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Galaxy Morphology in Clusters

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1. INTRODUCTION

In this study, I examined the morphological type of galaxies in clusters as a function of the distance from the galaxy to the cluster center ($\mathrm{d_{center}}$). Cluster quantities with overdensity 200 were used for this work. I separated the `GalWCat19` catalog into several mass bins and examined this trend in each of these subpopulations of massive clusters. The cumulative fraction of elliptical galaxies within an expanding bubble of radius $\mathrm{d_{center}}$ is displayed in the figure at the end of the report.

2. METHODOLOGY

To begin, I filter the cluster catalog to only include cluster masses greater than 1×10^{28} $\mathrm{M_\odot}$ and comoving distances less than 225 Mpc $\mathrm{h^{-1}}$, according to the catalog completeness thresholds (Abdullah et al. 2020b). I then sort the catalog of clusters into five mass bins. Subsections of the catalog are taken within these mass thresholds and processed according to the procedure below.

Within each mass limit, the galaxy catalog is cross matched with every cluster ID present in this mass bin. The distance from each galaxy to its host cluster's center is calculated by

$$\mathrm{d_{center}} = \sqrt{\mathrm{r_{gal}^2} + \mathrm{r_{cluster}^2} - 2\mathrm{r_{gal}}\mathrm{r_{cluster}}\cos\theta} \tag{1}$$

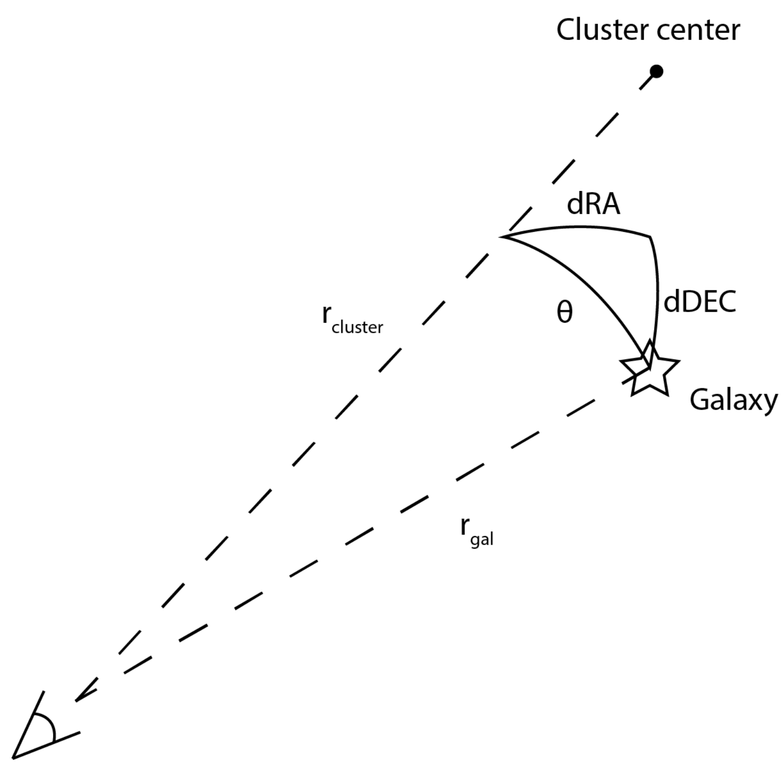


Figure 1. Schematic for calculating the distance from the galaxy to its cluster's center using the spherical law of cosines. θ is used to get the component of the distance along the sky with respect to the observer, and is found using the spherical law of cosines.

where r_{gal} is the line of sight comoving distance from the observer to the galaxy, and

$$\cos\theta = \cos\Delta_{RA}\cos\Delta_{DEC} + \sin\Delta_{RA}\sin\Delta_{DEC}\cos\pi/2 \tag{2}$$

with Δ_{RA} and Δ_{DEC} equal to the differences in RA and DEC between the cluster center and the galaxy, in radians.

The cluster center distances for all galaxies belonging to clusters in this mass bin are then tabulated along with a flag to indicate whether the galaxy is elliptical or not. Then, these galaxies are further binned by the distance to their cluster's center. The data is then plotted cumulatively to show how the fraction of elliptical galaxies changes as the threshold distance is increased outward from the cluster's center. A maximum distance is set at 10 Mpc h^{-1}, according to the GalWeight maximum projected radius (Abdullah et al. 2020a).

3. RESULTS

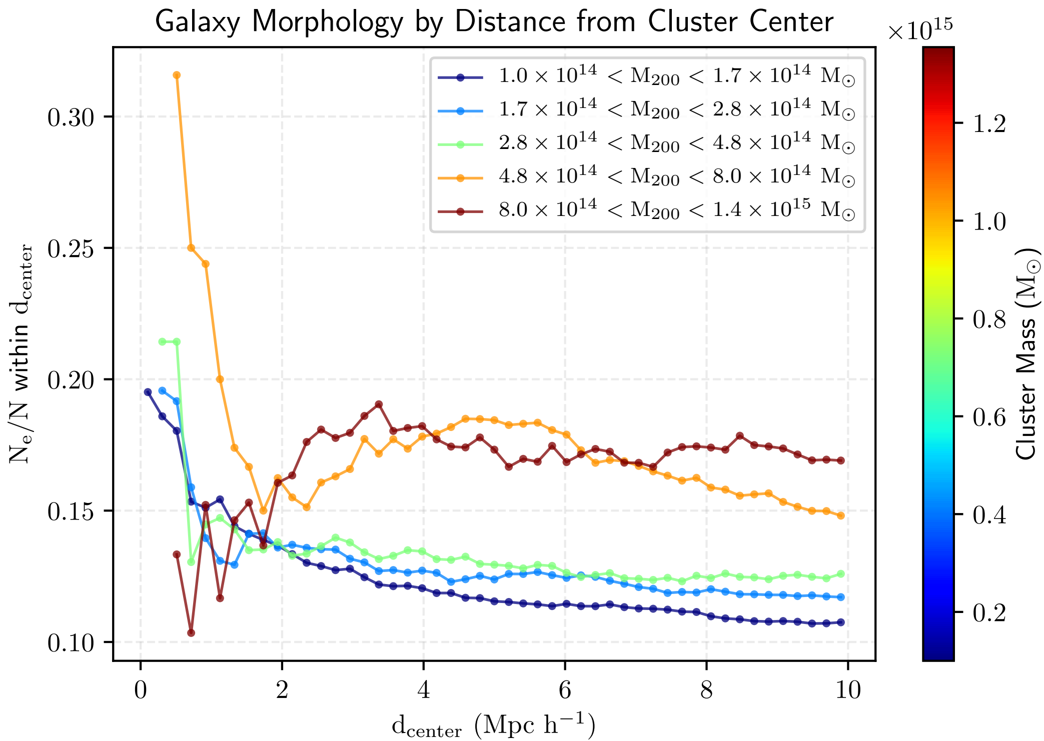
Examining the figure, it is found that in general low mass clusters have a denser relative concentration of elliptical galaxies at their centers. Further out in the low mass cluster, the fraction of elliptical galaxies decreases.

An entirely different trend emerges from the high mass clusters. Here, it appears that the very highest mass clusters have very few elliptical galaxies at their cores. This fraction steadily increases out to large center distances, meaning that the relative fraction of elliptical galaxies in high mass clusters peaks at around 4 - 6 Mpc h^{-1}, and drops slightly on either side.

REFERENCES

Abdullah, M. H., Klypin, A., & Wilson, G. 2020a, ApJ, 901, 90, doi: 10.3847/1538-4357/aba619

Abdullah, M. H., Wilson, G., Klypin, A., et al. 2020b, ApJS, 246, 2, doi: 10.3847/1538-4365/ab536e



Galaxy Morphology by Distance from Cluster Center
$1.0 \times 10^{14} < M_{200} < 1.7 \times 10^{14}\ M_\odot$
$1.7 \times 10^{14} < M_{200} < 2.8 \times 10^{14}\ M_\odot$
$2.8 \times 10^{14} < M_{200} < 4.8 \times 10^{14}\ M_\odot$
$4.8 \times 10^{14} < M_{200} < 8.0 \times 10^{14}\ M_\odot$
$8.0 \times 10^{14} < M_{200} < 1.4 \times 10^{15}\ M_\odot$
N_e/N within d_{center}
0.10
0.15
0.20
0.25
0.30
0
2
4
6
8
10
d_{center} (Mpc h^{-1})
$\times 10^{15}$
0.2
0.4
0.6
0.8
1.0
1.2
Cluster Mass ($M_\odot$)

```python
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.pylab as pl
import matplotlib
matplotlib.rcParams['text.usetex'] = True


def scinot(num):
    '''
    Formats numbers in scientific notation for LaTeX.
    '''
    numstrs = '{:.1E}'.format(num).split('E+')
    return r'${} \times 10^{{{}}}$'.format(numstrs[0], int(numstrs[1]))


# Set up figure
fig, ax = plt.subplots(1, 1)

# Collect data from external files
cluster_data = np.loadtxt('GalWCls19.txt', skiprows=41)
galaxy_data = np.loadtxt('GalWGal.txt', skiprows=9)

# Bin the clusters by mass
n_bins = 5
cluster_masses = cluster_data[:, 18]
cluster_distances = cluster_data[:, 5]

# Only take clusters larger than 10^14 for completeness
cluster_data = cluster_data[np.logical_and(
    cluster_masses >= 1e14, cluster_distances <= 225)]
cluster_masses = cluster_masses[np.logical_and(
    cluster_masses >= 1e14, cluster_distances <= 225)]

# Make mass bins, if necessary
mass_bins = np.logspace(np.log10(min(cluster_masses)), np.log10(max(cluster_masses)),
n_bins + 1)
inds = np.digitize(cluster_masses, mass_bins)

colors = pl.cm.jet(np.linspace(0, 1, n_bins))

# For each mass bin in the sample...
for i in range(1, n_bins + 1):

    # Narrow the sample to clusters in this mass range
    clusters = cluster_data[inds == i]
    center_distances = np.array([])
    elliptical_flags = np.array([])

    if len(clusters) == 0:
        continue

    # Loop over all the clusters in this group
    for j in range(len(clusters)):
        # Collect galaxies in this cluster by matching cluster ID
        galaxies = galaxy_data[galaxy_data[:, 10] == clusters[j, 0]]

        # Get distance information
        r_gal = galaxies[:, 3]
        r_c = clusters[j, 5]

        # Get angle between galaxy and cluster center
        dRA = (galaxies[:, 0] - clusters[j, 1]) * np.pi / 180.
```

```
        dDEC = (galaxies[:, 1] - clusters[j, 2]) * np.pi / 180.
        theta = np.arccos(np.cos(dRA)*np.cos(dDEC))

        # Distance from galaxies in this sample to this cluster's center
        d = np.sqrt(r_gal**2 + r_c**2 - 2.*r_gal*r_c*np.cos(theta))
        is_elliptical = galaxies[:, 9] == 2

        # Add data from this cluster to the mass group's data
        center_distances = np.concatenate((center_distances, d))
        elliptical_flags = np.concatenate((elliptical_flags, is_elliptical))

    # Bin by distance to create x and y data
    n_dist_bins = 50
    dist_bins = np.linspace(0, 10, n_dist_bins)
    dist_inds = np.digitize(center_distances, dist_bins)

    # Find fraction of ellipticals in each distance bin
    all_bincenters = (dist_bins[:-1] + dist_bins[1:]) / 2
    frac_ellip = []
    bincenters = []

    for k in range(1, len(dist_bins)):

        #    rule = dist_inds == k
        rule = dist_inds <= k # Cumulative
        if len(elliptical_flags[rule]) > 10:
            frac = sum(elliptical_flags[rule]) / len(elliptical_flags[rule])
            frac_ellip.append(frac)
            bincenters.append(all_bincenters[k - 1])

    # Plot results
    ax.plot(bincenters, frac_ellip, alpha=0.75, c=colors[i - 1], lw=1, marker='o',
markersize=2, label=r'{} $< \rm M_{{200}} < $ {} $\rm M_{{\odot}}
$'.format(scinot(mass_bins[i - 1]), scinot(mass_bins[i])))

if n_bins > 1:
    sm = plt.cm.ScalarMappable(cmap=pl.cm.jet,
norm=plt.Normalize( vmin=min(cluster_masses), vmax=max(cluster_masses)))
    cbar = fig.colorbar(sm)
    cbar.ax.set_ylabel(r'Cluster Mass ($\rm M_{\odot}$)', rotation=90)
ax.set_xlabel(r'$\rm d_{center}\ (\rm Mpc\ h^{-1})$')
ax.set_ylabel(r'$\rm N_e / N$ within $\rm d_{center}$')
ax.set_title('Galaxy Morphology by Distance from Cluster Center')

ax.grid(ls='--', alpha=0.25)
ax.legend(fontsize=8)
plt.show()
```