Galaxy Clusters:
The Local Effects on Star Synthesis

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Introduction

The Star Formation Rates (SFR) of galaxy clusters have been extensively studied both in close and far redshifts, but those of intermediate redshifts have yet to be observed to the same extent.

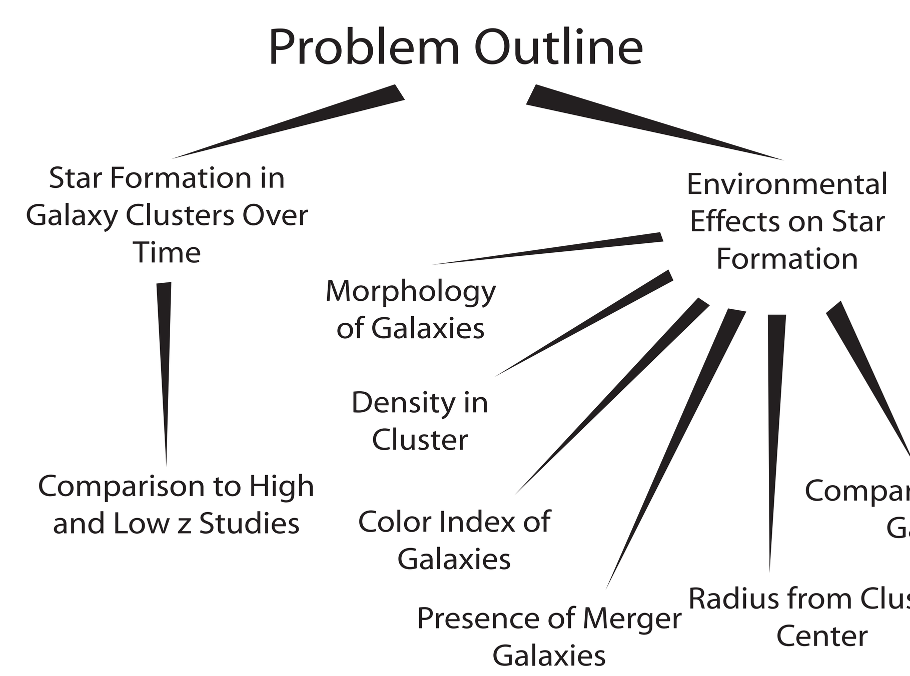
Three intermediate redshift galaxy clusters of differing masses and states of equilibrium were observed using the Spitzer Space Telescope as well as other data taken from the Hubble Space Telescope.

The SFR for each galaxy as well as for the entire cluster can be derived from the 24-micron flux. The 24-micron flux will give a more accurate representation of the SFR because it mostly penetrates through the dust and/or the dust will re-emit the extincted light, which can be quantified and redistributed to the total flux.

Problem

–How do the SFRs of intermediate redshift galaxy clusters compare to the SFRs of clusters at near and far redshifts? This is done by comparing the SFRs of the 3 intermediate redshift clusters in this study to 4 clusters each of high and low redshift from another study (Finn et al. 2005) to reveal possible trends in how SFR changes over time in the universe.

–What environmental factors affect the star formation rate of galaxies? Each cluster was analyzed to see how galaxy morphology, density within the cluster, radius from the cluster center, and presence of merging galaxies affects SFR, as well as examining field galaxies to see how being in a cluster can affect SFR.



Data

24-micron data was taken with the Spitzer Space Telescope's "Multiband Imaging Photometer for Spitzer" (MIPS) for wide-field, low-resolution imaging, which is used to derive Star Formation Rates (SFR). The Spitzer Space Telescope looks in the infrared wavelengths. The reason infrared data was used is because the light emitted primarily by young stars is absorbed and re-emitted by dust at infrared wavelengths, which is a good indication of the amount of star formation present in the galaxy.

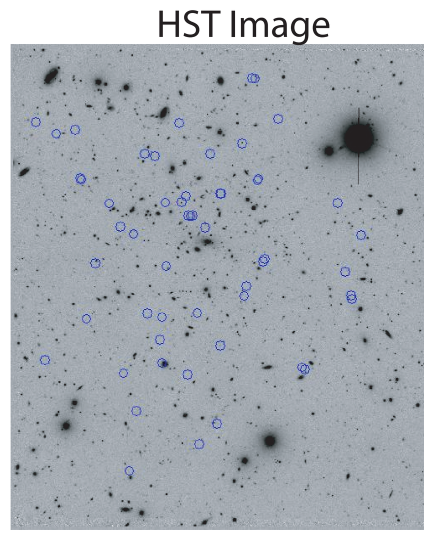
Imaging data from the Hubble Space Telescope's Advanced Camera for Surveys (ACS) was used to observe the shape of the cluster itself and the contained galaxies at a higher resolution.

Catalogues from the ESO Distant Cluster Survey (EDisCS) were used to get photometry and irregularity data of the galaxies.

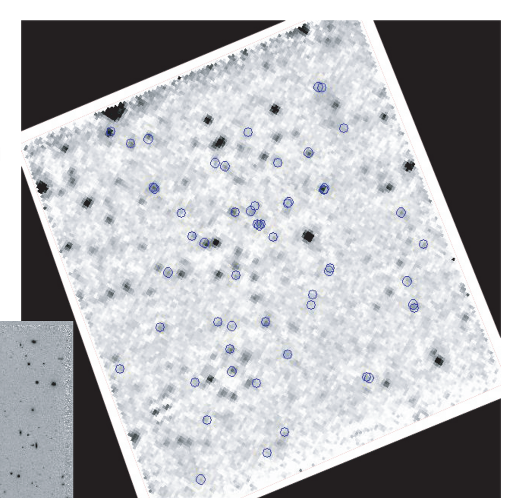
CL1232

–High Mass
–High Velocity Dispersion
–54 Member Galaxies
–Most Relaxed

HST Image



Cluster image from Hubble Space Telescope archives, edited by Zackery Schroeder



MIPS Image

Cluster Image from Spitzer Space Telescope Archives, edited by Zackery Schroeder

Procedure

Deriving Star Formation Rate (SFR)

Galaxies in the field of view are determined to be a part of the cluster photometrically and spectroscopically. The 24-micron flux is reduced to the infrared luminosity at 15-microns (L15). This is due to redshift, meaning that the light at 15 microns is actually observed at 24-microns. This wavelength is observed because the amount of blue light emitted without dust extinction is a strong correlation to the SFR. Applying the 5 template Spectral Energy Distribution curves (SEDs) to the L15 derives the total IR luminosity (Ltir). Applying the Ltir to a formula from previous literature yields 5 SFR values, which are averaged.

SFR (Msol/yr-1)=4.5 x 10-44 LTIR (ergs s-1)

There is a small source of error in the 24 micron flux observations, but is negligible in comparison to the error created by averaging the SED curves. Average SFR error between the three clusters is 13.7%

Mass Normalization of SFR

To compare the total SFR in each intermediate redshift cluster to those at high or low redshifts, it was necessary to normalize the SFR to account for the clusters having different masses.

In order to do so, the total SFR had to be calculated within 1/2 the virial radius because the number of star forming galaxies is related to the distance from the cluster center. This calculation was made in the other redshift studies as well, so it had to be done to compare them all.

The sum SFR within 1/2 the virial radius was then used to calculate the Sum SFR per cluster mass per 1e14 solar masses, or Sum SFR/Mcl/1*1014 Msol. Since each cluster has a different mass, their Sum SFR had to be divided by it to normalize them for comparing.

Identifying Merger Galaxies

If galaxies were visually very close to one another, appeared to exchange gas, and were cited in the irregularity data they were classified as merger galaxies. The merger galaxy SFRs were compared against the normal galaxies to find correlations between mergers and SFR.

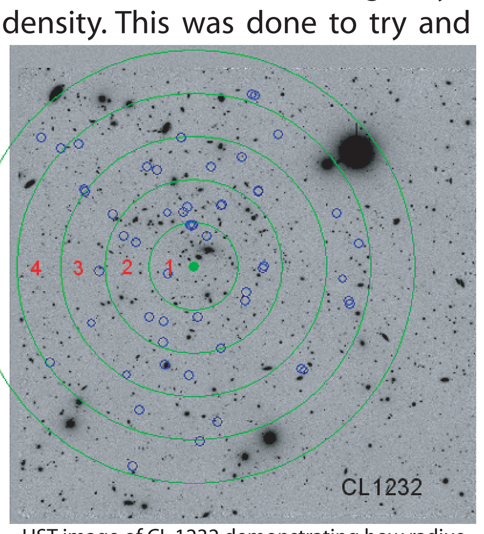
Morphology of Galaxies

Galaxies were binned into 4 groups according to the Hubble Tuning Fork, a progression model of different types of galaxies and their physical attributes. Each galaxy was binned into one of four groups: Elliptical galaxies, Early-type spiral galaxies, Late-type spiral galaxies, and Irregular galaxies.

Radius from Center and Density

Density – Annuli of .4 megaparsecs were placed around each cluster member. Each galaxy was then analyzed for the population density within its own annuli to rate each galaxy's environment in terms of density. This was done to try and find out how density of galaxies can affect SFR.

Radius – Sets of annuli were placed around the cluster center at regular intervals of .3 mega parsecs. These annuli were examined in regards to member population and average SFR within each annulus.



HST image of CL 1232 demonstrating how radius analysis is conducted.
Cluster image from Hubble Space Telescope archives, edited by Zackery Schroeder

Color Indices

Taking a color index of a galaxy (such as B-V) tells how blue or red the galaxy is. Color indices of R-K, I-K, and V-I were taken of each galaxy and compared to their average SFR to see if color relates to SFR.

Comparing to Field Galaxies

All field galaxies of all three clusters within a redshift of .49<z<.68 were examined to see how their morphologies, density, and color affected their SFRs, and were cross-correlated to the results of the cluster galaxies to give insight into how galaxies in and out of cluster differ as a function of their environment.

This redshift range was used because all field galaxies had different redshifts, and averaging their SFRs from all different redshifts produces no accurate result of how galaxies in clusters differ from those outside.

Analysis

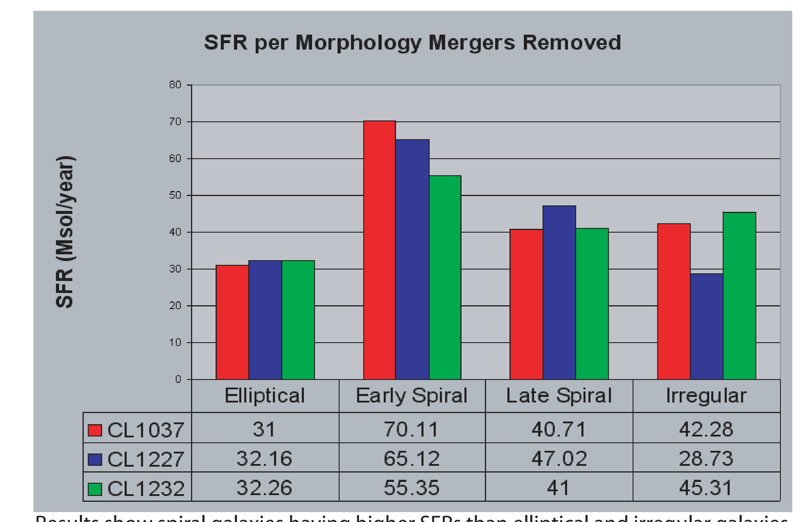
Analysis of Mergers

Most merger galaxies had no apparent difference in their SFRs from normal galaxies. However, galaxies with SFRs higher than 150 solar masses per year were merging galaxies, and they were inferred to be starburst galaxies. These starburst galaxies skewed the data in the other environmental studies, and were therefore excluded from them.

Analysis of Morphology

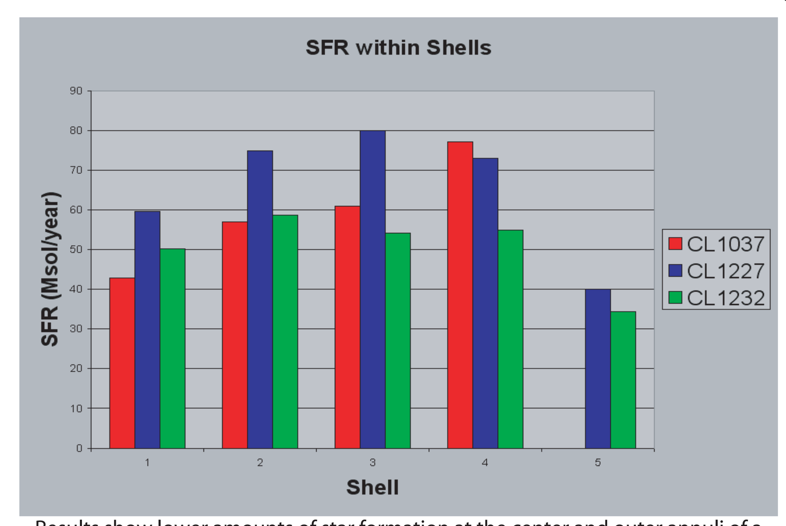
As seen on the graph, after removing starburst galaxies, early-type spiral galaxies had the highest SFRs, followed by late-type spirals, then irregulars, and finally ellipticals.

However, there is an anomaly in that early-type spiral galaxies had higher SFRs than late-type. This is in disagreement with current thought. This spike in early-type SFR can be attributed to Active Galactic Nuclei (AGN) contribution. An AGN is a strong source of emission in the core of a galaxy, and can skew the data. However, it could not be removed. The reason AGN are more likely present in early-type spiral galaxies is due to their larger central bulges. The AGN contribution cannot be removed without access to x-ray, 8 micron or radio data. None are available at this time.



Results show spiral galaxies having higher SFRs than elliptical and irregular galaxies.
Bar graph made with Microsoft Excel by Zackery Schroeder

Analysis of Radius and Density



Results show lower amounts of star formation at the center and outer annuli of a cluster, while having higher concentrations in the middle annuli.
Bar graph made with Microsoft Excel by Zackery Schroeder

Radius – As shown in the graph, average SFR increased and then decreased when travelling from the cluster center to the cluster edge. This could be due to two things: at the center of the cluster, less cool gas is present to condense and form stars, and at the edge of the cluster, newly-entering galaxies undergo a process called 'ram-pressure stripping' that strips the cool gas from the galaxy away, and thus SFR is stunted.

Density – It was found in two of the three clusters that as the density of the galaxy's environment increased, SFR decreased. This can be due to what is called 'galaxy harassment', where galaxies that are close to one another push and pull on each other and so cool gas has a hard time condensing to form stars.

	Avg SFR for each density group				
Cluster	1	2	3	4	6
CL1037	64.64	53.64	35.83	39.59	NA
Cl1227	86.32	49.29	55.58	NA	NA
CL1232	43.65	46.83	46.83	50.53	40.88

CL1037 and 1227 show inverse relationship with density and SFR.
Spreadsheet data made with Microsoft Excel by Zackery Schroeder

Analysis of Field Galaxies

Overall, galaxies not in a cluster had higher SFRs than those in a cluster. This difference in SFR of cluster and non-cluster galaxies was found to not be due to color index and morphology.

The difference in SFR between galaxies in and out of a cluster is most likely due to density. As previously mentioned, it was found that high density in most cases produces lower SFR in a galaxy, field galaxies, being in a considerably less dense environment, do not suffer from galaxy harrassment or ram-pressure stripping, and can thus sustain a higher, constant SFR rather than a lower, fluctuating SFR.

	SFR in Cluster	Field Galaxy SFR
CL1037	42.89	72.52
CL1227	67.37	44.17
CL1232	56.26	134.19
Average	**55.51**	**83.63**

Data shows higher SFRs in field galaxies.
Spreadsheet data made with Microsoft Excel by Zackery Schroeder

Analysis of Color Indices

The indices of R-K and I-K were averaged to try and compensate for error. Additionally, the V-I index was used to again see how SFR and color relate.

It was found that in both studies, the bluer the galaxy was (the lower its index group), the greater SFR it had. This agrees with current thought that red objects are generally older and cooler, while blue objects are younger and hotter. However, it is not that the color of the galaxy affects the SFR, but that having a certain color indicates a high or low SFR. Interpretation constraints were present with all color studies due to dust absorption, thus completely accurate results cannot be achieved.

	Avg SFR per R-K/I-K Index Group					Avg SFR per V-I Index Group				
Cluster	2	3	4	5	6	1	2	3	4	5
CL1037	80	54	59	56	53	51	46	58	37	54
CL1227	87	38	49	65	NA	NA	62	62	51	39
CL1232	50	59	58	51	47	NA	54	44	35	54

Data shows bluer galaxies tending to have higher SFRs.
Spreadsheet data made with Microsoft Excel by Zackery Schroeder

Conclusions and Discussion

Environmental Effects on SFR

Internal

These aspects of galaxies relate to their SFRs on an individual basis, meaning they happen regardless of whether or not they are in a cluster.

Morphology–
The type of galaxy has a considerable effect on the amount of star formation that is present. Both types of spiral galaxies exhibit high SFRs compared to elliptical and irregular galaxies, which confirms current thought that hotter, bluer galaxies would produce more stars.

Color–
Galaxies that have higher SFRs tend to be bluer, as expected from previous scientific thought. However, blue in color is merely an indicator of high SFR, not an affector.

Starburst–
Merging galaxies with abnormally high SFRs (>150 solar masses per year) can in most cases be classified as starburst galaxies, and thus merging with another galaxy can have a great effect on SFR.

External

These aspects affect the SFRs of the galaxies externally; meaning the individual galaxy itself is not a factor.

Density and Radius–
In the middle annuli, the average SFR of the galaxies is higher than at the center and edge of the cluster. This can be due to multiple factors. In the center of the cluster, there is less cool gas available to form stars and these galaxies are more likely to undergo a proccess called ram-pressure stripping. Star formation rates directly decrease with local density, which can be attributed to 'galaxy harassment', meaning close galaxies push and pull on each other and thus cool gas cannot condense and form stars.

Cluster vs. Field Galaxies–
Field galaxies' SFRs were 50% larger than cluster galaxies. This is due to the isolation of the field galaxies: No outside forces such as dark matter, galaxy harassment, or ram-pressure stripping can pull on their gas and they can therefore sustain a constant SFR.

Evolution of SFR over Time

In previous studies there was a decrease in SFR from high redshift to low redshift clusters, and model of an aging universe was proposed wherein as the universe aged, less cool gas was available to form stars, and thus SFR decreases.

However, in this study of intermediate redshift clusters, it was found that the average SFR is considerably higher (over 7 times) than both high and low redshift clusters. It is possible that there is evidence of a different model of the evolution of star formation in the universe: at the beginning of the universe, galaxies and galaxy clusters were very disorganized, that is to say that cool gas and dust were perhaps not as concentrated and thus galaxies did not create new stars very quickly. At the middle-aged universe (this study), galaxies and clusters were more organized (their dust and cool gas were concentrated) and began to create stars much more quickly. At the present age of the universe, the cool gas in the galaxies was exhausted from the high star formation during the middle ages of the universe, and thus lower SFRs are found.

Progression of SFR (Msol/yr/1e14 Msol) with z			
Redshift	Low z	Mid z	High z
Sum	6.97	372.78	52.18
SFR/Mcl/1e14	0.80	103.64	12.97
Msol in	1.78	369.74	19.33
Clusters	72.01		71.60
Average	**20.39**	**282.05**	**39.02**

Data shows enormous increase in SFR of galaxies at mid-z.
Spreadsheet data made with Microsoft Excel by Zackery Schroeder

Extensions

In order to make results more accurate, Active Galactic Nuclei (AGN)-containing galaxies would need to be identified and removed from the environmental studies. These can be identified through the examination of radio, x-ray, or 8-micron infrared data.

Additionally, since there was such a large increase in SFR of mid-redshift clusters, more research at mid-redshift ranges of galaxies needs to be conducted to find out exactly why this jump is occurring.