The Evolution of Red Spiral Galaxies

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BS-MS dual degree in Science.

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Certificate of Examination

This is to certify that the dissertation titled **"The Evolution of Red Spiral Galaxies"** submitted by **Ms. Kriti Kamal Gupta** (Reg. No. MS13022) for the partial fulfillment of BS-MS dual degree programme of the Indian Institute of Science Education and Research Mohali, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

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Dr. Smriti Mahajan
(Supervisor)

Dated : April 20, 2018

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Smriti Mahajan at the Indian Institute of Science Education and Research Mohali.

This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgment of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Kriti Kamal Gupta
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In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. Smriti Mahajan
(Thesis Supervisor)

Acknowledgement

Foremost, I would like to express my heartfelt gratitude to my thesis supervisor Dr. Smriti Mahajan, for giving me the opportunity to do my master's thesis under her supervision. Her continuous support and guidance helped me throughout the course of this thesis work. She consistently encouraged me to come up with my own ideas on how to proceed and at the same time, steered me in the right direction whenever needed.

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I would like to acknowledge GAMA, which is a joint European-Australasian project based around a spectroscopic campaign using the Anglo-Australian Telescope. The GAMA input catalogue is based on data taken from the Sloan Digital Sky Survey and the UKIRT Infrared Deep Sky Survey. Complementary imaging of the GAMA regions is being obtained by a number of independent survey programmes including GALEX MIS, VST KiDS, VISTA VIKING, WISE, Herschel-ATLAS, GMRT and ASKAP providing UV to radio coverage. GAMA is funded by the STFC (UK), the ARC (Australia), the AAO, and the participating institutions. The GAMA website is http://www.gama-survey.org/. This research also made use of the "K-corrections calculator" service available at http://kcor.sai.msu.ru/.

Finally, I must express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study. I am especially grateful to my sister, who has always been there for me when things didn't work out. I would also like to take this opportunity to thank my friends for their moral support and motivation which drives me to give my best. This thesis would not have been possible without them. Thank you.

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Abstract

The evolution of a galaxy is largely driven by its intrinsic properties as well as the environment it resides in. Both these factors contribute to the shape and the observed properties of a galaxy. Many studies in the past have shown that early-type galaxies are generally red and elliptical with an old stellar population whereas younger galaxies are blue and disc-dominated with active star formation. However, recent observations of red spiral galaxies have questioned this general trend. By making use of the photometric and spectroscopic data provided by the Galaxy and Mass Assembly (GAMA) survey, we have created a sample of red spiral galaxies in the redshift range 0.002 to 0.06. We aim to determine the reason for the optical red colour of these rare spiral galaxies. In order to do this, we have studied the different properties of these galaxies and compared them to their blue counterparts. Our analysis showed that red spiral galaxies are relatively more evolved. For some of them, their red colour can be attributed to their high metal content. These galaxies are in general more massive than the other spiral galaxies and have very low ongoing star formation. Also, red spirals are present in high density environments.

Chapter 1

Introduction

Galaxies are gravitationally bound systems consisting of stars, gas, interstellar medium and dust. They range in sizes from giant galaxies consisting of about a hundred trillion stars to dwarf galaxies with just a few million stars. Different properties can be used to classify galaxies eg. shape, size, colour, stellar mass, dust content, star formation rate etc.

1.1 Morphology of Galaxies

The morphology of a galaxy refers to its structure. On the basis of their shapes, galaxies are classified into three main classes: ellipticals, spirals and irregulars. A slightly more extensive description of galaxy types based on their appearance and specific characteristics like the openness of spiral arms, size and extent of bars, size of galactic bulges was given by Edwin Hubble (1926) in terms of the Hubble tuning fork diagram, shown in Fig 1.1.

Elliptical galaxies are smooth, featureless, amorphous systems with a continuously declining brightness distribution and no breaks, inflections, zones, or structures, as well as no sign of a disk. They are represented by the letter "E", followed by an integer n which characterises the ellipticity of the galaxy - "E0" is almost round, "E7" is very elliptical. Most ellipticals contain older, low-mass stars, and because they have very little gas and dust, there is little or no star formation occurring in them.

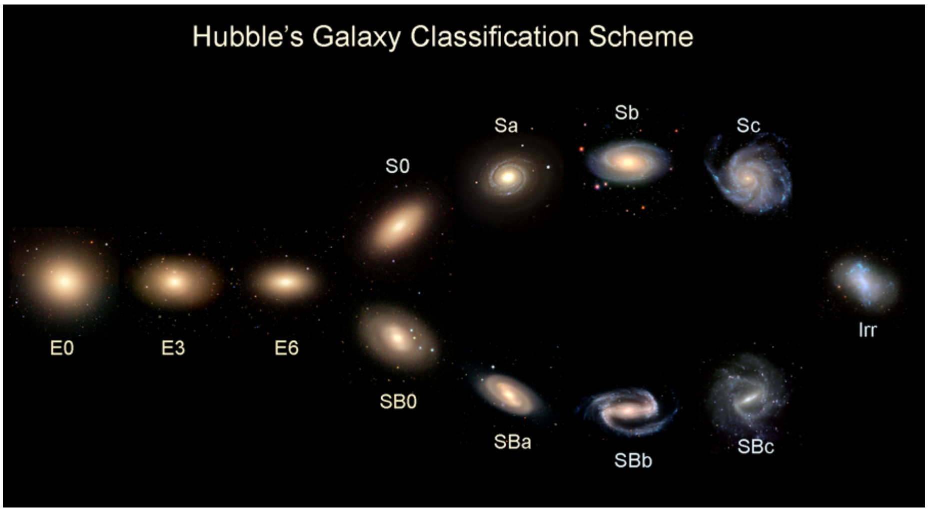

Figure 1.1: Hubble's Morphological Classification Scheme for Galaxies (Image courtesy: http://hendrix2.uoregon.edu/ imamura/123/lecture-3/lecture-3.html)

Spiral galaxies, as the name suggests, look like spirals, with long arms winding toward a bright bulge at the center. They are divided into two parallel classes: normal spirals and barred spirals. The normal spirals have arms that emanate from the nucleus, while barred spirals have a bright linear feature called a bar that straddles the nucleus, with the arms unwinding from the ends of the bar. The normal spirals are designated as 'S' and the barred varieties as 'SB'. Each of these classes is subclassified into three types (denoted with the lowercase letters a, b, and c) according to the size of the nucleus and the compactness of the spiral arms. "Sa and SBa" spirals, for example, are tightly wound whereas "Sc and SBc" spirals are more loosely wound. Also the round central regions in spirals called the nucleus or the central bulge increase in size the more tightly the spiral arms are wound. The arms of a spiral galaxy have lots of gas and dust and they are often areas where new stars are constantly forming. The bulge of a spiral galaxy is composed primarily of old, red stars with very little ongoing star formation.

Lenticular galaxies (S0) have a central bulge, but no spiral arms and are present in the transition zones between ellipticals and spirals. Just like spiral galaxies, some lenticular galaxies have a bar and are called "barred lenticular galaxies" denoted by SB0.

Irregular galaxies (Irr) usually do not have enough structure to characterise them as spirals or ellipticals. There are two subclasses in this group, Irr I galaxies appear to have some spiral structure which has been disrupted whereas Irr II galaxies are much more disturbed than type I and look like they have been victims of some type of violent event that has completely disrupted their original shape. Many irregular galaxies are found to contain young stars and experiencing significant ongoing star formation.

1.2 Parameters Quantifying Galaxy Morphology

The morphological classification of galaxies described above is based on the structural features present in a galaxy. However, we cannot simply rely on these physical attributes and need some quantitative parameters to quantify their classification. A few such parameters are listed below that give a quantitative measure of different properties of a galaxy.

1.2.1 Magnitude

The term magnitude or apparent magnitude is used as a measure of the brightness of a celestial object in the sky as seen from earth. However, this quantity is distant dependent, since smaller the distance between the observer and object, the greater will be the apparent magnitude. To solve this issue, the concept of absolute magnitude was introduced. The absolute magnitude of an object is the magnitude the star would have if it was placed at a distance of 10 parsecs from Earth. This quantity is useful if one wants to compare the real (intrinsic) brightness of different objects. By definition, higher values of absolute magnitude correspond to fainter objects and vice versa. Equation 1.1 can be used to calculate the absolute magnitude of an object from its apparent magnitude, if its distance from earth is known:

$$m - M = 5\log(\frac{d}{10}) \tag{1.1}$$

here, m = apparent magnitude,

M = absolute magnitude,

d = distance between the object and the observer (in parsec)

The expression *m* - *M* is called the distance modulus (μ) and is a measure of distance to the object. An object with a distance modulus of 0 is exactly 10 parsecs away. If the distance modulus is positive, the object is farther than 10 parsecs and its apparent magnitude is less bright than its absolute magnitude and vice versa.

1.2.2 Broadband Colour

The brightness of an object is a direct measure of its luminosity, which in turn is related to the radiations emitted by it in different wavelength bands. Hence, the absolute magnitude for any object can also be specified for different wavelength ranges corresponding to specified filters. Each filter, characterised by a single wavelength, is designed to let in light around that specific wavelength and blocking out light at other wavelengths. The colour of a celestial body is calculated by subtracting the magnitudes in different wavelength bands (Strateva et al 2001). For example, if the magnitude of a galaxy is measured in the 3 bands: ultraviolet (*u*), green (*g*) and red (*r*), then *u* - *g*, *g* - *r* and *u* - *r* correspond to the 3 different colours of that galaxy. Since, all these quantities involve magnitude, they decrease with increasing light output. As a result, a galaxy with a high *g* - *r* colour is redder compared to the one with a low *g* - *r* colour.

We know that galaxies are just collections of millions or billions of stars, along with surrounding gas and dust. Hence, if most of the stars in a galaxy are blue, the galaxy will appear generally blue whereas, if most of the stars are red, then the galaxy will appear generally red. The general colour of a galaxy can tell us about the stellar population present in the galaxy. However, the interpretation of galaxy colour is complicated by the presence of interstellar dust which absorbs light at shorter wavelengths and re-emits in the infrared region, thus making the galaxy appear redder. Another factor that can effect the colour of a galaxy is its inclination angle. An edge on galaxy will appear redder compared to a face on galaxy since the light emitted by the galaxy in the first case has to travel a larger distance to reach us, due to which all light except red is mostly scattered and the least scattered red light reaches us.

The colour of a galaxy has also been related to its morphology. There is a general trend that the brightest galaxies, elliptical in morphology, appear to be dominated by old stellar populations and are optically red. Whereas, young galaxies with current star formation have been shown to be disc-dominated and blue in colour. This, however is not strictly true for all the galaxies as there is a significant population of red spiral galaxies in the universe as well. We aim to determine the reason as to why do these galaxies deviate from the norm.

1.3 Environment

The environment of a galaxy also plays an important role in its evolution. Galaxies interact with their local environment, which may lead to processes which cause galaxies to lose their reservoir of hot gas, a process known as strangulation (Larson et al. 1980). Due to these interactions, galaxies may also lose their ionized and neutral gas by the process of ram-pressure stripping (Gunn Gott 1972), as well as their stars via tidal stripping (Kang & van den Bosch 2008; Pasquali et al. 2010). Harassment, due to fast encounters (Moore et al. 1998) and tidal interactions with their neighbouring galaxies can also remove gas and stars from galaxies.

Relation between the properties of galaxies and their environment was pointed out using morphology to characterise galaxies (Oemler 1974; Melnick & Sargent 1977; Dressler 1980), but in later studies, other photometric properties such as colour (Kauffmann et al. 2003a; Balogh et al. 2004a; Weinmann et al. 2006; Cooper et al. 2007) have been shown to correlate with environment as well. Now, it is well known, that the more massive, elliptical galaxies residing in dense regions tend to have an early-type morphology as well as older and metal-rich stellar populations and exhibit a rather low star-formation activity. On the contrary, spiral galaxies, experiencing a significant rate of star formation are typically found in low-density environments.

1.4 Why Red Spiral Galaxies?

The shape of a galaxy corresponds with its colour as well as its age. Spiral galaxies appear blue because they are still actively forming hot young stars. Elliptical galaxies, on the other hand are mostly old, dead, and red. But surprisingly, many international collaborations have separately identified a population of unusual red spiral galaxies. They have found that many of the red galaxies in crowded regions of galaxy clusters are actually spiral galaxies, bucking the trend for red galaxies to be elliptical in shape. The Galaxy Zoo team has already used the SDSS (Sloan Digital Sky Survey) data to investigate the physical processes which could have turned these galaxies red without disturbing their morphology (Masters et al. 2010).

We aim to - (1) create a catalogue of red spiral galaxies and (2) to determine the reason for the red optical colour of these spiral galaxies. The red optical colour of these galaxies can either be attributed to their old stellar population or to the presence of dust in these galaxies. We also intend to explore how much star formation is sustained in these red spiral galaxies and for how long, and most importantly if it is enough to explain the two major classes of galaxies found in the Universe.

Chapter 2

The Observational Data

In the following chapter, I have described in detail the dataset used for this work. I have given a brief description of the GAMA survey and the different parameters that I have used to study the properties and evolution of red spiral galaxies.

2.1 The GAMA Survey

The Galaxy And Mass Assembly Survey (GAMA) survey, is a multi wavelength photometric and spectroscopic survey of $\sim$ 300,000 galaxies down to r $<$ 19.8 mag over $\sim$ 286 degree square, carried out using the AAOmega multi-object spectrograph on the Anglo-Australian Telescope (AAT). This survey builds on, and is augmented by, previous spectroscopic surveys such as the Sloan Digital Sky Survey (SDSS), the 2dF Galaxy Redshift Survey (2dFGRS) and the Millennium Galaxy Catalogue (MGC).

The main objective of GAMA is to study structure on scales of 1 kpc to 1 Mpc. This includes galaxy clusters, groups, mergers and coarse measurements of galaxy structure (i.e., bulges and discs). GAMA has created an extraordinary multi-wavelength photometric and spectroscopic dataset with outstanding value to both the large-scale structure and galaxy evolution communities. By virtue of its unrivaled combination of area, spectroscopic depth, high spatial resolution and broad wavelength coverage, the GAMA dataset is uniquely capable of advancing low and intermediate-redshift galaxy studies.

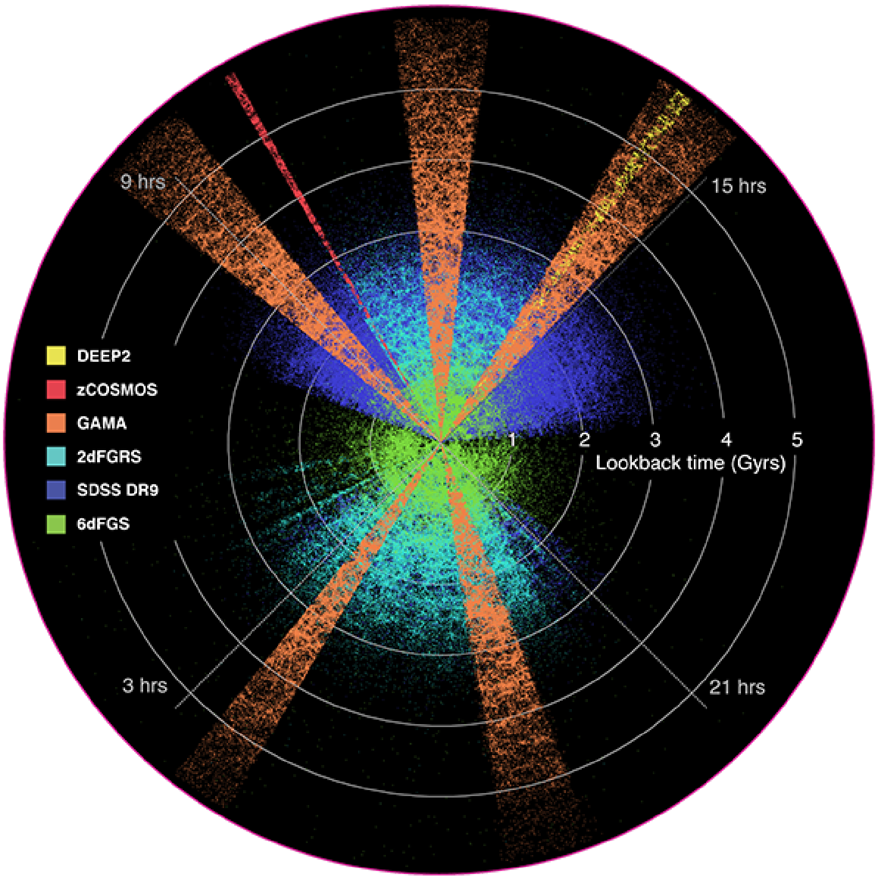

Figure 2.1: Each coloured dot on this diagram is a galaxy that has been observed as part of one of many survey projects conducted globally. (Photo Credit: Simon Driver and the GAMA team)

An overview of the GAMA survey regions is provided in Table 2.1.

Region	RA range	Dec range	Magnitude limit
G02	30.2 to 38.8	-10.25 to -3.72	r < 19.8
G09	129.0 to 141.0	-2 to +3	r < 19.8
G12	174.0 to 186.0	-3 to +2	r < 19.8
G15	211.5 to 223.5	-2 to +3	r < 19.8
G23	339.0 to 351.0	-35 to -30	r < 19.2

Table 2.1: GAMA Survey Regions

We have used the third GAMA data release (Baldry et al. 2018) which provides AAT/AAOmega spectra, redshifts and a wealth of ancillary information for 215,260 objects from the GAMA II survey. The GAMA II survey extends over three equatorial survey regions of 60 deg^2 each (called G09, G12 and G15) and two southern regions over $\sim$ 50 deg^2 each (called G02 and G23), down to a magnitude limit of r < 19.8 mag. However, we have only used the data from the three equatorial survey regions.

2.2 Optical Data

Each galaxy surveyed by the GAMA I survey has a unique GAMA id. The right ascension (RA) and declination (Dec), the redshift and the distance modulus of each of these galaxies is given in the *DistancesFrames* catalogue. The position angle of each of these galaxies are taken from the *SersicCatSDSS* catalogue. The apparent magnitudes corresponding to the SDSS optical filters *g* (green - 4686 Å) and *r* (red - 6166 Å) are obtained from the *LambdarSDSSg* and *LambdarSDSSr* catalogue respectively. The absolute magnitude in these two bands is then calculated by substituting the values of apparent magnitude and distance modulus in Eq 1.1. However, these magnitude values and the corresponding *g* - *r* colour values need to be k-corrected.

2.2.1 K-Correction

K-correction is a correction to an astronomical object's magnitude that allows a measurement of a quantity of light from an object at redshift z to be converted to an equivalent measurement in the rest frame of the object. The expansion of the universe allows astronomers to convert recession velocities to radial distances by making use of the following equation:

$$\frac{\lambda_o}{\lambda_e} = 1 + z \tag{2.1}$$

here, λ_o = observed wavelength,
λ_e = emitted wavelength,
z = redshift

This means that objects observed at different redshifts are sampled at different rest-frame wavelengths. As a result, for optical observations, the measured flux of the objects correspond to optical luminosity of nearby, or low redshift objects, whereas for higher redshift objects, it may correspond to the UV luminosity. Thus, when comparing objects at different redshifts, scaling of the observed flux or magnitude for that object is necessary. This was achieved by making use of the in-built function for k-correction (Chilingarian et al. 2010; Chilingarian et al. 2012) in TOPCAT. TOPCAT (Taylor et al. 2005) is an interactive graphical viewer and editor for tabular data which aims to provide most of the facilities that astronomers need for analysis and manipulation of source catalogues. To calculate the k-correction, one needs to specify the filter, the redshift value, the colour and the colour value. This correction is then subtracted from the absolute magnitude values of each band. Finally, subtracting the corrected absolute magnitude values, we get the k-corrected colour value (g - r).

2.2.2 Visual Morphology

The VMC provides a number of visual morphological classifications performed by various people for different samples of GAMA II galaxies in the equatorial survey regions, within the redshift range $0.002 < z < 0.06$. In the next chapter, we have made use of one such visual classification called the Hubble type classification which classifies galaxies on the basis of the visual classification criteria of Kelvin et al. 2014, into one of the following morphological classes:

(i) Ellipticals (E)
(ii) Little Blue Spheroids (LBS)
(iii) Spirals (S0-Sa, SB0-SBa, Sab-Scd, SBab-SBcd)
(iv) Spirals + Irregulars (Sd-Irr)

The classification was done independently by three classifier pairs on 30kpc x 30kpc postage stamps generated from images from the SDSS and VIKING or UKIDSS LAS, using the pi software written by Lee Kelvin. The final classifications were then compared and if all three classifications for a given galaxy were different, the one by Simon/Stephen was adopted, otherwise, the majority opinion was adopted.

2.2.3 The MAGPHYS Catalogue

MAGPHYS - Multi-wavelength Analysis of Galaxy Physical Properties is a self-contained, user-friendly model package to interpret observed spectral energy distributions of galaxies in terms of galaxy-wide physical parameters pertaining to the stars and the interstellar medium, following the approach described in da Cunha, Charlot Elbaz (2008). The analysis of the spectral energy distribution (SED) of an observed galaxy with MAGPHYS is done in two steps:

1. The assembly of a comprehensive library of model SEDs at the same redshift and in the same photometric bands as the observed galaxy, for wide ranges of plausible physical parameters pertaining to the stars and interstellar medium.

2. The build-up of the marginalized likelihood distribution of each physical parameter of the observed galaxy, through the comparison of the observed SED with all the models in the library.

In chapter 4, we have used the following physical parameters from the MagPhys catalogue:

1. Stellar Mass ($M^{\star}$ in units of $M_{\odot}$)
2. Dust Mass (M_d in units of $M_{\odot}$)
3. Star Formation Rate (SFR in $M_{\odot}/yr$)
4. Specific Star Formation Rate (sSFR in yr^{-1})
5. Metalicity (in units of $M_{\odot}$)

2.2.4 Environment Catalogue

The *EnvironmentMeasures* catalogue provides several different metrics of the local environment of galaxies in the G15 equatorial survey region. In chapter 5, we have studied the effect of environment on the evolution of galaxies and have made use of the distance to the 5th nearest neighbour (in Mpc) as a measure of the galaxy's local environment.

2.3 Infrared Data

The *WISECat* contains IR photometry of GAMA sources in the GAMA II equatorial survey regions detected in the WISE AllWISE survey. WISE surveyed the entire sky at 4 mid-infrared wavelengths: 3.4 micron (W1), 4.5 micron (W2), 12 micron (W3) and 22 micron (W4), and performed source detection in each band independently. Details of the photometry measurements and performance are discussed by Cluver et al. (2014).

A list of all the catalogues used in this work along with their version numbers is given in Table 2.2.

S. No.	Catalogue	Version	Reference
1	DistancesFrames	v14	I.K. Baldry et al. (2012)
2	SersicCatSDSS	v09	L.S. Kelvin et al. (2012)
3	LambdarSDSSg	v01	A.H. Wright et al. (2016)
4	LambdarSDSSr	v01	A.H. Wright et al. (2016)
5	VisualMorphology	v03	L. S. Kelvin et al. (2014)
6	MagPhys	v06	E.N. Taylor et al. (2011)
7	EnvironmentMeasures	v05	S. Brough et al. (2013)
8	LambdarWISEW1	v01	A.H. Wright et al. (2016)
9	LambdarWISEW2	v01	A.H. Wright et al. (2016)
10	LambdarWISEW3	v01	A.H. Wright et al. (2016)
11	LambdarWISEW4	v01	A.H. Wright et al. (2016)

Table 2.2: List of Catalogues

Chapter 3

The Sample of Red Spiral Galaxies

In this chapter, I describe our sample and the selection criteria used to choose red spiral galaxies. We started with a all galaxies including ellipticals, spirals and irregulars. From this, we created a sample of only spiral galaxies and further split it into red and blue spiral galaxies.

3.1 Master Sample - All Galaxies

- First of all, we created a master sample consisting of all the GAMA objects in the redshift range $0.002 < z < 0.06$. This redshift range corresponds to the redshift criterion applied on the galaxies that are part of the *VisualMorphology* catalogue, which will be later used to create a sample of spiral galaxies. So, intially we had 13,914 objects in the master sample as per the redshift value given by the *DistancesFrames* catalogue.

- As already mentioned in chapter 2, the GAMA II survey extends over three equatorial regions and two southern regions whereas the *VisualMorphology* catalogue has only classified galaxies in the equatrial regions. Hence, the master sample was further reduced to contain 9,637 objects on the basis of their position.

- Next, all the objects in the master sample were matched by their CATAID (unique GAMA id) with the objects in the *VisualMorphology* catalogue. We got a total of 7,595 matches, out of which, 39 objects had not been classified into any Hubble class. Of the remaining, there were 23 stars and 2 artifacts which had to be removed from the master sample so as to get a list of only galaxies within the redshift range $0.002 < z < 0.06$. After this, our master sample consisted of 9,612 galaxies.

- Next we checked if all the 9,612 galaxies were present in the other catalogues and if their photometric parameters were determined successfully. Here is a list of the number of matches we got corresponding to different GAMA catalogues we have used:

S. No.	GAMA Catalogue	Number of Matches	Number of Matches with Values
1	SersicCatSDSS	8,409	8,374
2	LambdarSDSSg	7,986	7,984
3	LambdarSDSSr	7,986	7,985
4	VisualMorphology	7,570	7,531
5	MagPhys	7,984	7,984

Table 3.1: List of Matches between the GAMA Catalogues and the Master Sample

- As can be seen in the table 3.1, all the required data is available for only 7,984 galaxies out of the 9,612 galaxies originally selected. Hence, finally our master sample of all GAMA galaxies within the specified redshift range contains 7,984 galaxies.

3.2 All Spiral Galaxies

- We now move on to the next step of preparing a sub sample that contains all the spiral galaxies. For this, we first created a sample of galaxies from the master sample that belonged to the S0-Sa, SB0-SBa, Sab-Scd, SBab-SBcd, Sd-Irr morphology classes based on the *VisualMorphology* catalogue. We had 5,788 such galaxies.

- Looking at each of the 5 morphology classes individually, we got the following information:

S. No.	Morphology Class	Description	Number of Galaxies
1	S0 - Sa	Lenticular and Spiral Galaxies	746
2	SB0 - SBa	Lenticular and Spiral Galaxies	80
3	Sab - Scd	Spiral Galaxies	1,232
4	SBab- SBcd	Spiral Galaxies	191
5	Sd - Irr	Spiral and Iregular Galaxies	3,539

Table 3.2: Description of the Morphology Classes including Spiral Galaxies

- In case of the first two morphology classes shown in table 3.2, although they contain lenticulars as well, we can keep all these galaxies in our sample of spiral galaxies, as the number of lenticulars is very small compared to the total number of spirals galaxies and so will not affect the final results much.
- The next two classes contain majority of the spiral galaxies and hence should be a part of the sub sample.
- As for the last class, we need to look at each galaxy individually in order to separate the majority of irregular galaxies form the Sd type spiral galaxies in this class. After visually classifying each of these galaxies, we got 3,276 irregular galaxies, 55 Sd type spiral galaxies and 208 galaxies that could not be classified into either of the two classes due to the lack of distinct features and the poor resolution of the SDSS images.
- We decided to include the unclassified galaxies in our sample of spiral galaxies as it is better to include a few irregular galaxies in our sample than to miss out on some spiral galaxies. So, finally our sub-sample of spirals comprise 2,512 galaxies.

3.3 The Red and Blue Spiral Galaxies

- Next we created samples of red and blue spiral galaxies from the sub sample created above, for which we used the k corrected (g - r) colour values (described in detail in section 1.2.2 and 2.2.1). We plotted the distribution in the colour value for the master sample (shown in Fig 3.1).

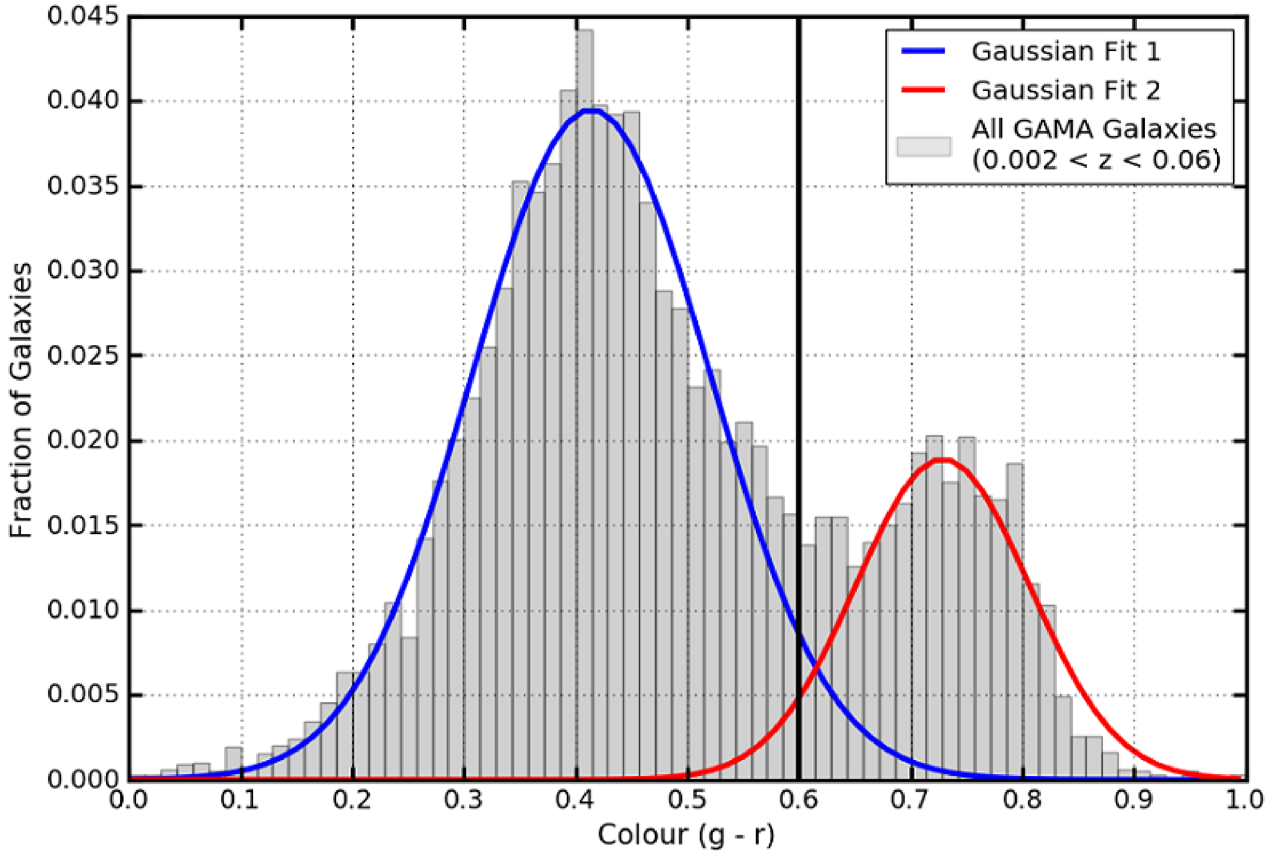

Figure 3.1: Colour (g - r) Distribution

- The distribution in colour (g - r) is clearly bimodal which describes the two populations of galaxies present in the Universe, red and blue. We have fitted two separate gaussians to the data, hence getting a bimodal gaussian distribution curve with the following specifications:

S. No.	Parameter	Value	Sigma
Gaussian 1	Mean (μ)	0.41	0.002
	Deviation (σ)	0.11	0.002
	Height (A)	0.04	0.001
Gaussian 2	Mean (μ)	0.73	0.001
	Deviation (σ)	0.08	0.004
	Height (A)	0.02	0.001

Table 3.3: Parameters for the Bimodal Gaussian Distribution

- By making use of the parameters defining the two gaussian distributions used to fit the colour (g - r) distribution plot, the value for the colour cut to separate the red galaxies from the blue galaxies can be determined as follows:

$$\mu_1 + x(\sigma_1) = \mu_2 - x(\sigma_2) \tag{3.1}$$

$$x = \frac{\mu_2 - \mu_1}{\sigma_1 + \sigma_2} \tag{3.2}$$

$$x = 1.71 \tag{3.3}$$

$$g - r = \mu_1 + x(\sigma_1) = \mu_2 - x(\sigma_2) = 0.59\ mag \tag{3.4}$$

- Using the value of colour cut $\sim$ 0.6 mag, the galaxy population in the master sample as well as the sub sample was divided into red and blue.

Sample File	Blue Galaxies (g - $r \leq$ 0.6 mag)	Red Galaxies (g - $r >$ 0.6 mag)
Master Sample - All GAMA Galaxies ($0.002 < z < 0.06$)	5,781 / 7,984	2,203 / 7,984
Sub Sample - All Spiral Galaxies + Unclassified Galaxies	1,463 / 2,512	1,049 / 2,512

Table 3.4: Fraction of Blue and Red Galaxies

- Finally, we have a sample of 1,049 red spiral galaxies and 1,463 blue spiral galaxies.

3.4 Redshift Distribution

We plotted the redshift distribution for the samples of all galaxies, all spiral galaxies and all red spiral galaxies, to check if they are consistent with each other. Since the plot of redshift distribution (Fig 3.2) only gives a qualitative picture, we run some statistical tests to get a qualitative idea about the similarity and differences in the redshift distribution of these different samples.

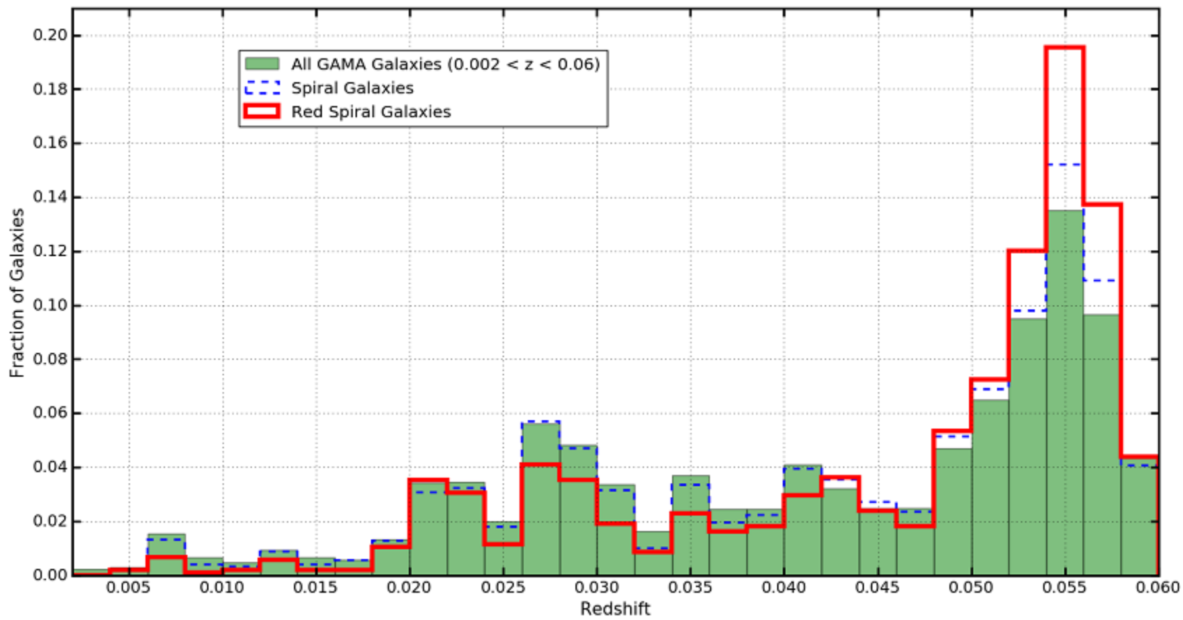

Figure 3.2: Redshift Distribution

3.4.1 Kolmogorov Smirnov Test

The Kolmogorov (KS) test is a non-parametric statistical test used to compare two samples. The KS statistic quantifies the difference between the cumulative distribution of two samples. The null hypothesis states that the samples are drawn from the same distribution. If the KS statistic is small or the p-value is high, then we cannot reject the null hypothesis whereas if the p-value is lower than a specified value, we can infer that the two distributions are statistically different. Throughout this thesis work, we will be considering p - value $<$ 5% or 0.05 as the criterion to reject the null hypothesis.

On carrying out the KS test for the redshift distribution for the three samples shown in Fig 3.2, we get the following results:

S. No.	Samples Compared	KS statistic	p - value
1	All GAMA Galaxies and All Spiral Galaxies	0.043	1.56 e-03
2	All GAMA Galaxies and Red Spiral Galaxies	0.144	3.18 e-17
3	All Spiral Galaxies and Red Spiral Galaxies	0.106	1.12 e-07

Table 3.5: KS Test Results for Redshift Distribution

It is therefore evident from that none of the samples are statistically consistent with each other (since all p-values are less than 0.05). One way to solve this problem is to consider different redshift bins and divide all our samples accordingly. Based on the ks test results, we divided the sample files into the following 3 redshift bins:

Bin 1 - $0.002 < z < 0.03$
Bin 2 - $0.03 < z < 0.045$
Bin 3 - $0.045 < z < 0.06$

The number of GAMA galaxies and red spiral galaxies in each of these redshift bins along with the respective KS test results comparing the redshift distributions of all galaxies and red spiral galaxies are shown in the following table:

Redshift Bin	No. of GAMA Galaxies	No. of Red Spiral Galaxies	KS statistic	p - value
Bin 1	2,843	194	0.096	7.25 e-02
Bin 2	2,141	173	0.110	4.05 e-02
Bin 3	4,628	682	0.057	4.32 e-02

Table 3.6: KS Test Results in Different Redshift Bins

Since the p-values are ≥ 0.05, we can state that the sample of all GAMA galaxies and red spiral galaxies are consistent in terms of their redshift distribution in each individual redshift bin. We have carried out all the further analysis using the binned as well as the unbinned data and discovered that all the results are similar in the two cases. Hence, there is no need for binning the data in redshift and we can safely continue without worrying about any redshift bias.

Chapter 4

Properties of Galaxies

In this chapter, we study different properties of the red spiral galaxies and compare them to the ones. We further use these comparisons to determine the reason for the optical red colour of same spiral galaxies to characterise them and study their evolution.

4.1 Stellar Mass

The stellar mass of a galaxy is the mass due to the stars present in the galaxy. It is measured in units of solar mass ($M_\odot$). The distribution in the stellar mass of red and blue spiral galaxies is shown in Fig 4.1(a).

4.2 Dust Mass

As the name suggests, the amount of dust present in a galaxy constitutes its dust mass. It is also measured in terms of solar mass and as mentioned earlier in section 1.2.2, effects the optical colour of a galaxy. Fig 4.1 (b) shows the distribution in dust mass of red and blue spiral galaxies.

4.3 Star Formation Rate

Another important quantity that is used to study galaxy evolution is star formation rate (SFR). It is quantified by the amount of gas converted to stars in the galaxy and is given in terms of solar mass per year. A galaxy with ongoing star formation will have high SFR relative to a galaxy with no ongoing star formation. However, the SFR per unit stellar mass is a more useful quantity, as unlike SFR it is not correlated with the stellar mass of a galaxy. This quantity is known as the specific star formation rate (sSFR) and is expressed in units of per year. The distribution in the SFR and sSFR of red and blue spirals is shown in Fig 4.1(c) and (d) respectively. We have also plotted the correlation of SFR with dust mass as well as stellar mass (Fig 4.2 and 4.3).

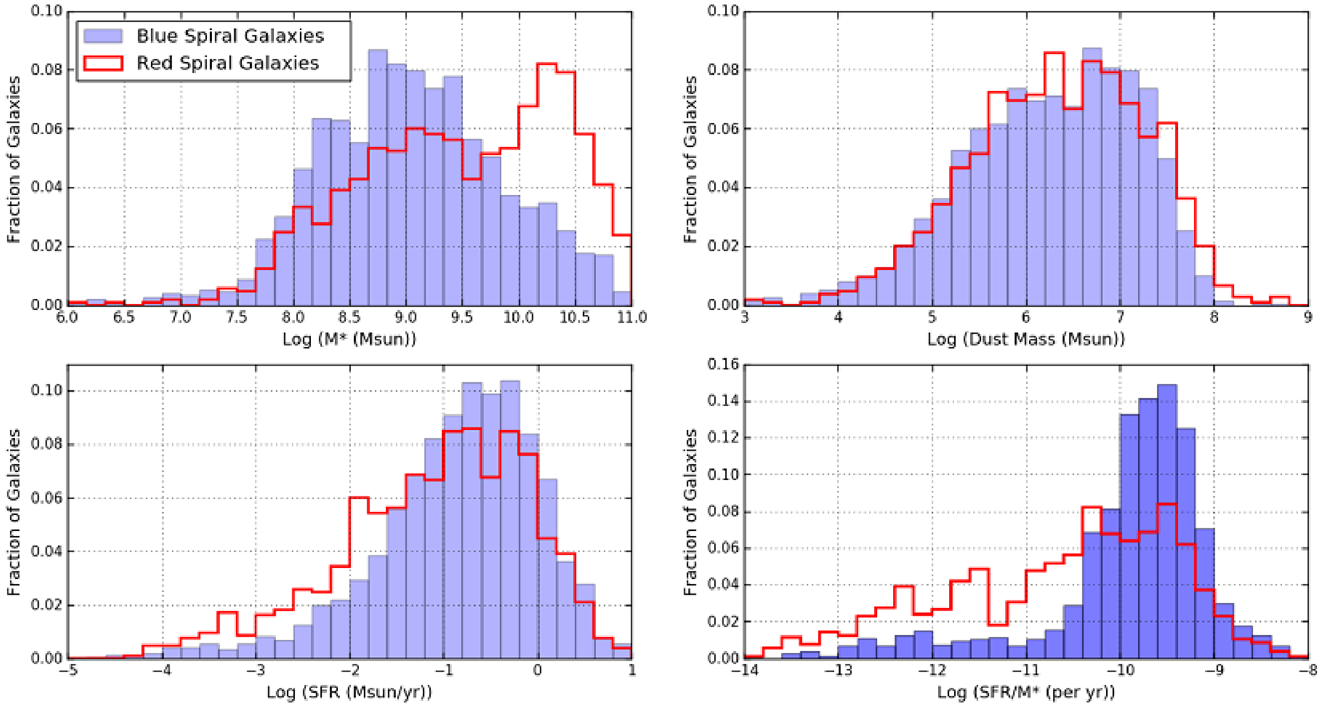

Figure 4.1: (a) Stellar Mass Distribution, (b) Dust Mass Distribution, (c) SFR Distribution and (d) sSFR Distribution for Red and Blue Spiral Galaxies

The following properties of red spiral galaxies can be inferred from Fig 4.1:

1. Red spiral galaxies have higher stellar mass compared to the blue spiral galaxies.
2. The specific star formation rate for red spiral galaxies is lower when compared to the blue spiral galaxies.
3. The dust mass distribution is almost similar for the two types of spiral galaxies.
4. Although the SFR distribution for both red and blue spirals are similar, there is a significant fraction of red spirals with low SFR.

Table 4.1 shows the KS test results for all these properties for the red and blue spiral galaxies.

S. No.	Property	KS statistic	p - value
1	sSFR	0.346	1.96 e-64
2	Stellar Mass	0.256	1.10 e-35
3	Dust Mass	0.045	1.72 e-01
4	SFR	0.131	1.18 e-09

Table 4.1: KS Test Results for Red and Blue Spiral Galaxies

The KS test results agree with the interpretations we made earlier. All the properties except for the dust mass, have different distributions for red and blue spiral galaxies.

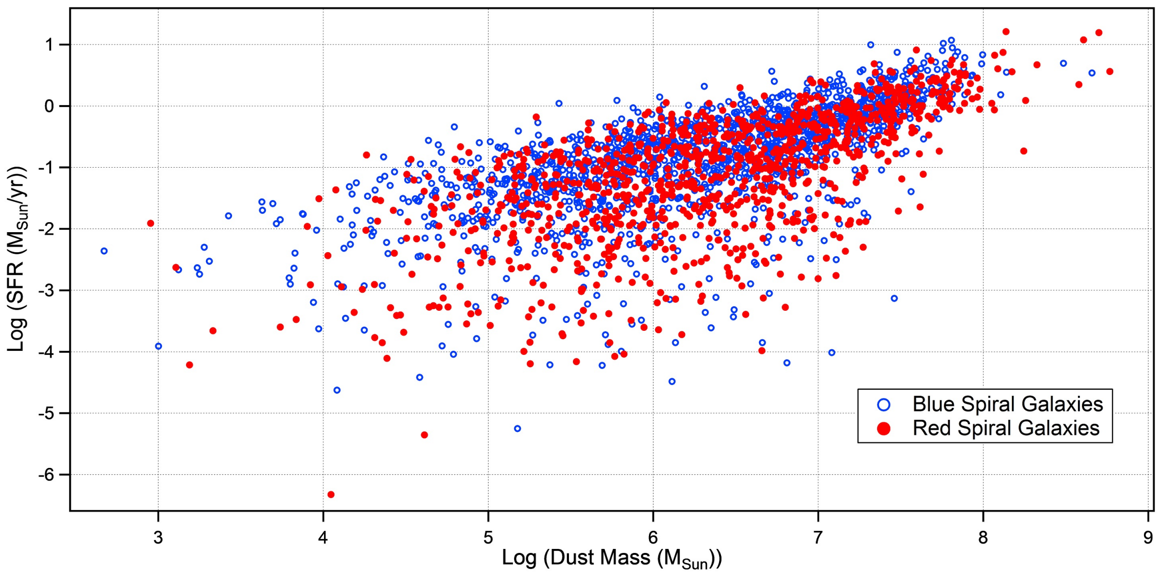

Figure 4.2: SFR vs Dust Mass

The Fig 4.2 shows a direct correlation between the dust mass and SFR for both red and blue spirals. This might be interpreted as the consequence of star formation induced by the presence of dust as seeds for star formation or due to the production of dust following massive star formation (Hjorth et al. 2014).

SFR is also seen to be directly correlated with the stellar mass (Fig 4.3). However, this correlation is observed to be fairly tight for blue spiral galaxies compared to the red ones, which show higher dispersion.

In Fig 4.4, we have plotted the specific star formation rate with respect to the stellar mass. The plot shows that the sSFR decreases with stellar mass for all spiral galaxies.

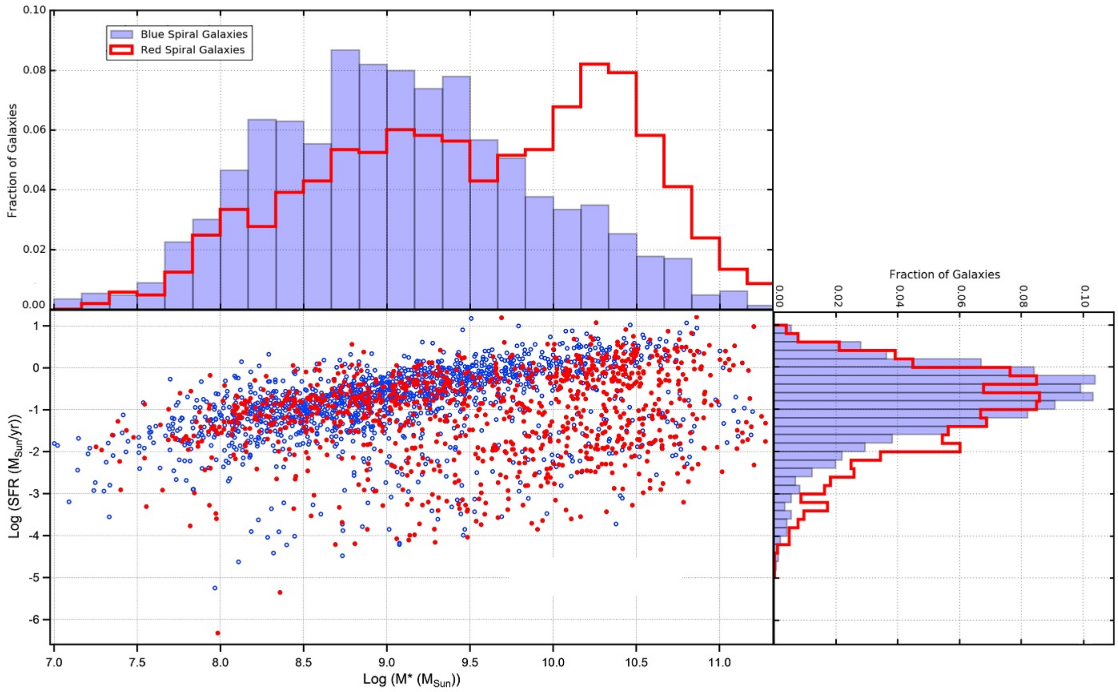

Figure 4.3: SFR vs Stellar Mass

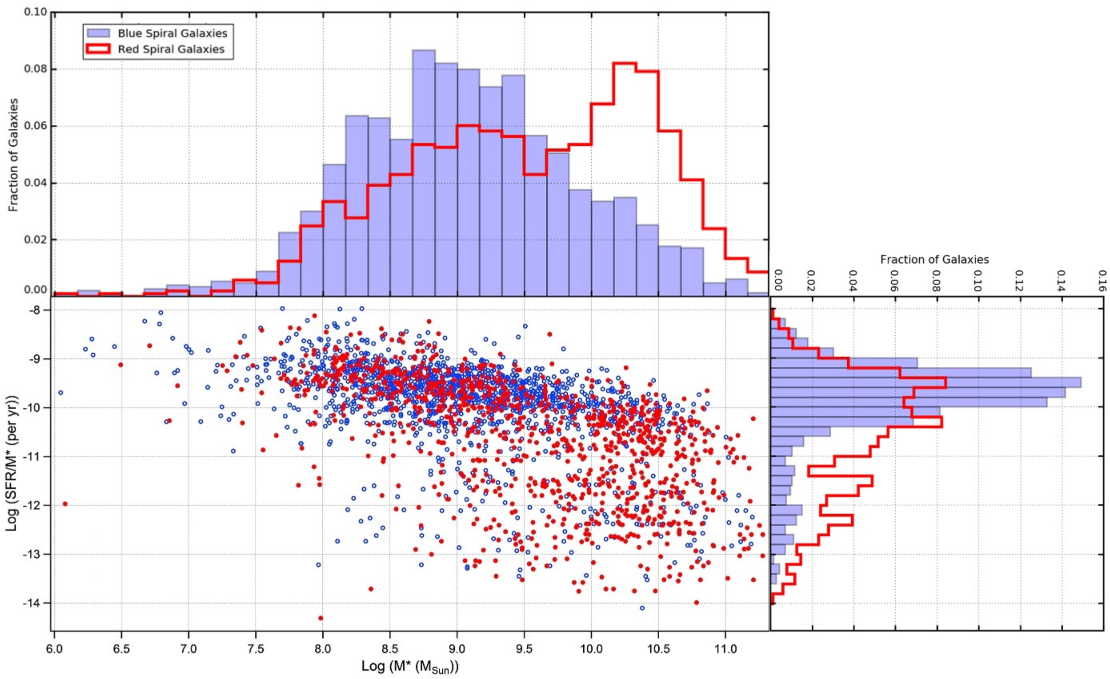

Figure 4.4: sSFR vs Stellar Mass

4.4 Dust Mass to Stellar Mass Ratio

The dust to stellar mass ratio can be used to study evolution of galaxies (Calura et al. 2017). This quantity is a true measure of how much dust per unit stellar mass survives the various destruction processes in galaxies and is observable. The distribution in the dust to stellar mass ratio for the red and blue spiral galaxies shown in Fig 4.5 indicates that the dust mass per unit stellar mass is lower for red spiral galaxies whereas the blue spiral galaxies are dusty (higher dust mass to stellar mass ratio) due to ongoing star formation.

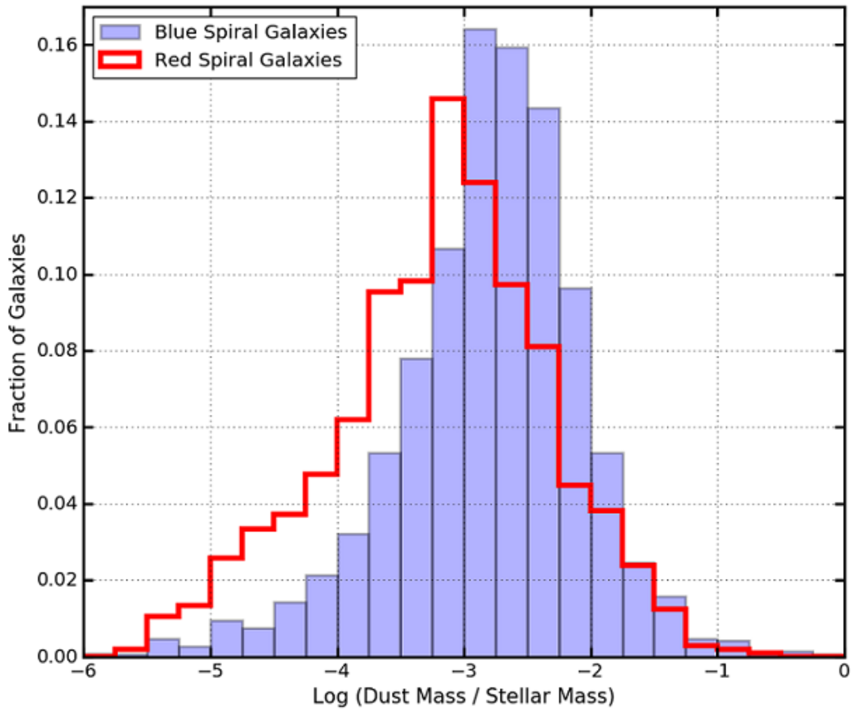

Figure 4.5: Dust Mass per unit Stellar Mass Distribution

4.5 Metallicity

Metallicity (Z) is the fraction of mass of a galaxy that is not in hydrogen or helium. As most of the baryons in the universe are in the form of hydrogen and helium, the word metals is used as a convenient short term for all other elements. Z of a galaxy is an approximate estimation of their chemical abundances that change over time by the mechanism of stellar evolution and therefore provides an indication of its age. It has been shown that metallicity is tightly related not only with the stellar mass, but also with the star formation rate of a galaxy. Here, we have plotted the distribution in metallicity for red and blue spiral galaxies. Fig 4.6 clearly indicates that red spiral galaxies are more metal rich compared to their blue counterparts.

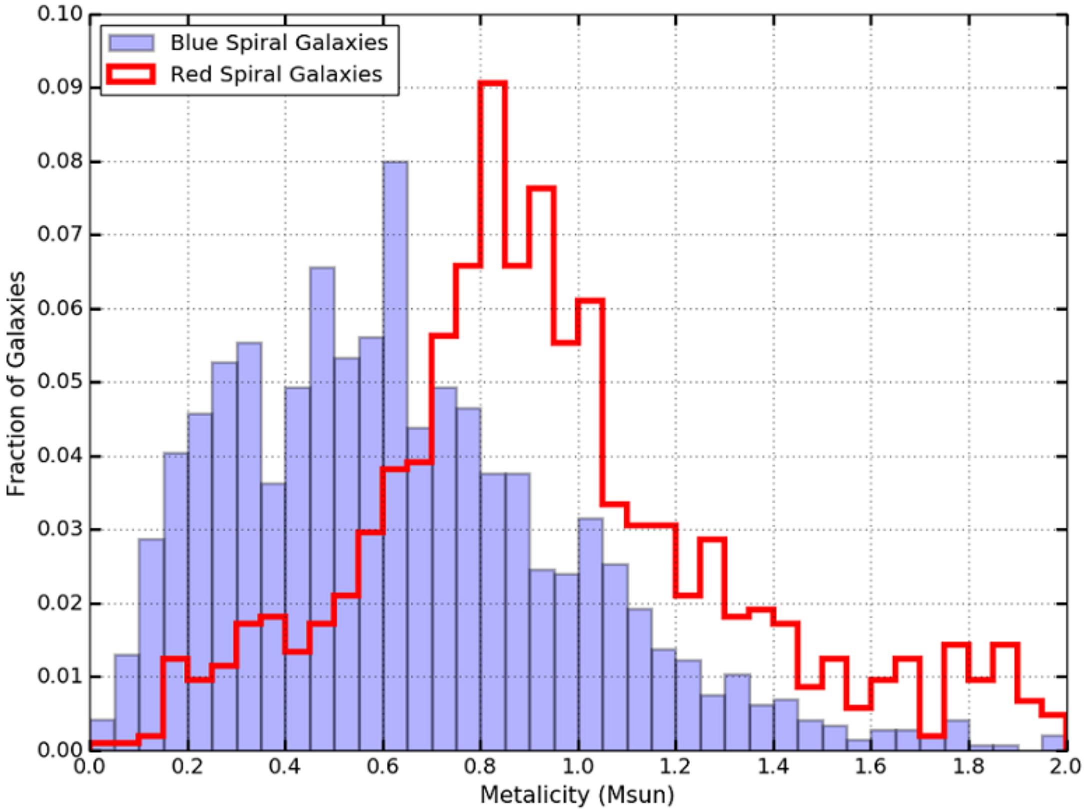

Figure 4.6: Metallicity Distribution for Red and Blue Spiral Galaxies

4.6 Infrared Colour

Using the infrared data collected by the WISE survey, we also looked at the infrared colours (Nikutta et al. 2014) of the galaxies in our sample. We plotted the infrared colour-colour diagrams for W1 - W2, W2 - W3 and W3 - W4 colours, but the relationships between these colour indices was similar for all spiral galaxies with very less scatter. Hence, nothing could be concluded.

Chapter 5

Inclination Angle and Environment of Galaxies

In this chapter, we have studied the effect of environment on the evolution of red spiral galaxies. We have also looked at the effect of orientation on the colour of the galaxy.

5.1 Inclination Angle

We plotted the distribution in the inclination angle of red and blue spiral galaxies. Fig 5.1 shows that this distribution is similar for all spiral galaxies irrespective of their optical colour. Therefore, red colour of some spiral galaxies is not a result of their orientation.

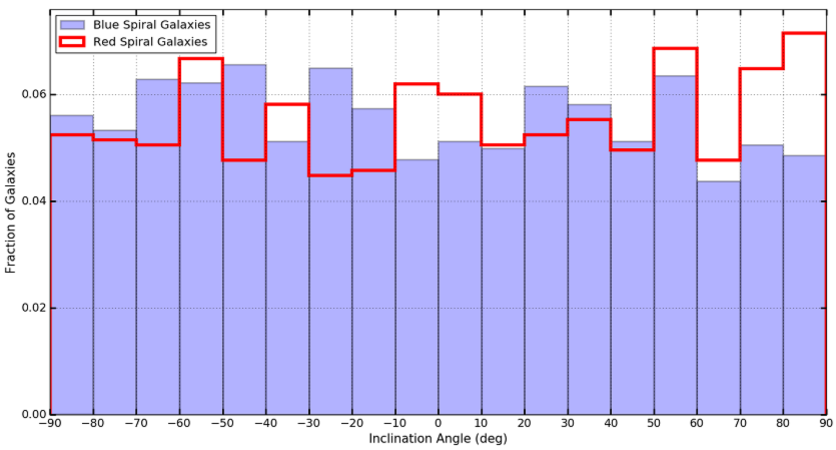

Figure 5.1: Inclination Angle of Red and Blue Spiral Galaxies (p value = 1.95 e-02).

5.2 Environment

It is well established that galaxy mass and environment together concur to shape galaxy properties and that most galaxies preferentially live in aggregates whose size and mass range from galaxy pairs to groups and clusters. Studies have shown that the more massive galaxies residing in dense regions tend to have an early-type morphology as well as older and metal-richer stellar populations, and exhibit a rather low star-formation activity (aka the density - morphology relation, Dressler 1980). On the contrary, galaxies experiencing a significant rate of star formation are typically found in low-density environments (Hashimoto et al. 1998).

Fig 5.2 shows the spread in the distance to the 5th nearest neighbour for the red and blue spiral galaxies. It is clear from this plot that the red spiral galaxies reside in the high density environments as the distance to the 5th nearest neighbour is small compared to the blue spirals.

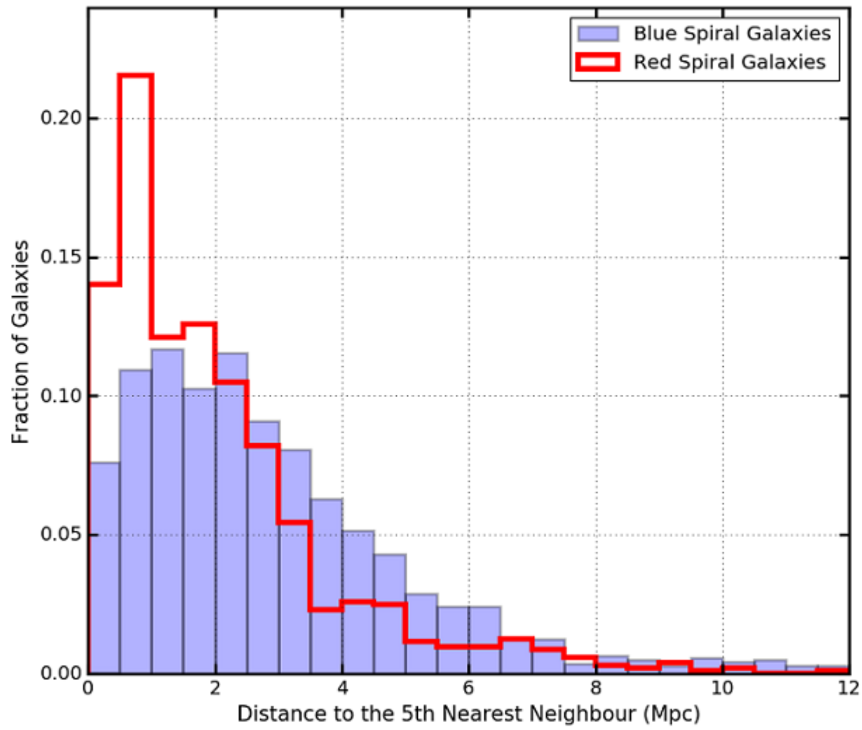

Figure 5.2: Environment of Red and Blue Spiral Galaxies

Chapter 6

Conclusions

The aim of this thesis was to create a sample of red spirals and study their properties. We also intended to determine the reason for their optical red colour.

We started with a sample of all GAMA galaxies in the redshift range 0.002 to 0.06 and from this sample created a sub sample of spiral galaxies and finally a sample of blue and red spiral galaxies each. We then analysed different properties like stellar mass, dust mass, metallicity etc for both the red and blue spiral galaxies which helped us to determine the reason as to why some of the spiral galaxies are optically red. Our results (chapter 4) show that the optical colour of red spiral galaxies is a consequence of their being more evolved due to which they are metal rich as well as more massive and have a low sSFR compared to the blue spiral galaxies. And although the dust mass distribution is similar for all spiral galaxies, the dust-to-stellar-mass-ratio provides a better picture and we can conclude that while the blue spiral galaxies are dusty because they are actively forming stars, the red spiral galaxies have a low dust mass per unit stellar mass. Based on the one to one correlations plotted in the SFR, stellar mass, dust mass and sSFR, we can also state that while the star formation rate of galaxies is directly related to their dust mass and stellar mass, the specific star formation rate is low for massive galaxies. Also, the SFR is more tightly correlated to the stellar mass for blue spiral galaxies as compared to the red ones.

We also found that the red spiral galaxies reside in high density environments, which in turn can be related to their low star formation rates compared to blue spirals. Also, we checked for the effect of orientation on the colour of the spiral galaxies and found that the inclination angle of the blue as well as the red spiral galaxies were uniformly distributed throughout. So, we cannot attribute the optical colour of these galaxies to their orientation.

Finally, we can conclude that not all spiral galaxies are star forming and blue. There exist a significant population of red spiral galaxies as well, which are passive and more evolved. These galaxies are more massive compared to the more common blue spiral galaxies and have less ongoing star formation. They are red because of their higher metal content and are mostly found in high density regions of the Universe. These red spiral galaxies have evolved from the blue spiral galaxies and due to lack of gas are no longer forming stars.

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