**ASTR 303: Extragalactic Astronomy**

**Computational Assignment I – Virial Mass of Coma Cluster with SDSS-DR 13 DATA**

**Objective:** By compiling SSDS data for the central RA & Dec values, redshift, redshift error, r magnitudes, error in r magnitudes, and extinction in r band, the aim is to recreate Fritz Zwicky’s procedure that allowed him to hypothesize the existence of dark matter from a few galaxy clusters when the M/L (virial mass to luminosity ratio) was acquired.

1. First, a query was submitted to the SSDS to retrieve the data:

A picture containing bird

Description automatically generated

From photometry data, Object ID, ra and dec values (in degrees), apparent magnitude in the r band, the error in r magnitude, and extinction in r band were retrieved. From spectroscopic data, the redshift and redshift error values constrained between 0.05 and 0.005 were obtained. The velocity dispersion values were also queried but never used.

A screenshot of a cell phone

Description automatically generated

1. Visualizing the Data:

Putting all the (ra,dec) values into separate arrays, a scatter plot of the cluster was created, 761 points. It can be seen from the multitude of straying points that this is an over-density of galaxies spread across a small patch of sky between 193.5º and 196.5º and 26.0º and 29.5º.

1. Finding the weighted mean RA and Dec

The r-magnitude values were used as weights; in order to weight up the bright galaxies and weight down the faint galaxies, the r-magnitudes were converted to a flux value using MSUN = 4.76 in m – M = 2.5log10(f/fsun), and the flux ratio was used as the weights in the following formula: where the summed values of wi are the weights (flux ratios) and xi are the ra and dec values. The center of the galaxies was approximated to be (194.88º, 27.95º).

1. Using the suggested bin size of 0.001, a histogram of the redshifts was plotted and fit with a Gaussian. The mean redshift as determined by the mean of the fit was 0.0235. The value from Epoch J2000 states redshift value to be around 0.0231, so I expected the velocity value calculate in the next step may be an overestimate. The sigma value is the 1 value, which was found to be 0.0044.

A picture containing large, sitting, white, table

Description automatically generated

1. Using the mean redshift to calculate the recessional velocity of the cluster using the Doppler shift formula, a recessional velocity of

7049.5 km/s was determined. As stated above, this value is an overestimate since my mean value for the redshift is slightly more. I suspect the sample I am using is rather large and non-member galaxies are contributing to the value: using the expected mean value, the recessional velocity is around 6.9e3 km/s. The distance to the cluster was calculated as 103.9 Mpc, again it appears to be an upper limit as the stated value is closer to 102.9 Mpc.

1. The projected radial distances from coma’s center (determined in step 3 to be at (194.88º, 27.95º))are calculated in array p in the code: first the average values of dec from the center dec coordinate (denoted B) was found, and the values in array 𝛼𝑔 use the cos correction: such that 𝛼𝑔(ra) = (ra\_values•(cos(average dec)). The value for the angle of sight was determined by the following formula: 𝑐𝑜𝑠𝜃=𝑠𝑖𝑛(𝛿)𝑠𝑖𝑛(𝛿𝑔)+𝑐𝑜𝑠(𝛿)𝑐𝑜𝑠(𝛿𝑔)𝑠𝑖𝑛(𝛼−𝛼𝑔) where 𝛿 is the dec value at the center, 𝛿𝑔 refers to all the dec values of galaxies, 𝛼 is the center ra value and 𝛼𝑔 is as above, the corrected ra values. The angle of sight value was converted to seconds of arc, and distances (I used array R2, distances to all individual galaxies, all roughly 103.9Mpc) in parsecs to calculate the projected radial distances from the cluster’s center using the small angle formula. The majority of galaxies appear to be within 2-3 Mpc of the galactic center, and a few are at about 4 Mpc (I suspect this value is too far from center to consider them member galaxies).
2. A screenshot of a cell phone

   Description automatically generatedThe member galaxies were found in two steps: first I selected the clusters with values of projected radial distances of less than or equal to 1.5 Mpc, and enumerated the array for the condition to output the indices where the corresponding values meeting the condition are located.

This sufficiently narrowed my data to 169 member galaxies whose projected radial distance lay within a radius of 1.5Mpc.

A close up of text on a white background

Description automatically generatedSelecting z values meeting the criterion of being between +/-3 posed more difficulty since my sigma value was not enough to select an appropriate sample of galaxies, so I tried increasing the bound to +/-4 and +/-5; however from the indices I noted not a lot of galaxies met both aspects of the criterion; this is likely a result from an oversampling of galaxies from the query resulting in the sigma value of 0.044. I use z[output] (where output corresponds with the indices of the galaxies meeting the <= 1.5Mpc criteria rather than the redshift bounds) for further plots, which as expected impacted my results.

The main difficulty I had was trying to find a method to use the indices to match member galaxies that meet both conditions. This resulted in a sample which may have been to large for the member galaxies.

1. As discussed above, there were issues selecting member galaxies that met both conditions, so the sample of 169 galaxies was used to get a better estimate of the center RA and Dec mean values:

A screenshot of a cell phone

Description automatically generated

1. Recreating the plot from step 2 with the selected member galaxies, I overlaid the galaxies meeting the <= 1.5 Mpc condition and the bounds between +/-5 condition: as can be seen that some of the blue dots (member galaxies) lie outside of the red circle representing the 1.5 Mpc region line, those galaxies had a redshift between +/-5 but a projected radial distances that was greater than 1.5Mpc. From the sample, I would expect a larger number of galaxies to meet both conditions, but due to the difficulties in combining both conditions, that is why there is still an overabundance of cobalt points (representing all galaxies from the original data set) within the circle.

A close up of a piece of paper

Description automatically generated

A redshift histogram was plotted again

using z-values with indices corresponding

to the indices of redshifts that meet the +/-5 condition, in the array OP. The

resulting histogram was fitted and has a mean value of 0.0243 and a sigma value

of 0.0027. Additionally I plotted the histogram using the indices of redshifts that correspond to the values meeting the <= 1.5 Mpc condition and the resulting mean and sigma value proved to be a

A close up of a map

Description automatically generatedbetter fit.

To the right is the histogram from z[OP] values,

giving a mean that is an overestimate for the coma cluster.

Beneath is the histogram from z[output] values, the mean value is still an overestimate for coma but

not as much as for z[OP].

A close up of a map

Description automatically generated

1. In order to calculate the absolute

A picture containing knife

Description automatically generatedr-band magnitudes of the galaxies, the following formulae were used:

where m values are the apparent magnitudes, M is the absolute magnitude, A is the

extinction, and d corresponds to galaxy

distances. The error was calculate as the

quadratic sum of the magnitude error and

error in distance (delta d). The error in

log10 was also considered in calculation as 0.4343.

1. The r-band absolute magnitude values were used to find the luminosity ratio: A screenshot of a cell phone

   Description automatically generatedthe length of the array is 169 as the same

Conditions for the sample are used as above.

1. The cumulative luminosity function for the member galaxies was found as a function of the

radial distances. First the values in the luminosity ratio array were sorted and normalized

A close up of a map

Description automatically generated(sort(L\_ratio/L.sum()) and passed onto a new variable, the range between 1 and

len(var)+1/len(var) so that at each distance value, r, the luminosity is x or less. The function is step-wise but otherwise close to what I expected for a sample of this size; I fit a polynomial of varying degrees (degree 10 gave the closest fit) to interpolate the plot.

1. Using the polynomial fit (blue line) to

interpolate the effective radius at a radial

distance of 1.03Mpc, which corresponded with CDF = 0.500. The effective radius was calculated to be 0.66 Mpc, and from that, = 0.88 Mpc. This value is the half-mass radius, which from further calculations appears to be an underestimate. The CDF for all galaxies was also plotted as well to observe the trend.

1. Using z[output] to calculate the line-of-sight velocities and the corresponding peculiar velocities, gave values that varied between approximately -2000 and 2000 km/s.

A screenshot of a cell phone

Description automatically generated

1. Plotting the histogram for the peculiar velocities, I re-used the same code as for the histograms for redshifts but with a bin size of 50 to better encompass the range of the velocities. While I was able to determine the standard deviation needed to determine the virial mass, the Gaussian fit would not work.

A screenshot of a cell phone

Description automatically generated

1. A screenshot of a cell phone

   Description automatically generatedUsing the sigma value (above stated as uncertainty) I calculated M1/2 = 31/2 / G. As expected, due to the velocity distribution, the binding mass is an overestimate as cited values range around 7e14 solar masses; from the *Early History of Dark Matter* by Sidney van den Bergh (DAO), Zwicky’s value for the velocity dispersion using a sample of eight galaxies was about 1019 360 km s-1, and the value found in the histogram above is even larger at 1216 km s-1 so it was expected that the mass would not be consistent with the literature values but falls (roughly) within the range in terms of magnitudes. Modern values cited are closer to 1082 km s-1.

The resulting mass is 9.13e14 solar masses, about 1.3 times the expected value.

1. Interpolating the normalized CDF of luminosity at r1/2 (green point on the CDF plot) and scaling it with the total luminosity, the luminosity within the ½ radius was determined to be around 1.55e12 Lsun; using this value to calculate the ratio (after dividing the mass value by the solar mass to get it in terms of Msun/Lsun (was initially in kg), the final value is **587.7 Msun/Lsun**. As expected, due to the considerable overestimate of the mass at half radius, the value is also an overestimate (values from 50-200 Msun/Lsun are cited); the luminosity also seems to be an overestimate since calculating M/L ratio using 7e14 as the cluster mass still results in a value that is about 100 over.
2. This result still indicates that the coma cluster has an apparent overabundance of matter and unexpectedly high velocities, which in turn points to the presence of unseen matter. Zwicky’s results showed velocities of approximately 400 times the expected value from the luminosities. In repeating this exercise, I would change the value of selected member galaxies, firstly to actually include both conditions as specified, and secondly to limit the sample to about 100 galaxies. Zwicky’s initial overestimate for the mass-to-light ratio (van den Bergh) is due to an incorrectly assumed Hubble parameter of 558 km s-1 Mpc-1 as opposed to the 67.8 km s-1 Mpc-1 value used in this exercise. The mass-to-light ratio, although an overestimate, can still be interpreted as an indicator to unseen matter within the Coma cluster.

**Please see the appendix for the code.**