Article

Centralities of galaxies in the weighted network model of the Local Group

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Abstract
Little is known about the structures and characteristics of the networks behind galaxy clusters. Considering that the essential interaction between the elements of a cluster is the gravitational attraction, the study has modeled the Local Group, a local galaxy cluster of which the Milky Way is a member, as a weighted network according to gravitational attraction. After the galaxies' unknown masses have been calculated from their apparent and absolute magnitudes, the gravitational attraction matrix, being the adjacency matrix of the network, would be formed from the matrix of their positions relative to each other. Various centrality measurements known as fundamental network metrics were thus performed to determine if the massive galaxies of the cluster have high centrality values. In the proposed weighted network model, direct and indirect correlations have been observed between centrality values and masses of the galaxies.

Keywords network; centrality; gravity; Milky Way; Local Group.

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1 Introduction

Examination of the large-scale structure of the universe has been thought with a network model for a while. As large-scale networks are required to be modeled in such investigations, the study of the intergalactic space has been one of the models where galaxies represent nodes. Some network analyses, both from simulation and observational data, investigate the topological properties of the connected galaxies on a web-like basis called the cosmic web (Coutinho et al., 2016; Forero-Romero et al., 2009; Aragon-Calvo et al., 2010; Bond et al., 1996; Shandarin et al., 2010), which is a comprehensive concept to include the holding of galaxies together by gravity, the gas stretched between them and distribution of the dark matter. A network and its edges formed between galaxies could be modeled by merely gravitational interactions. Thus, it would be the right choice to study the local clusters of galaxies where the Hubble law could not be observed (Freedman and Feng, 1999). Keeping galaxies together in a local cluster requires them not to move away from each other by the expansion of the universe. This makes local galactic clusters suitable to create a network model which galaxies have been held by gravity and do not move at relativistic speeds within the cluster. Since the Modified Newtonian Dynamics (MOND) does not adequately account for the observed characteristics of these clusters and if the galaxies inside a cluster are considered to be point-like objects, Newton's law of universal gravitation would, therefore, produce weights of edges between galaxies. Einstein's equations are more critical in relativistic speeds. Moreover, size of local clusters or even that of superclusters is much smaller than the possible radius of the curvature of the universe where the curved geometry would not be taken into account. For several such reasons as the above, local galaxy clusters and their weighted network models could be studied sufficiently within the scope of the Newtonian gravity (Bergshoeff et al., 2015; Verlinde, 2011; Gherghetta et al., 2000).

Our galaxy, the Milky Way, moves alongside a local galaxy cluster known as the Local Group, which spans a volume more than 3 Mpc in diameter. Over fifty galaxies constitute this cluster with two massive spiral galaxies, one medium spiral, and many elliptical, irregular, and spherical dwarf galaxies. Two massive spiral galaxies of the cluster– Andromeda (M31) and the Milky Way - are close to each other by mass, except that Andromeda is larger (McMillan, 2011; Kafle et al., 2018). They together contain more than half of the entire mass of the Local Group. Many of the dwarf galaxies of this cluster are satellite ones orbiting around the Milky Way and Andromeda. The Milky Way is the one with more satellites likely to be found as time goes by (Newton et al., 2018). The present study has mentioned 54 galaxies of the Local Group, but the count is still increasing in that there could be some tiny galaxies difficult for us to detect blocking gas and dust having originated from our galaxy through the view. It requires one significant ingredient, the total mass of each galaxy, which would determine the weight of each edge of the network to express the gravitational interaction between galaxies of the Local Group as a weighted network.

The basic geometric structures of galaxies encountered in the universe are elliptical, spiral and irregular ones surrounded by their haloes. They all include dark matter as well as baryonic matter such as stellar halo and galactic corona (Rix et al., 1997; Navarro and Steinmetz, 2000; Cote et al., 2000). Thus, to estimate the total mass of a galaxy, the sum of the mass of everything inside the halo volume might be approximated. The study includes the total mass of some galaxies of the Local Group, obtained from the literature. Galaxy masses not included in the literature are estimated from their apparent magnitudes and distances to us. This method is explained in detail in the following section, Masses of galaxies. Weighted Network Model section embraces the weighted network model of the Local Group. Results and Discussion section contains the centrality measurements of each galaxy and final section is the conclusion.

2 Material and Methods

2.1 Masses of galaxies

In the literature, the total masses of most galaxies in Local Group are estimated by adding their stellar mass, stellar corona mass, galactic corona mass, and dark matter masses (Table 1). For galaxies whose masses are unknown, first, absolute magnitudes have been obtained based on their measured apparent magnitudes and distances from us, as follows:

$$M_{abs} = M_{app} + 5 - 5\log(D) \tag{1}$$

where M_{abs} and M_{app} are absolute and apparent magnitudes respectively, and D is the distance to Earth which has been assumed as the distance of related galaxy to the Milky Way. Then the absolute magnitude could be converted to solar luminosity which is given as follows:

$$\frac{L_{gal}}{L_{\odot}} = 10^{-0.4(M_{abs}-M_{abs,\odot})} \tag{2}$$

where $L_{gal}/L_{\odot}$ is the ratio of the galaxy luminosity to the solar luminosity and $M_{abs,\odot}$ is the absolute magnitude of the sun, which is 4.83. Next, one must assume that mass-to-light ratio (*M*/*L*) depends on the galaxy type, age, metallicity, and also star-forming history (Ricotti and Gnedin, 2005).With the estimation of the mass-to-light ratio, the total mass of a galaxy could be calculated approximately in terms of solar mass below:

$$\frac{M_{gal}}{M_{\odot}} = \frac{L_{gal}}{L_{\odot}} \times \frac{M}{L} \tag{3}$$

Of 54 galaxies, those whose masses are unknown are Andromeda VI, Aquarius Dwarf, Canes Venatici II, Leo IV, Andromeda V, Andromeda XI, Andromeda XII, Andromeda XIII, Tucana Dwarf, Ursa Major II, and Coma Berenices Dwarf. Alongside with dark matter containing dwarf irregular galaxies (dIrr), especially dwarf spheroidal galaxies (dSph) have extended distributions of dark matter around their visible stars and dust, which increase their mass-to-light ratio. Since all these dSph and dIrr galaxies involvea significant amount of dark matter (Read et al., 2016; Penarrubia et al., 2008; Strigari et al., 2008; Randall and Scholtz, 2015; Chapman et al., 2005), the *M*/*L* ratio has been approximated to 100 for total masses of all. Thus, their total masses have been estimated considering their apparent magnitudes and distances (McConnachie et al., 2005; Willman et al., 2005; Zucker et al., 2004; Zucker et al., 2007; Zucker et al., 2006a; Zucker et al., 2006b; Irwin et al., 2007; Mateo, 1998; Avila-Vergara et al., 2016; Belokurov et al., 2007; Belokurov et al., 2006) to the Milky Way. Table 1 shows the approximate masses of galaxies in the Local Group and whether they are satellites of any galaxies. Galaxies have been sorted from large to small according to their diameters. The last column exhibits where the total masses have been obtained from.

2.2 Weighted network model

While constructing the gravity-based weighted network model of the Local Group, the priority is locations of all galaxies. Their distances to the Milky Way, their galactic latitudes and longitudes (McConnachie et al., 2005; Willman et al., 2005; Zucker et al., 2004; Zucker et al., 2007; Zucker et al., 2006a; Zucker et al., 2006b; Irwin et al., 2007; Mateo, 1998; Martin et al., 2006; Belokurov et al., 2007; Belokurov et al., 2006) of every Local Group member could be transformed into cartesian coordinates as follows:

$$x_i^1 = D_i \cos\left(b_i^{\circ} \frac{\pi}{180}\right) \cos\left(l_i^{\circ} \frac{\pi}{180}\right) \tag{4}$$

$$x_i^2 = D_i \cos\left(b_i^{\circ} \frac{\pi}{180}\right) \sin\left(l_i^{\circ} \frac{\pi}{180}\right) \tag{5}$$

$$x_i^3 = D_i \sin\left(l_i^{\circ} \frac{\pi}{180}\right) \tag{6}$$

where x_i^1, x_i^2 and x_i^3 are three dimensions of a particular galactic position to the origin (location of the Milky Way), D_i the distance, b_i° and l_i° latitude and longitude of the ith galaxy, respectively. According to the calculations, positions of galaxies of the Local Group have been plotted in Fig. 1.

There are two points needed to be highlighted regarding the map in Fig. 1. The first is that Hubble Law does not apply to the local clusters of galaxies, but entire Local Group galaxies are moving with respect to each other under gravitational attraction (Irwin, 1999). With the assumption that galaxies are moving slowly concerning each other, the study has accepted that they are as if they remained stable in figure 1. From that map, likely to assume that distances between galaxies remain stable, it follows that a matrix of gravitational attraction could be generated. Since this matrix would be the adjacency matrix of the weighted network model of the Local Group, every element should be determined by the force of attraction between ith and jth galaxies. In order to obtain the approximate numerical value of the attraction between galaxies, $|\boldsymbol{F}_{ji}| = Gm_i m_j/|\boldsymbol{r}_j - \boldsymbol{r}_i|^2$ could be written, where $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ are displacement vectors from the origin. However, the second is that comparison of the galaxies' sizes and distances between them shows galaxies' sizes to tend to be so minuscule that they could be regarded as point objects.

Table 1 Masses of all spiral large, elliptical, irregular and spherical dwarf galaxies of the Local Group. Equations (1), (2) and (3) are used for those whose masses are calculated.

Observed diameter (ly)	Name	Approximate mass	Satellite of	Reference
$\mathbf{1.4 \times 10^5}$	Andromeda (M31)	$\sim 1.2 \times 10^{12} M_\odot$	-	(Kafle et al., 2018)
$\mathbf{9 \times 10^4}$	Milky Way	$\sim 1.2 \times 10^{12} M_\odot$	-	(McMillan, 2011)
$\mathbf{5.5 \times 10^4}$	Triangulum (M33)	$\sim 5 \times 10^{10} M_\odot$	-	(Corbelli, 2003)
$\mathbf{2.5 \times 10^4}$	NGC 3109	$\sim 2.3 \times 10^{9} M_\odot$	-	(van den Bergh, 2000)
$\mathbf{2.5 \times 10^4}$	Large Magellanic Cloud	$\sim 4.8 \times 10^{10} M_\odot$	Milky Way	(Belokurov et al., 2017)
$\mathbf{2.0 \times 10^4}$	Sagittarius Dwarf	$\sim 1.2 \times 10^{9} M_\odot$	Milky Way	(Ibata and Lewis, 1998)
$\mathbf{1.5 \times 10^4}$	Small Magellanic Cloud	$\sim 6.5 \times 10^{9} M_\odot$	Milky Way	(Bekki and Stanimirovic, 2009)
$\mathbf{1.5 \times 10^4}$	NGC 205 (M110)	$\sim 7.4 \times 10^{8} M_\odot$	Andromeda	(Mateo, 1998)
$\mathbf{1 \times 10^4}$	IC 1613	$\sim 7.9 \times 10^{8} M_\odot$	-	(Mateo, 1998)
$\mathbf{1 \times 10^4}$	NGC 147	$\sim 1.1 \times 10^{8} M_\odot$	Andromeda	(van den Bergh, 1998)
$\mathbf{1 \times 10^4}$	WLM	$\sim 1.5 \times 10^{8} M_\odot$	-	(Bekki and Stanimirovic, 2009)
$\mathbf{1 \times 10^4}$	Sextans A	$\sim 4 \times 10^{8} M_\odot$	-	(Bekki and Stanimirovic, 2009)
$\mathbf{8 \times 10^3}$	NGC 6822	$\sim 1.6 \times 10^{9} M_\odot$	-	(Mateo, 1998)
$\mathbf{8 \times 10^3}$	NGC 185	$\sim 1.3 \times 10^{8} M_\odot$	Andromeda	(Mateo, 1998)
$\mathbf{8 \times 10^3}$	M32	$\sim 2.1 \times 10^{9} M_\odot$	Andromeda	(Mateo, 1998)
$\mathbf{8 \times 10^3}$	IC 10	$\sim 1.6 \times 10^{9} M_\odot$	-	(Mateo, 1998)
$\mathbf{8 \times 10^3}$	Sextans B	$\sim 8.9 \times 10^{8} M_\odot$	-	(Mateo, 1998)
$\mathbf{6 \times 10^3}$	Canes Venatici I	$\sim 2.7 \times 10^{7} M_\odot$	-	(Simon andGeha, 2007)
$\mathbf{6 \times 10^3}$	Pegasus Dwarf	$\sim 5.8 \times 10^{7} M_\odot$	Andromeda	(Mateo, 1998)
$\mathbf{5 \times 10^3}$	Fornax Dwarf	$\sim 6.8 \times 10^{7} M_\odot$	Milky Way	(Mateo, 1998)
$\mathbf{5 \times 10^3}$	Andromeda X	$\sim 5.5 \times 10^{6} M_\odot$	Andromeda	(Kalirai et al., 2010)
$\mathbf{4 \times 10^3}$	Hercules Dwarf	$\sim 3.7 \times 10^{6} M_\odot$	Milky Way	(Aden et al., 2009)
$\mathbf{4 \times 10^3}$	Leo A	$\sim 1.1 \times 10^{7} M_\odot$	-	(Mateo, 1998)

$\mathbf{4 \times 10^3}$	Andromeda IX	$\sim 5 \times 10^6 M_\odot$	Andromeda	(Harbeck, 2005)
$\mathbf{3 \times 10^3}$	Sculptor Dwarf	$\sim 6.4 \times 10^6 M_\odot$	Milky Way	(Mateo, 1998)
$\mathbf{3 \times 10^3}$	Sextans Dwarf	$\sim 1.9 \times 10^7 M_\odot$	Milky Way	(Mateo, 1998)
$\mathbf{3 \times 10^3}$	Ursa Major I	$\sim 1.2 \times 10^6 M_\odot$	Milky Way	(Willman, 2005)
$\mathbf{3 \times 10^3}$	Leo II	$\sim 9.7 \times 10^6 M_\odot$	Milky Way	(Mateo, 1998)
$\mathbf{3 \times 10^3}$	Leo I	$\sim 2.2 \times 10^7 M_\odot$	Milky Way	(Mateo, 1998)
$\mathbf{3 \times 10^3}$	Andromeda II	$\sim 7 \times 10^7 M_\odot$	Andromeda	(Kalirai et al., 2010)
$\mathbf{3 \times 10^3}$	Andromeda III	$\sim 8.6 \times 10^6 M_\odot$	Andromeda	(Kalirai et al., 2010)
$\mathbf{3 \times 10^3}$	Cetus Dwarf	$\sim 7 \times 10^6 M_\odot$	-	(Avila-Vergara et al., 2016)
$\mathbf{3 \times 10^3}$	Andromeda VI	$\sim 1.2 \times 10^8 M_\odot$	Andromeda	Calculated
$\mathbf{3 \times 10^3}$	Aquarius Dwarf	$\sim 2.1 \times 10^8 M_\odot$	-	Calculated
$\mathbf{3 \times 10^3}$	SagDIG	$\sim 9.6 \times 10^6 M_\odot$	-	(Mateo, 1998)
$\mathbf{3 \times 10^3}$	Antlia Dwarf	$\sim 1.2 \times 10^7 M_\odot$	NGC 3109	(Mateo, 1998)
$\mathbf{2 \times 10^3}$	Boötes Dwarf	$\sim 1.8 \times 10^7 M_\odot$	Milky Way	Calculated
$\mathbf{2 \times 10^3}$	Ursa Minor Dwarf	$\sim 2.3 \times 10^7 M_\odot$	Milky Way	(Mateo, 1998)
$\mathbf{2 \times 10^3}$	Draco Dwarf	$\sim 2.2 \times 10^7 M_\odot$	Milky Way	(Mateo, 1998)
$\mathbf{2 \times 10^3}$	Carina Dwarf	$\sim 1.3 \times 10^7 M_\odot$	Milky Way	(Mateo, 1998)
$\mathbf{2 \times 10^3}$	Canes Venatici II	$\sim 1.8 \times 10^6 M_\odot$	-	Calculated
$\mathbf{2 \times 10^3}$	Leo IV	$\sim 9.5 \times 10^5 M_\odot$	Milky Way	Calculated
$\mathbf{2 \times 10^3}$	Leo T	$\sim 7 \times 10^6 M_\odot$	Milky Way	(Ricotti, 2008)
$\mathbf{2 \times 10^3}$	Phoenix Dwarf	$\sim 3.3 \times 10^7 M_\odot$	-	(Mateo, 1998)
$\mathbf{2 \times 10^3}$	Andromeda VII	$\sim 5.7 \times 10^7 M_\odot$	Andromeda	(Kalirai et al., 2010)
$\mathbf{2 \times 10^3}$	Andromeda I	$\sim 8.7 \times 10^7 M_\odot$	Andromeda	(Kalirai et al., 2010)
$\mathbf{2 \times 10^3}$	LGS 3 (Pisces Dwarf)	$\sim 1.3 \times 10^7 M_\odot$	Triangulum	(Mateo, 1998)
$\mathbf{2 \times 10^3}$	Andromeda V	$\sim 4 \times 10^7 M_\odot$	Andromeda	Calculated
$\mathbf{2 \times 10^3}$	Andromeda XI	$\sim 7 \times 10^6 M_\odot$	Andromeda	Calculated
$\mathbf{2 \times 10^3}$	Andromeda XII	$\sim 3.1 \times 10^6 M_\odot$	Andromeda	Calculated
$\mathbf{2 \times 10^3}$	Andromeda XIII	$\sim 4.9 \times 10^6 M_\odot$	Andromeda	Calculated
$\mathbf{2 \times 10^3}$	Tucana Dwarf	$\sim 4.3 \times 10^7 M_\odot$	-	Calculated
$\mathbf{1 \times 10^3}$	Ursa Major II	$\sim 4.6 \times 10^5 M_\odot$	Milky Way	Calculated
$\mathbf{1 \times 10^3}$	Coma Berenices Dwarf	$\sim 2.6 \times 10^6 M_\odot$	Milky Way	Calculated

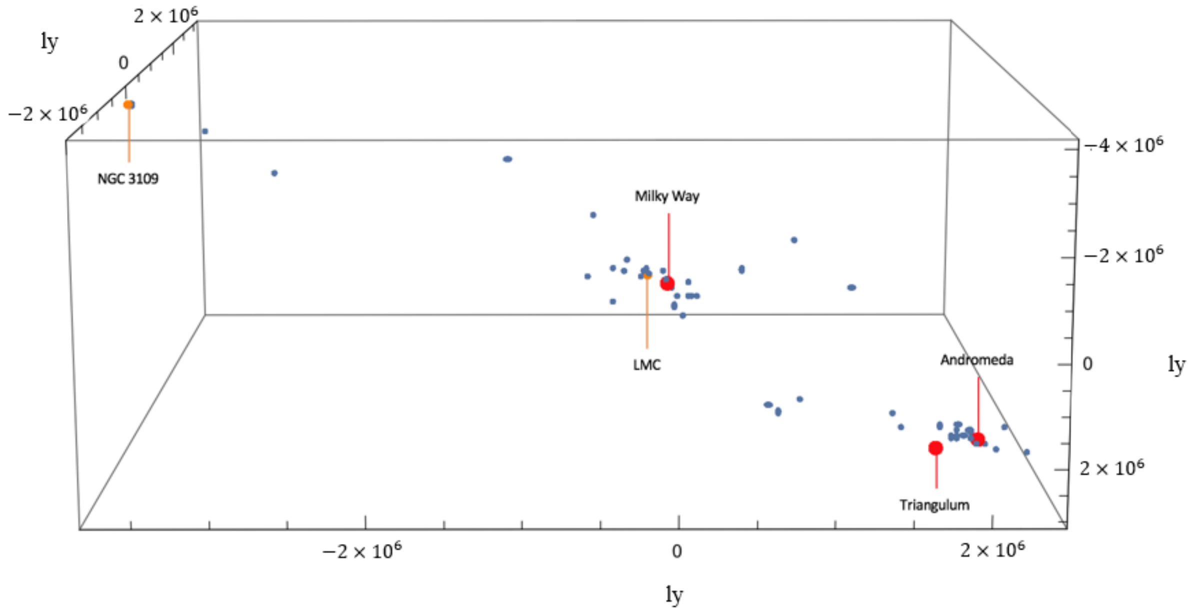

Fig. 1 Map of the Local Group with Milky Way in origin. Red dots show the three most massive galaxies whereas orange dots show the two large galaxies of Large Magellanic Cloud (LMC) and NGC 3019,which are close to and the far from the origin, respectively. Blue dots show the positions of the other 49 galaxies. Note that the dots have not been scaled.

In our former simulation, the gravitational attraction of all galaxies to each galaxy was obtained alongside a fully connected weighted network. However, in regards to galaxies with great distances between them (e.g. NGC 3109 and Andromeda), the gravitational attraction remains negligible compared to those close to each other. Thus, while the weighted network has been modeled depending on galaxies' locations, four galaxies have been selected as central nodes, which are the Milky Way, Andromeda, Triangulum, and NGC 3109. Although the masses of the LMC and SMC (Small Magellanic Cloud) galaxies are more significant than that of NGC3109, the reason of which NGC3109 is selected as the central node is its position inside the Local Cluster. NGC 3109 is located away from the two massive galaxies and is a relatively large galaxy. Therefore, it may have its own satellites.

Satellite galaxies have been connected only to closest central nodes, which they are satellite of and the non-satellite ones to the two closer central nodes for an equilibrated gravitational position. It could be explained in the following example why they are linked to the two closest central nodes: From the galaxies of Sextans A and B, it follows that they are closer to the NGC 3109 than to Milky Way. Although the Milky Way is more massive than the NGC 3109, the gravitational effect of NGC 3109 is obviously on these two galaxies. In line with these approaches, a more suitable adjacency matrix has been created for the model. The following weighted network has been shown in the color map in Fig. 2. Note that the weighted network becomes undirected since the gravitational interactions are bidirectional between the two objects, making the edges of the network weighted undirected.

In the color map of Fig. 2, it is seen that the edge weights between massive and closer galaxies are higher than others. The most weighted yellow edge on the top left is between Milky Way and LMC. Distinct edge weights in weighted networks have the necessity for centrality measurements to tell us the most critical nodes (Opsahl et al., 2010). A highly centralized network is dominated by central nodes that control information flow. This concept could also be applicable to physical interactions such as gravity.

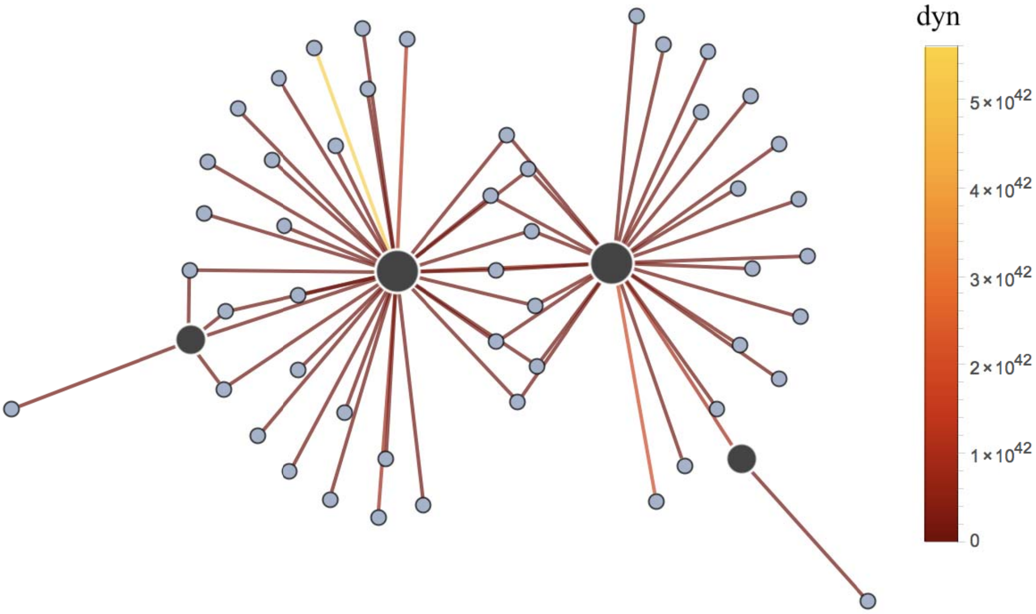

Fig. 2 Weighted network model of the Local Group, where weights have been illustrated as edge colors. From left to right, dark-larger dots are central nodes corresponding to the galaxies NGC 3109, Milky Way, Andromeda, and Triangulum, respectively.

3 Results and Discussion

For the centrality measurements in gravitational interactions, one could suggest that the prominent nodes should be those to maintain the integrity of the cluster. The main idea of centrality measurements is that the higher the value, the more central a node is. Degree centrality is one of the most straightforward measurement being generally extended to the sum of edge weights in weighted networks. For an undirected and weighted network, it is given by

$$C_D^w(i) = \sum_{j=1}^{N} w_{ij} \tag{7}$$

where N is the number of nodes and w_{ij} an element of the adjacency matrix (Barrat et al., 2004). The closeness centrality of an undirected and weighted network is as follows:

$$C_C^w(i) = \left[\sum_{j=1}^{N} d^w(i,j)\right]^{-1} \tag{8}$$

which indicates the inverse sum of the shortest distances to all other nodes from a specific node (Haliki et al., 2017), where $d^w(i,j)$ is the weighted shortest path between ith and jth nodes definable as *min* ($1/w_{ih}+\ldots+1/w_{hj}$). The reason why the inverse of edge weights are chosen here is that edges contain strong gravitational interactions. The edges in weighted networks could indicate the traffic flow costs in some network models. But here, it is the magnitudes of weights which are more important. There is also the betweenness centrality measure to assess a node lies on the how many shortest paths between the two other nodes. Betweenness centrality is given by

$$C_B^w(i) = \frac{g_{jk}^w(i)}{g_{jk}^w} \tag{9}$$

where g_{jk}^w is the sum of the weights of the paths between j and k, and $g_{jk}^w(i)$ is the sum of the weights of the paths involving node i (Opsahl et al., 2010). Considering this all, it is clear that the galaxies with high centrality values must be massive and close to the cluster center. The Local Group's centrality scores are given in Table 2.

Table 2 Scores of the weighted degree, closeness and betweenness in each galaxy of the Local Group.

Galaxy	Centrality Measures		
	Degree	**Closeness**	**Betweenness**
Andromeda (M31)	3.622×10^{42}	8.518×10^{35}	798
Milky Way	8.075×10^{42}	1.115×10^{36}	1013
Triangulum (M33)	8.700×10^{41}	8.517×10^{35}	52
NGC 3109	4.293×10^{38}	4.816×10^{33}	52
Large Magellanic Cloud	5.599×10^{42}	1.115×10^{36}	0
Sagittarius Dwarf	1.102×10^{42}	1.115×10^{36}	0
Small Magellanic Cloud	7.446×10^{41}	1.115×10^{36}	0
NGC 205 (M110)	1.316×10^{41}	8.515×10^{35}	0
IC 1613	3.387×10^{39}	8.242×10^{35}	0
NGC 147	2.087×10^{40}	8.500×10^{35}	0
WLM	2.806×10^{38}	6.207×10^{35}	0
Sextans A	8.232×10^{37}	4.803×10^{35}	0
NGC 6822	4.180×10^{39}	1.074×10^{36}	0
NGC 185	7.864×10^{37}	5.449×10^{35}	0
M32	1.868×10^{42}	8.517×10^{35}	0
IC 10	6.641×10^{40}	8.241×10^{35}	0
Sextans B	2.140×10^{38}	5.217×10^{35}	0
Canes Venatici I	2.902×10^{38}	9.293×10^{35}	0
Pegasus Dwarf	1.748×10^{38}	6.796×10^{35}	0
Fornax Dwarf	2.039×10^{39}	1.084×10^{36}	0
Andromeda X	1.580×10^{38}	6.653×10^{35}	0
Hercules Dwarf	1.081×10^{38}	7.257×10^{35}	0
Leo A	2.526×10^{37}	2.410×10^{33}	0
Andromeda IX	1.650×10^{39}	8.295×10^{35}	0
Sculptor Dwarf	5.527×10^{38}	1.009×10^{36}	0
Sextans Dwarf	9.543×10^{38}	1.051×10^{36}	0
Ursa Major I	1.304×10^{38}	7.717×10^{35}	0
Leo II	2.030×10^{38}	8.673×10^{35}	0
Leo I	1.859×10^{38}	8.498×10^{35}	0

Andromeda II	6.447×10^{38}	7.970×10^{35}	0
Andromeda III	1.095×10^{39}	8.187×10^{35}	0
Cetus Dwarf	1.823×10^{37}	1.285×10^{35}	0
Andromeda VI	1.227×10^{39}	8.221×10^{35}	0
Aquarius Dwarf	1.796×10^{38}	6.810×10^{35}	0
SagDIG	6.555×10^{36}	6.013×10^{34}	0
Antlia Dwarf	2.068×10^{37}	4.759×10^{33}	0
Boötes Dwarf	5.845×10^{39}	1.104×10^{36}	0
Ursa Minor Dwarf	1.839×10^{39}	1.081×10^{36}	0
Draco Dwarf	9.799×10^{38}	1.053×10^{36}	0
Carina Dwarf	3.489×10^{38}	9.561×10^{35}	0
Canes Venatici II	4.669×10^{37}	4.974×10^{35}	0
Leo IV	1.426×10^{37}	2.201×10^{35}	0
Leo T	2.364×10^{37}	3.229×10^{35}	0
Phoenix Dwarf	8.207×10^{37}	2.733×10^{35}	0
Andromeda VII	1.163×10^{39}	8.205×10^{35}	0
Andromeda I	4.042×10^{40}	8.508×10^{35}	0
LGS 3 (Pisces Dwarf)	1.147×10^{37}	1.752×10^{35}	0
Andromeda V	3.101×10^{39}	8.398×10^{35}	0
Andromeda XI	1.762×10^{39}	8.309×10^{35}	0
Andromeda XII	8.938×10^{38}	8.116×10^{35}	0
Andromeda XIII	7.895×10^{38}	8.065×10^{35}	0
Tucana Dwarf	4.055×10^{37}	2.148×10^{35}	0
Ursa Major II	2.892×10^{38}	9.288×10^{35}	0
Coma Berenices Dwarf	8.420×10^{38}	1.043×10^{36}	0

When the centrality measurements in Table 2 are examined, three galaxies with the highest degree of magnitude are Milky Way, LMC, and Andromeda. The reason for lower weighted degrees of the other central nodes, Triangulum and NGC 3109, is because high-mass galaxies, such as LMC, SMC, and M32, are close to Milky Way and Andromeda and thus produce more weighted edges. Betweenness values are different from zero for four central nodes and highest in Milky Way and Andromeda.

Due to the undirected structure of the network, there is not a significant difference between the closeness centrality values of galaxies. Here Milky Way has the highest whereas Andromeda has a much lower value. From the dot charts of three centrality measurements (Fig. 3), it is clear that the galaxies with masses above the cluster's average, especially Milky Way and Andromeda (order of $10^{12} M_{\odot}$), have the higher centrality values. This indicates that the galaxies of high gravitational attraction provide the integrity of the cluster in the weighted network models where the central node (hub) is selected.

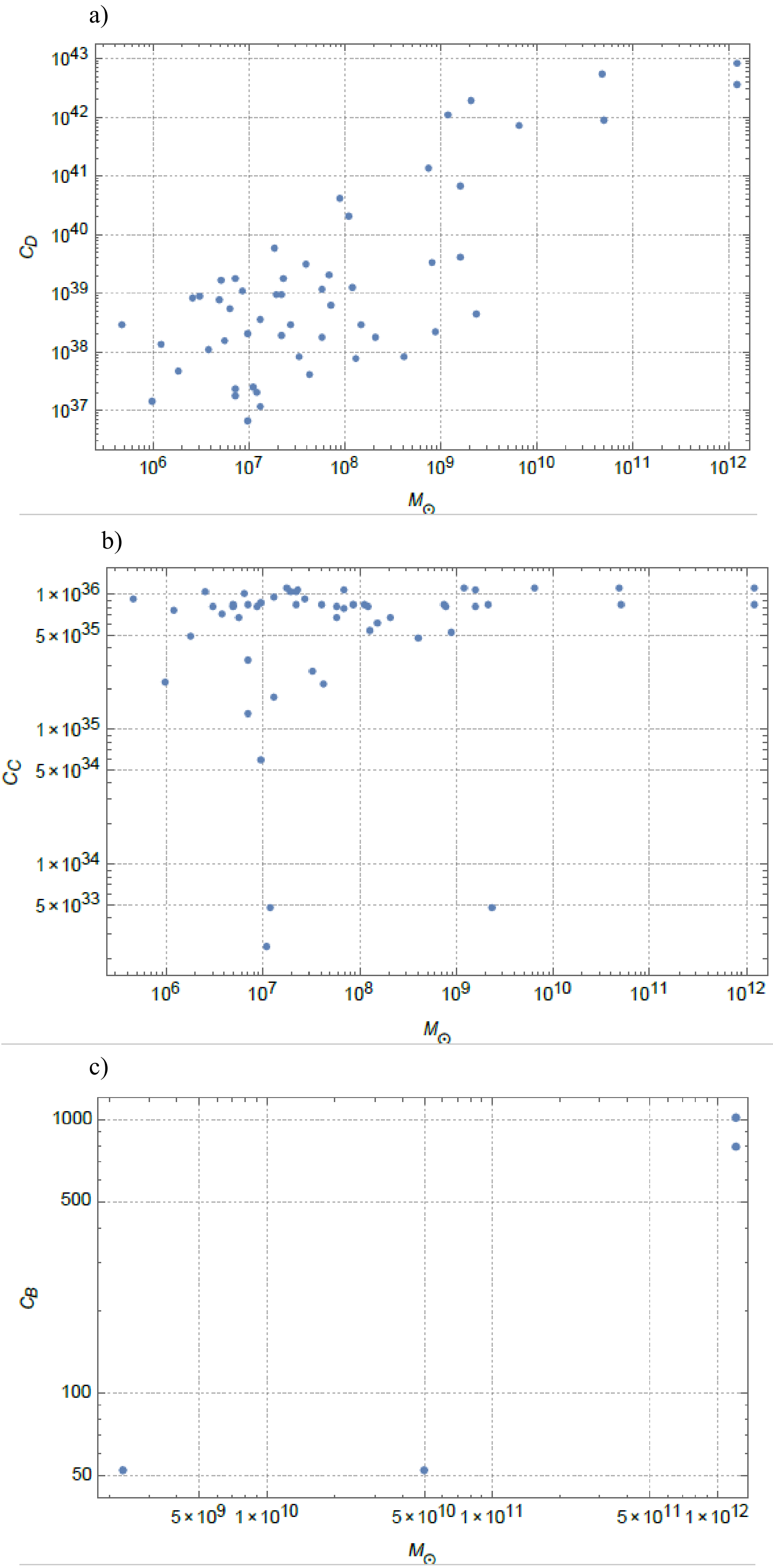

Fig. 3 Dot charts of weighted a) degree, b) closeness, and c) betweenness centralities of galaxies of the Local Group. The two points to the rightest of three graphs correspond to Milky Way (upper) and Andromeda (below).

4 Conclusion

Based on the idea that galaxy clusters could be modeled in the concept of weighted networks, galaxies have been examined, which are the nodes of the Local Group. Gravitational effects between the galaxies of this cluster are constructed using a weighted network model. The reason for choosing the Local Group is its familiarity, which includes almost exact positions of every galaxy and masses of many. Nevertheless, mass estimations of some galaxies which are not known have been calculated by their absolute and apparent magnitudes and an estimation of the *M*/*L* ratio involving the mass contribution of the dark matter. The gravitational attraction matrix has been formed considering the positions of galaxies concerning each other.

Central nodes, which are the galaxies, not satellites of any galaxies by their location, have been determined, and all other edges have been adjusted based on them. The final structure of the network was already weighted and undirected. Massive and central galaxies have more weighted edges than others. However, centrality measurements show to what extent a galaxy is or is not central are those for centrality. The highest values in degree, closeness, and betweenness centrality measurements have been found for our galaxy, the Milky Way. The results indicate that Milky Way in a position that could be central to the whole group according to the Local Group's map and with a mass larger than in other galaxies is the most central node of the system. For Andromeda, another massive galaxy, the measurements have given similar consequences. The obtained results show that there are correlated states between centrality measurements and mass.

For the proposed weighted network model, degree centrality measure could be counted as directly correlated with the mass. Edge weights increase in accordance with the massiveness of any galaxy in the model. Betweenness centralities are indirectly correlated with the mass, but considering a galaxy with a mass greater than the cluster's average; it can attract several dwarf galaxies as satellites making itself a hub called a central node. On the other hand, betweenness scores are high since the massive galaxies will have more satellites than the other ones and as the non-satellite galaxies tend to be connected to them to ensure cluster integrity. The reason why there is no direct correlation between closeness centrality and mass could be interpreted as the network's undirected structure. In undirected networks, the closeness value of each node can be the same as each other (Okamoto et al., 2008). Now that all edges are bidirectional, the shortest distances between them become shortened.

Since gravitational attraction is an inter-object and bidirectional concept, it has to be modeled in an undirected and weighted fashion. The present model indicates that massive galaxies seem to be central nodes that maintain the integrity of the Local Group's structure. However, it is known that if relatively massive galaxies remain near or close to those who are more massive than them, they could inevitably be their satellites. Centrality values of galaxies are correlated with how many satellites they could have.

References

Adén D, Wilkinson MI, Read JI, Feltzing S, Koch A, Gilmore GF, et al. 2009. A new low mass for the Hercules dSph: the end of a common mass scale for the dwarfs? The Astrophysical Journal Letters, 706(1): L150

Aragón-Calvo MA, Platen E, van de Weygaert R, Szalay AS. 2010. The spine of the cosmic web. The Astrophysical Journal, 723(1): 364

Avila-Vergara N, Carigi L, Hidalgo SL, Durazo R. 2016. Chemical history of isolated dwarf galaxies of the Local Group–I. dSphs: Cetus and Tucana. Monthly Notices of the Royal Astronomical Society, 457(4): 4012-4020

Barrat A, Barthelemy M, Pastor-Satorras R, Vespignani A. 2004. The architecture of complex weighted networks. Proceedings of the national academy of sciences, 101(11): 3747-3752

Bekki K, Stanimirović S. 2009. The total mass and dark halo properties of the Small Magellanic Cloud. Monthly Notices of the Royal Astronomical Society, 395(1): 342-350

Belokurov V, Erkal D, Deason AJ, Koposov, SE, De Angeli F, Evans DW, et al. 2017. Clouds, Streams and Bridges: redrawing the blueprint of the Magellanic System with Gaia DR1. Monthly Notices of the Royal Astronomical Society, 466(4): 4711-4730

Belokurov V, Zucker DB, Evans NW, Wilkinson MI, Irwin MJ, Hodgkin S, et al. 2006. A faint new Milky Way satellite in bootes. The Astrophysical Journal Letters, 647(2): L111

Belokurov V, Zucker DB, Evans NW, Kleyna,JT, Koposov S, Hodgkin ST, et al. 2007. Cats and dogs, hair and a hero: a quintet of new Milky Way companions. The Astrophysical Journal, 654(2): 897

Bergh S. 1998. The binary galaxies NGC 147 and NGC 185. The Astronomical Journal, 116(4): 1688

Bergh S. 2000. The Galaxies of the Local Group (Vol. 35). Cambridge University Press, USA

Bergshoeff E, Rosseel J, Zojer T. 2015. Newton–Cartan (super) gravity as a non-relativistic limit. Classical and Quantum Gravity, 32(20): 205003

Bond JR, Kofman L, Pogosyan,D. 1996. How filaments of galaxies are woven into the cosmic web. Nature, 380(6575): 603-606

Chapman SC, Ibata R, Lewis GF, Ferguson AM, Irwin M, McConnachie A, Tanvir N. 2005. A keck deimos kinematic study of Andromeda IX: Dark matter on the smallest galactic scales. The Astrophysical Journal Letters, 632(2): L87

Corbelli E. 2003. Dark matter and visible baryons in M33. Monthly Notices of the Royal Astronomical Society, 342(1): 199-207

Côté S, Carignan C, Freeman KC. 2000. The various kinematics of dwarf irregular galaxies in nearby groups and their dark matter distributions. The Astronomical Journal, 120(6): 3027

Coutinho BC, Hong S, Albrecht K, Dey A, Barabási AL, Torrey P, et al. 2016. The network behind the cosmic web. arXiv preprint arXiv:1604.03236

Forero–Romero JE, Hoffman Y, Gottlöber S, Klypin A, Yepes G. 2009. A dynamical classification of the cosmic web. Monthly Notices of the Royal Astronomical Society, 396(3): 1815-1824

Freedman WL, Feng LL. 1999. Determination of the Hubble constant. Proceedings of the National Academy of Sciences, 96(20): 11063-11064

Gherghetta T, Roessl E, Shaposhnikov M. 2000. Living inside a hedgehog: Higher-dimensional solutions that localize gravity. Physics Letters B, 491(3-4): 353-361

Harbeck D, Gallagher JS, Grebel EK, Koch A, Zucker DB. 2005. Andromeda IX: Properties of the faintest M31 dwarf satellite galaxy. The Astrophysical Journal, 623(1): 159

Haliki E, Yoltas A, Abaci O, Haliki-Uztan A. 2017. Weighted network analysis of out-group candidates in a phylogenetic Tree of *B. bassiana*. Feb-Fresenius Environmental Bulletin, 7444

Ibata RA, Lewis GF. 1998. Galactic indigestion: Numerical simulations of the Milky Way's closest neighbor. The Astrophysical Journal, 500(2): 575

Irwin M. 1999. Proper motions of Local Group satellites. In Symposium-International Astronomical Union (Vol. 192). 409-419, Cambridge University Press, USA

Irwin MJ, Belokurov V, Evans NW, Ryan-Weber EV, De Jong JT, Koposov S, et al. 2007. Discovery of an unusual dwarf galaxy in the outskirts of the Milky Way. The Astrophysical Journal Letters, 656(1): L13

Kafle PR, Sharma S, Lewis GF, Robotham AS, Driver SP. 2018. The need for speed: escape velocity and dynamical mass measurements of the Andromeda galaxy. Monthly Notices of the Royal Astronomical Society, 475(3): 4043-4054

Kalirai JS, Beaton RL, Geha MC, Gilbert KM, Guhathakurta P, Kirby EN, et al. 2010. The SPLASH survey: internal kinematics, chemical abundances, and masses of the Andromeda I, II, III, VII, X, and XIV dwarf spheroidal galaxies. The Astrophysical Journal, 711(2): 671

Martin NF, Ibata RA, Irwin MJ, Chapman S, Lewis GF, Ferguson AMN, et al. 2006. Discovery and analysis of three faint dwarf galaxies and a globular cluster in the outer halo of the Andromeda galaxy. Monthly Notices of the Royal Astronomical Society, 371(4): 1983-1991

Mateo M. 1998. Dwarf galaxies of the Local Group. Annual Review of Astronomy and Astrophysics, 36(1): 435-506

McConnachie AW, Irwin MJ, Ferguson AMN, Ibata RA, Lewis GF, Tanvir N. 2005. Distances and metallicities for 17 Local Group galaxies. Monthly Notices of the Royal Astronomical Society, 356(3); 979-997

McMillan PJ. 2011. Mass models of the Milky Way. Monthly Notices of the Royal Astronomical Society, 414(3): 2446-2457

Navarro JF, Steinmetz M. 2000. Dark halo and disk galaxy scaling laws in hierarchical universes. The Astrophysical Journal, 538(2): 477

Newton O, Cautun M, Jenkins A, Frenk CS, Helly JC. 2018. The total satellite population of the Milky Way. Monthly Notices of the Royal Astronomical Society, 479(3): 2853-2870

Okamoto K, Chen W, Li XY. 2008. Ranking of closeness centrality for large-scale social networks. In: International Workshop on Frontiers in Algorithmics. 186-195, Springer, Berlin, Heidelberg, Germany

Opsahl T, Agneessens F, Skvoretz J. 2010. Node centrality in weighted networks: Generalizing degree and shortest paths. Social networks, 32(3): 245-251

Penarrubia J, Navarro JF, McConnachie AW. 2008. The tidal evolution of local group dwarf spheroidals. The Astrophysical Journal, 673(1): 226

Randall L, Scholtz J. 2015. Dissipative dark matter and the Andromeda plane of satellites. Journal of Cosmology and Astroparticle Physics, 2015(09): 057

Read, JI, Agertz O, Collins MLM. 2016. Dark matter cores all the way down. Monthly Notices of the Royal Astronomical Society, 459(3): 2573-2590

Ricotti M. 2008. Effects of reionization on dwarf galaxy formation. Proceedings of the International Astronomical Union, 4(S255): 142-146

Ricotti M, Gnedin NY. 2005. Formation histories of dwarf galaxies in the local group. The Astrophysical Journal, 629(1): 259

Rix HW, De Zeeuw PT, Cretton N, van der Marel RP, Carollo CM. 1997. Dynamical modeling of velocity profiles: The dark halo around the elliptical galaxy ngc 2434. The Astrophysical Journal, 488(2): 702

Shandarin S, Habib,S, Heitmann K. 2010. Origin of the cosmic network in Λ CDM: Nature vs nurture. Physical Review D, 81(10): 103006

Simon JD, Geha M. 2007. The kinematics of the ultra-faint Milky Way satellites: solving the missing satellite problem. The Astrophysical Journal, 670(1): 313

Strigari LE, Koushiappas SM, Bullock JS, Kaplinghat M, Simon JD, Geha M, Willman B. 2008. The most dark-matter-dominated galaxies: predicted gamma-ray signals from the faintest Milky Way dwarfs. The Astrophysical Journal, 678(2): 614

Verlinde E. 2011. On the origin of gravity and the Laws of Newton. Journal of High Energy Physics, 2011(4): 1-27

Willman B, Dalcanton JJ, Martinez-Delgado D, West AA, Blanton MR, et al. 2005. A new Milky Way dwarf galaxy in URSA major. The Astrophysical Journal Letters, 626(2): L85

Zucker DB, Belokurov V, Evans NW, Kleyna JT, Irwin MJ, Wilkinson MI, et al. 2006. A curious milky way satellite in Ursa Major. The Astrophysical Journal Letters, 650(1): L41

Zucker DB, Belokurov V, Evans N W, Wilkinson MI, Irwin MJ, Sivarani T, et al. 2006. A new Milky Way dwarf satellite in canes venatici. The Astrophysical Journal Letters, 643(2): L103

Zucker DB, Kniazev AY, Bell EF, Martínez-Delgado D, Grebel EK, et al. 2004. Andromeda IX: a new dwarf spheroidal satellite of M31. The Astrophysical Journal Letters, 612(2): L121

Zucker DB, Kniazev AY, Martínez-Delgado D, Bell EF, Rix HW, Grebel EK, et al. 2007. Andromeda X, a new dwarf spheroidal satellite of M31: photometry. The Astrophysical Journal Letters, 659(1): L21