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

September 24, 2021

Abstract

Data from the Galaxy and Mass Assembly (GAMA) project [1] was examined looking for relationships between an elliptical galaxy's characteristics, colour, mass and metallicity and their local environment. Whilst a direct and obvious relationship was not found, some correlation between the characteristics of a galaxy's local group and its environment were noted. This correlation also indicated that it maybe possible to classify red elliptical galaxies into two sub groups based on the distance from the centre of the local group, the larger of the two sub groups being redder and more distant and a smaller group not as red and nearer the centre of the local group. In addition other aspects of a galaxy's local group were investigated.

1 Introduction

1.1 Objective

Galaxy formation is understood to be subject to a number of processes

- Evolution of star members due to nucleosynthesis.
- Galaxy mergers.
- Star formation.

Previous research [2, 3, 4] has established a strong dependence of galactic properties, morphology, star formation rate and colour on its local environment and also the dependency of a galaxy's light function on local density [5, 6, 7]. The objective was to investigate possible relationships between colour redness and local galaxy environment.

1.2 Units

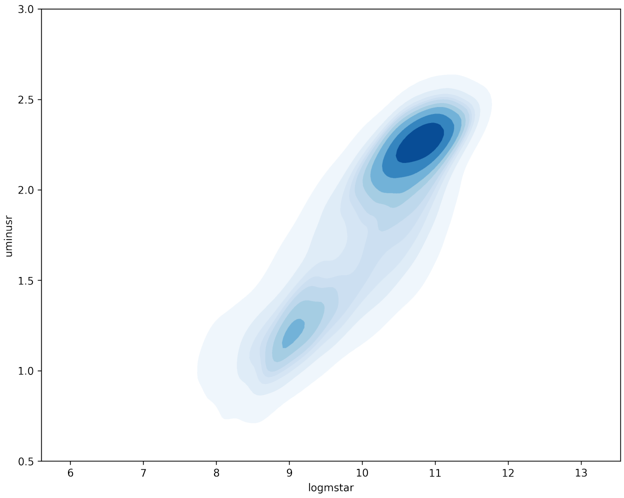
Thoughout the report

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

1.3 Two galaxy groups

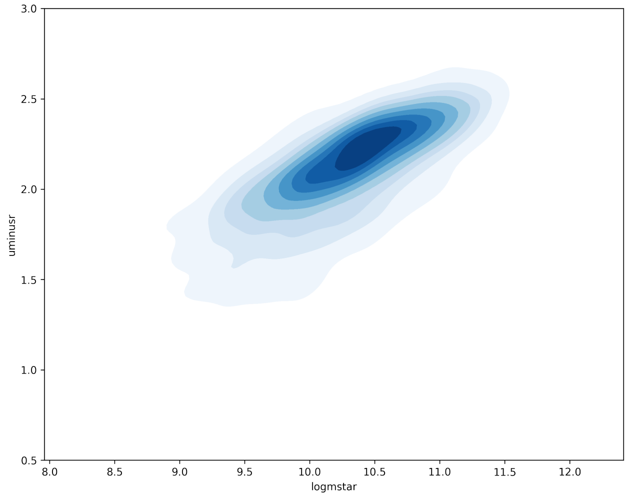
It has been well researched that galaxies fall into two groups [8, 9]. This can be seen by a density map plot of redness (uminusr) versus the log of the galaxy star mass (logmstar) see figure 1

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



One could select a subgroup based on uminusr and logmstar as in [4, 9], 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

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

2 Galaxy environmental measures

The GAMA survey provides the following as the main measures of a galaxy's local environment

- Count In Cylinder
- Distance to 5nn
- Surface Density
- AgeDenPar

2.0.1 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 $+/-1000km/s$. The overdensity is given by $CountInCyl/(nba\_ref * volume\_of\_cylinder)$ where $nbar_ref = 0.00911Mpc^-3$ is the average number density of the density defining population.

2.0.2 Distance to 5nn

The distance to 5th nearest neighbour

2.0.3 Surface Density

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

2.0.4 AgeDenPar - Age Density

This column provides the adaptive Gaussian density parameter, as introduced by Schawinski et al [10] and later described by Yoon et al[11]. To calculate this density parameter, we first identify all (other) galaxies from the density defining population in an adaptive Gaussian ellipsoid defined by

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

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 $sigma = 2Mpc$.

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

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

2.1 Density plots & correlations

Density map plots and correlation fits were produced for the four environmental measures see figure 3 and table 2 and also the log of the same measures, figure 4 and table 3.

Figure 3: uminusr density plots for environmental measures

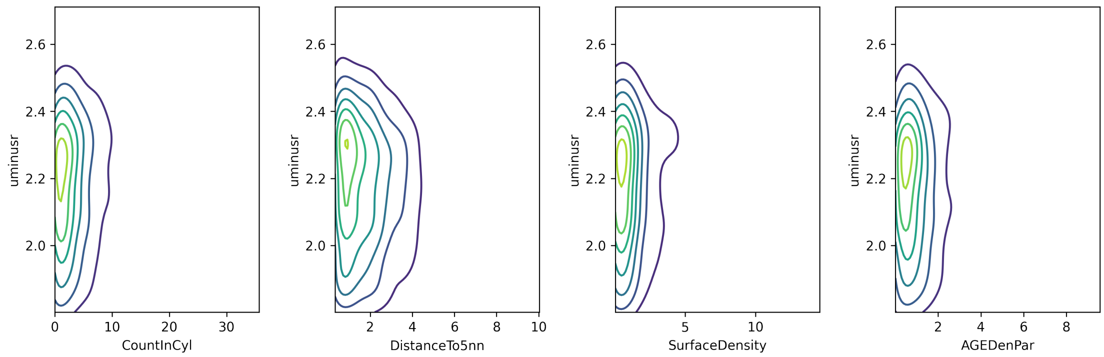
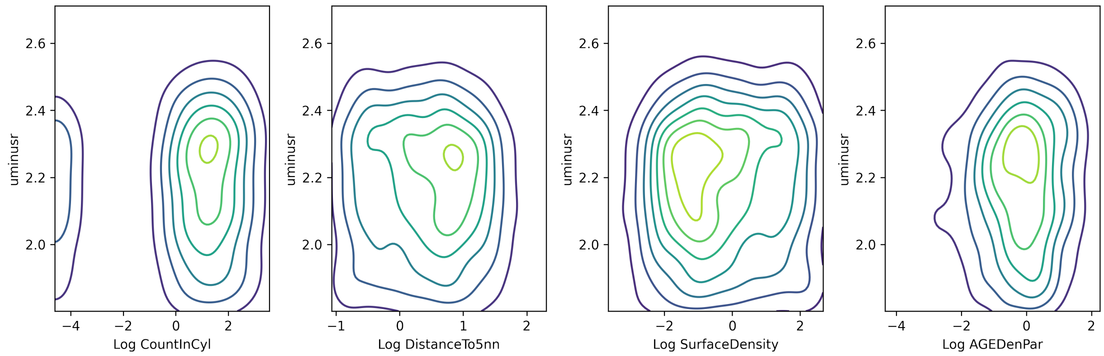


Table 2: uminusr - Environmental measures - correlation values

Environment Measure	Pearson		Spearman	
	Correlation value	p-value	Correlation value	p-value
CountInCyl	0.0283	0.228	0.0575	0.0142
DistanceTo5nn	-0.0753	0.0013	-0.0692	0.0031
SurfaceDensity	0.0327	0.163	0.0694	0.003
AGEDenPar	0.368	0.116	0.0493	0.0354

Figure 4: Density Plots for log(Environmental measures)



As can be seen from the plots, there is no obvious relationship between the colour (uminusr) of a 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 3 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)

Table 3: uminusr - log(Environmental measures) - correlation values

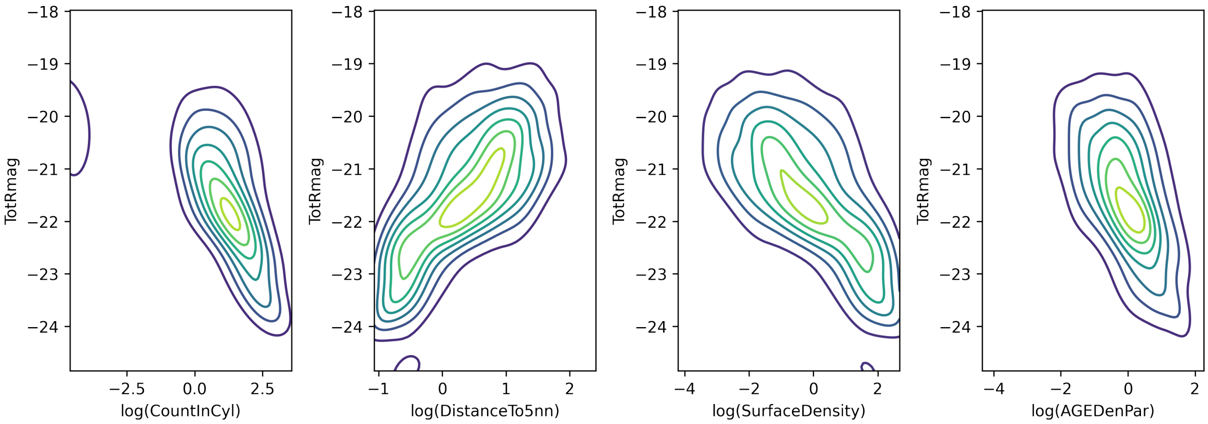
Environment Measure	Pearson		Spearman	
	Correlation value	p-value	Correlation value	p-value
Log(CountInCyl)	0.0552	0.0184	0.0575	0.0142
Log(DistanceTo5nn)	-0.0724	0.0020	-0.0692	0.0031
Log(SurfaceDensity)	0.0716	0.0023	0.0695	0.0030
Log(AGEDenPar)	0.0494	0.0352	0.0493	0.0354

3 Local group information

3.1 Group redness - TotRmag

Unlike the straight galaxy measures of galaxy colour, the total red magnitude of a galaxy's local group TotRMag do show some degree of correlation see figure 4 and table 4. This is a little surprising in that within a local group there are a number of galaxies all with potentially different environmental measures and not necessarily with the same red magnitude. However, on the other hand as a high density of galaxies is likely to produce a larger group magnitude and the individual galaxy environmental measures are indicative of its local density, some degree of correlation might be expected.

Figure 5: Density plots - group redness (TotRmag) versus log(environments) for elliptical galaxies



The results of running linear regression tests are documented in table 4

Table 4: Linear regression of group redness (TotRmag) with log(galaxy environment measures)

Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log(CountInCyl)	-0.602	6.10e-150	-0.737	1.01e-259	-0.385	-21.34
Log(DistanceTo5nn)	0.682	7.46e-208	0.699	5.93e-222	1.099	-21.85
Log(SurfaceDensity)	-0.681	1.88e-206	-0.700	2.153	-0.534	-21.58
Log(AGEDenPar)	-0.497	4.06e-99	-0.458	3.512	-0.613	-21.69

3.2 Sum of local group

3.2.1 Sum redness (uminusr) group versus environmental measures

As TotRmag would include the contribution of spiral and other galaxies, a follow up exercise of calculating the sum of elliptical galaxies was carried out. The sum of elliptical galaxies was obtained by processing GAMA group table G3CGalv10 which was joined with the StellarMasses table and the sum of uminusr determined as follows

$$\Sigma\, uminusr = -2.5 log(\Sigma\, 10^{-0.4\, uminusr})$$

The density plots are shown in figure 6 and correlation information in table 5

Figure 6: Sum of uminusr for local group versus log(environments) for elliptical galaxies

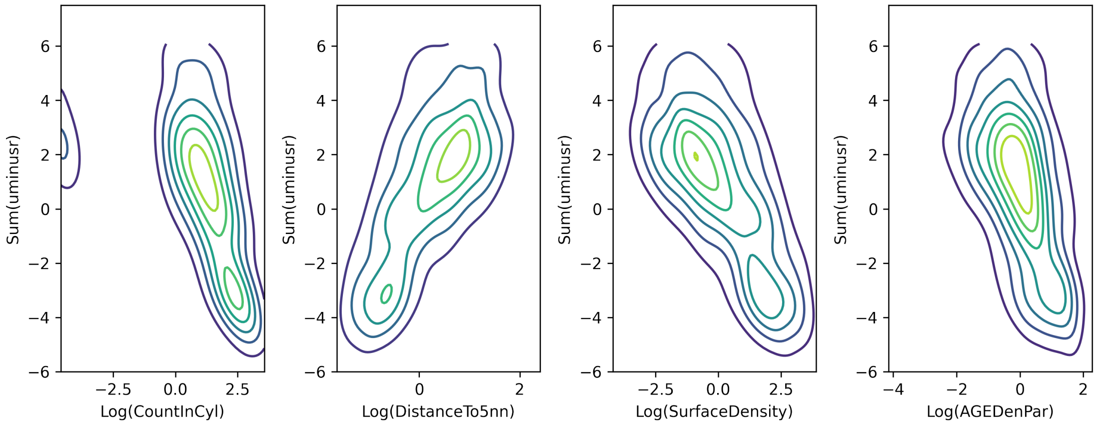


Table 5: Linear regression of group sum of uminusr with log(galaxy environment measures)

Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log(CountInCyl)	-0.679	2.77e-193	-0.504	1.01e-92	-0.754	1.229
Log(DistanceTo5nn)	0.652	34.05e-173	0.648	3.82e-170	2.367	0.190
Log(SurfaceDensity)	-0.655	2.15e-175	-0.650	2.153e-175	-1.155	0.784
Log(AGEDenPar)	-0.490	3.52e-87	-0.480	3.37e-83	-1.35	0.502

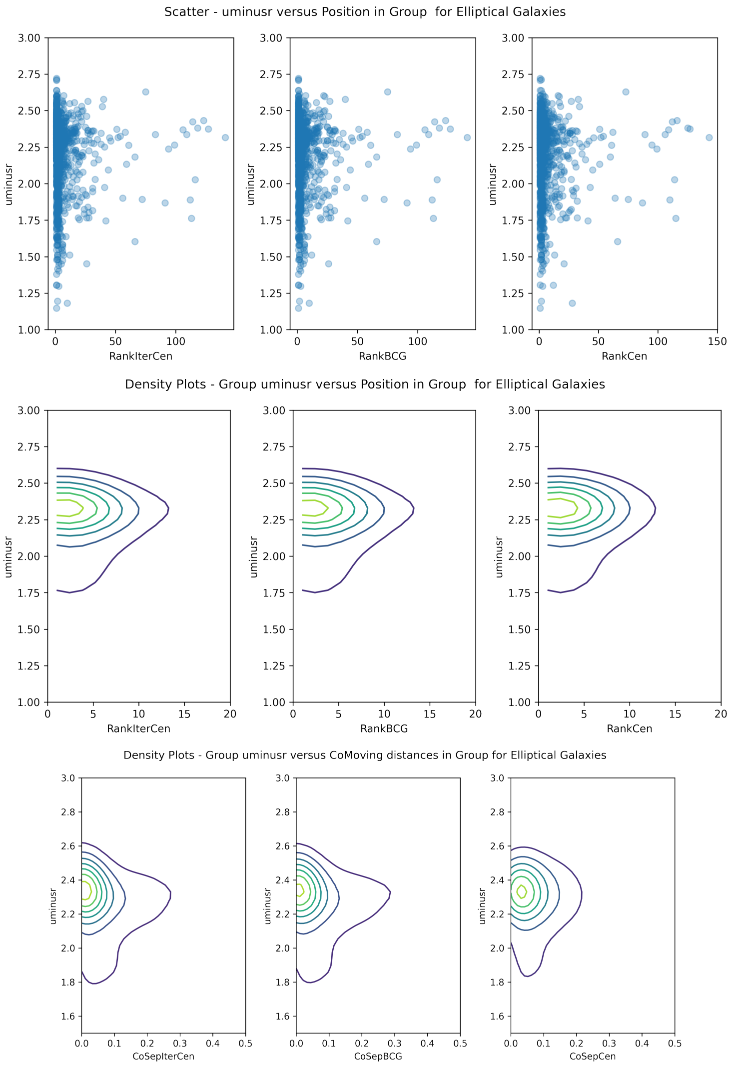
Observations

- It was also noted that the G3CGalv10 table had a large number of GroupID's of zero i.e. galaxies that were not allocated to a local group.
- There were some differences between using the $\Sigma uminusr$ for the supplied local groups and GAMA supplied TotRmag value for the local group.
- It should be remembered that TotRmag would have the contribution of non ellipticals, whereas summing of uminusr just sums the contribution of elliptical galaxies.
- Looking at the density plots, there are indications of two peaks suggesting that red elliptical galaxies might subdivide into two groups, one small group with a high magnitude close to the centre of the local group (small DistanceTo5nn) and a larger group further away.

3.2.2 Positions within local group - uminusr

Group table G3CGal provide the relative positions of galaxies within their local group. Figure 7 documents the scatter plots and density maps for elliptical galaxy positions within their local group.

Figure 7: Elliptical galaxies - colour (uminusr) versus relative position



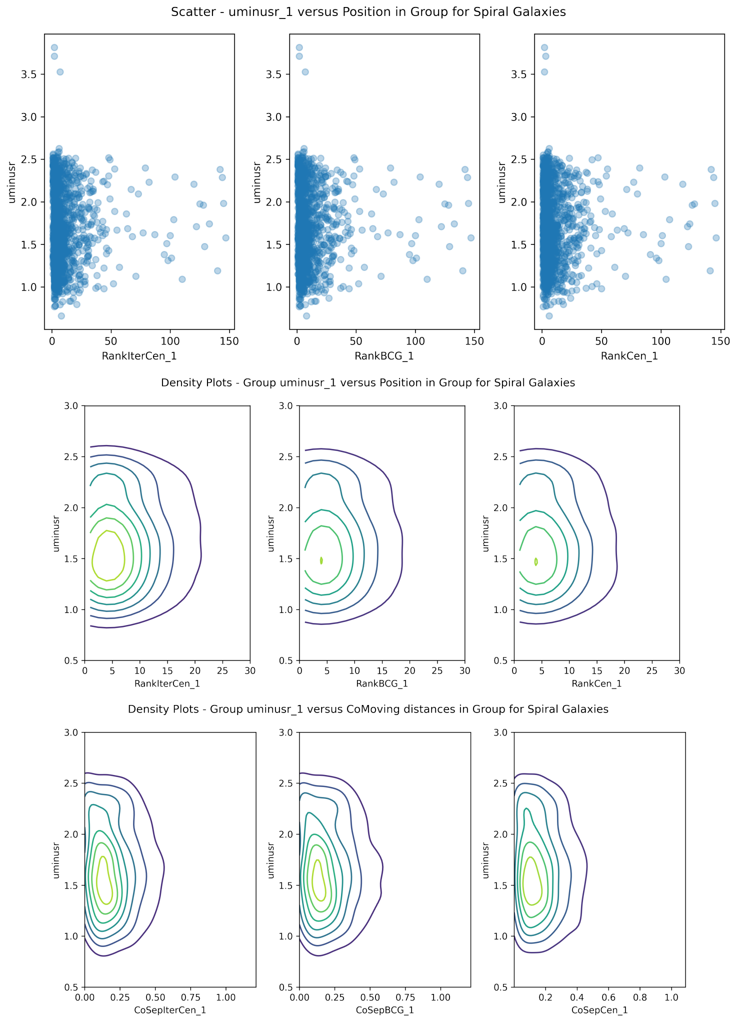
When looking at the positional information, it is important to remember that galaxies are three dimensional whereas the data is represented in two dimensions. From the various plots, the following can be observed

1. uminusr - median : 2.286 mode : 2.232
2. The spread of values below the mode is larger than that above.
3. Galaxies close to the centre of the local group have a much larger range of values than more distant galaxies.
4. The more distant galaxies are likely to have uminusr values similar to the mode of the group.

3.2.3 uminusr for spiral galaxies in the same local groups

A similar exercise was performed for spiral galaxies within the same groups see figure 8

Figure 8: Spiral galaxies - colour (uminusr) versus relative position



Using the above for spiral galaxies

1. The values of uminusr are more evenly spread
2. uminusr - medium : 1.651 mode : 1.422
3. There is a larger range above the mode
4. Galaxies at some distance also have a considerable range of values.

3.3 Group mass - logmstar versus environmental measures

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

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

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 9: Sum of logmstar for local group versus log(environments) for elliptical galaxies

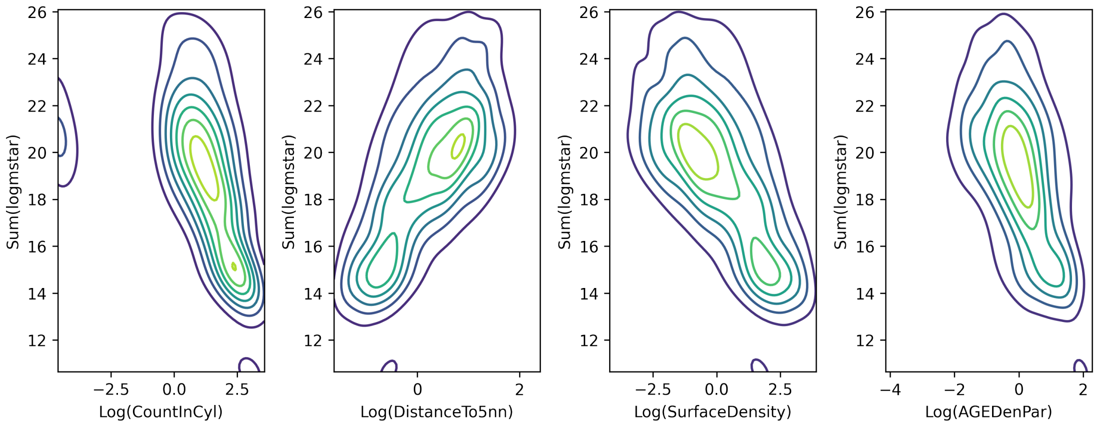


Table 6: Linear regression of group sum of logmstar with log(galaxy environment measures)

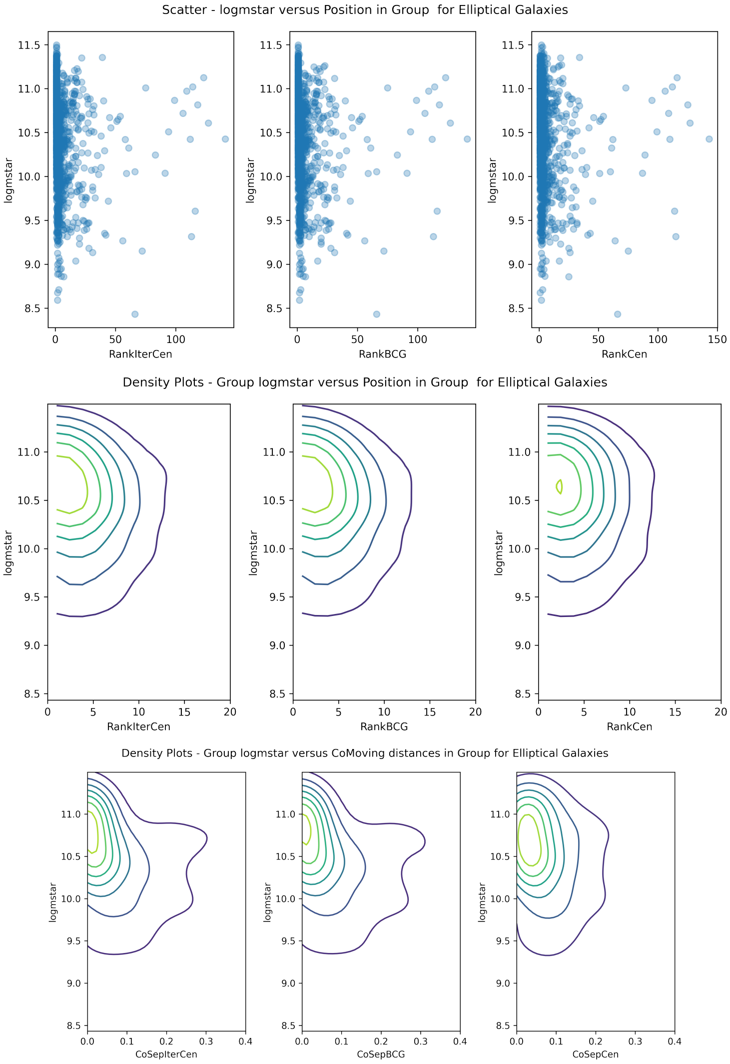
Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log(CountInCyl)	-0.654	1.34e-174	-0.472	7.34e-80	-0.776	19.67
Log(DistanceTo5nn)	0.634	1.50e-155	0.625	3.68e-155	2.522	18.58
Log(SurfaceDensity)	-0.637	1.498e-163	-0.627	6.53e-157	-1.232	19.21
Log(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.

3.3.1 logmstar group positions

Table G3CGal provides the relative positions of galaxies within their local group. A subset of elliptical galaxies produced the scatter and density plots in figure 10

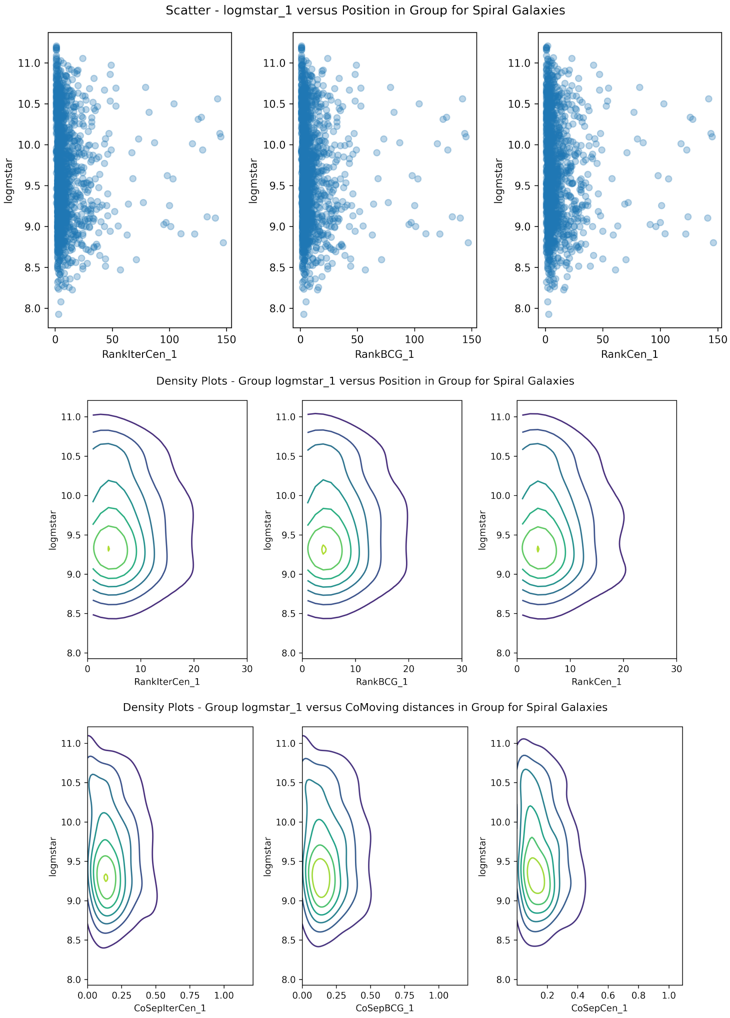
Figure 10: logmstar relative position plots



- logmstar - median : 10.528 mode : 9.894
- Looking at the mass (logmstar) distribution in local groups figure 10, there are marked differences from the red colour uminusr figure 7, most notably there is no bulge for distant galaxies corresponding to the mode of the group.

3.3.2 logmstar for spiral galaxies in the same local group.

Figure 11: Spiral galaxies (same local group) logmstar versus relative positions



- logmstar - medium : 9.560 mode : 10.474
- Looking at figure 11, details of logmstar of spiral galaxies (within the same local group as elliptical galaxies) versus various measures of position from the centre of the local group produced very similar results as details of uminusr for spiral galaxies figure 8

3.4 Metallicity - metal

$$\Sigma\, metal = \Sigma metal$$

Figure 12: Sum of metal for local group verses log(environments) for elliptical galaxies

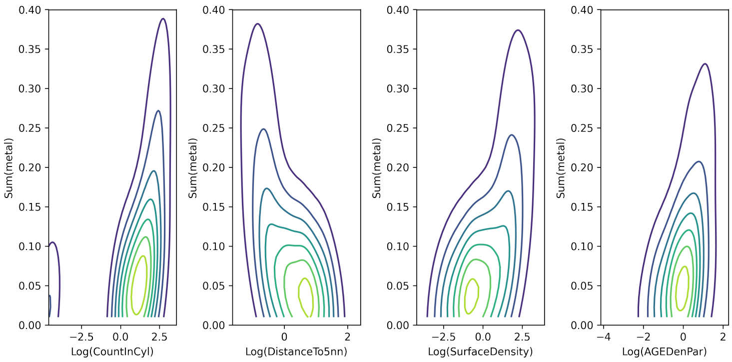


Table 7: Linear regression of group sum of metal with log(galaxy environment measures)

Environment Variable	Pearson		Spearman		Linear Regression	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value	m	c
Log(CountInCyl)	0.369	2.55e-47	0.714	5.68e-223	0.042	0.090
Log(DistanceTo5nn)	-0.462	1.54e-76	-0.683	1.58e-196	-0.12	0.147
Log(SurfaceDensity)	0.465	1.62e-77	0.686	3.62e-199	0.063	0.115
Log(AGEDenPar)	0.389	9.86e-53	0.508	1.49e-94	0.083	0.131

4 Galaxy structure classifications

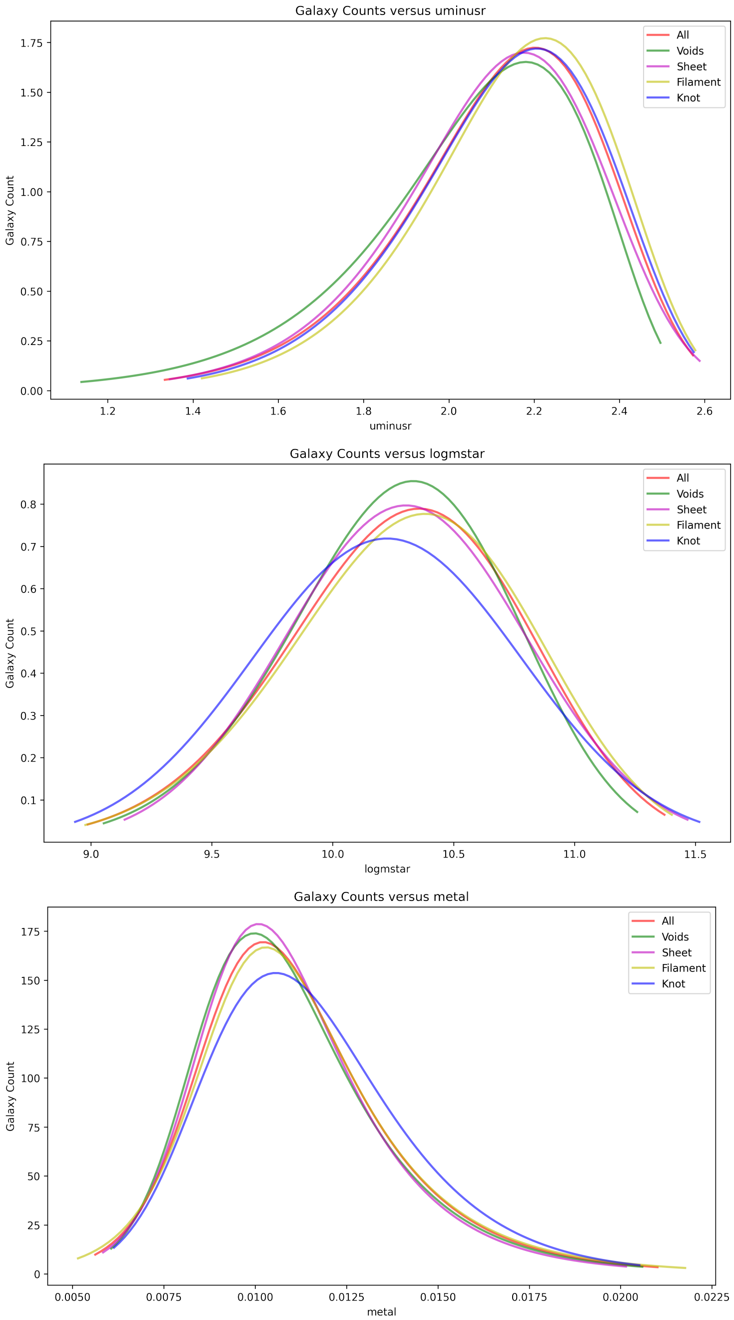
Whilst on very large scales, the universe is homogeneous, we know that on lesser scales there is structure influenced by the distribution of dark matter. For GAMA II, equatorial regions were classified at each point as either

- Void
- 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 [12]. 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.

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

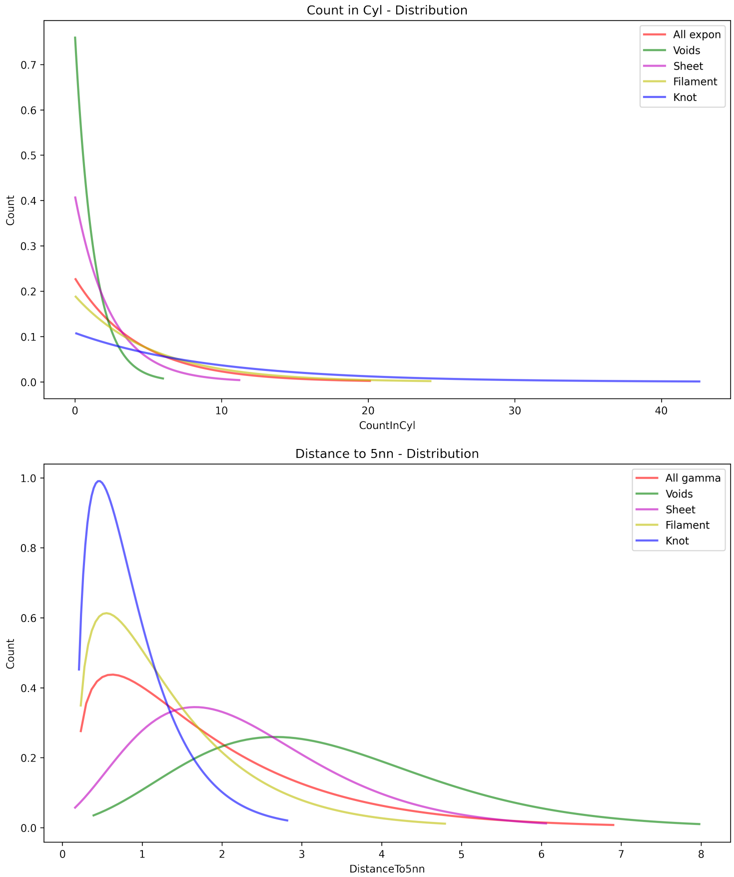
Figure 13: Galaxy counts for galaxy characteristics by galaxy structure type



Apart from the case of environment type knot, the distributions for the various galaxy environment types are similar see figure 13

4.2 Distributions of galaxy environment measures by galaxy structural type

Figure 14: Distributions of environmental measures for galaxy structure types

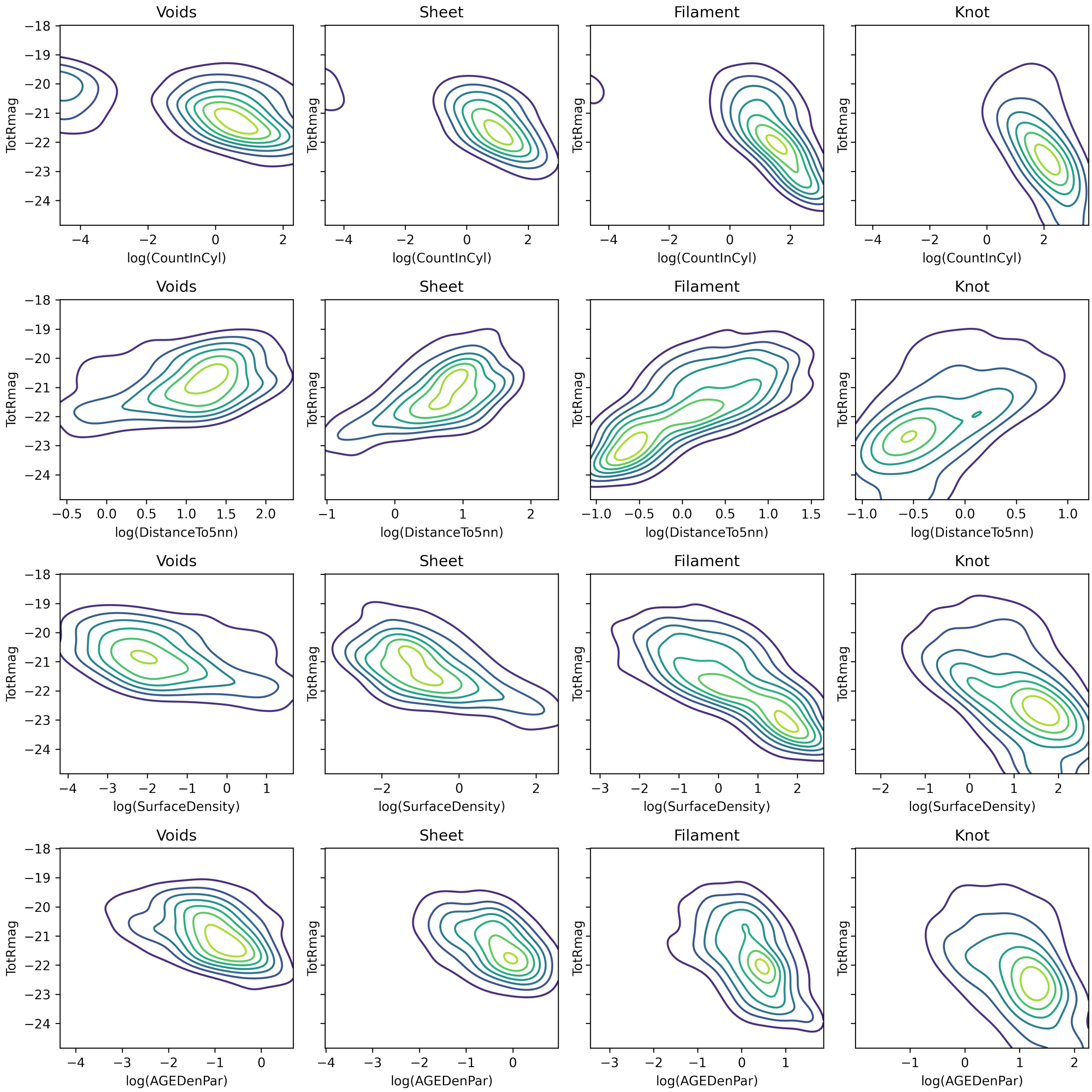


With the possible exception of the knot, the distribution of galaxy characteristics are not dissimilar between structural types. On the other hand, the galaxy environmental measures do have marked variation between galaxy structural types see figure 13

4.3 Local group redness TotRmag by galaxy structural type

Splitting the data on structural type, density plots were produced for group redness TotRmag versus environment measures see figure 15

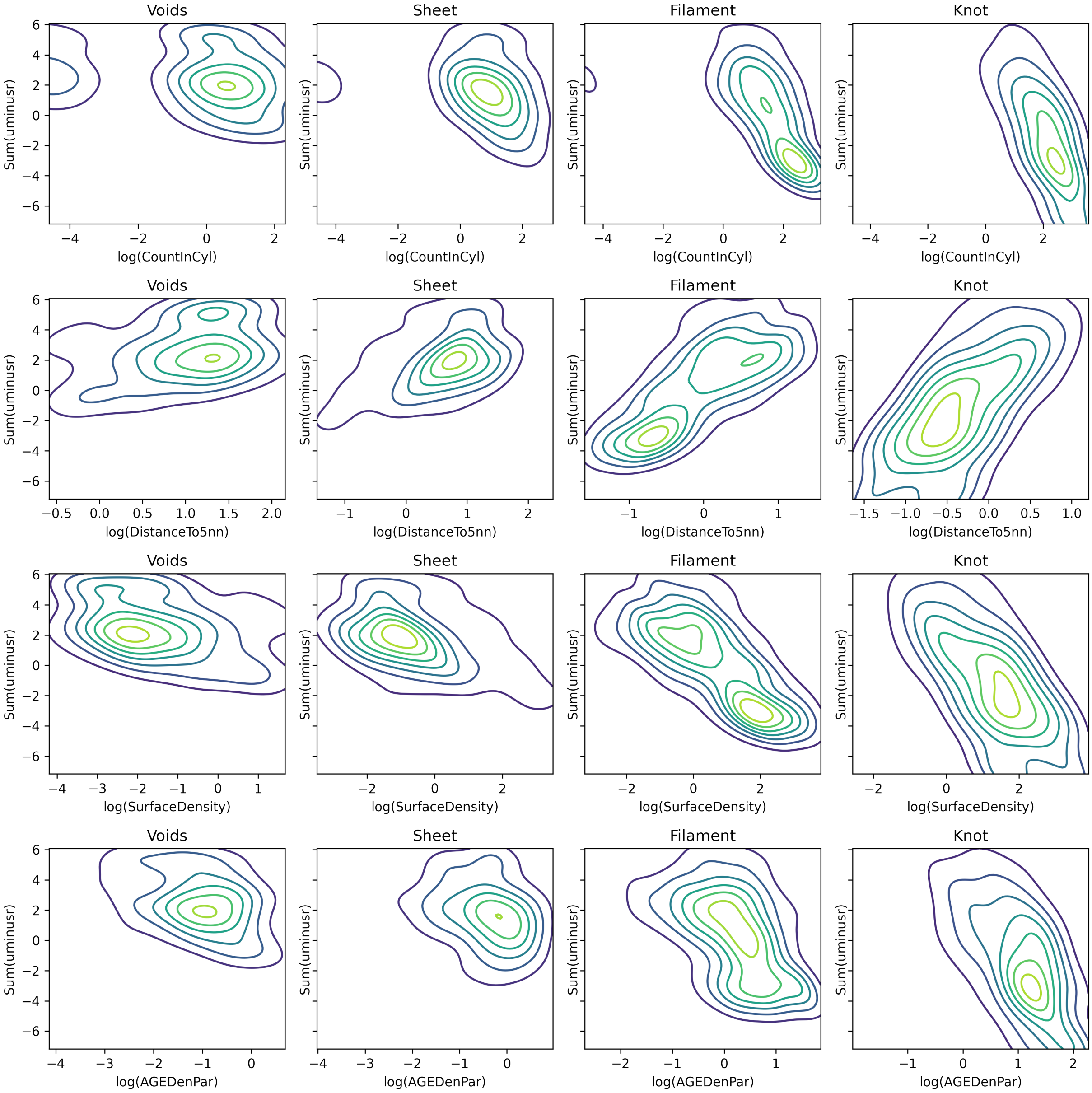
Figure 15: Group Redness(TotRmag) for galaxy types



4.4 Density maps for sum of uminusr for local group by galaxy structural type

Similarly density plots were produced for redness sum of local group versus environment measures see figure 16

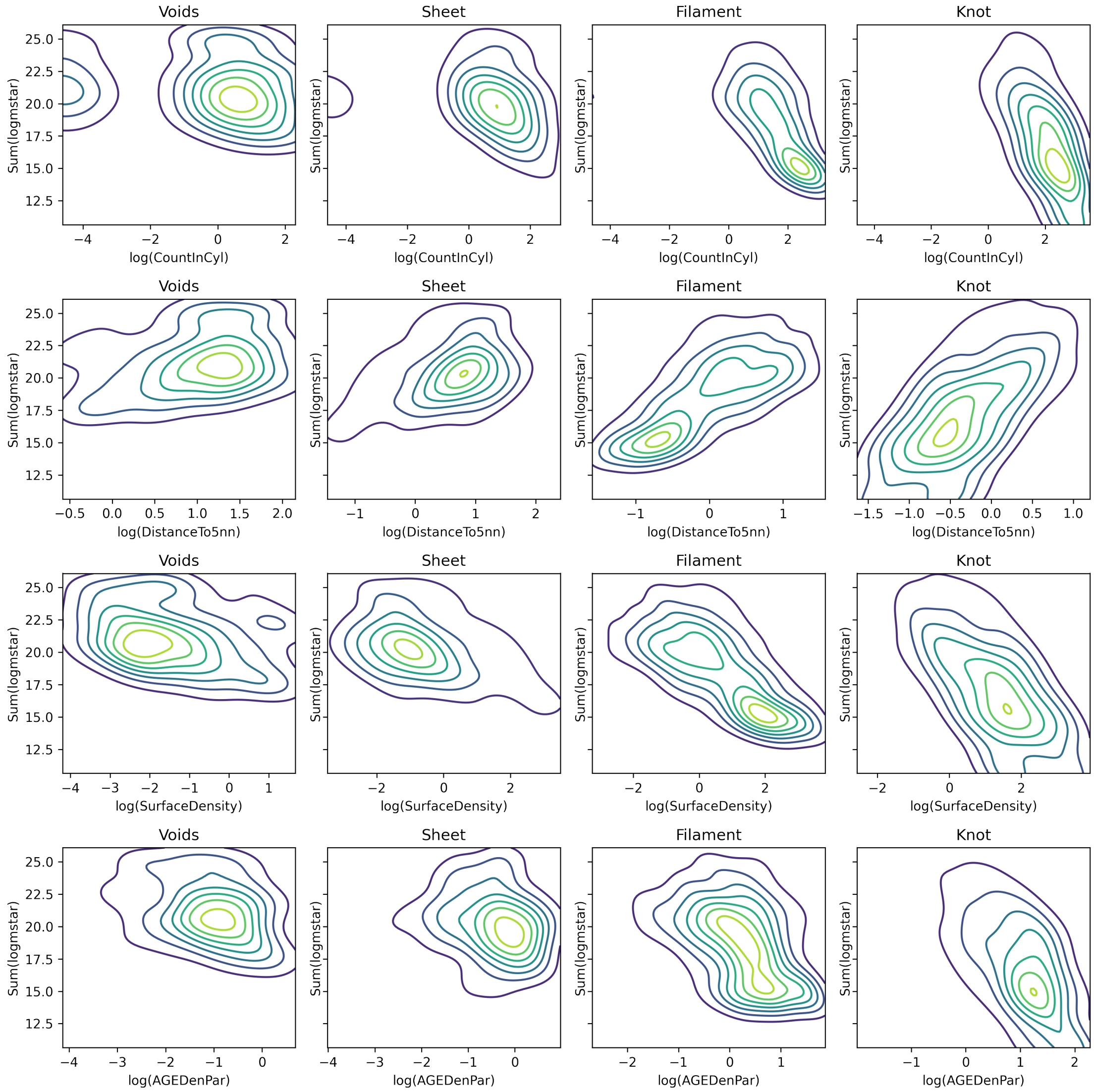
Figure 16: Group redness sum of uminusr versus environmental measure for galaxy types



4.5 Local group mass - sum logmstar by galaxy 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 17

Figure 17: Group mass sum (logmstar) versus environmental measures for galaxy types



For galaxy structural types filament and knot there is a clear correlation between the local group attribute and environment meaures. The correlation is less clear for structural types voids and sheet.

When broken down into galaxy structure types, the density maps for sum of local groups versus log(environmental measures) for uminusr figure 16 look very similar to logmstar figure 17 but quite different between galaxy structure types, again emphasising the fact that galaxy environmental measures change quite significantly between galaxy structure types.

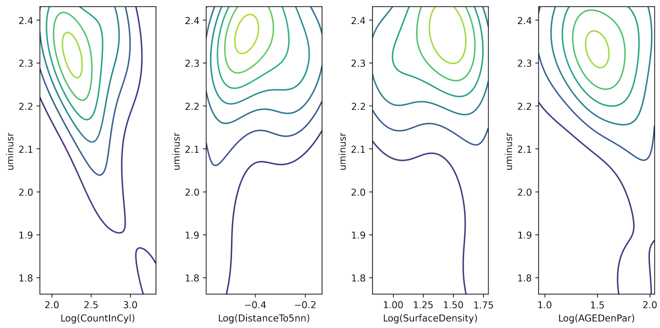
The possibility that there are two groups of red elliptical galaxies, as was indicative in the sum of group measures, is most obvious in galaxies allocated to a galaxy structure type of filament.

5 Inner and outer galaxies within their local group

Revisiting any correlations between galaxy redness and their environments for inner and outer galaxies within their local group

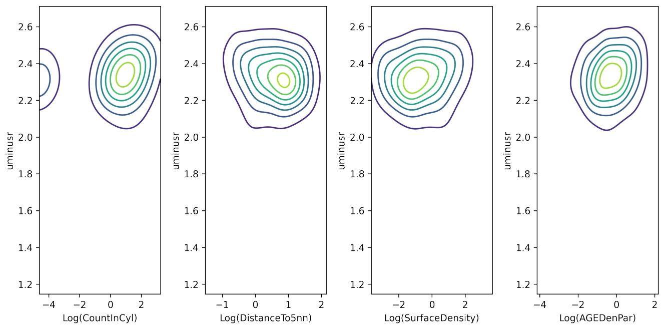
5.1 Outer galaxies

Figure 18: uminusr versus log(environment measures) for outer galaxies in local group.



5.2 Inner galaxies

Figure 19: uminsur versus log(environment measures) for inner galaxies in local group



In the case of outer galaxies there does appear to be a correlation between uminusr and log(CountinCyl) but this is not seen in the case of inner galaxies.

6 Summary of results

- On an individual galaxy basis, there is no obvious correlation between a galaxy's environment and parameters (redness, mass, metallicity).
- There is a degree of correlation between the sum of local groups and individual galaxy environment measures. This correlation is more obvious in galaxy structure types filament and knot.
- Looking at galaxies that are in the outer 5% of their local group, there does appear to be a link with environmental measure CountInCyl.
- Galaxy environment measures vary quite considerably between galaxy structural types.
- There is some variation between galaxy characteristics for different galaxy structure types.

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7 Investigation into distributions

7.1 Discussion

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. The result is 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.

However galaxy evolution is a complex process

- 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.

The result is that inferences from distributions are at best likely to give hints of the physical process involved and better understandings can be obtained by creating models and testing if these produce results similar to actual observations. If the results do not match, then efforts are made to improve the model. If the models produce good results then this gives support to the proposition that physical reality is being well modelled.

7.2 Distributions

Figure 20 plots the histograms and distribution functions for the main galaxy attributes - redness uminusr, logmass and metallicity.

Figure 20: Distributions

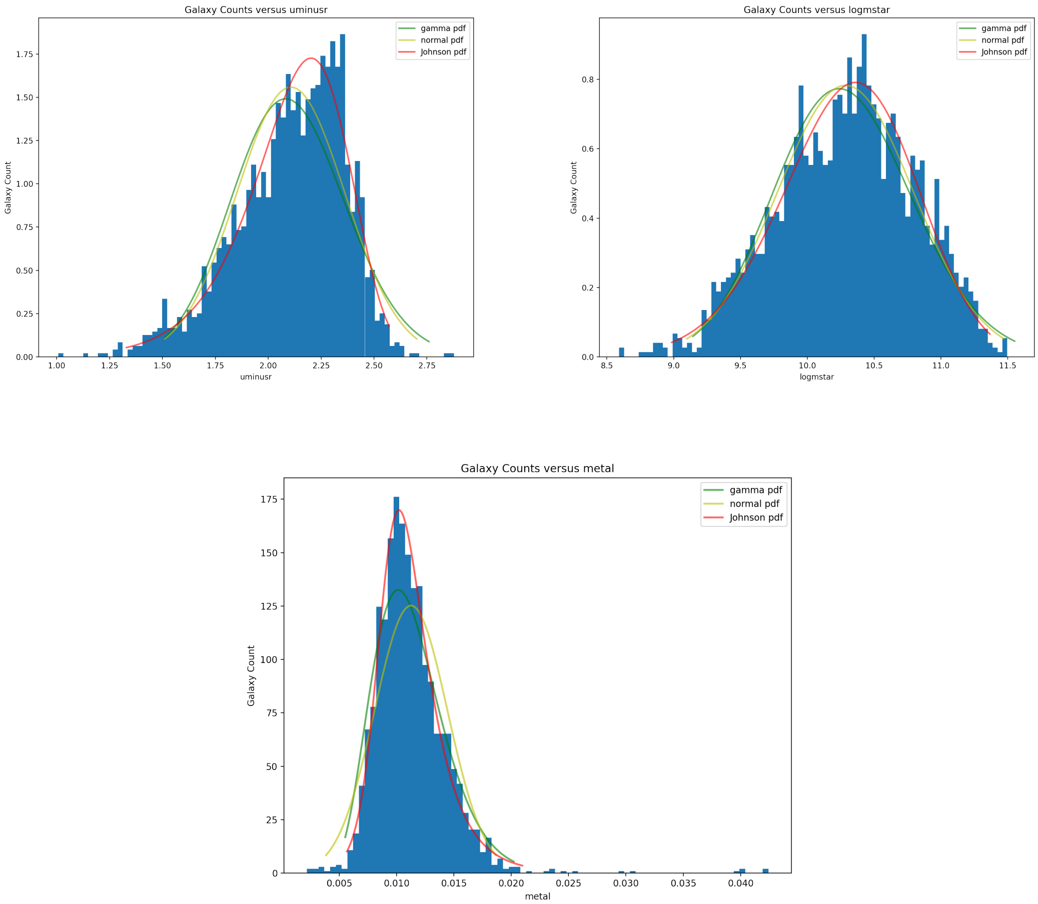


Table 8: Distribution fits for elliptical galaxies

Characteristic	Johnson Fit			
Redness(uminusr)	3.23	2.92	2.7	0.42
Mass (logmstar)	16.4	10.11	15.06	1.95
Metallicity(metal)	-1.02	1.68	0.008	0.003

If a process involves random variables then the expected distribution for the variable is a Normal/Gaussian distribution. Looking at the distributions for redness(uminusr), mass(logmstar) metallicity(metal) figure 20, one could attribute the differences from a normal distribution to statistical variation. However to investigate if the deviation from a normal distribution could possibly be related to any of the galaxy environment measures, Cox Box transformations were applied.

7.3 Cox Box transformation

The Cox Box transformation [13] is a statistical process to apply a transformation to a distribution so that the resulting distribution is Normal/Gaussian. The transformation is of the form

$$y_{i+1}^{(\lambda)} = \left\{ \begin{array}{cc} \frac{y_i^{\lambda}-1}{\lambda} & if\,\lambda \neq 0 \\ ln\,y_i & \lambda\, = \,0 \end{array} \right\}$$

A best fit value for λ can be determined and its confidence interval is given by

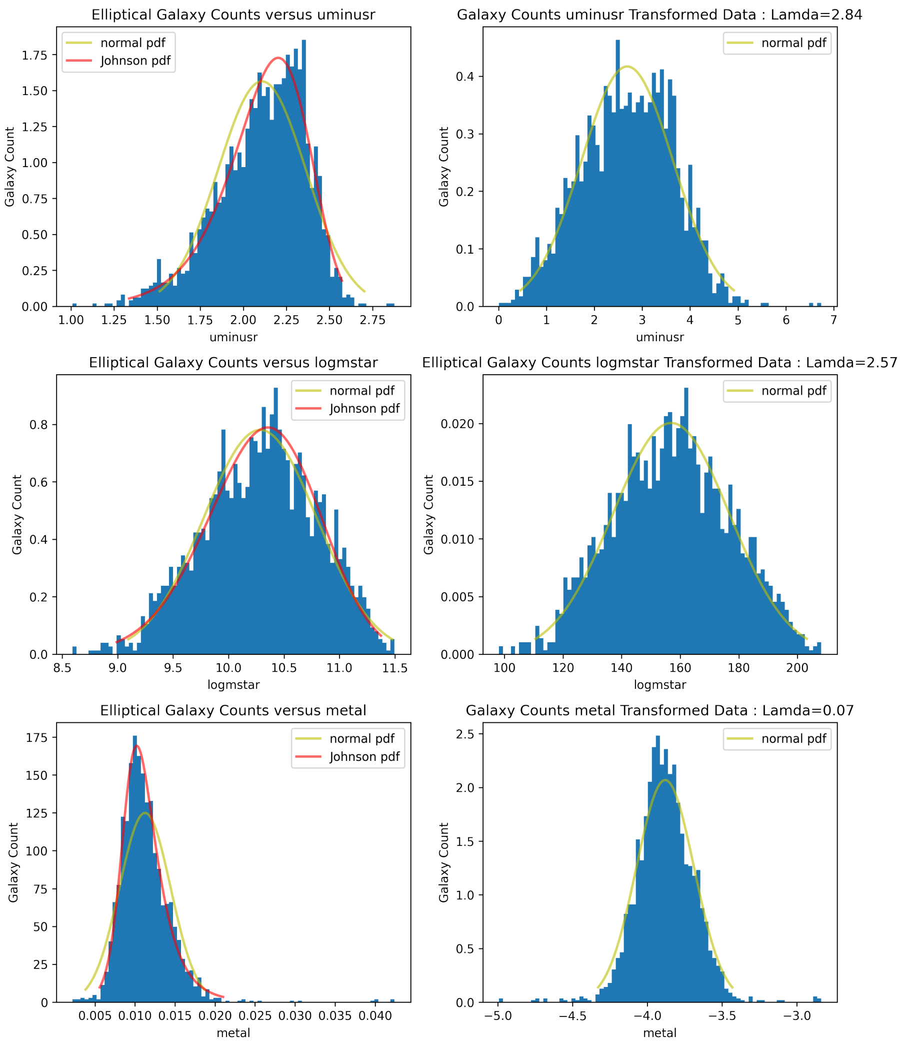
$$llf(\hat{\lambda})\, -\, llf(\lambda) < \frac{1}{2}\chi^2(1-\alpha, 1)$$

$$where\, llf\, is\, log\, is\, the - likelihood\, function$$

$$\alpha\, is\, the\, confidence\, interval\, i.e.\, 0.05\, is\, 95\%$$

Lambda λ values were determined for the Cox Box transformations which provide the best fit to a normal distribution. The main galaxy characteristic distributions (uminusr, logmstar, metal) and transformed distributions are shown in the left and right hand columns respectively of the charts in figure 21. The derived values of Lambda λ are documented in table 9.

Figure 21: Distributions



Elliptical galaxies

Table 9: Cox Box for elliptical galaxies

Characteristic	*Lamda* λ	Confidence Interval		Shapiro test for normality			
		min	max	Before Transform	p	After Transform	p
Redness(uminusr)	2.84	2.53	3.15	0.971	4.89e-20	0.994	9.24e-08
Mass (logmstar)	2.57	1.8	2.35	0.993	9.24e-08	0.996	1.85e-05
Metallicity(metal)	0.07	-0.02	0.16	0.862	2.05e-39	0.969	9.35e-21

A Shapiro test for normality was performed on the distribution before and after the Cox Box transformation. The distributions before the transformation showed high values for the test meaning the variations can be purely attributed to statistical variation. However as no obvious correlation was found between galaxy measures and environmental measures, then it is still possible that environment measures are not totally random and do have an influence for which the small variation from normality is a tracer.

7.4 Inverse transform

To get to the observed distribution from a normal distribution then the transform that would need to be applied is the inverse of the Cox Box transform which for a non zero value of λ is given by

$$\frac{\lambda}{y^{\lambda} - 1}$$

Using the determined values of λ, figure 22 plots the graphs of the inverse functions required to transform the distributions of uminusr, logmstar and metal to normal distributions. For comparison an exponential distribution is included as two of the distributions of environmental measures have reasonable fits with an exponential distribution see figure 22

Figure 22: Inverse transforms

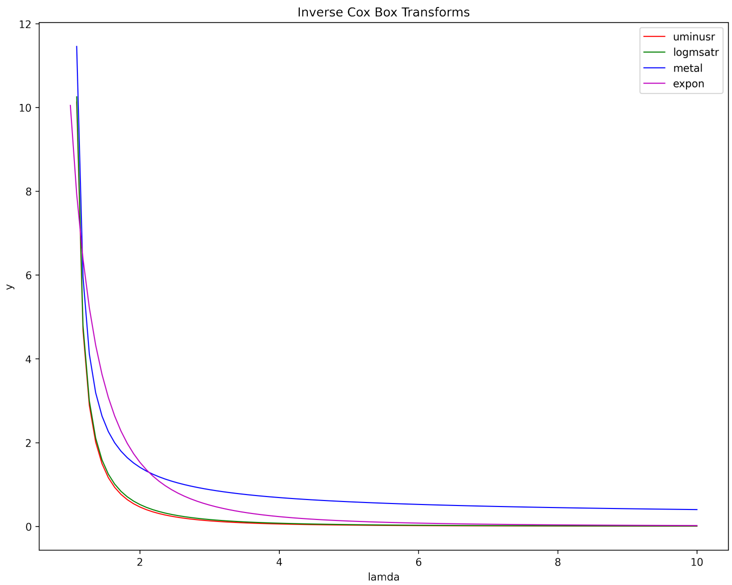
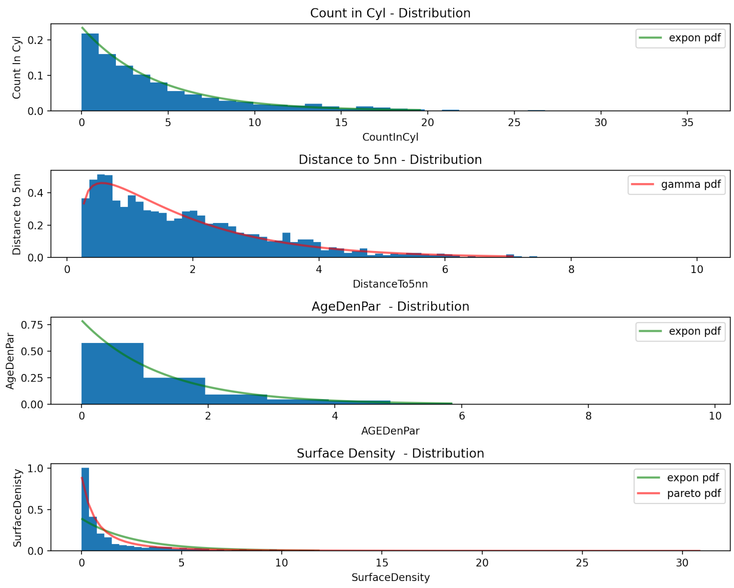


Figure 23: Distributions of environmental measures



7.5 Results from distributions

An inference drawn from the distributions would depend on some very large assumptions

- How an environmental measure would effect the distribution would be limited to a scalar factor.
- Also it has been assumed that the formation of galaxies has given rise to a Gaussian distribution, where as the distribution may be more like a Plank distribution or an ill defined distribution due to the processes involved.
- The Shapiro tests for normality before any Cox Box transformation are high.

so, as was stated in 7.1, could not solely be relied upon and would need to be supported by other research such as modelling.

8 Conclusions

- Looking at galaxies as a whole, there does not appear to be a correlation between galaxy characteristics and environmental measures. However, in some circumstances such as galaxies in the outer region of their local group, then a degree of correlation is found.
- There is a degree of correlation between the sums of galaxy characteristics for a local group i.e. uminusr, logmstar and metallicity and a galaxy's environmental measures.
- One possible explanation for why there is this correlation is that an early stage of the universe's evolution i.e. shortly before the initial creation of stars, the distribution of interstellar material corresponds to what will become over time local groups. Over further time, the material then subdivides into smaller groups to form stars which then make up galaxies. The galaxies form with dark matter halos and black holes at their core, this subdivision giving rise to galaxies with a full range of colour(uminusr) and mass (logmstar). The fact that the material that makes up a local group was at one time a single entity would explain why there is a relationship with the sum of group characteristics.

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