Substructure Statistics for Galaxy Clusters

Jon Stefkovich (UMBC), David S. Davis (UMBC/CRESST/NASA-GSFC)   Poster Category: Science

ABSTRACT:

Galaxy clusters are the largest gravitationally bound systems in the Universe. We know that clusters accrete mass and grow, but understanding the manner and rate at which this growth occurs is still being studied. The purpose of our research was to better understand the formation process of galaxy clusters by analyzing clusters for evidence of substructure. Understanding galaxy clusters dynamical states and how they grow will improve our cosmological models, and thus improve our understanding of the evolution of the Universe. Substructure in the galaxy clusters is studied using the Dressler-Shectman test, which was calibrated through extensive Monte Carlo simulations of galaxy clusters similar to real ones. We apply this method to the 35 clusters with 100 or more members with measured velocities from the SDSS data release 8. We present the results of the substructure tests and identify those clusters with the strongest substructure for further analysis.

INTRODUCTION:

Understanding how substructure is formed and the role substructure plays in galaxy evolution is very important in improving our cosmological models. Substructure is the presence of two or more groups of galaxies within the larger cluster of galaxies. What determines whether a group of galaxies is indeed a group is distinct spatial or velocity structure. Substructure is a clear sign of incomplete relaxation in a cluster and/or of cluster formation. A relaxed cluster will have no substructure and present signs of unimodality in the spatial and velocity distributions. Unrelaxed clusters analyzed as if they are relaxed, complicate analysis of mass, radii, and overall evolution due to the complicated and limited understanding of the nature of substructure.

We investigate for evidence of mulitmodality in spatial and velocity distributions through one dimensional statistical tests ,that refers to the velocity distribution of a cluster, and three dimensional tests that analyzes the sky coordinates as well as the radial velocity distribution. The Dressler-Schectman test is a popular test for it's high sensitivity to detecting evidence of substructure. The test does however also have a high detection rate of non-substructures in the presence of elongation and velocity dispersion gradients.   For the purpose of this project we only investigate for possible substructure and present those clusters for further analysis of substructure through other statistical means.

METHODS:

We use the one dimensional tests for skewness and kurtosis of the velocity distribution of galaxies in a cluster. For Kurtosis, the initial calculated values are subtracted by 3 to equate the value of 0.0 to Gaussianity. A skewness value of 0.0 also signif es a Gaussian distribution. The closer skewness and kurtosis are to a Gaussian velocity distribution, the more likely it is that the cluster is relaxed and exhibits little to no substructure. These one dimensional skewness and kurtosis tests are not particularly effective at detecting substructure due to their low sensitivity to the presence of sub clusters.

The three dimensional Dressler-Schectman test(1) (also "DS Test") has been used in several different analyses for cluster substructure. It's good sensitivity and effectiveness in producing signif cant results makes it a reliable test to be used.

1) $$\delta=\sqrt{\left(\frac{(N_{nn}+1)}{\sigma^2}\right)\left[(v_{local}^2-v_{avg})^2+(\sigma_{local}-\sigma^2)\right]}$$

The N parameter in the DS test is the number of galaxies in a local group. σ and v are the velocity dispersion and mean velocity of the cluster, respectively. σ_{local} and V_{local} are the local velocity dispersion and local mean velocity within a group of the closest N galaxies.

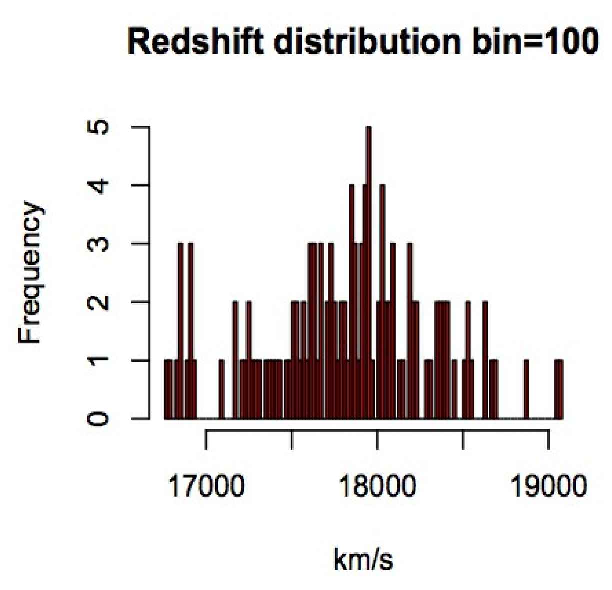
Using the statistical package R, the DS test was calculated on each galaxy in a cluster and the resulting δ values were summed to give $\Delta = \Sigma^{N}_{i=1} \delta_i$. We also used R to produce bubble plots, plotting the position of all galaxies in a cluster with point sizes proportional to the δ value for that galaxy. This is a good way to locate by eye areas of possible substructure.

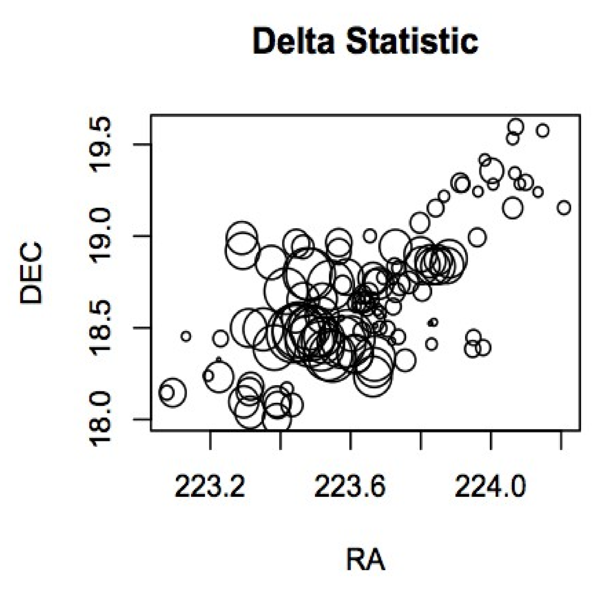
To test for the signif cance of the Δ result, we implemented Monte Carlo simulations. The positions of the galaxies were kept consistent with the original data set, but the velocities of the galaxies were randomly shuff ed, and Δ was recalculated. For this project, we ran the Monte Carlo simulations 1000 times for each cluster to get a large enough distribution to use the student-t test on our simulated distribution.

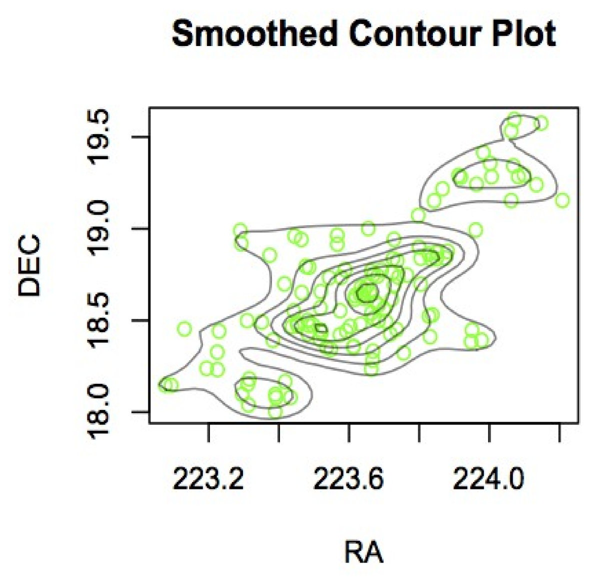
The student-t test was calculated by taking the mean value of the Monte Carlo simulations, X_M, the sum of our δ values, Δ, the standard deviation of the Monte Carlo Simulations, σ_M, and the square root of the number of Monte Carlo simulations -1, $(N_m - 1)^{1/2}$, which for our analysis was 999.

2) $$t=(X_M-\Delta)/\sigma_M$$

Using the pt function in R gives the distribution function from the calculated t value. By shuff ing the velocities of the galaxies among the positions, the resulting value gives the probability that our calculated Δ result was by chance, thus giving a conf dence level to our Δ values.







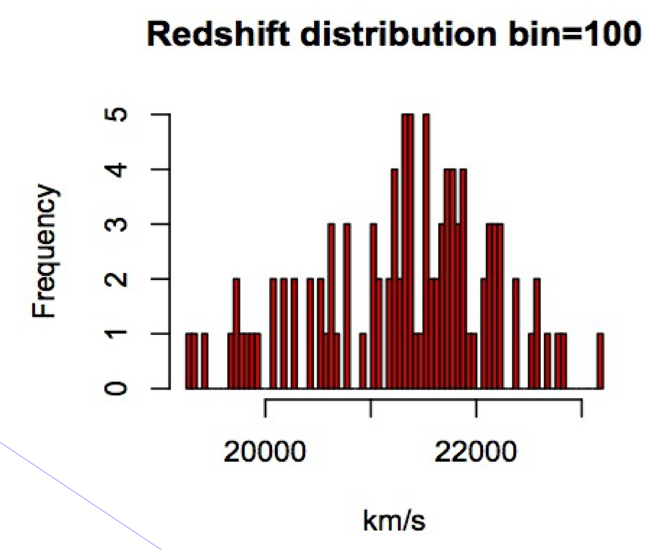
Number of Galaxies: 124
Cluster ID: 62138
Delta: 237.34
Kurtosis: -0.153
Skewness: -0.096
Velocity Dispersion(km/s): 456.4
Mean Velocity(km/s): 17820

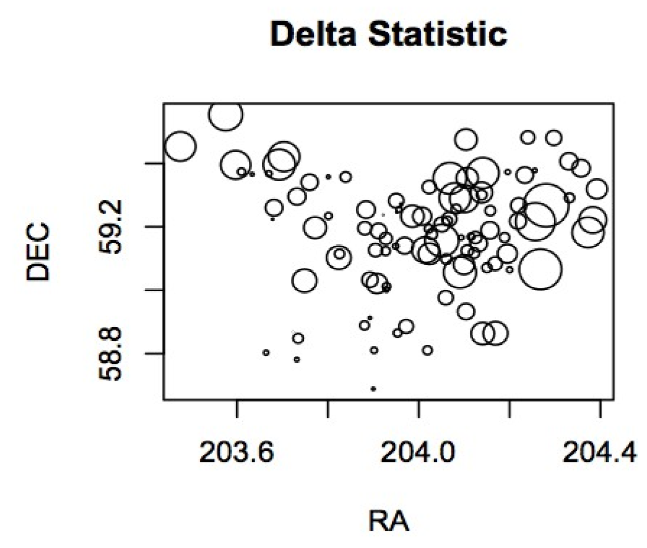
Data

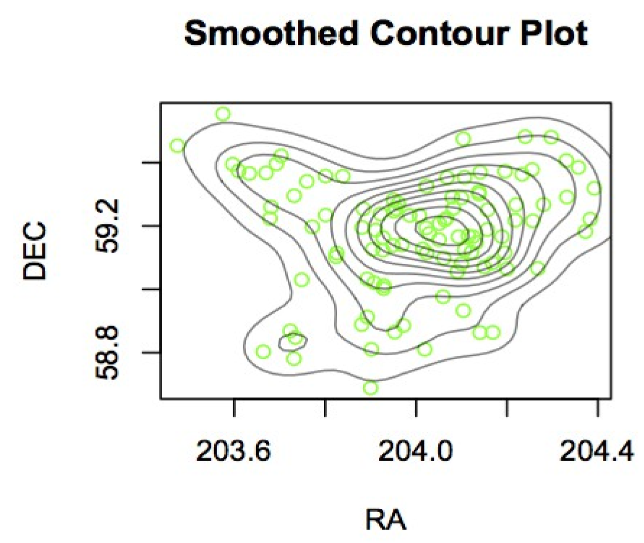
Results

Cluster ID	Substructure?	p-value	Skewness	Kurtosis	Velocity (km/s)	Velocity Dispersion (km/s)
793	Yes	0.00	-0.22	-0.327	12 498	515.3
914	Yes	0.00	-0.23	-0.452	26 127	657.4
3210	No	0.38	-0.20	0.17	8295	406.1
4844	Yes	0.00	0.18	0.32	1124	380.6
9349	Yes	0.00	0.01	-0.17	10 536	626.5
12 540 *	No	0.55	-0.46	-0.27	21 312	764.4
13 462	Yes	0.00	0.25	0.01	9171	591.7
14 256	No	0.10	0.61	-0.11	10 131	621.8
20 575	Yes	0.00	0.02	-0.41	7077	735.5
22 027	No	0.07	-0.49	1.12	7536	273.3
23 374	Yes	0.01	-0.11	-0.83	18 939	662.1
24 918	Yes	0.00	0.63	0.01	11 328	1000.3
29 587	Yes	0.00	0.28	0.06	26 973	740.3
33 851	No	0.18	0.38	0.00	12 213	354.6
34 726	Yes	0.00	0.35	0.38	13 680	506.2
34 727	Yes	0.00	-0.21	-0.42	23 808	825.9
38 087	No	0.30	0.19	-0.16	22 818	541.6
39 489	Yes	0.00	0.22	-0.38	21 624	1061.8
39 752 *	Yes	0.02	0.10	0.04	19 854	514.8
40 870	Yes	0.00	-0.19	0.04	21 888	717.4
42 171	Yes	0.00	-0.01	-0.55	9402	522.5
42 643	Yes	0.00	-0.45	-0.11	7350	396.3
44 121	Yes	0.00	-0.09	-0.43	10 293	626.0
44 471	Yes	0.00	-0.10	0.41	14 301	464.1
49 298	Yes	0.01	-0.35	-0.17	7233	809.3
50 631	No	0.35	0.44	-0.55	14 382	636.5
53 663	No	0.14	-0.20	-0.27	7065	331.2
57 317	Yes	0.00	-0.01	-0.91	16 056	516.4
58 101	Yes	0.00	-0.05	-0.57	23 217	614.5
58 305 *	Yes	0.00	-0.83	1.26	13 650	401.8
60 539	No	0.20	-0.24	-0.18	23 403	830.5
62 138 *	Yes	0.00	-0.09	-0.15	17 820	456.4
64 635	Yes	0.00	0.53	0.62	16 491	489.4
68 376	No	0.52	-0.69	-0.20	23 409	671.5
73 088	Yes	0.00	-0.49	-0.15	21 651	631.9

* clusters referenced in the paper.







Number of Galaxies: 103
Cluster ID: 12540
Delta: 120.65
Kurtosis: -0.271
Skewness: -0.459
Velocity Dispersion(km/s): 764.4
Mean Velocity(km/s): 21312

Data

CONCLUSIONS:

From this we can conclude that the 10 galaxy clusters that show no evidence of substructure using these tests are most likely more relaxed than the clusters that do show signs of substructure. While these tests do indicate the presence of substructure other processes such as recent cluster-cluster gravitational interactions or a recent merger with another cluster can also inf uence these tests. We use these tests to select a subsample of clusters for further study with more sophisticated statistical tests. These tests along with modeling will allow us to determine more information about these clusters, such as the mass, dynamical state and composition of the sub-components.

DISCUSSION

Using one and three dimensional statistical tests for substructure for the analysis of 35 galaxy clusters with a richness of greater than 99 galaxies reveals that for our sample, 28% of the clusters are relaxed clusters and demonstrate no evidence of substructure with 95% conf dence. This conf dence interval is def ned as the probability that our calculated Δ for the cluster was not the result of random chance, and we reject the null hypothesis at conf dence greater than 95% or 3 sigma.

The insensitivity of the one dimensional skewness and kurtosis tests can be noticed especially for clusters 39752 and 58305. Cluster 39752 spatially shows two subgroups, and is supported by the DS test that substructure is present, however the cluster has a skewness and kurtosis of 0.10 and 0.04 respectively. These values indicate that the velocity distributions are close to Gaussianity, which indicates a false positive. In contrast, Cluster 58305 exhibits higher skewness and kurtosis values of -0.83 and 1.26, respectively. These values show the velocity distribution is not near Gaussianity and it does indicate substructure. The one and three dimensional tests indicate this cluster is believed to have substructure. The one dimensional tests can be correct as in Cluster 58305, but they can also be insensitive like in Cluster 39752. Skewness and kurtosis tests are good tests for a Gaussian distribution and are good at detecting non-Gaussian deviations, but lose sensitivity as you move closer to the plane of the sky.

Acknowledgements:

I would like to thank Dave Davis for giving me the opportunity to conduct this research with him and directing me throughout this process. I came to him as an open book, and I have learned a lot from him throughout this project. I would also like to thank Ian George for putting my in contact with Dave Davis to make any of this possible. I want to thank NASA Goddard Space Flight Center and Telophase for coordinating this poster session and allowing me to present my research.