lower redshift galaxies to $z \sim 1$ and reidentifying their clumps and found no bias in selecting larger clumps at higher redshifts.

I studied the physical properties of pixels belonging to red and blue clumps in galaxies as well as the properties of the pixels in the underlying green disk. I found that blue clumps on average are not regions of high star formation surface density in the disk and rather regions of higher specific star formation. This finding suggests that studies of clumps based on $H\alpha$ observations should do the identification based on the EW of the line rather than the luminosity. The median ages of blue clumps, green pixels and the bulge are respectively $\sim 0.15, 0.3, \text{ and } 1 \text{ Gyr}$ which are of the order of several to tens of orbital times ($\sim 50 \text{ myr}$ measured from rotation curves for galaxies in this sample). This age gradient is consistent both with the migration of clumps inward and an inside-out growth of the galaxy.

Using the dual mode feature of SExtractor I measured stellar mass and SFR surface density of individual clumps inside galaxies. I found that more massive galaxies have on average more massive clumps. I have also found a bimodal distribution in the red clumps consisting of bulges (very massive and close to the center of the galaxy) and dustier less massive regions (in the

outer disk). However, the average properties of red clumps is mostly dictated by the larger contributor which is the bulge and separating the two classes did not change the qualitative results.

To study the evolution of clumps in galaxies, I had to cut the sample into a smaller range of host galaxy stellar mass ($9.0 < \log(M_*/M_\odot) < 10.5$) and redshift ($0.4 < z < 0.9$) to avoid selection biases. In this subsample, I found no significant evolution in the covering fraction of blue clumps with either redshift or stellar mass, while the covering fraction of red clumps increases with increasing stellar mass and decreases with time. This suggests that we are not witnessing any growth in the bulge size at this redshift and stellar mass range. At this redshift and mass range the covering fraction of blue clumps is about 5% , smaller compared to higher redshift studies and about half the contribution of the red clumps. Blue clumps are found to always be at further distances from the center compared to red clumps with average distance of 6 – 8 kpc. Average distances of red clumps do not evolve with either time or stellar mass but I found an increase in the average distance of blue clumps with increasing stellar mass of the galaxy and no significant evolution with time (discussed in more details in the previous section).

While the relation between the global star formation rate and stellar mass of galaxies is studied extensively, the exact physics behind the evolution of the relation with redshift and the physics behind the scatter around the scatter is not yet fully understood. In this chapter I studied the relation between star formation rate and stellar mass surface density at resolution elements inside individual galaxies as well as among clumps in the larger sample of galaxies.

Since both star formation rate and stellar masses are measured through the SED fitting process and therefore dependent on one another, a smaller scatter is found as expected compared to studies which use other star formation diagnostics such as $H\alpha$ or IR luminosities. We found very interesting trends in individual galaxies, which can explain parts of the scatter around the global main sequence relation. That is, eventhough the galaxies are selected through emission-line strenghts and therefore would be selected as star forming in similar studies, the resolved maps reveal features such as double nuclei, a very blue center (AGN in this case) or a quenched

center which will have different star formation rate- stellar mass surface density gradients and scatter as shown in this chapter.

The very tight relation between the blue clumps regardless of the redshift of the galaxies is fundamental in understanding the physics of the global main sequence evolution with redshift, since if the evolution is caused due to a higher efficiency of converting gas into stars then the same would have been seen inside blue clumps rather if the evolution is due to change in the amount of gas and therefore overall disk morphology and clumpiness then we would not expect to see this evolution inside individual clumps.

I demonstrated the importance of sample selection specifically in investigating the main sequence relation slope and scatter. I used a larger sample of galaxies from the CANDELS at specific stellar mass and redshift without any further selection criteria on the morphology or star formation and constructed the maps and the main sequence for these galaxies. In the future I will extend this to higher redshifts and other stellar masses to study galaxies closer to the peak of the cosmic star formation density.

Using the spectroscopic data, I have measured dust extinction along the major axis of eight emission-line disk galaxies at $z \sim 0.4$. I have used pixel-by-pixel SED fitting and Keck/DEIMOS spectra to infer stellar and nebular dust extinction, respectively. While the sample size is small to draw robust statistical inferences about galaxy populations in general, I developed the methodology that can be practically used on much larger samples to measure dust inside galaxies at different radii from the center, using optical spectra to $z \sim 0.5$ and infrared spectra at higher redshifts.

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The relation between the stellar mass and color excess has been studied at various redshifts (e.g. Garn & Best 2010, Sobral et al. 2012, Domínguez et al. 2013). Here, I extended this relation to substructures inside galaxies, by studying the variation of nebular color excess as a function of stellar mass surface density and found an increasing amount of nebular color excess in regions with higher stellar mass surface density. This also explains to some extent, the lack of a correlation in the nebular attenuation as a function of distance from the center in lower mass galaxies in which the stellar mass surface density range covered is lower, when compared to higher mass galaxies.

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density to gas surface density and the dust mass surface densities which are all measured from local observations and might not hold true at higher redshifts. Resolved FIR observations with the Atacama Large Millimeter/submillimeter Array (ALMA) will be essential to examine the validity of these assumptions.

In studies of evolution of galaxies, samples are often divided into very broad population classess. Studying resolved photometric maps of galaxies at kpc-scales as well as the resolved emission-line ratios along the disk of galaxies, I found different modes of galaxy growth within a given galaxy, with very different physical properties for instance specific star formation rates differing over an order of magnitude (sometimes even more) from region to region. By overlooking the small-scale properties of galaxies when studying their global properties, the whole picture of galaxy evolution can not be revealed.

6.1 Future works

I exploit the techniques (discussed in detail in this thesis) I developed for studying the resolved properties of galaxies on different samples in three ongoing projects using different sampls. (1) Galaxies in the MOSFIRE Deep Evolution Field (MOSDEF) survey with near infrared spectroscopic data from MOSFIRE on Keck I telescope. Using this sample extends the works in this thesis to higher redshifts. (2) Galaxies from the supernova survey in CANDELS, for which we have processed the pre-supernova images and resolved SED fitting of the supernova hosts would further help in their diagnostics based on the physical properties of the position where the supernova happens.(3) And the galaxies from the Frontier Fields which I will descibe in some detail here.

Over the last decades, many works have focused on the effect of the environment on global properties of galaxies (such as star formation activity) finding contradictory results (e.g. Darvish et al. 2014, Scoville et al. 2013, Cooper et al. 2008). Also, over the last years, multi-waveband resolved (kpc-scale or larger) galaxy studies have been performed, to explain the evolution of galaxies, specifically transition from starforming to passive evolution through sec-

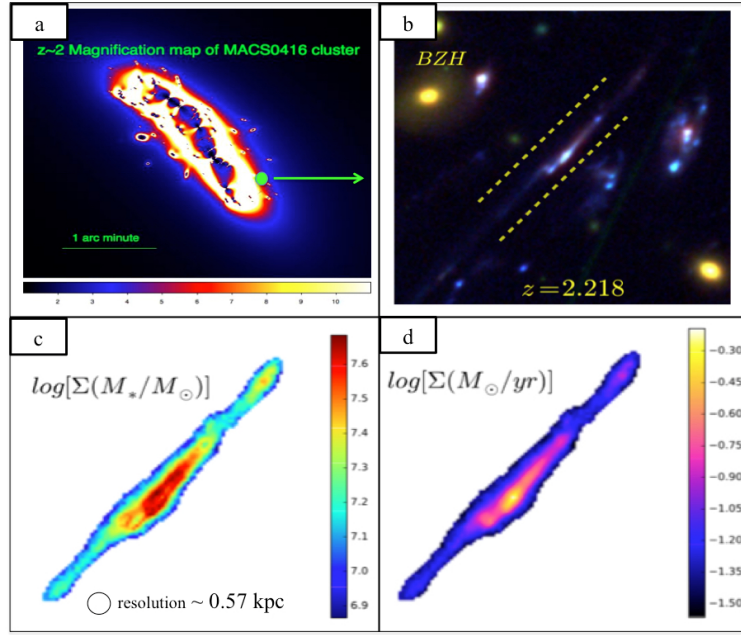


Figure 6.1: Stellar mass and SFR surface density maps of a lensed galaxy at $z=2.218$ behind the macs0416 cluster. (a) Based on the magnification map of this cluster (from CATS team), this galaxy is $6\times$ magnified. The galaxy is stretched and therefore the spatial resolution is increased. Lensing preserves the surface brightness and therefore the total flux is also magnified. (b) shows the stacked HST F435W, F814W and F160W of this lensed galaxy. By Pixel-by-pixel fitting of the 6 band HST data with stellar population synthesis models, we generated high resolution maps of stellar mass surface density (c) and SFR surface density (d) with the resolution of 570 pc; more than two times better than unlensed galaxies at similar redshift observed by HST.

ular processes (e.g. Förster Schreiber et al. 2009, Hemmati et al. 2014). To understand the origin of the observed correlations among the global (integrated) properties of galaxies, resolving to small scales is key. However, this is entangled to the environment. For the first time, we can now address these issues, using high spatial resolution HST images for both the HFF and CANDELS galaxies to construct resolved maps of a statistically large sample of galaxies in different environments. I will also be able to see the effect of having higher physical resolutions ($\lesssim 1\text{kpc}$) by studying background galaxies magnified by the HFF clusters.

Through this project, I aim to optimize the sample selection criteria based on brightness, size and inclination of galaxies to maximize the number of galaxies with high spatial S/N. Galaxies which meet the selection criteria will be divided into two main categories, based on their redshift. (1) Galaxies at the redshift of the HFF clusters ($z \sim 0.3 - 0.5$). I will select cluster members, as well as galaxies in the same redshift in the parallel fields and the CANDELS field, to study the effect of environment on substructures in galaxies. (2) lensed background galaxies at higher redshifts ($z \sim 0.6 - 3$).

By taking advantage of magnification due to strong gravitational lensing in the HFF clusters, we can achieve higher spatial resolutions. I can also reduce the bias due to selecting only the brightest of galaxies and will be able to resolve galaxies down to kpc-scale at higher redshifts. In Figure 6.1 I plot an example lensed galaxy at $z = 2.21$ behind the MACS0416 cluster along with the stellar mass and SFR surface density maps. I will perform the same practice for all lensed galaxies in the HFF and construct 2D maps of their physical properties. Studying clumps in a sample of galaxies with better spatial resolution but otherwise similar physical properties such as stellar mass, SFR and environment will clearly outline the effect of resolution. We will study in detail the covering fraction and radial variation of clump properties such as mass, SFR and age to constrain the models for the evolution of substructures in galaxies.

It is not clear whether the internal, secular processes or external environmental factors play a more fundamental role in the evolution of galaxies. To understand the role of secular processes in the evolution of galaxies, specifically in quenching the SFR, one needs to study small scale properties of galaxies with the highest spatial resolution. At the other end, environmen-

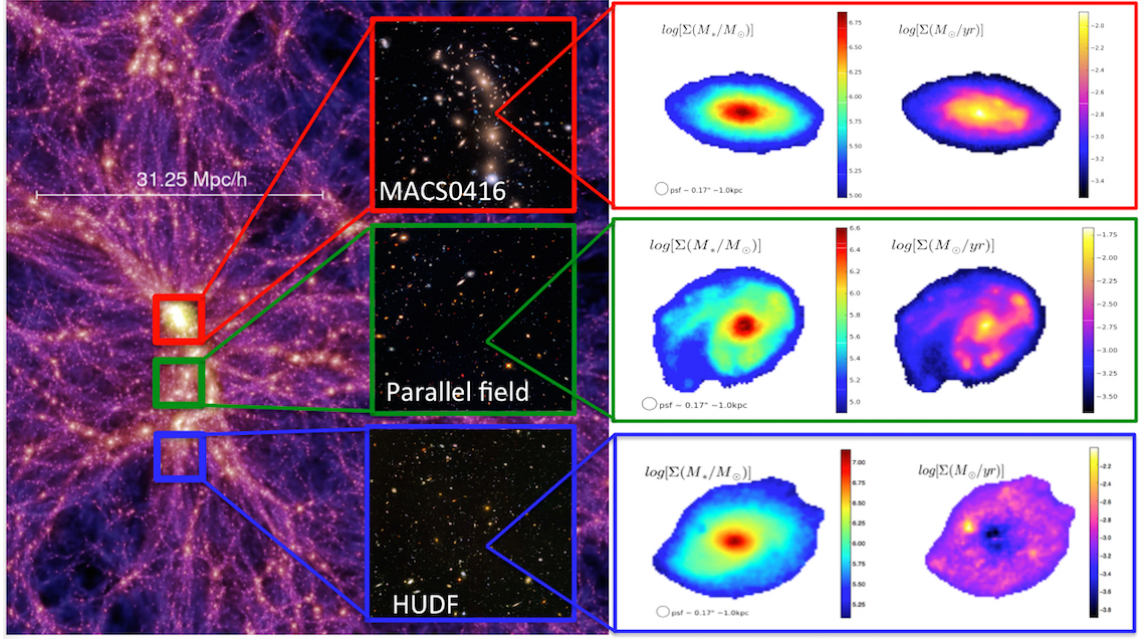


Figure 6.2: Only through the combination of small and large scales a thorough understanding of the galaxy evolution is possible. The background image in the left (from the Millennium simulation) is showing dark matter halos in a 60×70 Mpc/h box at $z = 0$. While we do not observationally have access to very large volumes with high spatial resolution, we now have samples from the different environments from the HST. The red, green and blue boxes (on the right) are the HST stacked image of the MACS0416 cluster field, its parallel field and the HUDF respectively. We will study resolved sub-kpc properties of galaxies for statistical samples of galaxies in these different environments at the redshift of HFF clusters. On the right part of the image we show three examples of stellar mass and SFR surface density maps generated for galaxies at $z \sim 0.4$ (macs0416 is at $z=0.396$) from the HFF cluster, parallel field and the HUDF from CANDELS fields respectively.

tal studies have focused on very large areas and hence not enough resolution. The dynamical range in density that can be probed by the HFF clusters, parallel fields and the CANDELS fields, for the first time, provides the means to connect the small-scale properties of galaxies to their large-scale environment. In Figure 6.2 I show maps of stellar mass and SFR surface density of example galaxies residing in these different environments. I will perform a careful analysis on the effect of environment on resolved properties of galaxies such as SFR surface density by selecting galaxies which have similar integrated stellar mass.

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