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Research Article

PREFERRED ALIGNMENTS OF ANGULAR MOMENTUM VECTOR OF GALAXIES IN THE SDSS SUPERCLUSTER S[231+030+0117]

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ABSTRACT

The distribution of angular momentum vectors of 1,172 galaxies in the Supercluster S[231+030+0117] with redshift in the range 0.107 to 0.123 was studied. Present work aimed to check any deviation from isotropic distribution in the galaxy orientation study and interpret those deviations with the existing theoretical models that describe galaxy evolution in the Superclusters. For this purpose, two-dimensional observed parameters received from the SDSS telescope was transformed into the three-dimensional. Random simulation technique was applied to remove the selection effects in our database and obtain the expected isotropic curves using numerical simulation. Then the observed and expected distribution curves were compared using the three statistical tests namely: Chi-square, Auto-correlation, and the Fourier test. From statistical analysis, the study confirm that the evolution of galaxies in the Supercluster supports the `Hierarchy model' suggesting the angular momentum vectors of galaxies tends to be oriented randomly to the equatorial coordinate system. Besides, the magnitude of galaxies was found to be independent of angular momentum vectors and its projections in the Supercluster.

Keywords: Evolution, Galaxies, Orientation, Substructure, Supercluster

INTRODUCTION

The Universe is built up by various large scale structures. Stars are collected together into galaxies, galaxies aggregated into galaxy groups, and galaxy groups are gathered together into galaxy clusters. These are held together by gravity. Hence, galaxy clusters are gravitationally bound large scale structures in the universe. To understand the evolution of galaxy and galaxy clusters, it is essential to know when and how they were formed and how their structures and constituents have been changing with time. The galaxy evolution processes are not well understood to date. One reason behind it is that the galaxies are made of three very different entities: stars, an interstellar medium (gas, dust, etc.), and dark matter. We have more information about the star, only a few about the interstellar medium and almost nothing about the dark matter. The orientation of angular momentum vectors of galaxies can reveal its kinematics.

Weizsaker (1951) and Gamow (1952) postulated that the observed rotations of galaxies are important for cosmology. According to them, the fact that galaxies rotate should provide a clue for the physical conditions under which these systems were formed. Thus, the angular momentum vectors of galaxies are important, which help reveal the directional preference of the galaxy. To explain the origin of the angular momentum of galaxies and their evolution, there are mainly three theoretical models namely: `Primordial vorticity model', `Pancake model' and `Hierarchy model'. According to the `Primordial Vorticity Theory' (Ozernoy, 1978; Stein 1974), the spin vectors of galaxies are distributed primarily perpendicular to the cluster plane. The `pancake model' (Doroshkevich, 1973; Doroshkevich & Shandarin, 1978) predicts that the angular momentum vectors of galaxies tend to lie within the cluster plane. The `Hierarchy model' (Peebles, 1969) predicts that the directions of the angular momentum vectors should be distributed randomly. According to this scenario, galaxies were first formed and then their angular momentum was obtained by tidal forces while they were gathering gravitationally to form a cluster with no dissipation.

The redshift of any astronomical object is the displacement of its spectral features to longer wavelengths due to a combination of the gravitational redshift, Doppler motions, and the general expansion of the Universe. Using Hubble's law, the redshift can be used to calculate the distance of an object from the Earth. By combining redshift with an angular position data, a redshift survey maps the 3D distribution of matter within a field of the sky. These observations are used to measure the properties of the large-scale structure of the universe. By systematically and sensitively observing a large fraction of the sky, the Sloan Digital Sky Survey (SDSS) (York *et al.*, 2000) will have a significant impact on astronomical studies as diverse as the large-scale structure of the Universe, the origin and evolution of galaxies, the relation between dark and luminous matter, the structure of Milky Way, and the properties and distribution of the dust from which stars like the sun were created. The SDSS has made enormous contributions across a wide span of astronomical fields, including contributions to many of the discoveries. It has exemplified a new mode of astronomical discovery, with teams of scientists cooperating in organized, systematic surveys to produce large data sets that are made publicly available and support a rich variety of investigations. The SDSS will be a new reference point, a field guide to the Universe that will be used by scientists for decades to come.

An investigation to study the spatial orientation of angular momentum vectors of 1,172 galaxies in the SDSS Supercluster S[231+030+0117], intended to answer following questions: (1) Do the orientation of galaxies in the Supercluster show a directional preference? (b) If yes, which theoretical model supports this preference? (3) Does inhomogeneity in the magnitude (or brightness) of galaxies play any roles in the preferred alignments of the angular momentum of galaxies in the Superclusters? The novelty of this work is to test the cosmological principle (isotropy and inhomogeneity) in the ground of galaxy evolution in large scale structure.

MATERIALS AND METHODS

Data compilation

In this paper, a Supercluster S[231+030+0117] was chosen with all photometric data obtained from Sloan Digital Sky Survey (SDSS) data release 7 (Percival *et al.*, 2010). The SDSS database was compiled in collaboration with the Institute of Astrophysics, Innsbruck University, Austria. At first, the values of the intrinsic flatness of galaxies were used to find the values of the inclination angle of galaxies (Heidmann *et al.*, 1972). The inclination angle of 15 galaxies could not be determined due to their unknown morphology. Finally, we have 1,172 galaxies in this Supercluster S[231+030+0117] of which the positions (right ascension and declination), position angle, and inclinations were known.

Godlowskian transformation

Transformation to the Supergalactic co-ordinate systems is essential to calculate angular momentum vectors using position angle (PA hereafter) and inclination angle of a galaxy to a given coordinate system. Based on the PA to the equatorial system (P), the PA concerning the Supergalactic co-ordinate system (p) can be calculated, which was first observed by Jaaniste and Saar (1978) and explained by Flin and Godlowski (1986). The `Godlowskian transformation' is the method to obtain three-dimensional information of the angular momentum vectors of galaxies. The method was epitomized as follows. At first, position of the galaxy, its magnitude, diameters, and the position angles were compiled using SDSS database. The inclination angle *i* was calculated by using Holmberg formula (1946).

$$\cos^2 i = \frac{(\frac{b}{a})^2 - q^{*2}}{1 - q^{*2}} \tag{1}$$

Where, *b*/*a* is the axial ratio and *q** is a true axial ratio that represents the intrinsic flatness of the galaxy. The intrinsic flatness factor of the disk galaxy depends upon the morphological type. Heidmann *et al.* (1972) suggested a value of *q**= 0.33 for elliptical and *q**= 0.20 for oblate spheroid.

The spatial (three dimensional) orientation of the angular momentum vector of a galaxy can be expressed by two angles namely, the polar angle (θ), the angle between the normal to the galaxy and the equatorial plane, and azimuthal angle (ϕ), the angle between the projection of this normal on the equatorial plane and directed towards the equatorial center. These angles were given by Flin and Godlowski (1986) in the 'Godlowskian transformation' equations as follows:

$$\sin\theta = -\cos i \sin\alpha \pm \sin i \sin p \cos\delta \tag{2}$$

$$\sin\varphi = (\cos\theta)^{-1}[-\cos i \cos\delta \sin\alpha + \sin i(\mp \sin p \sin\delta \sin\alpha \mp \cos p \cos\alpha)] \tag{3}$$

Where, $\mp$ & $\pm$ signs indicate two possible solutions.

Here, i, δ, α and p represent the inclination angle, declination, right ascension, and position angles respectively.

Considering the ambiguity of the rotation direction of the galactic disk, there is more than one solution of the spatial distribution for a galaxy. All the possibilities were counted independently in the analysis. As a theoretical reference, a spatial isotropic distribution of spin vectors of galaxies was assumed. In the next step, the observations (the distribution of two angles) were compared with these isotropic distribution curves and analyzed by statistical methods to detect any non-random trends.

According to the Hierarchy model, galaxies grow by subsequent merging of proto-galactic condensations or even by merging of already fully formed galaxies. Peeble (1969) assumed that the torque experienced by a young galaxy is the product of its quadrupole moment and the tidal field due to other galaxies.

To find quadrupole moment of a young galaxy, a homogeneous ellipsoid of revolution model was taken into consideration. The quadrupole moment is given by (Peeble, 1969),

$$Q = \int \rho(3z^2 - r^2)d^3r \tag{4}$$

Where, ρ represent volume charge density, *z* and *r* position of field point, and position of source point, respectively.

Considering another neighbor galaxy having mass *M*, is at a distance *r* away in a direction *Θ* relative to the z-axis,the magnitude of the torque exerted by the tidal field of this galaxy was given by,

$$\tau = \frac{3}{4}\frac{GMQ}{r^3}\sin 2\theta \quad (5)$$

Now ensemble average value was determined by considering point masses and two-point distribution function. The expression for the mean square torque takes this form,

$$\tau^2 >= (\frac{3}{4}GMQ)^2 \int p(r) d^3r \frac{\sin^2 2\theta}{r^6} \quad (6)$$

Here, *p(r)* is the two-point distribution function which gives the probability that a galaxy is at $r_0 + r$, given that a galaxy is at r_0 is the position of reference point. The radius of the volume belonging to each galaxy was found to be,

$$D \sim (\frac{3M}{4\pi\rho})^{\frac{1}{3}} \quad (7)$$

Therefore, the ensemble average of torque was given by,

$$\tau^2 >^{\frac{1}{2}} (\frac{2\pi}{5})^{\frac{1}{2}} \frac{GMQ}{D^{\frac{3}{2}}} (\frac{\rho}{M})^{\frac{1}{2}} = \frac{1}{3}(\frac{2}{15})^{\frac{1}{2}} \frac{Q}{t^2} \quad (8)$$

Where, $t^2 = \frac{2R^3}{(9GM)}$

A few globular clusters can be disrupted because of tidal interactions between merging fragments. In the hierarchical merger model, the disrupted systems would have led to the present distribution of halo stars throughout the spheroid. It can be expected that there is no net rotation of objects in the halo because of many random mergers. Besides, this model predicts that a few proto-galactic fragments should still be out there. A significant number of small galaxies orbiting the Milky Way and nearby Andromeda are possible examples.

Method of analysis

To remove selection effects from the database and determine expected isotropic distribution curves (Θ and ϕ) we adopted the numerical simulation method as proposed by Aryal and Saurer (2000). For this, a true spatial distribution of the galaxy rotation axis was assumed to be isotropic. Theoretically, the isotropic distribution curve for the polar angle is *cosine* and that for azimuthal angle is the *average*, with the restriction that the database is free from selection effects. Numerical simulation was performed by generating 107 virtual galaxies to find the expected distribution of angular momentum vectors of galaxies (Malla *et al.*, 2020).

Figure 1 shows the observed distribution of positions (right ascension or longitude and declination or latitude), position angle and inclination angle of galaxies in the Supercluster S[231+030+0117]. In each histogram, fluctuations were noticed either throughout the range or at the middle. These fluctuations suggest applying simulation by creating a large number of virtual galaxies in each bin, to satisfy the cosmological principle (isotropy and homogeneity). For this, we adopt the method suggested by Aryal and Saurer (2000) which satisfied the cosmological principles by removing selection effects in the SDSS database (observed fluctuations in Fig. 1). They concluded that any selections imposed on the database may propose severe changes in the shapes of the predicted isotropic distribution curves.

In their method, a true spatial distribution of the galaxy rotation axis was assumed to be isotropic. Because of the projection outcomes, the inclination angle (i) and latitude (B) were distributed as ∝ sini, and ∝ cosB, respectively, and the variables longitude (α) and position angle (p) are distributed randomly (Aryal & Saurer, 2000). Now the equations (2) and (3) can be used to calculate the corresponding values of polar (Θ) and azimuthal (ϕ) angle. Also, we ran simulations to define predicted isotropic distribution curves for each of the Θ and ϕ distributions creating virtual galaxies. The isotropic distribution curves for both polar and azimuthal angles were based totally on simulations including 10^7 virtual galaxies. At first, the distribution α, δ, p, and *i* were found for the galaxies in the samples and distributed with the aid of growing 10^7virtual galaxies for respective parameters. Those numbers were used to make an input file and the predicted distribution by simulating in MATLAB 15.0.

These observations (observed data set) were compared with the isotropic distribution curves (obtained from simulation) in both Θ and ϕ distributions. For this comparison, four different statistical tests were used i.e.: chi-square probability, First-order Fourier coefficient (Δ11/σ (Δ 11)), Fourier probability (P > Δ 1) and autocorrelation test (C/C (σ)). For the all sky distribution of galaxies, the ORIGIN 5.0 was used whereas for the redshift distribution of galaxy (the contour plot of Supercluster was done), in the ORIGIN 8.0.

The number of galaxies was found to increase with right ascension (RA) and declination (Dec.) in the beginning and decrease finally (Fig. 1). The number of galaxies was found to be fluctuating with the position angle (P). Interestingly, the inclination angle (i) distribution seems to show normal distribution in Fig. 1.

RESULTS AND DISCUSSION

The all sky distribution of the total number of galaxies in the Supercluster S[231+030+0117], as shown in Fig. 2(a).

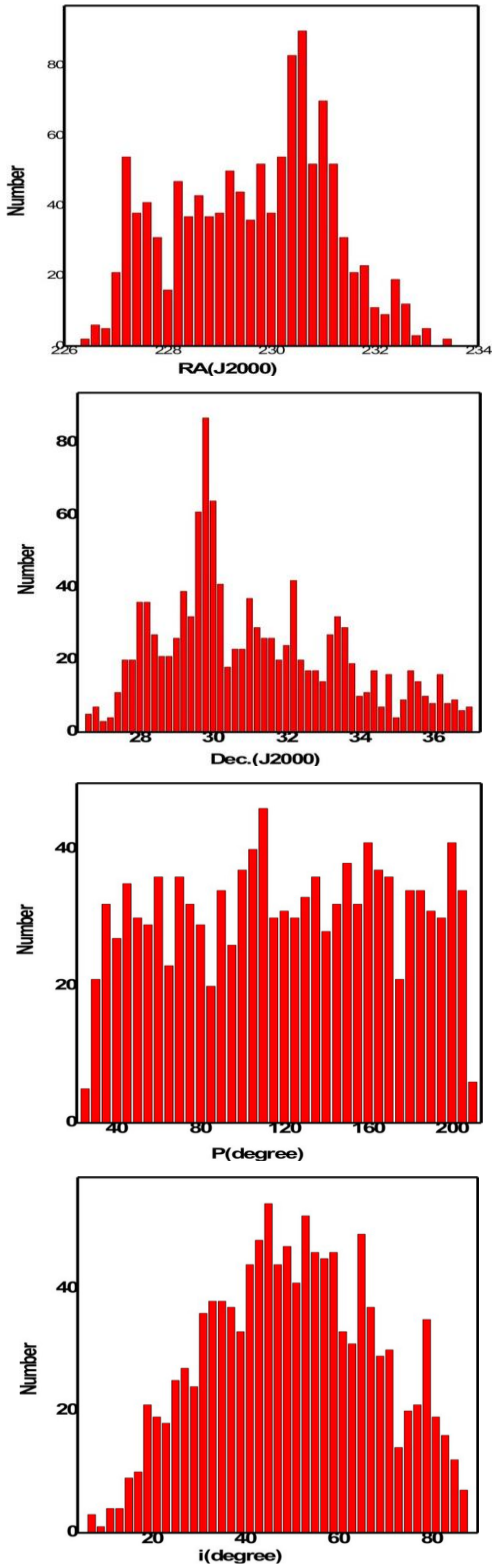


Fig. 1. The observed distributions of right ascension (α), declination (δ), position angle (P), and inclination angle (i) of the galaxies in the Supercluster S[231+030+0117]

The homogeneous distribution of galaxies according to cosmological principles was expected. But the figure shows that the galaxies are not equally distributed throughout the whole region i.e. a heterogeneous distribution. The galaxies are distributed homogeneously within the range of right ascension 226.4° to 233.5° and declination 26.5° to 37°. Morphologically, this Supercluster can be classified as filament type. Figure 2(b) shows the redshift distribution of galaxies in this Supercluster where low red-shifted galaxies in the substructure region can be seen. High red-shifted galaxies were found to be distributed randomly. The mean redshift of Supercluster is 0.114. The contour levels are at the redshift 0.108, 0.112, 0.115, 0.119, 0.123. In the substructure region, galaxies hardly have identical redshifts.

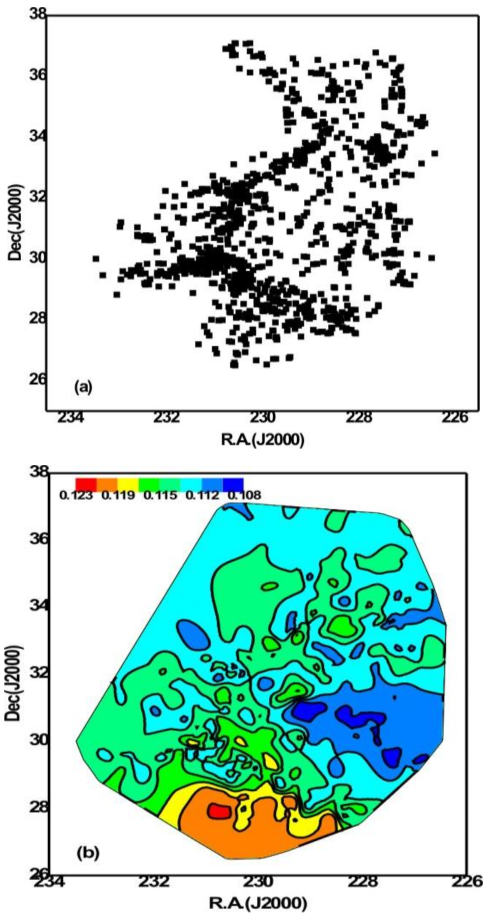


Fig. 2. (a) All sky distribution of galaxies in the supercluster S[231+030+0117] and (b) redshift map of the same region. The levels of the contours are shown

The color map shows that the velocity dispersion is minimum in the region where the number density of the galaxy is minimum, as shown in Fig. 2(b). In the substructure region at 28° declination, the redshift is found to be maximum (Δ z = 0.114).

Figure 3 shows the magnitude map of galaxies in the Supercluster S [231+030+0117]. The SDSS r-magnitude (m_r) refers to the peak wavelength 6165.0 Å with the bandwidth 702.8 Å. This wavelength range covers Hα, ionized Oxygen, and ionized Nitrogen lines as well as respective continuum. In the substructure region, the mean magnitude was identical in both filters. In the u-filter (m_u), the substructure located in the northern region has a higher magnitude. As it is known, the higher the magnitude, the lower is the brightness. Therefore, substructure regions are UV inactive regions, suggesting a lower abundance of newly formed stellar objects.

Gaussian fits in both magnitudes of the Supercluster S [195+027+0022] can be seen in Figs. 3 (c) and (d). The solid curve represents a Gaussian fits. The Gaussian center was found to be at 17.364 for r- and 19.769 for u-magnitudes. Here, in both cases, distribution deviated from standard Gaussian distribution. This indicates that the magnitude distributions of galaxies in the Supercluster might be different from that of the field galaxies.

The main purpose of this study was to find the non-random effects in the galaxy alignments. Any deviation from the expected isotropic distribution will be tested using four statistical parameters, namely chi-square probability ($P > \chi^2$), autocorrelation coefficient ($C/C(\sigma)$), first-order Fourier coefficient ($\Delta_{11}/\sigma(\Delta_{11})$), and first-order Fourier probability ($P > \Delta_1$). For anisotropy, the limit of chi-square probability $P(>\chi^2)$ was <0.050, autocorrelation coefficient ($C/C(\sigma)$) was>1.0, first-order Fourier coefficient ($\Delta_{11}/\sigma(\Delta_{11})$) was>1.5 and Fourier probability $P(>\Delta_1)$ was <0.150 respectively. These statistical limits were proposed by Godlowski (1993, 1994) in galaxy orientation studies.

In the statistics of Θ, if the value of the first-order Fourier coefficient is negative then it suggests that the spin vectors of galaxies tend to be oriented parallel to the equatorial coordinate system. Similarly, if the value of the first-order Fourier coefficient is positive then it suggests that the spin vectors of galaxies tend to be oriented perpendicular to the equatorial coordinate system. Whereas, in the statistics of ϕ, a positive ($\Delta_{11}/\sigma(\Delta_{11})$) with significant value suggests that the spin vector projections of galaxies tend to point radially towards the center of the equatorial coordinate system. Similarly, a significant negative value of ($\Delta_{11}/\sigma(\Delta_{11})$) implies that the spin vector projection of galaxies tends to orient tangentially to the equatorial coordinate system. In addition to the statistical tests, this paper also studies the `humps' (bins with more solutions than the expected) and `dips' (bins with fewer solutions than the expected) in the polar and azimuthal angle distributions.

In the plot of the Θ –distribution, as shown in Fig. 4(a), a dip (or hump) at $\Theta < 45°$ suggests that the spin vectors of galaxies tend to orient perpendicular (or parallel) to the

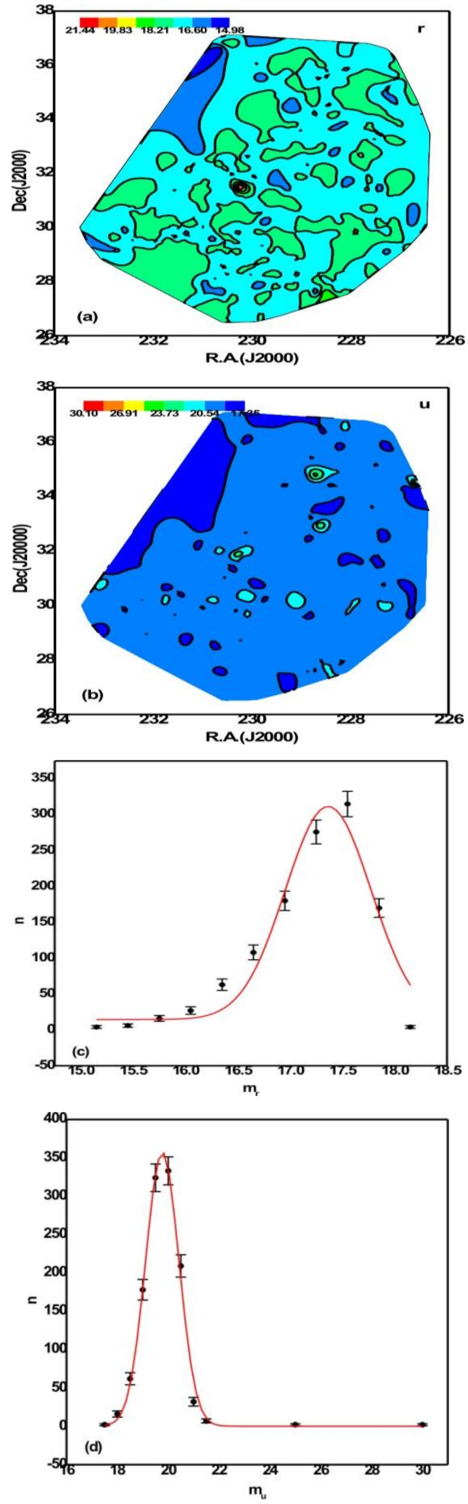


Fig. 3. Magnitude maps of the galaxies in the Supercluster S[231+030+0117]: (a) r-magnitude (m_r), (b) u-magnitude (m_u). The color bars are shown. The contour levels are at 14.98, 16.00, 18.21, 19.83, 21.44 for r magnitude and 17.35, 20.54, 23.73, 26.91, 30.10 for u-magnitude, respectively. (c) r-magnitude (m_r) and u-magnitude (m_u) distributions

equatorial coordinate system. Similarly, a hump (or dip) in the larger Θ (> 45°) indicates that the spin vectors of galaxies tend to be oriented perpendicular to the equatorial coordinate system. In the plot of the ϕ -distribution [Fig. 2(b)], the humps and dips were not easy to interpret as compared to Θ -distributions. It is because the range of ϕ is -90° to +90°. In plot, ϕ = 0° means spin vector projections tend to point radially towards the center of the equatorial coordinate system. A hump in the middle (central eight bins) of the histogram suggests that the spin vector projections of galaxies tend to point towards the center of the chosen coordinate system. Similarly, a hump at the first four and last four bins indicates that the spin vector projections of galaxies tend to be oriented tangentially to the chosen reference coordinate system. The statistics of polar angle (Θ) and azimuthal (ϕ) angle distribution of galaxies in this Supercluster S [231+030+0117] are given in Table 1.

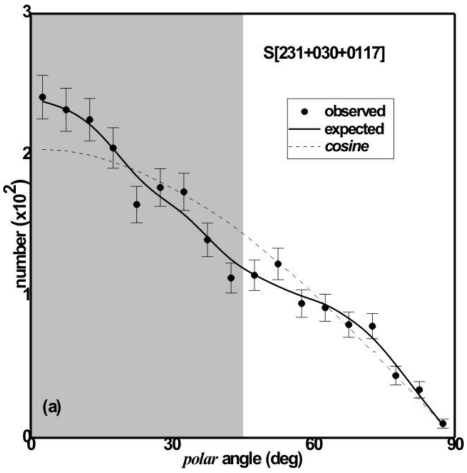
Table 1. Statistical parameters of the polar (Θ) and azimuthal (ϕ) angle distributions of galaxies in the Supercluster S [231+030+0117]

Parameters	Polar angle (θ)	Azimuthal angle (ϕ)
$P(>\chi^2)$	0.884	0.779
C/C(σ)	-0.601	-0.077
$\Delta_{11}/\ \sigma\ (\Delta_{11})$	0.012	0.181
$P(>\Delta_1)$	0.999	0.905

The statistics for the polar angle distribution in Supercluster S [231+030+0117] showed that the value of chi-square probability (P $(>\chi^2)$ was 0.884 i.e., 88.4 % (Greater than the significant level 0.050 i.e., 5.0 %). The auto-correlation coefficient (C/C (σ)) was found to be -0.601 (Smaller than 1σlimit). The first order Fourier coefficient (Δ_{11}/σ (Δ_{11})) was 0.012 (less than 1.5σthe limit). The first order Fourier probability (P> (Δ_1)) was 0.999 i.e., 99.4 % (more than 0.15 i.e., 15 %). All the statistical tests suggest very strong isotropy.

The number of observed solutions for Θ< 45° was found to be 1559, whereas the expected solutions was 1554, as shown in Fig. 4(a). Thus, the number of observed solutions or galaxies was greater by 5 than that of the expected. There was one dip at an angle 22.5° and one hump at an angle 32.5° with 1.5σ and 1σ error limit. At the bimodal region i.e., (Θ ~45°), the number of observed and expected solutions was 228 and 240 respectively. This indicates that the number of observed galaxies is less by 12 than that of expected galaxies. For large angles (Θ> 45°), the observed number of solutions (557) exceeded the expected solutions (550) by 7. There was one significant hump at an angle 52.5° with a 1.5 σ error limit. The hump and dip observed in this distribution was due to the local effect. Thus, in the conclusion, no preferred alignment of spin vectors of galaxies is found was polar angle distribution.

The statistics for the azimuthal angle distribution in Supercluster S [231+030+0117] showed the value of chi-square probability (P $(>\chi^2)$) to be 0.779 i.e., 77.9 % i.e., (more than the significant level 0.050 i.e., 5.0 %). The auto-correlation coefficient (C/C (σ)) was found to be -0.077 (Smaller than 1σlimit). The value of first-order Fourier coefficient (Δ_{11}/σ (Δ_{11})) was 0.181 (less than 1.5σ the limit) and the first-order Fourier probability (P> (Δ_1)) was 0.905 i.e., 90.5 % (Greater than 0.15 i.e., 15 %). All these statistical tests suggest that there was a strong isotropy.



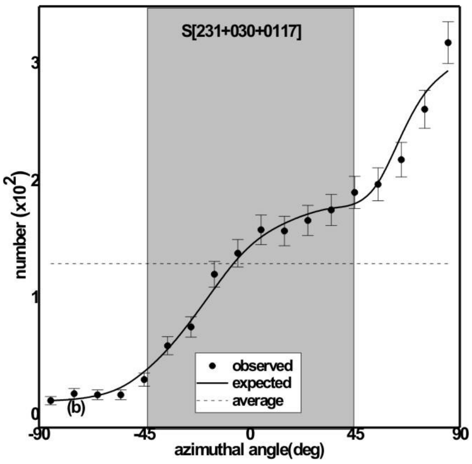


Fig. 4. (a) The polar (Θ) and (b) azimuthal (ϕ) angle distributions of galaxies in the Supercluster S[231+030+0117]

In Fig. 4(b), the observed solutions in eight central bins ϕ ~ (+45°,-45°) was found to be 1056 and that of expected solutions is 1052. This shows that the observed solution exceeds the expected by 4, but no humps and dips were observed in this region. In the bimodal region (ϕ ~ ±45°), the observed solutions (222) was 6 greater than expected (216).

The first four bins (ϕ<-45°), the observed solution (68) exceeded the expected (67) by only 1. Moreover, for the last four bins (ϕ> 45°), the observed and expected solutions were 998 and 1009 respectively. This indicates that the observed solution is less than the expected by 11. One hump was observed at an angle of 85° within 2 σ error limit, which was due to the local effect. Thus, no preferred alignment was noticed in azimuthal angle distribution. Thus, after a careful study of both statistics and graphs of polar and azimuthal angles, it was concluded isotropy in spin-vector orientation of galaxies in the Supercluster and lack of preferred alignment. This supports the hierarchy model of galaxy evolution.

Yadav *et al.* (2017) studied preferred alignments of angular momentum vectors of galaxies in six clusters having multiple number-density peaks with a spatial segregation of high- and low-velocity galaxies. The position angle - inclination method was used to convert two-dimensional parameters into three-dimensional parameters (e.g., positions, diameters, PA). The observed and expected isotropic distributions were compared using five statistical tests, namely chi-square, autocorrelation, Fourier, K-S, and Kuiper-V. Thus, no preferred alignment was noticed for all six clusters, supporting the hierarchy model as predicted by Peebles (1969).

Aryal *et al.* (2012), studied the spatial orientation of spin vector orientation of 410 zone of avoidance (ZOA) galaxies found in the region 20° <ℓ<80°, -10°<b<-5° on the first Palomar Observatory Sky Survey. To find the three-dimensional rotation axis of galaxies from two-dimensional, the position angle-inclination method was used (Flin & Godlowski, 1986). Moreover, this paper used the preferred alignments of spin vectors of galaxies to equatorial, galactic, and supergalactic coordinate systems and obtained all three possible scenarios (Pancake, Primordial vorticity, and Hierarchy model).

CONCLUSION

We studied orientation of 1172 galaxies in the Supercluster S[231+030+0117] with redshift in the range 0.107-0.123. We used the method proposed by Flin & Godlowski (1986) and Aryal & Saurer (2000) to find angular momentum vectors (polar and azimuthal angles) of galaxies for observed and expected distributions, respectively. Then, three statistical methods were used to check whether the distribution of angular momentum vectors throughout the Supercluster is isotropic or not. We conclude our results as follows:

1. No preferred alignment of angular momentum vectors of galaxies was noticed in the supercluster S [231+030 + 0117].
2. The redshift distribution of galaxies in supercluster showed Gaussian like nature, suggesting the distribution of galaxies within the supercluster is random.
3. The magnitude distribution of galaxies in the supercluster was found to be independent of the distribution of angular momentum vectors and its projections, supporting Hierarchy model of galaxy formation.
4. In the future, the substructure analysis should be carried out within the supercluster region.

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