Title - Investigation of local environments of elliptical galaxies from the Galaxy and Mass Assembly (GAMA) project

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Abstract

Data from the Galaxy and Mass Assembly (GAMA) project[1] was examined looking for relationships between elliptical galaxies characteristics, colour, mass and metallicity and their local environments. Whilst a direct and obvious relationship was not found, some correlation between the characteristics of a galaxy's local group, especially averages of environmental measures were noted. In addition other aspects of a galaxy's local group were investigated such as separation within the local group. Looking at environment measures for galaxies in the various types of large scale structure, differences were observed especially for those deemed to be in a knot structure. In a similar way to previous research on a galaxy's satellites, local groups with five or more galaxies were investigated looking at galaxy types and red fraction and their dependance on environment.

1 Introduction

The presiding inference from a large body of research is that the universe we see today is initially the result of very small deviations which have grown over a very long timescale from the time when the universe was a plasma. We have evidence of the nature of the plasma before the recombination epoch in the form of the cosmic background radiation which has today cooled and is a uniform 2.725 Kelvin with variations of only 0.0002K. The profile of the radiations wavelength follow a Planck function so well that it is stated to be a nearly perfect blackbody.

We know that dark matter makes up around 27% of the universe and the consensus is that an initial primordial field of dark matter has evolved under the influence of gravity over a very long time, giving rise to the variations in regional density that we see today. That a galaxy's local environment is strongly influenced by dark matter halo mass, research such as[2] has shown that there is a correlation between galaxy/halo/dark matter and the environment. Older galaxies are also more strongly clustered in denser environments. Data from the Galaxy Redshift Survey[3] and the Sloan Digital Sky Survey[4] accord very well with the premiss that large-scale structure formation is formed as a result of the cold dark matter (CDM) paradigm[5]

Intensive studies of galaxy clusters have demonstrated a clear connection between galaxy properties and environment[6] with possible evolution[7] leading to the conclusion that for red early-type galaxies which dominate galaxy clusters, their properties depend on their environment.

With such a large body of research indicating that the redness of early type galaxies is related to their environment then one would expect to find obvious and direct relationships between a galaxy's redness and its environmental measures. The aim was therefore to examine the results of the GAMA survey for the relationships between a galaxy's characteristics and its environmental measures.

1.1 Data & Method

1.1.1 GAMA Survey[1]

The objective of the GAMA survey is the collection of data from various projects to facilitate study of cosmology and galaxy formation. It covers approximately 375,000 galaxies with magnitudes down to 19.8 rmag, over a 360 degree region of the sky looking at the structure at scales of 1kpc to 1Mpc.

The prime sources of the data are

- Anglo Australian Telescope
- Data from the Sloan digital sky survey (SDSS)
- 2dF Galaxy Redshift Survey
- Millennium Galaxy Catalogue (MGC)

1.1.2 Method

The GAMA Survey website suggests that for python usage, the data could be accessed using astroquery[8] but as astroquery does not have facilities for selectively joining and manipulating tables, a more flexible approach was to download the GAMA data and then process with the python package astropy table[9] that has facilities to subset and join tables. Details of the tables and their contents are available at the GAMA survey website[10]. Python programs were created in Jupyter[11] and the data analysed using the following python packages

- Astropy Tables
- Matplot, numpy, scipy, seaborn and pandas

Red elliptical galaxies

- For single elliptical galaxy information, the following tables were joined on CATAID, StellarMasses, EnvironmentMeasures and VisualMorphology. A subset was created by just selecting

$$ELLIPTICAL\,CODE = 1 \; i.e \; elliptical \; galaxy.$$

- Prior to the join, tables were subsetted to select only valid measurements and ranges.

Local groups

- For local group information
  - G3CGalv was used as the primary table joining others such as the above using CATAID.
  - Selecting out GroupID = 0 to remove galaxies not in a local group.
  - For galaxy information within its local group, a new table was created using the group_by(GroupID) facility and performing such calculations of mean etc.
  - The resulting table was then joined with G3CFoFGroup using GroupID in order to obtain local group information such as TotRMag.
- Test Pearson and Spearman correlations between variables.
- Produce density maps and other charts.

1.2 Units

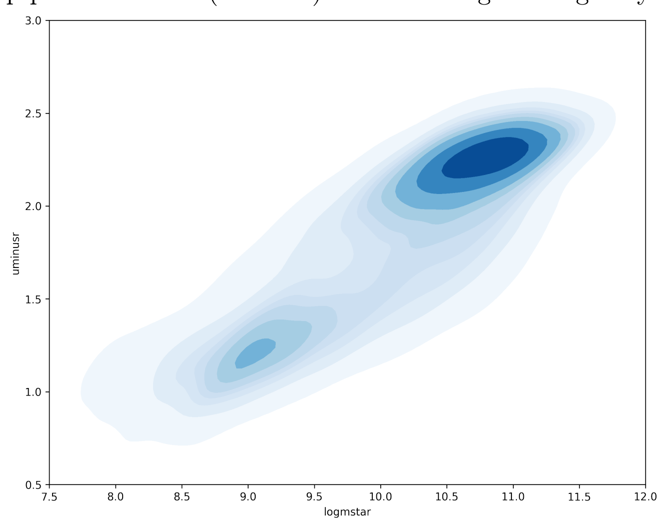
Throughout the report

- Colour redness uminusr is in magnitudes
- Mass logmstar is in dex(Msun) which is $10^x \times M_\odot$

1.3 Two galaxy groups

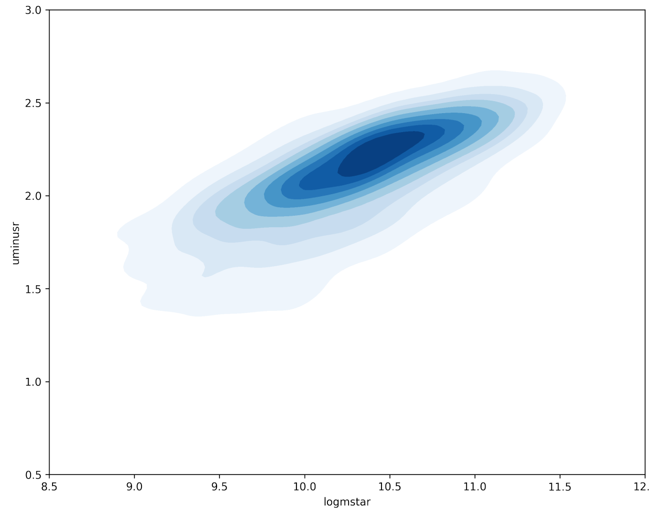
It has been well researched that galaxies fall into two colour spaces[12, 13]. This can be seen by a density map plot of redness (uminusr) versus the log of the galaxy star mass (logmstar) see figure 1

Figure 1: Density map plot of redness (uminusr) versus the log of the galaxy star mass (logmstar)



By explicitly choosing the x range and y range, one could select a subgroup based on uminusr and logmstar as in[12, 13]. However the GAMA survey also has categories of galaxies based on visual information. By selecting a subset of galaxies marked as visually elliptical and repeating the uminusr/logmstar density as shown in figure 2 , confirms that elliptical galaxies are redder and form one of the groups.

Figure 2: Density plot for elliptical galaxies redness (uminusr) versus the log of the galaxy star mass (logmstar)



The results of correlation and linear regression tests are documented in table 1

Table 1: Correlation results of colour versus log mass

Correlation	Value	p
Pearson	0.709	0
Spearman	0.741	0
Regression	Slope	Intercept
Linear regression	0.360	-1.590

2 Galaxy environmental measures

The measurement of local galaxy environment is covered in a number of papers[14, 15, 16, 17]. The GAMA survey provides the following as the main measures of a galaxy's local environment

- CountInCyl
- DistanceTo5nn
- SurfaceDensity
- AgeDenPar

2.1 CountInCyl - Count In Cylinder

The number of other galaxies from the density defining population within a cylinder of co-moving radius 1 Mpc and a velocity range of $\pm 1000 km/s$.

The over density is given by $CountInCyl/(nba\_ref * volume\_of\_cylinder)$ where $nbar\_ref = 0.00734 Mpc^{-3}$ is the average number density of the density defining population.

2.2 DistanceTo5nn - Distance to 5nn

The distance to 5th nearest neighbour in comoving units within $\pm 1000 km/s$.

2.3 SurfaceDensity - Surface Density

The surface density based on the distance to the 5th nearest neighbour among the density defining population in a velocity cylinder of $+/-1000 km/s$, i.e. $5/(Pi * DistanceTo5nn^2)$.

2.4 AgeDenPar - Age Density

The adaptive Gaussian density parameter, as introduced by Schawinski et al[18] and later described by Yoon et al[19]. The value is calculated by first identifying all other galaxies from the density defining population in an adaptive Gaussian ellipsoid, defined by the following

$$(r\_a/(3 * sigma))^2 + (r\_z/(AGEScale * 3 * sigma))^2 <= 1,$$

where r_a and r_z are the distances from the centre of the ellipsoid (i.e. from the position of the galaxy in question) in the plane of sky and along the line-of-sight in co-moving Mpc, respectively, and $sigma = 2Mpc$.

$$AGEScale = 1 + (0.2 * n\_gals\_with\_2Mpc)$$

is used to scale the value of sigma along the redshift axis

$$AGEDenPar = 1/sqrt(2*pi)/sigma*SUM\_i \quad exp(-0.5*((r\_a, i/sigma)^2+(r\_z, i/AGEScale*sigma)^2))$$

Effectively, this parameter is equivalent to a weighted local volume density of galaxies, where closer galaxies receive more weight than more distant ones.

3 Main characteristic measures

3.1 Galaxy

- uminusr - Rest frame (u-r) colour from Spectral Energy Distribution (SED) fit - units magnitude.
- logmstar - Stellar mass within the photometric aperture i.e. not allowing for mass that falls outside of the aperture used for the spectral energy density measurement.

3.2 Local group

- TotRmag
- $\Sigma\, logmstar = log_{10}(\Sigma 10^{logmstar})$

4 Investigation of correlations

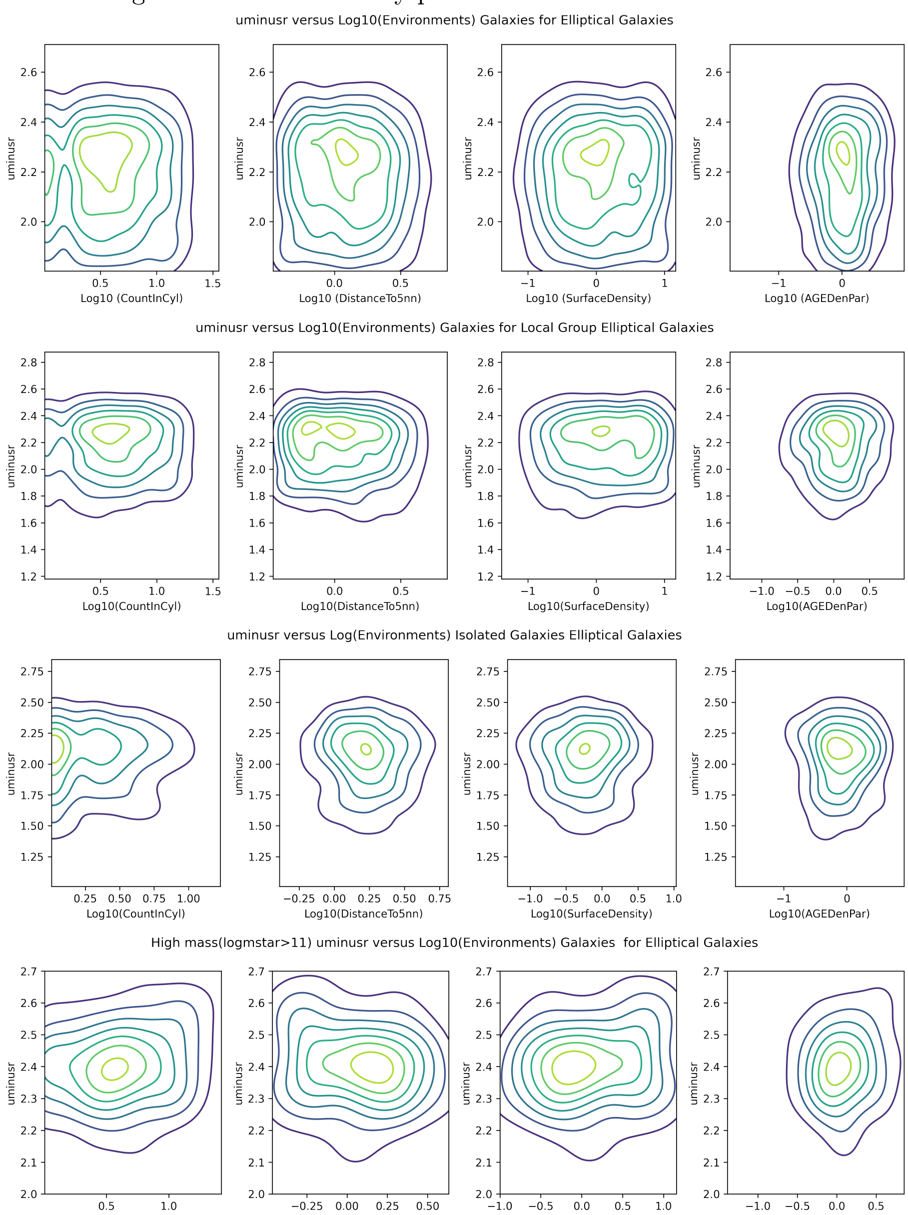
4.1 Redness uminusr density plots & correlations for elliptical galaxies

4.1.1 All elliptical galaxies

Density map plots and correlation uminusr versus log_{10} of the environmental measures for four sets of elliptical galaxies see figure 3 and table 2

- All elliptical galaxies.
- Elliptical galaxies that were in a local group of more than one galaxy.
- Isolated elliptical galaxies i.e. unique GroupID.
- Set of elliptical galaxies with logmstar $>$ 11.

Figure 3: Redness density plots for environmental measures



As can be seen from the plots, there is no obvious relationship between the colour (uminusr) of an elliptical galaxy and the four main environmental measures. The full range of uminusr values extends over the full range of environmental measures. Pearson and Spearman correlation values are documented in table 2 and also show no obvious relationship. Pearson and Spearman are standard statistical correlation tests. The reason for including a Spearman test was because it gives a better measure when dealing with outlying and logarithmic values. Similar results were obtained for mass (logmstar)

The rational for trying galaxies with logmstar>11 was that research had indicated a possible relationship in high density environments.

Table 2: uminusr - log(Environmental measures) - correlation values

Environment Measure	Pearson		Spearman	
	Correlation value	p-value	Correlation value	p-value
Log(CountInCyl)	0.0552	0.0184	0.0575	0.0142
Log(DistanceTo5nn)	-0.0724	0.0020	-0.0692	0.0031
Log(SurfaceDensity)	0.0716	0.0023	0.0695	0.0030
Log(AGEDenPar)	0.0494	0.0352	0.0493	0.0354

4.2 Absolute red magnitude absmag_r density plots & correlations for elliptical galaxies in a local group

Using absolute red magnitude also did not show any correlation.

5 Local group information

Two local group measures were looked at

- TotRmag - being the r-band absolute magnitude of the group, obtained by adding up all the r-band luminosities of its members
- Sum of logmstar within the local group $\Sigma\, logmstar = log_{10}(\Sigma 10^{logmstar})$

5.1 Method

The analysis of the group information was carried out on data downloaded for the GAMA website and loaded into astrotables. The tables were then processed as follows

- Table GroupFindings - G3CFoFGroup contains TotRmag which is computed as the r-band absolute magnitude of the group, obtained by adding up the r-band luminosities of its members.
- Table GroupFinding - G3CGal contains unique galaxy identifies CATAID and which group they are in GroupID, single galaxies having a GroupID of 0.
- G3CGal was joined with EnvironmentMeasures to add environmental measures information.

A local group to galaxy is a one to many relationship. Joining G3CGAL with G3CFFGroup on GroupID results in a table with a unique key of CATAID (galaxy identifier) and group information being repeated for each galaxy in the group.

As such, differences between environmental measures of galaxies with the local group will work against the calculation of correlation and be a spread in the density plots.

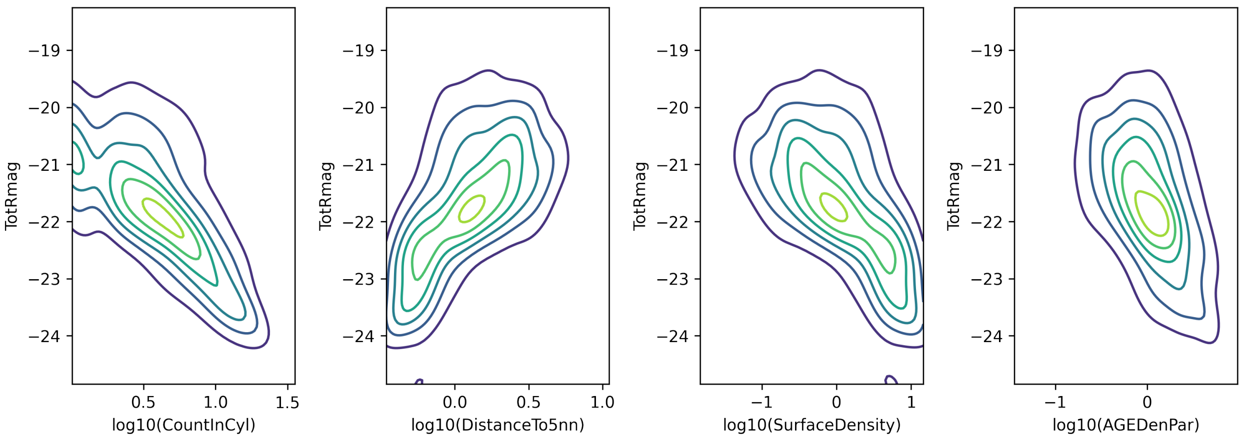
Means for group environmental measures were calculated using the GroupBy facility.

5.2 Group characteristics verses log10(Environment measures)

5.2.1 Group absolute red magnitude - TotRmag total versus log10(Environmental measures)

One would not normally expect a high degree of correlation looking at a characteristic of a group versus different characteristics of individual members of the group. However a degree of correlation was found between group measures and the log of environmental measures of the galaxies within the local group. The fact that members of the local group have different environmental measures means these differences act as a sort of noise signal on any density plot or calculated Pearson, Spearman correlation see figures 4

Figure 4: Density plots - group redness (TotRmag) versus log10(environments) for elliptical galaxies



The results of running linear regression tests are documented in table 3

Table 3: Linear regression of group redness (TotRmag) with log10(galaxy environment measures)

Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log10(CountInCyl)	-0.639	7.731e-144	-0.646	4.86e-148	-2.105	-20.46
Log10(DistanceTo5nn)	0.577	3.599e-111	0.619	3.279e-132	2.298	-21.87
Log10(SurfaceDensity)	-0.576	6.448e-111	-0.620	4.705e-133	-1.123	-21.62
Log10(AGEDenPar)	-0.379	1.100e-43	-0.410	1.223e-51	-1.132	-21.68

The diagonal nature of the contours show there is a correlation.

5.2.2 Group mass - sum logmstar versus log10(Environmental measures)

A similar exercise was carried out for galaxy mass - logmstar within their local group using the following calculation

$$\Sigma \, logmstar = log_{10}(\Sigma 10^{logmstar})$$

Density map plots and regression analysis were produced for the sum of local group logmstar versus the four galaxy environmental variables CountInCyl, DistanceTo5nn, SurfaceDensity and AGEDenPar.

Figure 5: Sum of logmstar for local group versus log10 (Environments) for elliptical galaxies

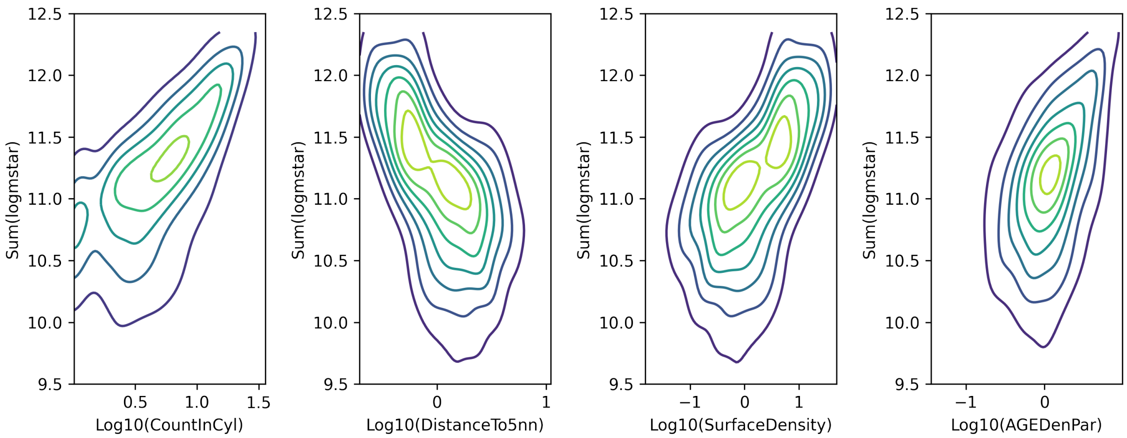


Table 4: Linear regression of group sum of logmstar with log(galaxy environment measures) for elliptical galaxies

Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log10(CountInCyl)	-0.654	1.34e-174	-0.472	7.34e-80	-0.776	19.67
Log10(DistanceTo5nn)	0.634	1.50e-155	0.625	3.68e-155	2.522	18.58
Log10(SurfaceDensity)	-0.637	1.498e-163	-0.627	6.53e-157	-1.232	19.21
Log10(AGEDenPar)	-0.475	5.80e-81	-0.460	1.15e-75	-1.433	18.91

As was found for colour uminusr, the sum of the masses for the local group had some correlation with galaxy environment measures and is supported by the diagonal nature of the contours.

5.3 Group characteristics verses Means of log10(Environment measures)

In order to achieve a one to one correspondence between a group characteristic and an environmental measure, a similar exercise was performed on the group characteristics versus the means of logs of the environmental measures see figures 6 and 7. the use of means being a different way of handling the differences within the local group. Given the differences between galaxies with a local group one would not expect to see values as high as 0.8 - 0.9 but the observed correlation values of 0.6 - 0.7 show there is some correlation. The most likely explanation as to why such correlations do not show up with the analysis of individual galaxies, is that there are a wide range of values for individual galaxies. It is only when you subset them on a group basis that some correlation is observed as a result of the group characteristics being influenced by the density within the universe which is also effecting the individual environmental measures.

5.3.1 Group absolute red magnitude - TotRmag total versus log10 of Mean(Environmental measures) within the local group

Figure 6: Elliptical galaxies density Plots for TotRmag versus Log10 (Means of Environments)

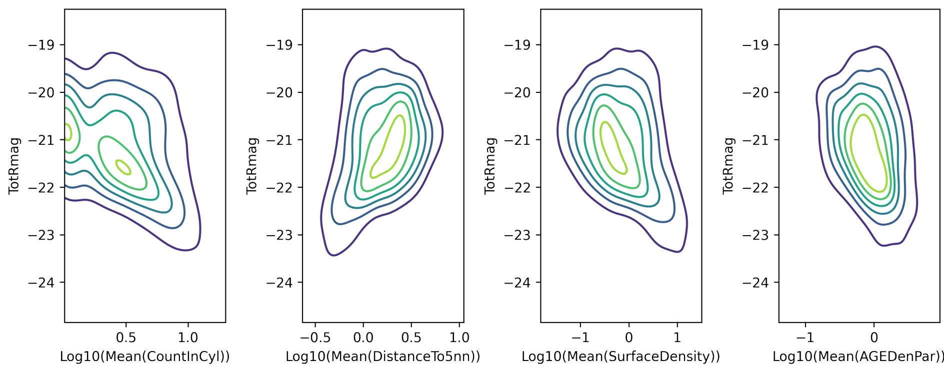


Table 5: Correlations and linear regression results for TotRMag versus log10(Mean(Environment Measures))

Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log10(CountInCyl)	-0.353	4.01e-21	-0.380	1.56e-24	-1.152	-20.58
Log10(DistanceTo5nn)	0.326	4.35e-18	0.369	3.6e-23	1.29	-21.34
Log10(SurfaceDensity)	-0.339	1.59e-19	-0.385	3.22e-25	-0.64	-21.18
Log10(AGEDenPar)	-0.256	1.55e-1	-0.254	2.13e-11	-0.702	-21.15

Figure 9shows contours that have a degree of diagonality and table 5shows the degrees of correlation.

5.3.2 Group mass - sum logmstar versus log10 (Means(Environmental measures) within the local group.

Figure 7: Elliptical galaxies of logmstar for local group versus log10 (Mean(Environments))

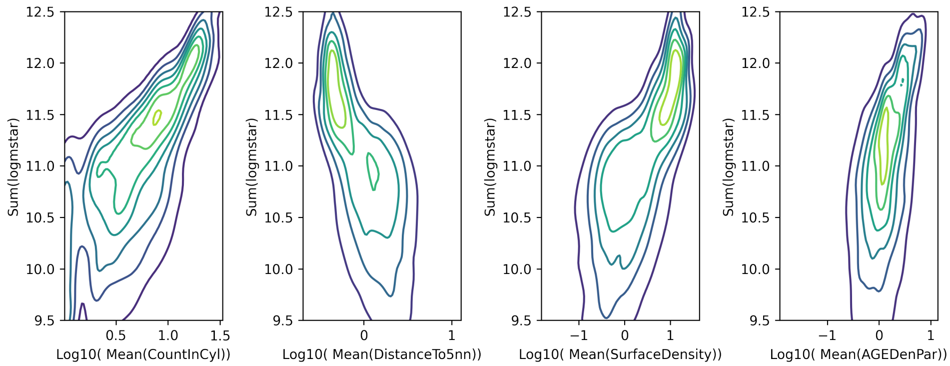


Table 6: Linear regression of group sum of logmstar with log(Mean galaxy environment measures) for elliptical galaxies

Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log(CountInCyl)	0.680	0	0.673	0	1.396	9.93
Log(DistanceTo5nn)	-0.647	0	-0.608	0	-1.61	10.89
Log(SurfaceDensity)	0.671	0	0.639	0	0.777	10.67
Log(AGEDenPar)	0.524	0	0.534	0	1.141	10.742

Comparing the results in table 6 with those of table 4 which is using single measure of the mean of all galaxies within the group, produced slightly better degrees of correlation in contrast to the results for TotRMag.

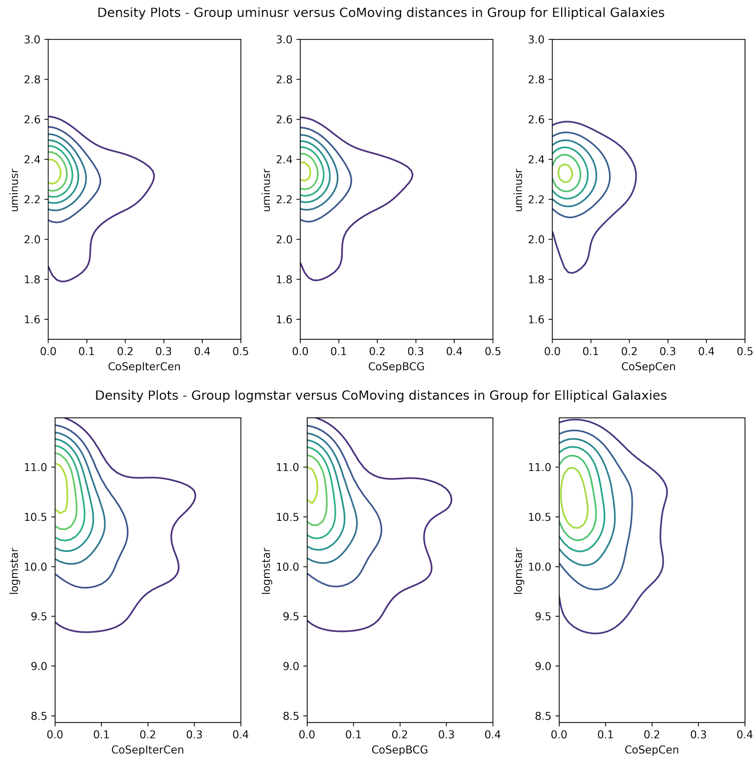
The density maps for the mean environment measures show a small degree of correlation between TotRMag but comparing table 3 with 5, the Pearson and Spearman coefficients for the mean of environmental measures are less when comparing the individual galaxies grouped by local group.

5.4 Elliptical galaxies - variations of measures with positions within local group

5.4.1 Density Plots

Group table G3CGal provide the relative positions of galaxies within their local group. Density plots for the three types of comoving distance of a galaxy from the centre of its local group CoSepIterCen, CoSepBCG, CoSepCen are shown in figure 8 .

Figure 8: Elliptical galaxies uminusr & logmstar density plots for comoving distances to the centre of the galaxies local group.



When looking at the positional information, it is important to remember that galaxies are three dimensional whereas the data is represented in two dimensions, the y axis being the measure uminusr or logmstar and the x axis the distance from the centre of the local group. There are a number of ways of defining the centre of a group. The most common measure quoted in astrophysics literature is CoSepBCG.

- The centre of light - Cen
- The Brightest Cluster Galaxy - BCG
- The brightest galaxy left after iteratively removing the most distant galaxies from the group centre of light - IterCen

The statistics for local groups measures uminusr and logmstar are summarised in table 7.

Table 7: Statistics for measures uminusr and logmstar

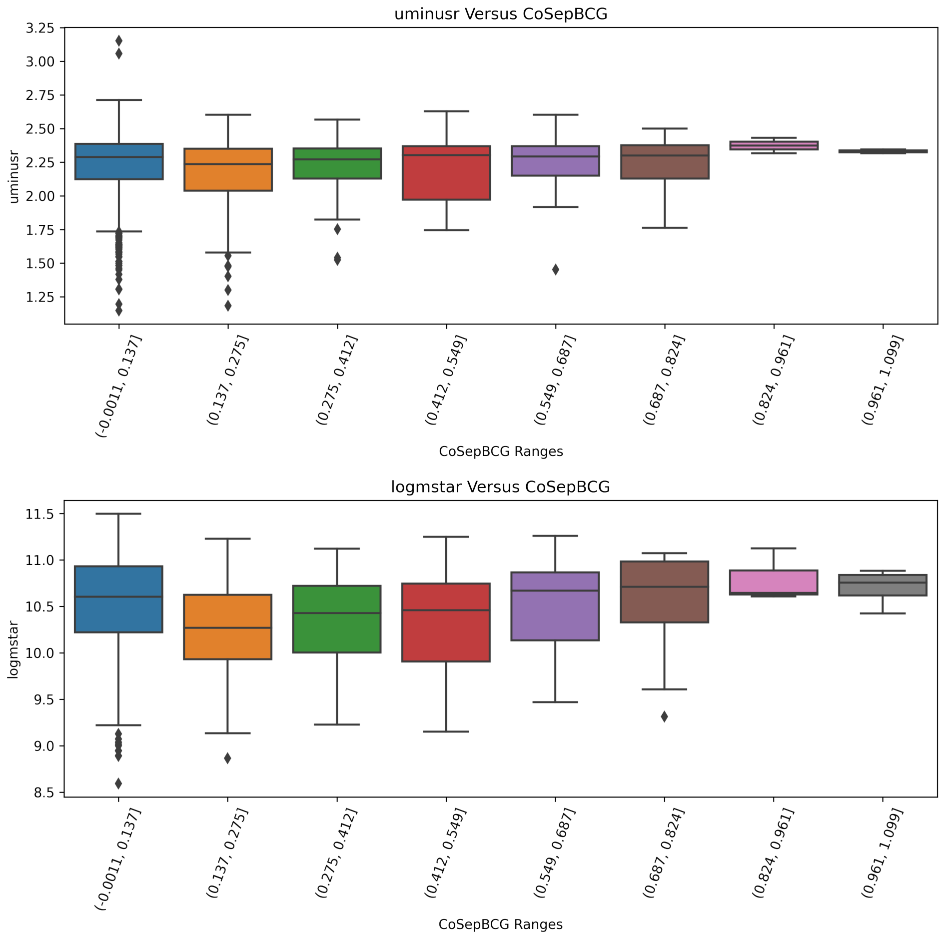
Measure	Median	Mode
uminusr	2.286	2.232
logmstar	9,560	10,474

5.4.2 Histogram ranges

The comoving distances from galaxies to the brightest cluster galaxy BCG (this being the commonest measure of centre of a local group) are split into eight equal ranges and a histogram of uminusr values for the range created. A second histogram is created for logmstar across the ranges, see figure 9.

The data uminusr & logmstar was also plotted as box plots for eight equal ranges of CoSepBCG

Figure 9: Elliptical galaxies uminusr & logmstar versus ranges of CoSepBCG



5.4.3 Observations

- As can be seen from the density plots 8 and box plot histograms 9, the central core of uminusr and logmstar values occur over only a small range of CoSepBCG, approx 0.25 for uminusr and 0.75 for logmstar
- That this same core extends out for the first 6 of the 8 ranges i.e. 75% of CoSepBCG ranges
- Closer to the centre of the local group there are a small number of galaxies which have a larger range of values, especially with values below the mean.
- From the density plots, the spread of values below the mode for the local group is larger than that above.

6 Galaxy types within local group

Several research papers[20, 21, 22] have shown a correlation between the fraction of red satellite galaxies within a radial distribution, although there is some uncertantity over the best environmental measure to use.

It was decided to perform a similar exercise on the galaxy types with local groups with more than 5 members. Looking at all groups did not produce clear information and in a group of five a single galaxy would represent 20%

6.1 Galaxy type and CoSepBCG

Galaxy types within ten equal ranges of the comoving distances to the centre of local groups as measured from the brightest cluster galaxy were investigated. Figure 10 shows the galaxy counts in each range and figure 11 the counts expressed as percentages.

As can be seen from the charts

- The number of all galaxies decreases rapidly with the comoving distance
- Spiral galaxies far out number older red elliptical galaxies
- That the mixture of galaxy type does not change significantly with the comoving distance

Figure 10: Galaxy type by range of CosepBCG

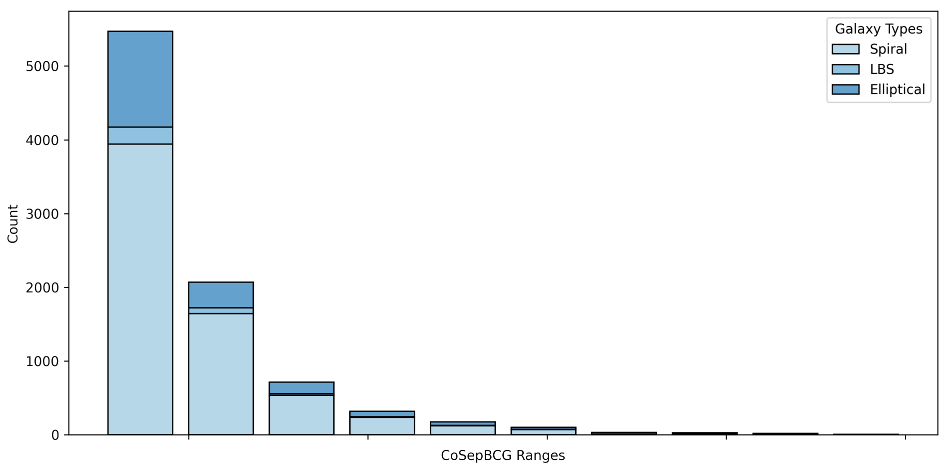
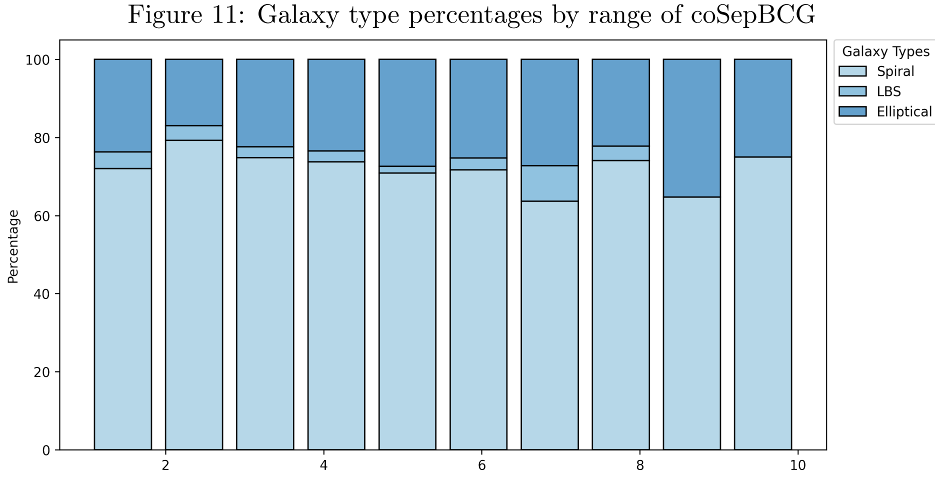


Figure 11: Galaxy type percentages by range of coSepBCG



6.2 Galaxy type within ranges of the sum of masses within local groups.

A similar exercise was carried out for galaxy type within ten equal ranges of the sum of the masses of galaxies with the group, the sum being calculated as

$$\Sigma\, logmstar = log_{10}(\Sigma 10^{logmstar})$$

Counts are shown in figure 12 and percentages in figure 13
It can clearly be seen that

- The number and ratio of red elliptical galaxies increases in local groups of larger mass.
- That low mass groups are dominated by spiral galaxies
- The occurrence of Large Blue Stars (LBS) decreases in larger mass groups

Figure 12: Local group : galaxy type by range of sum(logmstar)

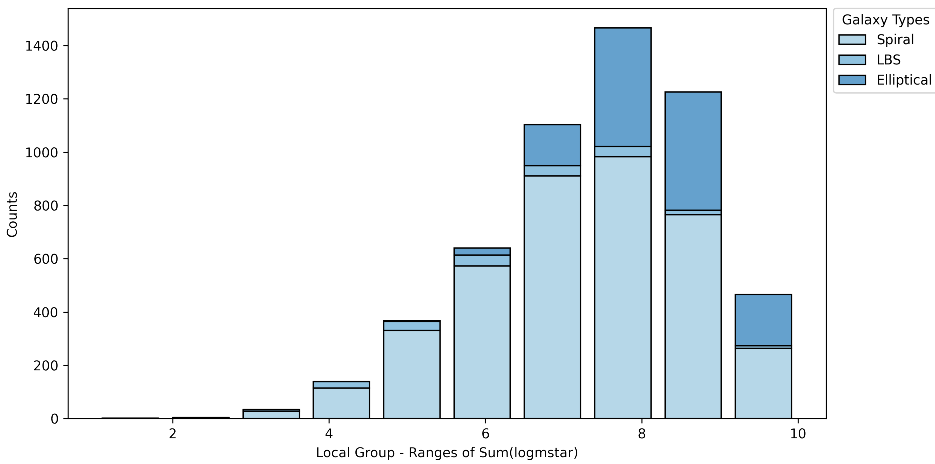
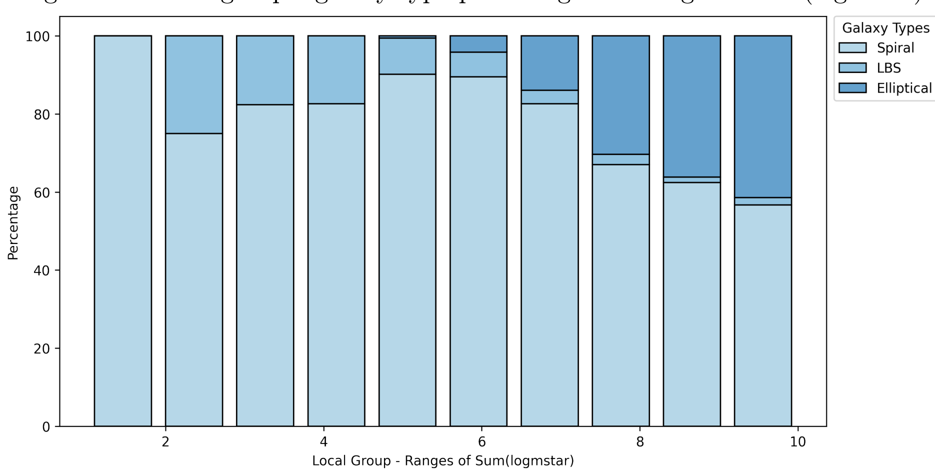


Figure 13: Local group : galaxy type percentages for ranges of sum(logmstar)



6.3 Galaxy type percentages versus mean of log10 Environments

Again the papers[20, 21, 22] had shown a relationship between the percentage of red satellite galaxies and the environment so a similar exercise was carried out for local groups which contained more than 5 galaxies. The resulting density plots are shown in figure 14 and the correlation results and linear regression in table 8. As can be seen, there is a reasonable degree of correlation with the various environmental measures apart from AGEDenPar.

Figure 14: Density Plots : Elliptical galaxies in local groups with more than 5 galaxies versus log10(Mean(Environment Measures)

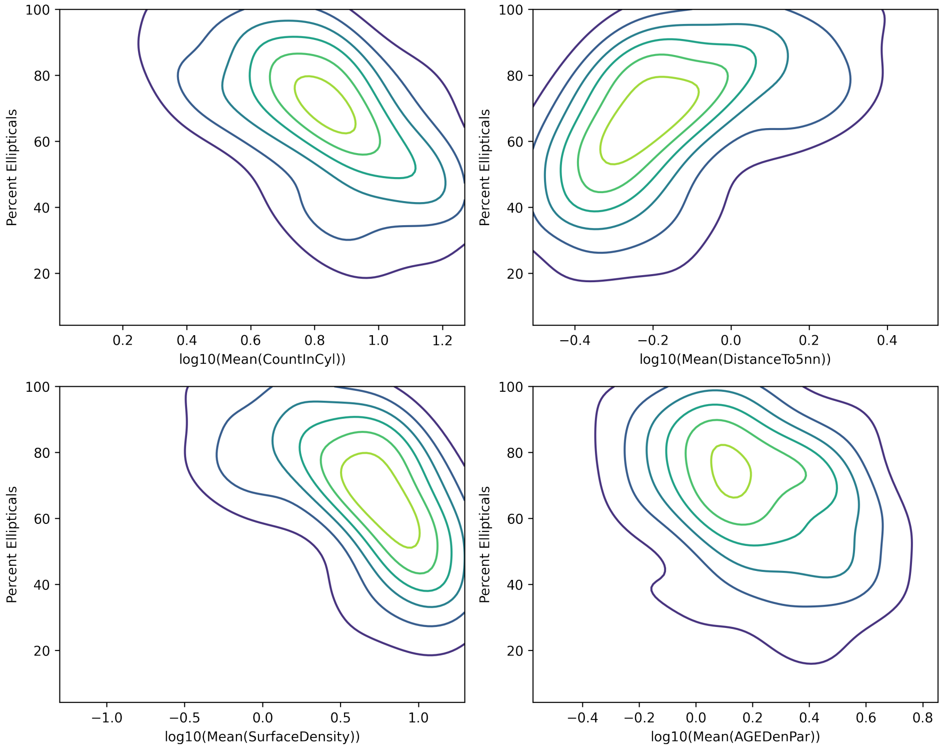


Table 8: Correlation and Linear Regression for Percentage of red elliptical galaxies and log10(Mean(Environment Measures))

Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log10(CountInCyl)	-0.541	3.07e-13	-0.556	5.03e-14	-44.86	103.40
Log10(DistanceTo5nn)	0.480	2.38e-10	0.522	2.68e-1	44.62	72.65
Log10(SurfaceDensity)	-0.504	2.01e-11	–0.557	4.25e-14	-21.20	79.07
Log10(AGEDenPar)	-0.284	3.0e-4	-0.287	2e-4	-22.20	71.11

6.4 Galaxy characteristics versus measures for local groups with more than 5 members

Having established a degree of correlation between the percentage of elliptical galaxies and environments for galaxies in local groups with more than 5 galaxies, it was decided to revisit investigating any relationship between uminusr and logmstar for the subset of such galaxies. However, the density plots and correlation results did not indicate any direct relationship see figures 15 and 16.

Figure 15: Density Plots : uminusr versus log10(environments) for the subset of elliptical galaxies in local groups containing 5 or more galaxies

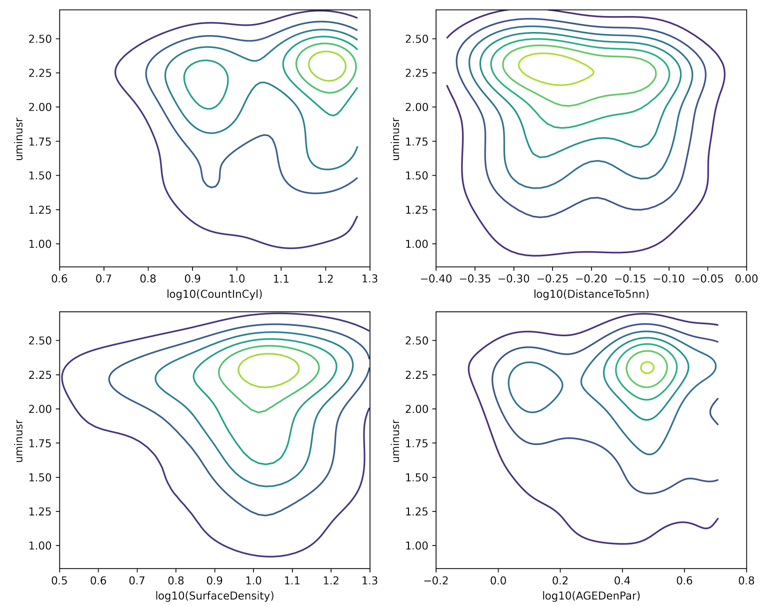
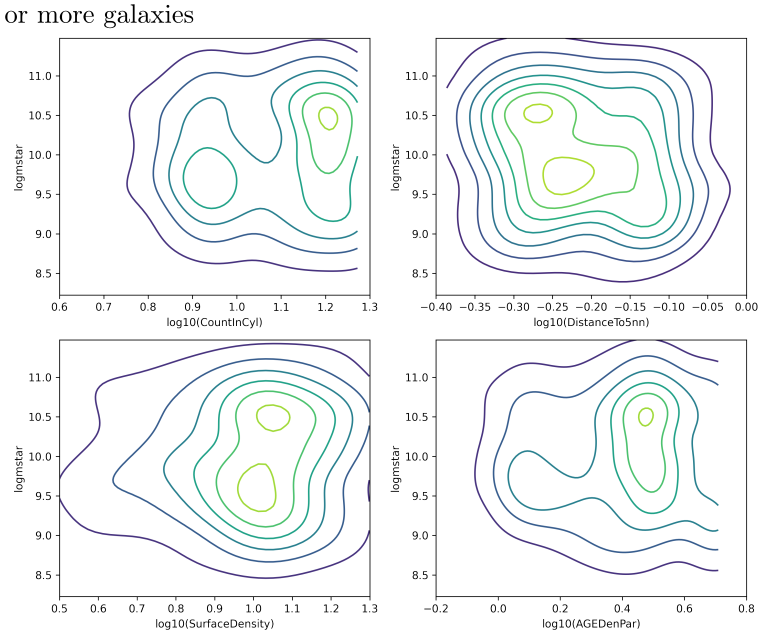


Figure 16: Density Plots : logmstar versus log10(environments) for the subset of elliptical galaxies in local groups containing 5 or more galaxies



7 Galaxy structure classifications

Whilst on very large scales, the universe is homogeneous. We know that on lesser scales there is structure influenced by the distribution of dark matter. For GAMA II, equatorial regions were classified at each point as either in a

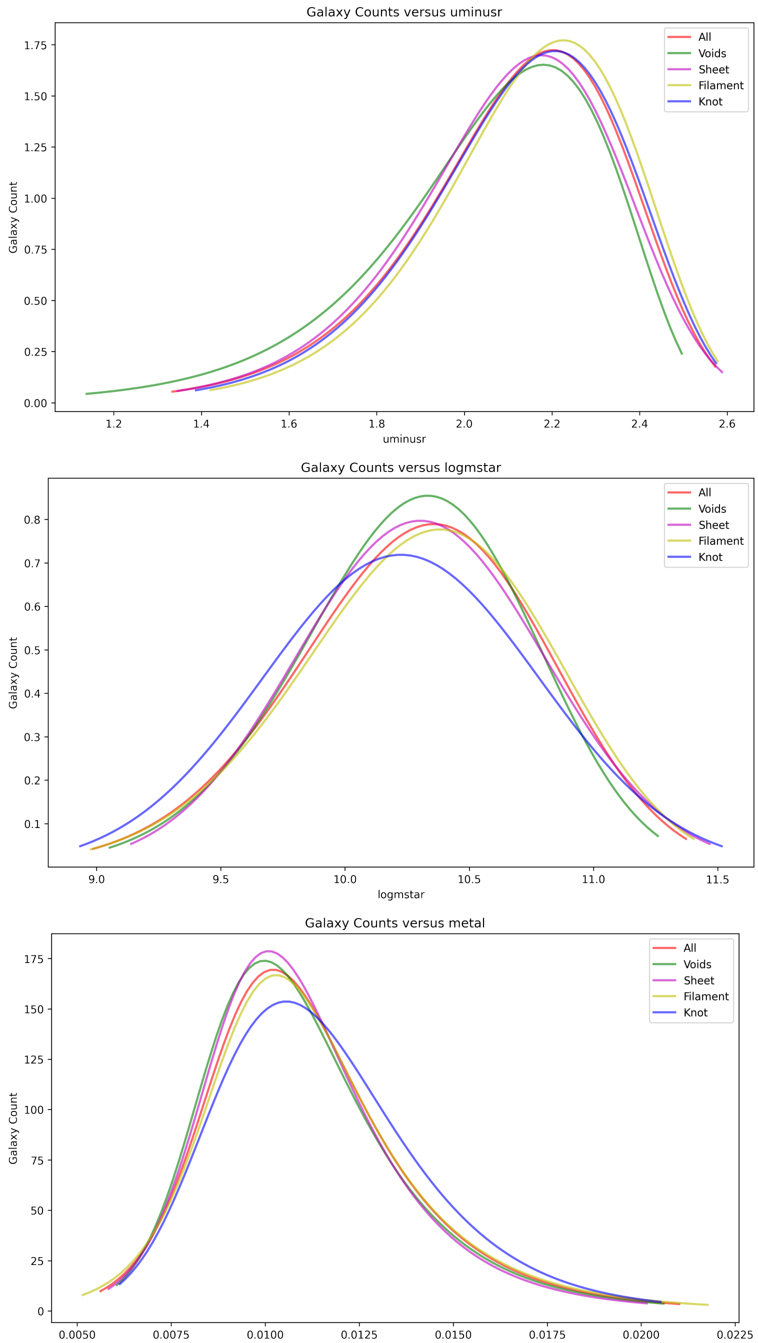
- Void - no other galaxy with the range of 1 to 10 Mpc. approx.
- Sheet
- Filament
- Knot

The classification system is based on evaluation of the deformation tensor (i.e. the Hessian of the gravitational potential) on a grid[23]. The number of eigenvalues above an imposed threshold indicates the number of collapsed dimensions of structure at that location - either 0, 1, 2 or 3, corresponding to a void, sheet, filament or knot, respectively. The classification of the grid, as given in the GeometricGrid table, allows the geometric environment of any object within the grid (any object in the G09, G12 or G15 regions with $0.04 < z < 0.263$) to be determined by assigning the object the same environment as the cell of the grid in which the object is located.

7.1 Distributions of galaxy counts by characteristic measures for the different galaxy structural types

Figure 17 show fitted distribution curves for galaxy measures uminusr, logmstar and metal(metallicity) for elliptical galaxies. Apart from the case of environment type knot, which has higher characteristic masses, the distributions for the various galaxy environment types are similar

Figure 17: Elliptical galaxy counts for galaxy characteristics by galaxy structure type



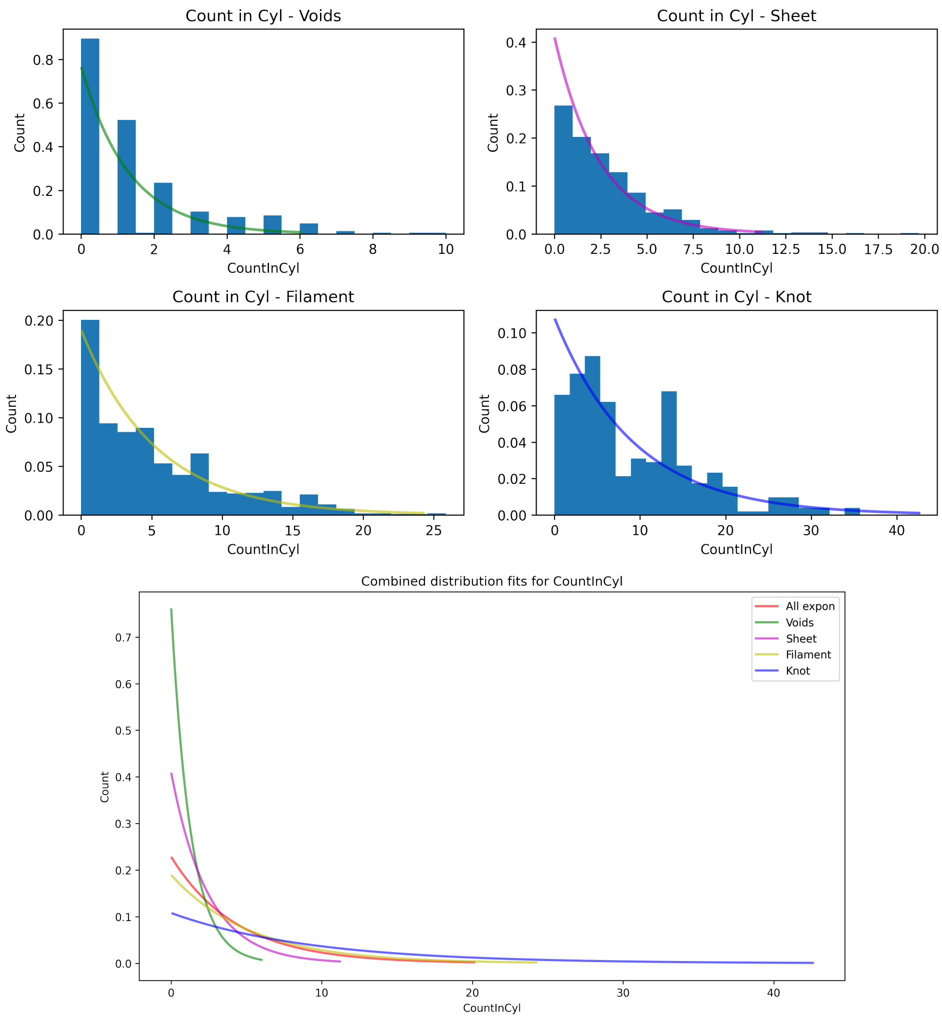
7.2 Distributions of galaxy environment measures by galaxy structural type

The distribution of environmental measures between the four large scale structure types were examined and a distribution curve fitted to the counts versus environmental measures. The distribution curves were then plotted on the same chart. This illustrates that there are marked differences in the environmental measures between large scale structure types and was most obvious for the measures Distanceto5nn and AgeDenPar.

7.2.1 CountInCyl

Figure 18 provides for CountInCyl, a histogram and fitted distribution for each of the galaxy structural types and a combined fitted distribution for all structural types on one plot.

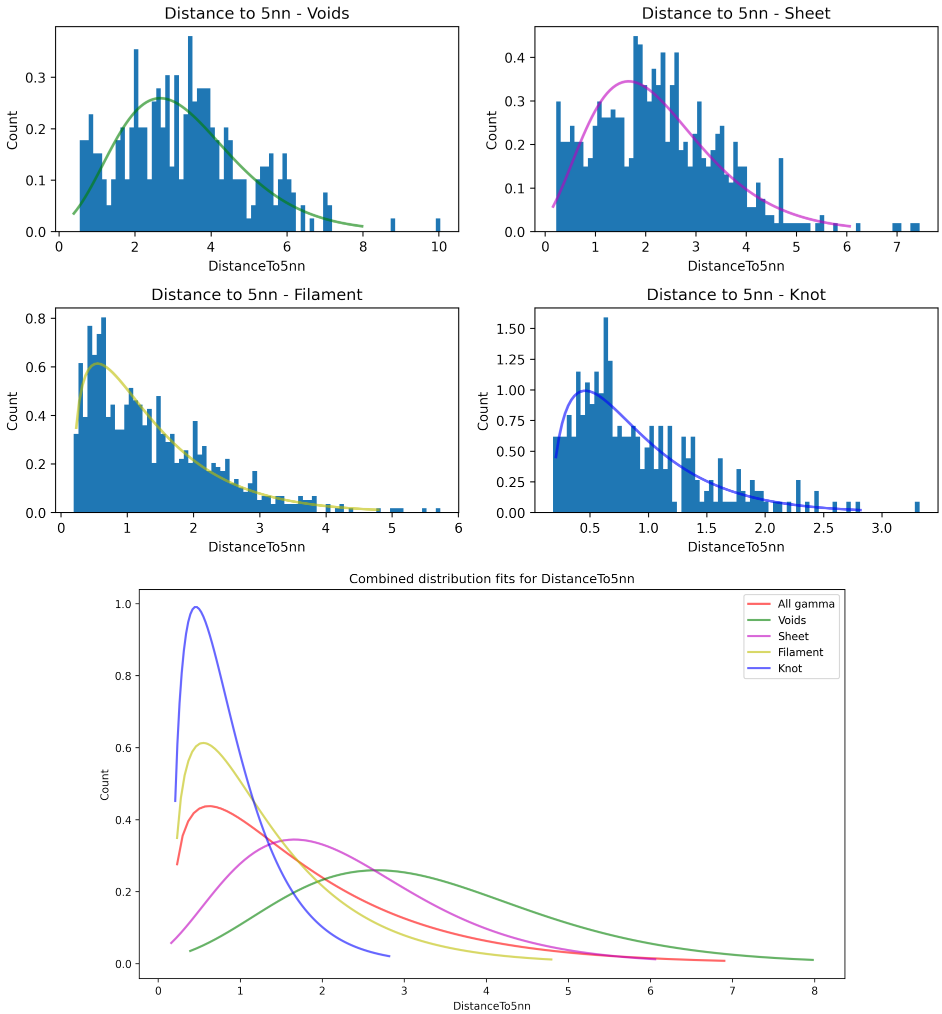
Figure 18: Elliptical galaxies histogram and distributions plots for DistanceTo5nn



7.2.2 DistanceTo5nn

Figure 19 provides for DistanceTo5nn, a histogram and fitted distribution for each of the galaxy structural types and a combined fitted distribution for all structural types on one plot

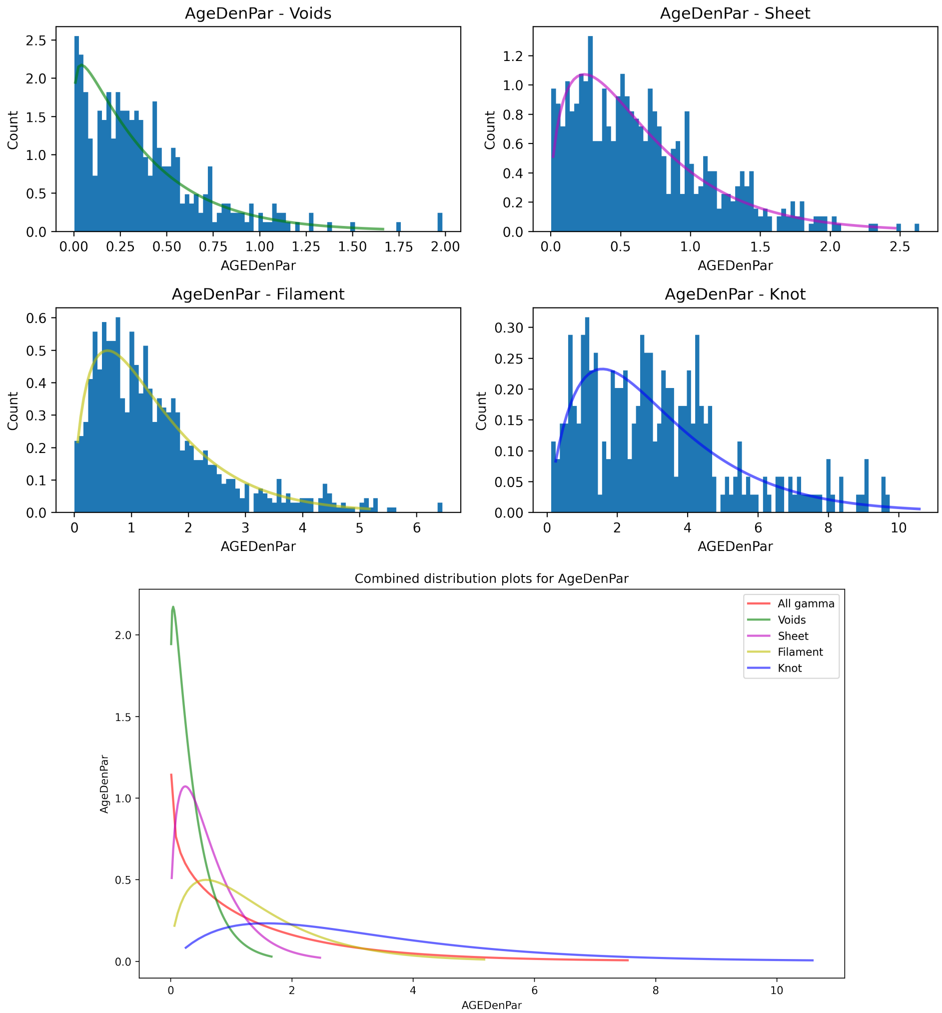
Figure 19: Elliptical galaxies histogram and distributions plots for DistanceTo5nn



7.2.3 AgeDenPar

Figure 20 provides for AgeDenPar, a histogram and fitted distribution for each of galaxy structural types and a combined fitted distribution for all structural types on one plot.

Figure 20: Elliptical galaxies histogram and distributions plots for AgeDenPar



7.2.4 Observations

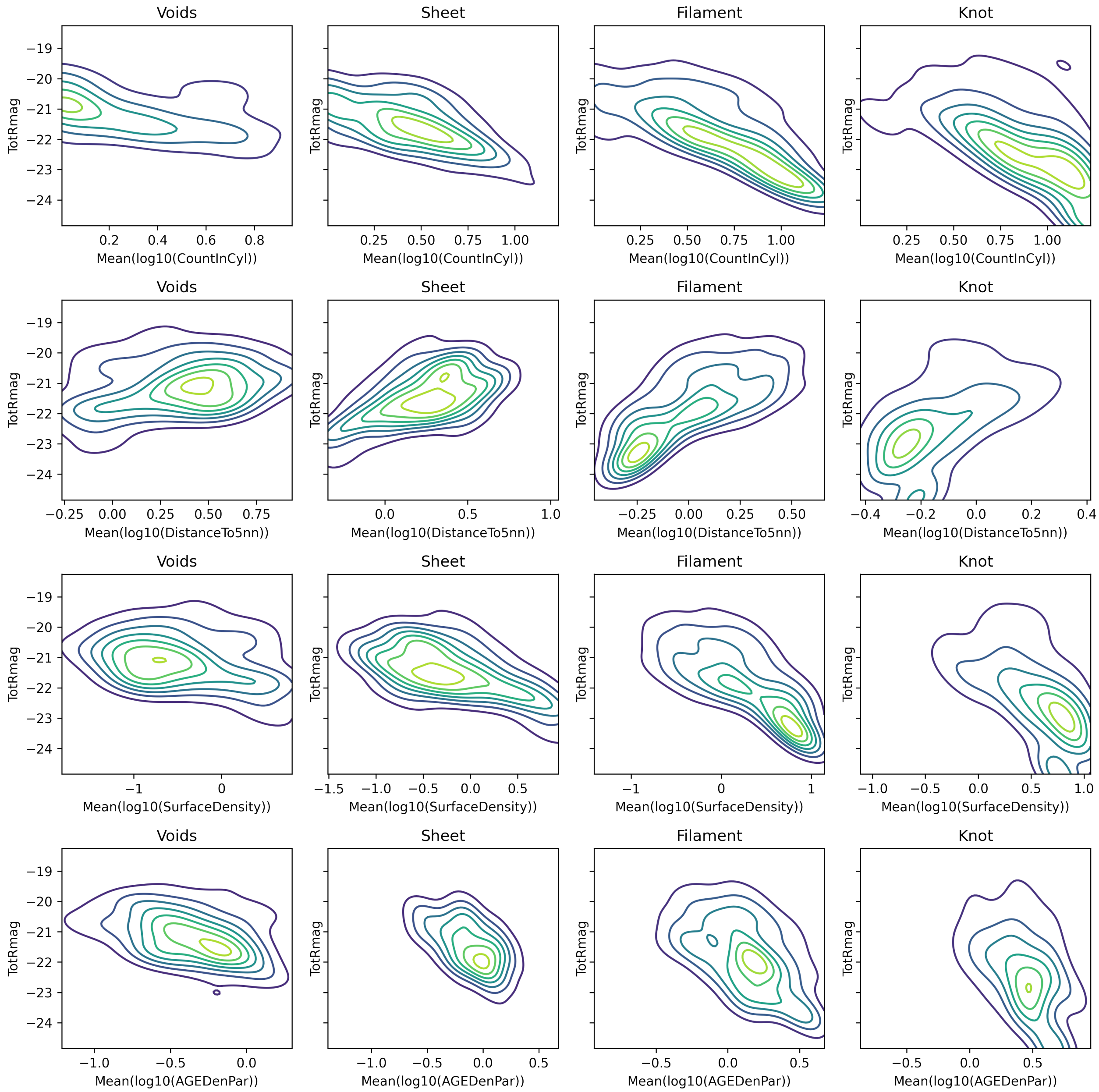
The combined fitted distribution plots for all environmental measures show significant differences between large scale structural type whereas the difference between the distribution of galaxy characteristics apart from knot was quite small see figure 17.

7.3 Local group redness TotRmag by galaxy structural type

Splitting the data on structural type, density plots were produced for group redness TotRmag versus mean of log10(environment measures) see figure 21

Given that the density of the universe increases from voids through sheets and filaments to knots, so does the total red magnitude TotRmag. The relationship between TotRmag and environment is clearest with galaxies classified as being part of a sheet or filament. It is important when viewing these plots to remember that the environmental measures change considerably between structural types see combined plots in figures 18, 19, 20.

Figure 21: Local group - TotRmag versus Mean(Log10(Environment Measures)) for galaxy types

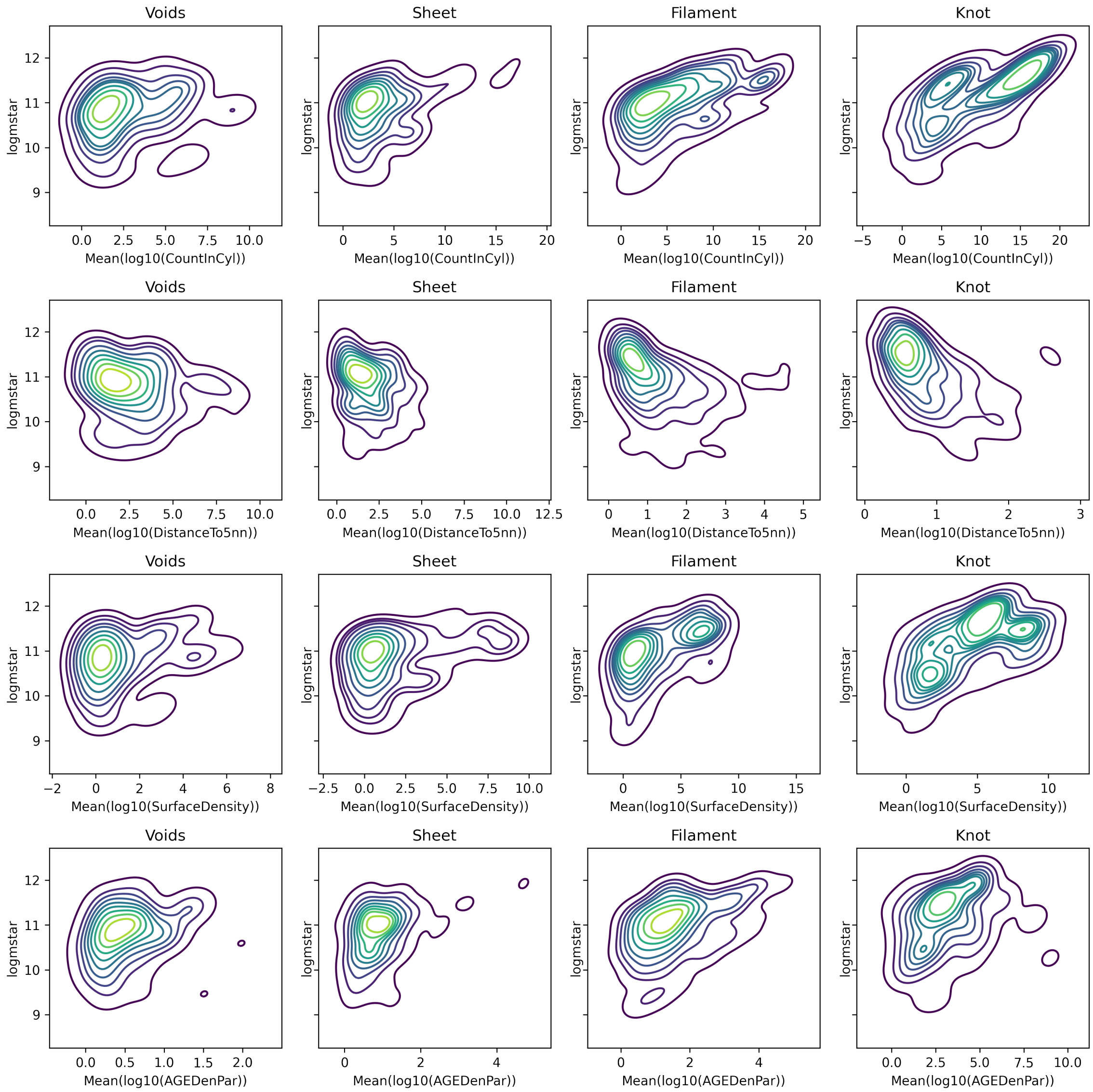


The density plots clearly show diagonal contours indicating a relationship between TotRmag and the mean of log environmental measures.

7.4 Local group mass - sum logmstar for elliptical galaxies by galaxy structural type

The splitting of data on galaxy structure type also allowed density maps to be produced for sum of logmstar versus galaxy environment measures see figure 22

Figure 22: Group sum (logmstar) mass versus environmental measures for galaxy types



7.4.1 Observations

- The clearest indication of a correlation between the sum of logmass and environmental measures is shown in the degree of diagonality in the contours for filament and knot and is less clear for structural types void and sheet.
- Looking at environmental measures SurfaceDensity and CountInCyl for elliptical galaxies in structural types filament and knot, there are hints of two groups.

8 Investigation into distributions

8.1 Distributions

Lots of processes in astrophysics happen on large time scales, often many orders of magnitude longer than a human lifetime or the timescale of our scientific knowledge. For a lot of processes, we are not able to make measurements on timescales that would provide meaningful results. However, as there are billions of stars in our own galaxy and billions of galaxies, we can use the fact that we can observe a very large number of stars and galaxies to draw conclusions. The use of distributions is an attempt to gain insights by looking at the properties of various distributions. Distributions at different redshifts would prove useful but given the timescales for galaxy evolution, a differences in redshift of z=0.5 is generally required and this is not available with the GAMA data due to the flux limited nature of the collected data.

Figure 23 plots the histograms and distribution functions for the main galaxy attributes - redness uminusr, logmstar and metallicity.

Figure 23: Distributions

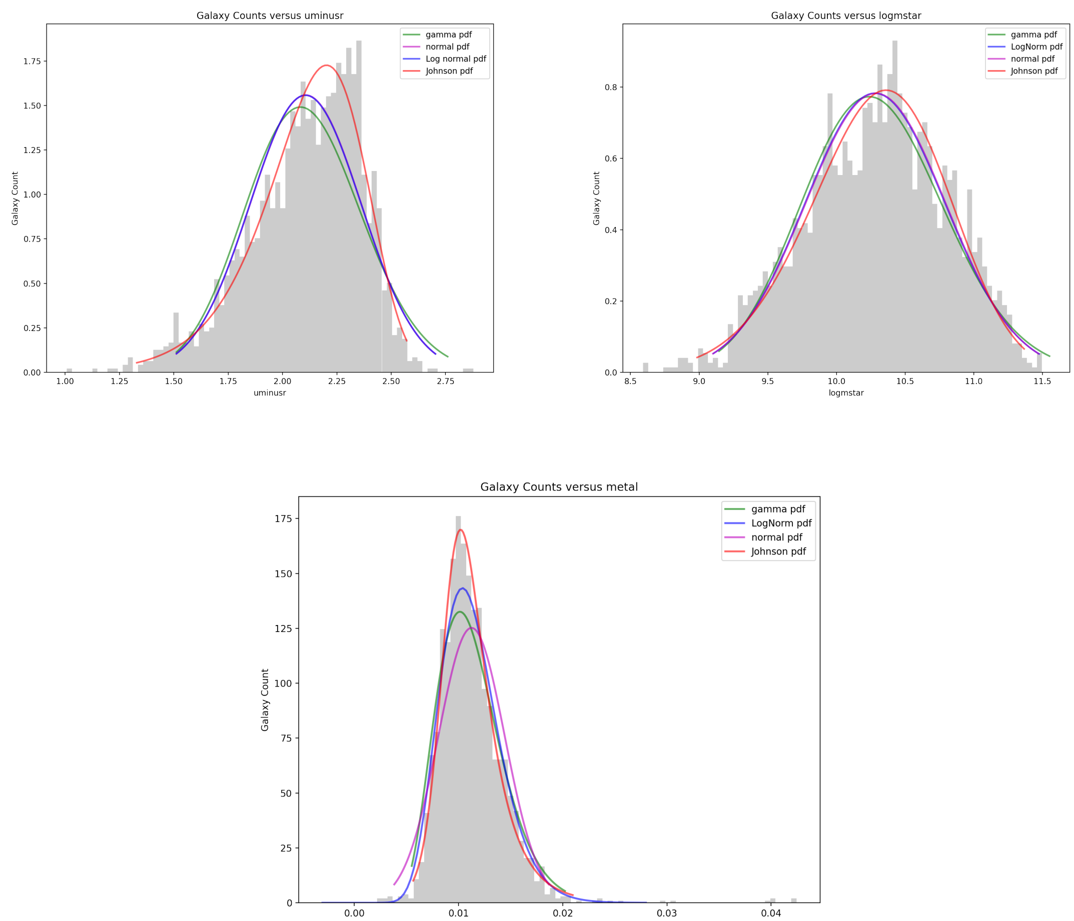


Table 9 summaries the fit variables for the various distribution types.

Table 9: Distribution fits for elliptical galaxies

Characteristic	Johnson Fit				Gamma Fit			
	a	b	loc	scale	k	loc	β(scale)	$\vartheta = 1/\beta$
Redness(uminusr)	3.162	2.875	2.693	0.413	153.88	-1.22	0.022	45.45
Mass (logmstar)	13.720	9.196	14.520	1.994	136.68	4.23	0.044	22.72
Metallicity(metal)	-1.051	1.698	0.008	0.003	8.157	0.002	0.001	1000

Characteristic	Normal		Log Normal		
	μ	σ	a	b	c
Redness(uminusr)	2.107	0.256	0.0026	-94.40	96.50
Mass (logmstar)	10.286	0.509	0.0055	-81.79	92.07
Metallicity(metal)	0.011	0.003	0.2028	-0.003	0.014

8.2 Galaxy formation and evolution

Now according to research[24, 25, 26], the distribution of galaxies in the universe conform to lognormal distributions. Lognormal distributions come about from the statistical realisation of a multiplicity set of actions of many independent variables each with a positive contribution.

For galaxy formation these complex processes are

- The stars in the galaxy undergo nucleosynthesis.
- Star formation from interstellar material.
- Larger stars which are bluer, exhaust their material quicker at which point they cease to contribute to the light of the galaxy.
- Main sequence stars become red giants.
- Galaxy mergers.
- Metallicity of stars which comes from stars that have completed a previous life cycle.
- Accretion of new gas, leading to star creation
- Expelling of gas via feedback, so not available for star creation

It would not be surprising that the distribution of galaxies turn out to be lognormal distributions. Now in the distant past, the things that initially effected galaxy distribution were probably distributed normally. We know from detailed measurements of the cosmic background that at the time of recombination, matter in the universe was very uniformly distributed. At the much later time for initial star formation from clouds of gas, it is standard procedure to assume normal distributions when modelling the early stages of galaxy evolution[27, 28, 29, 30, 31]. It is not unreasonable to assume that gaseous matter and/or primordial dark matter that predates and leads to galaxy evolution, is highly random and hence has a normal/Gaussian distribution.

8.3 Probability Distribution Function PDF

The standard way of describing a distribution is with a Probability Distribution Function PDF

$$PDF = \int_a^b f(x)\,dx$$

8.3.1 PDF of Normal distribution

The PDF for a Normal Distribution is given by

$$PDF\ Normal\ Distribution = \int_{-\infty}^{\infty} f(x)\,dx = \int_{-\infty}^{\infty} \frac{1}{\sigma_1\sqrt{2\pi}} e^{-\frac{[x-\mu_1]^2}{2\sigma_1^2}}\,dx$$

where μ_1 is the mean of the distribution and σ_1 is the variance of the distribution.

8.3.2 PDF of Log Normal Distribution

$$PDF\ Log\ Normal\ Distribution \int_{-\infty}^{\infty} g(y)\,dy = \frac{1}{y\sigma_2\sqrt{2\pi}} e^{-\frac{[ln(y)-\mu_2]^2}{2\sigma_2^2}}\,dy$$

The mean is given by

$$Mean = exp(\mu + \frac{\sigma^2}{2})$$

and the variance

$$Variance = \big(exp(\sigma^2) - 1\big)\,exp(2\mu + \sigma^2)$$

8.3.3 Transforming the distribution of one variable into a distribution of another

It is possible to transform the probability distribution function PDF $f(x)$ of one variable into the PDF of another variable $g(y)$. [32, 33]

For the transform to work, the following conditions need to be meet.

- $f(x)$ has a single value for all x
- $f(x) \geq\ 0$ for all x
- $\int_{-\infty}^{\infty} f(x)\,dx = 1$

Then for a PDF $\int_a^b f(x)\,dx$ with a transformation function $y(x)$ and inverse $x(y)$

The PDF of the transformed variable $\int_{y(a)}^{y(b)} g(y)\,dy$ is given by

$$g(y) = \int_{y(a)}^{y(b)} f(x(y))\frac{dx}{dy}dy \tag{1}$$

8.3.4 Transform of normal distribution of variable x to log normal variable y

So taking a variable of x with a normal distribution PDF f(x) which describes the gaseous/primordial dark matter, a variable y distribution PDF g(y) which describes the log normal distribution of galaxies, the relationship between the two PDFs would conform to the following differential equation (2)

$$g(y) = f(x) \mid \frac{dx}{dy} \mid \tag{2}$$

As a result of the above processes where the process of conversion of variable x to y is a transformation function t(x) and inverse s(y) and the derivative of s(y) is $s^{'}(y)$

Then the relationship between the two PDFs is as follows

$$\int_{-\infty}^{\infty} \frac{1}{y\sigma_1\sqrt{2\pi}} e^{-\frac{[ln(y)-\mu_1]^2}{2\sigma_1^2}} = \int_{-\infty}^{\infty} \frac{1}{\sigma_2\sqrt{2\pi}} e^{-\frac{[s(y)-\mu_2]^2}{2\sigma_2^2} s^{'}(y)}$$

Two sides of the equation equate when
$\mu_1 = \mu_2$ and $\sigma_1 = \sigma_2$ and $s(y) = ln(y)$ and $s^{'}(y) = \frac{1}{y}$

So assuming primordial gas and dark matter are distributed normally and research determines that galaxies have a log normal distribution, then the mathematics indicates that given a mean and variance of the initial normal distribution of μ and σ the mean and variance of the observed lognormal distribution should be

$$Mean = exp(\mu + \frac{\sigma^2}{2})$$

and variance

$$Variance = \left(exp(\sigma^2) - 1\right) exp(2\mu + \sigma^2)$$

8.3.5 Observed distributions from GAMA data

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The distributions obtained from GAMA do not appear to be normal or log normal see figure 23 but a Johnson distribution which has a PDF of

$$PDF = \int_{-\infty}^{\infty} \frac{\delta}{\lambda\sqrt{2\pi}} \frac{1}{\sqrt{1+t^2}} e^{-\frac{1}{2}\gamma\left(1+log(t)+\sqrt{1+t^2}\right)}$$

where

$$t = \frac{x - \varepsilon}{\lambda}$$

does not lend itself to the equating of the two PDFs

8.4 Transform from normal distribution to observed distribution.

What is really required is to determine the transformation that would take a normal distribution and produce the observed galaxy distributions we see today.

Taking a similar approach to CoxBox but assuming the transformation function $t(x)$ takes the form $y = x^{-a}$ so has an inverse $s(y) = y^a$ and a derivative $s'(y) = a.y^{a-1}$ and using equation (1) we have

$$\int_{-\infty}^{\infty} \frac{1}{\sigma_1\sqrt{2\pi}} e^{-\frac{[x-\mu_1]^2}{2\sigma_1^2}} dx = \int_{-\infty}^{\infty} \frac{1}{\sigma_2\sqrt{2\pi}} e^{-\frac{[s(y)-\mu_2]^2}{2\sigma_2^2} s'(y)}$$

$$\int_{-\infty}^{\infty} \frac{1}{\sigma_1\sqrt{2\pi}} e^{-\frac{[x-\mu_1]^2}{2\sigma_1^2}} dx = \int_{-\infty}^{\infty} \frac{1}{\sigma_2\sqrt{2\pi}} e^{-\frac{[y^a-\mu_2]^2}{2\sigma_2^2} a.y^{a-1}}$$

so the observed distribution should fit with

$$g(y) = \frac{1}{\sigma_2\sqrt{2\pi}} e^{-\frac{[y^a-\mu_2]^2}{2\sigma_2^2} a.y^{a-1}} \tag{3}$$

8.4.1 Fitting of curve to distribution.

Figures 24 and 25 are histogram plots of the distributions of uminusr and logmstar and the results of fitting equation (3). For comparison purposes, fitted Johnson and normal distributions are also shown. The fitting variables for equation (3) are documented in table 10.

Figure 24: Galaxy counts versus uminusr

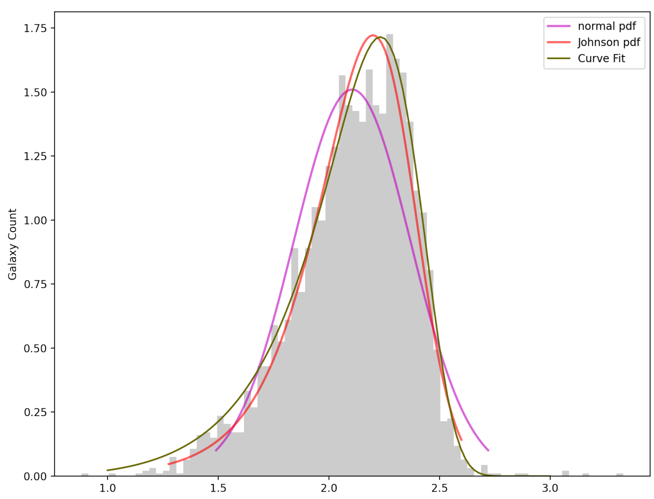

Figure 25: Galaxy counts versus logmstar

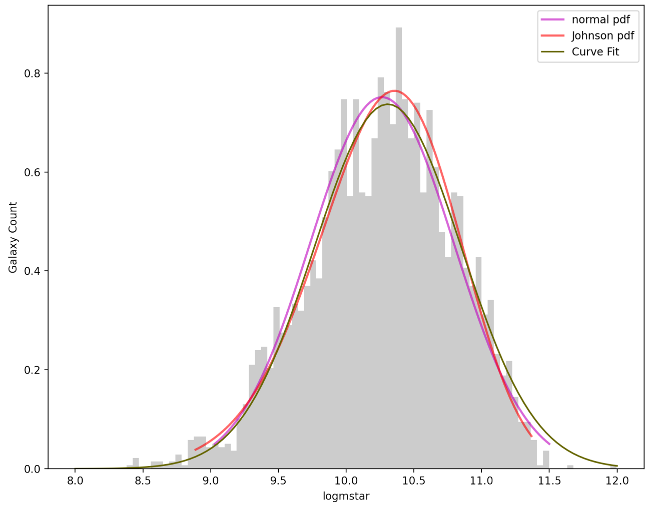

Table 10: Curve fit variables

	a	μ_2	σ_2	s(y)	t(x)
uminusr	6.371	84.516	127.863	$y^{6.371}$	$x^{-6.371}$
logmstar	2.780	10.256	0.545	$y^{2.78}$	$x^{-2.78}$

8.4.2 Observations

- In the case of redness uminusr, the distribution fitted curve to equation 2 matches the histogram quite well.
- For logmstar, the distribution looks quite normal/Gaussian
- In reality given the complexity of galaxy evolution as described in 8.3, the transform function and its inverse are highly likely to be quite complex functions.

8.5 Further work

- Take into account error estimation and confidence ranges.
- With advice from theorists on galaxy evolution, are there more promising transfer and inverse functions?
- The newly launched James Webb Telescope should be able to observe light from the time of star and galaxy formation and hence supply suitable distribution information.
- The GAMA survey is limited due to the flux limited nature of the collected data. Future surveys will hopefully allow the change of distribution for different redshift on galaxy evolution scales.

8.5.1 Transformation of multiple variables

As well as transformation of one variable into another, a similar approach[34] can be carried out for bivariable distributions, the relationship being

$$g(y_1, y_2) = f(x_1(y_1, y_2), x_2(y_1, y_2)) \left| \frac{\partial (x_1, x_2)}{\partial (y_1, y_2)} \right|$$

with transform functions

$$t_1(x_1, x_2) \; and \; t_2(x_1, x_2)$$

and inverse functions

$$s_1(y_1, y_2) \; and \; s_2(y_1, y_2)$$

Given suitable distributions of primordial dark matter and star forming gas clouds, x_1 a variable describing dark matter and x_2 a variable describing gas cloud information and a resulting galaxy distribution, it should be possible to test possible transformation functions.

9 Overall Conclusions

Just to remind ourselves,

- Given the nature of star and galaxy evolution, Redness as measured by uminusr is a measure of age.
- That elliptical galaxies have evolved from spiral galaxies are older and redder (have a larger measure of uminusr).
- The environmental measures are a measure of the density of the local universe.

Conclusions

- Looking at the complete set of elliptical galaxies in the GAMA dataset there does not appear to be a direct correlation between galaxy characteristics and environmental measures. There is sufficient variation in uminusr and the environmental measures that any correlation between the two is not obviously revealed. Even just looking at the set of galaxies with large logmass, no obvious relationship is revealed. Looking at subsets of galaxies based on large scale structure type, the fitted distributions for uminusr and logmstar are similar see figure 17 whereas there is considerable variation in environmental measures for the various large scale structure types see figures 18, 19 and 20 which would also indicate that there is not an obvious correlation. Finally whilst there are some similarities between plot for large scale structure type figures 21 and 22 there are also differences.
- Where one does see a degree of correlation is with local group characteristics TotRMag and sum of logmstar and the means of environmental measures. Now the environmental measures of a galaxy in a local group are strongly influenced by the local density, for example DistanceTo5nn is a measure of the distance to the five nearest neighbours. Where a local group is in a dense part of the universe, the environmental measures of galaxies within the group will exhibit more dense environment measures. Likewise if the local group is in a less dense part of the universe, the galaxy environmental measures will reflect this. Galaxies within a local group are likely to have formed at similar times.
- Looking at the red fraction of galaxies within local groups produces similar results to research into satellite galaxies [20, 21]see figure 14.
- That studying of distributions has some promise and may prove fruitful as advances in telescopes allow us to look at distributions from earlier times and over larger values of redshift.

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