Spatial orientation of galaxies in the Zone of Avoidance

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Abstract. We present spatial orientation of spin vectors of galaxies found in the region $20° \le \ell \le 80°$, $-10° \le b \le -5°$ in the first Palomar Observatory Sky Survey. The inclination angle and intrinsic flatness of a galaxy are used to determine the spin vector and spin vector projections of the galaxy. We studied the preferred alignments of spin vectors of galaxies with respect to equatorial, Galactic and supergalactic coordinate systems. We have carried out Kolmogorov-Smirnov (K-S), Kuiper-V and Fourier tests in order to examine non-random effects. It is found that the spin vectors of galaxies tend to lie in the equatorial plane whereas these vectors tend to be oriented perpendicular the Local Supercluster plane. A random alignment of spin vectors of galaxies is noticed with respect to the Galactic plane. Possible explanation of the results are discussed.

Keywords : catalogues – surveys – galaxies: evolution – galaxies: statistics

1.   Introduction

The Zone of Avoidance (ZOA, hereafter) is the region of the sky that is obscured by the Galactic plane of the Milky Way. The dust and gas in the Milky Way cause extinction at optical wavelengths, and foreground stars can be confused with background galaxies, obstructing our view of around 20% of the extragalactic sky at visible wavelengths. Because of this, optical catalogues are usually incomplete close to the Galactic plane. In recent years, many projects (Weinberger et al. 1995; Huchtmeier et al. 1995; Seeberger & Saurer 1998; Marchiotto et al. 1999; Marchiotto 2000) have attempted to bridge the gap in our knowledge caused by the ZOA. The effect of extinction drops at longer wavelengths, such as the infrared, and the Milky Way is effectively transparent at radio wavelengths. Surveys in the infrared, such as the Infrared Astronomical

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Satellite (IRAS) survey and and Two Micron All Sky Survey (2MASS), have given us a more complete picture of the extragalactic sky. Two very large nearby galaxies, Maffei 1 and Maffei 2, were discovered in the ZOA by Paolo Maffei by their infrared emission in 1968 (Maffei 1968). In spite of this, approximately 10% of the sky remains difficult to survey as extragalactic objects can be confused with stars in the Milky Way. Projects to survey the ZOA at radio wavelengths, particularly using the 21-cm emission line of neutral atomic hydrogen, have detected many galaxies (e.g., Dwingeloo Galaxy 1 and Dwingeloo Galaxy 2) that could not be detected in the infrared (Ryan-Weber et al. 2002 and the references therein).

Kerton & Brunt (2003) studied the association of CO emission with IRAS sources in the outer Galaxy using data from the FCRAO Outer Galaxy Survey (OGS). they found that $\sim 25\%$ of candidate ZOAGs are Galactic objects. They discovered two new far outer Galaxy star-forming regions, and six bright molecular clouds. Ryan-Weber et al. (2002) presented 138 HIPASS BGC (H I Parkes All-Sky Survey Bright Galaxy Catalog) galaxies that had no redshift measured prior to the Parkes multibeam H I surveys. The majority (57) of the newly catalogued galaxies lie within 10° of the Galactic plane and are missing from optical surveys as a result of confusion with stars or dust extinction. Zone of Avoidance survey finds new H I galaxies which lie hidden behind the Milky Way, and also provides redshifts for partially obscured galaxies known at other wavelengths. Donley et al. (2005) presented the results of the northern extension of the H I Parkes Zone of Avoidance Survey, a blind H I survey utilizing the multibeam receiver on the Parkes 64 m telescope and detected 77 H I galaxies, 20 of which have been previously detected in H I. In addition, they found several filaments crossing the Galactic plane, one of which appears to be the continuation of a sine-wave-like feature that can be traced across the whole southern sky. Henning et al. (2010) observed two low-latitude precursor regions, totaling 138 deg^2, with 72 H I galaxies.

In order to understand the evolution of galaxies it is essential to know when and how they have formed and how their structures and constituents have been changing with time. Our aim is to examine non-random effects in the galaxy alignments, in the framework of three different scenarios: 'pancake model' (Doroshkevich 1973; Shandarin 1974), the 'hierarchy model' (Peebles 1969) and the 'primordial vorticity theory' (Ozernoy 1978). The 'pancake model' predicts that the rotation axes of galaxies tend to lie within the cluster plane. According to the 'hierarchy model' the directions of the rotation axes should be distributed randomly. The 'primordial vorticity theory' predicts that the rotation axes of galaxies are primarily distributed perpendicular to the cluster plane. In this work, we intend to study the spin vector orientations in order to understand the evolution of galaxies in the ZOA.

2. The sample: Zone of Avoidance galaxies

As the final part of the extensive Innsbruck ZOA galaxy project (e.g. Weinberger et al. 1995; Seeberger & Saurer 1998; Marchiotto et al. 1999), Marchiotto (2000) presented the galaxy searches for the region $20° \leq \ell \leq 80°$, $-10° \leq b \leq -5°$ on first Palomar Observatory Sky Survey (hereafter POSS I) with the aid of a microscope having 16× magnification. The POSS I was carried out
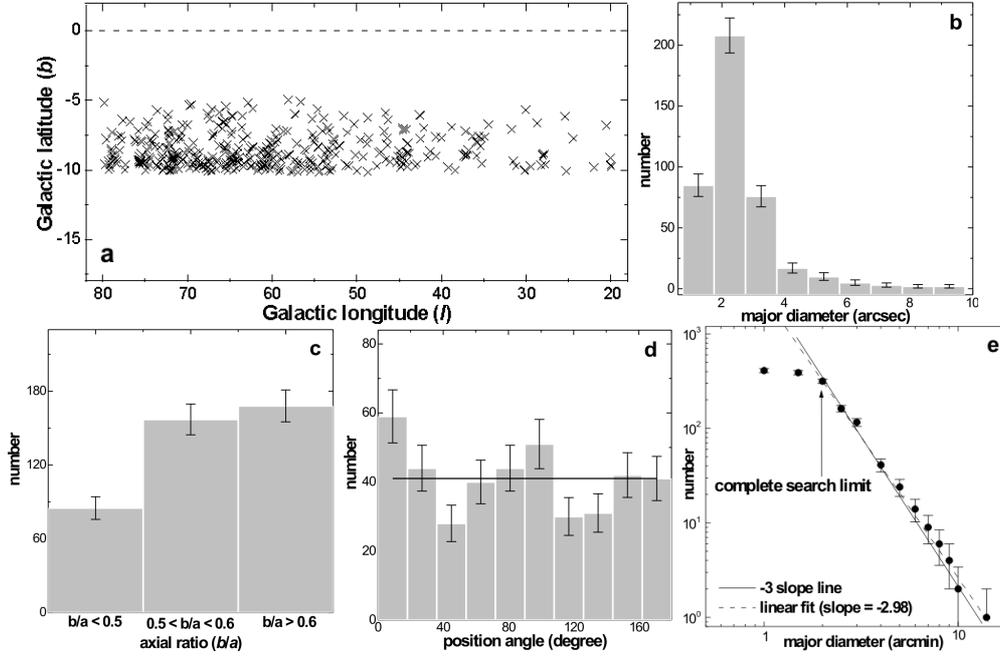
Figure 1. All sky distribution of 410 Zone of Avoidance galaxies in the region $20° \leq \ell \leq 80°$, $-10° \leq b \leq -5°$ (a). The major diameter (b), axial ratio (c) and equatorial position angle (PA) distributions (d) of galaxies. The solid line represents the expected distribution. (e) The distribution of the major diameter (in arcmin) of galaxies in the ZOA. The axes are in logarithm scale. The solid and dashed lines represent the theoretical line having slope '−3' and the best fit line, respectively. The statistical $\pm 1\sigma$ error bars are shown.

on the Oschin Schmidt Telescope in 1950-57 using 103aO and 103aF plates. POSS I continues to be one of the most frequently used astronomical resources; paper or glass copies of the plates are to be found in most of the world's observatories and a digitized version is available on line from the Space Telescope Science Institute. Altogether 410 galaxy candidates are listed; about 5% have counterparts in the IRAS PSC. The position angle (PA) and diameters of the galaxies are available on-line[1]. All-sky distribution of these ZOA galaxies are shown in Fig. 1a. Inhomogeneous distribution of galaxies can be seen. The major diameter (*a*), axial ratios (*b/a*) and equatorial PA distributions of these galaxies are shown in Figs. 1b,c,d. Marchiotto et al. (1999) concluded that the distribution is approximated by an exponential falling off in number density between $b = -5°$ to $-10°$ and a roughly linear falling off between $\ell = +80°$ to $+20°$. No obvious clustering of galaxies, pointing to a possible rich galaxy cluster, is evident in the region surveyed. The chi-square and Fourier probability is found to be less than 5% in the PA-distribution, suggesting anisotropy. This result motivates us to study the spin vector orientation of these 410 ZOA galaxies with respect to suitable reference coordinate system.

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[1] http://www.ncra.tifr.res.in/ basi/toc12March.htm

The distribution of the apparent diameters of the galaxies can give information about the completeness of the optical catalogue. Aryal, Bachchan & Saurer (2010) discuss a 'toy model' by assuming a homogeneous distribution of galaxies in space having equal linear diameter. They ignored the effect of clustering in the model. Due to this assumption one expect to get large deviations from the −3 slope line in the diameter distribution of cluster galaxies. Fig. 1e shows the distribution of the apparent diameters of ZOA galaxies. In the figure, the solid and dashed lines represent the −3 slope and the best fit lines, respectively. The slope of the best fit line is found to be −2.98. The observed distribution is found to deviate from these lines. The point at which the diameter starts to deviate from the solid line (−3 slope line) is taken as the 'limit' up to which the optical catalog is assumed to be complete. In the ZOA, this limit is found to be 2.0 arcmin. So, the catalog of galaxies in ZOA that have apparent major diameter ≥2.0 arcmin is complete. In other words, the diameter distribution of 316 galaxies (about 77%) is found to be fit with the model. This value rules out the existence of heavy clustering phenomena in the ZOA. However, the existence of groups and subclusters in the region of interest cannot be denied.

The Great Attractor is situated at a distance 45−50 Mpc from the Milky Way, in the direction of the constellations Hydra and Centaurus (Mieske, Hilker & Infante 2005). The objects in that direction lie in the ZOA and are thus difficult to study at visible wavelengths. X-ray observations have revealed that the region of space is dominated by the Norma cluster (Abell 3627), containing a large number of old galaxies, many of which are colliding with their neighbors, and/or radiating large amounts of radio waves. X-ray survey of ZOA reported that the Great Attractor was actually only one tenth the mass that scientists had originally estimated. The survey also confirmed earlier theories that the Milky Way galaxy was in fact being pulled towards a much more massive cluster of galaxies near the Shapley Supercluster which lies beyond the Great Attractor (Tonry et al. 2000).

3.   Method

We adopt 'PA-inclination' method originally proposed by Öpik (1970), applied by Jaaniste & Saar (1978) and significantly modified by Flin & Godłowski (1986) and Godłowski (1993, 1994) in order to convert two dimensional given parameters (i.e., PA) into three dimensional parameters (i.e., spin vectors and spin vector projections of galaxies). The selection effects in the database are removed and the expected isotropic distribution for spin vectors (SVs hereafter) and spin vector projections of galaxies are determined using the method proposed by Aryal & Saurer (2000). The observed and expected distributions are compared with the help of appropriate statistical tests.

3.1   Observed distribution: spin vectors of galaxies

We convert two-dimensional given parameters (R.A., Dec. and equatorial PA) into three-dimensional (spin vectors or polar/azimuthal angles) parameters using axial ratios and intrinsic flatness of galaxies. For this, we adopt the method described by Flin & Godłowski (1986) and calculate
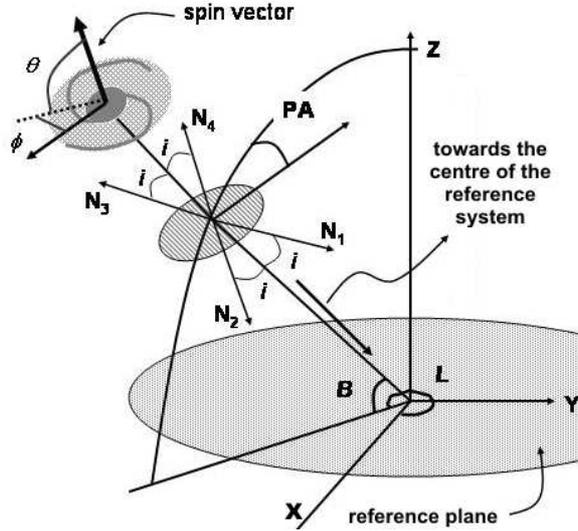
Figure 2. Schematic illustration of θ (polar angle between the galaxy SV and the LSC plane) and ϕ (azimuthal angle between the projection on the LSC plane of the galaxy SV and the supergalactic X-axis), whose distribution we examined. L and B are the supergalactic longitude and latitude. The four possible normals are denoted by N_1, N_2, N_3 and N_4. See text for the explanation.

the polar (θ) and azimuthal (ϕ) angles of galaxies. In their method, the three dimensional orientation of the SV of a galaxy is characterized by polar and azimuthal angles. The polar angle (θ) represents the angle between the galactic SV and a reference plane (Fig. 2). The angle between the projection of a galactic SV on to this reference plane is the azimuthal angle (ϕ). The formulae to obtain θ and ϕ in SCS are as follows (Flin & Godłowski, 1986):

$$\sin \theta = -\cos i \sin B \pm \sin i \sin P \cos B \tag{1}$$

$$\sin \phi = (\cos \theta)^{-1}[-\cos i \cos B \sin L + \sin i(\mp \sin P \sin B \sin L \mp \cos P \cos L) \tag{2}$$

where L, B and P are the supergalactic longitude, latitude and position angle, respectively. The angle i is the inclination angle, estimated with Holmberg's (1946) formula: $\cos^2 i = [(b/a)^2 - q^2]/(1-q^2)$ where b/a is the measured axial ratio and q is the intrinsic flatness of disk galaxies. The method of determination of intrinsic flatness of galaxies is the same as in Aryal et al. (2007).

There is no information from which we can define a physically-based reference frame for the ZOA galaxies. The reference plane might be complex because of large number of HI galaxies investigated in the past few years (Henning et al. 2010 and the references therein). There is no information from which we can define a physically based reference frame for ZOA galaxies. In this situation, we study the spatial orientation of SVs of ZOA galaxies with respect to three well

known coordinate systems: equatorial (ECS hereafter), Galactic (GCS hereafter) and supergalactic (SCS hereafter). In the Galactic coordinate system, the principal axis is the Galactic equator (the intersection of the plane of the Milky Way with the celestial sphere) and the reference points are the north Galactic pole and the zero point on the Galactic equator; the coordinates of a celestial body are its Galactic longitude and latitude. In this system, the zero point on the Galactic equator has the equatorial coordinates R.A. (J2000) = $17^h 39.3^m$ and Dec. (J2000) = $-28°55^m$; this lies in the direction of the center of our Galaxy, the Milky Way. We adopt the SCS as defined by Tammann & Sandage (1976).

The above formulae show that there are two possible solutions for a given galaxy. Because the normals (N_1, N_2, N_3, N_4) shown in Fig. 2 cannot be determined unambiguously, because we do not know the side of the galaxy which is nearer/farther from us, and the direction of rotation. Thus, there are four solutions of the SV orientation for a galaxy. We count all four possibilities independently in our analysis.

3.2 Expected distribution: numerical simulations

Godłowski (1993) noted that if some galaxies were excluded from the sample, the theoretical isotropic distribution must be obtained from random simulations. Aryal & Saurer (2000) were the first who discussed this problem in detail. Aryal & Saurer (2000) noticed that any selections on the data may cause severe changes in the shapes of the expected isotropic distribution curves in galaxy orientation study. They found that the isotropic θ distribution is independent of positions only when the range of i is full. The isotropic ϕ distribution is independent of latitude (B) provided the range of i and longitude (L) is full. Their method has been applied by several authors in galaxy orientation studies (Hu et al. 2006; Aryal et al. 2008, 2012 and references therein). Three kinds of selection effects are noticed in our database: (1) inhomogeneous distribution of positions of galaxies (see Fig. 1a), (2) lack of knowledge of PAs of nearly face-on galaxies and (3) lack of edge-on galaxies (see Fig. 1c). These selection effects are removed and the expected isotropic distribution curves (θ and ϕ) are determined using the numerical simulation method as proposed by Aryal & Saurer (2000). Because our galaxy samples are from a limited region of the sky it is of importance to remove both the positional and the inclination effects. This problem is crucial in the ZOA because of shape of the survey (Fig 1a). This lack could even be real if the alignment is connected with galaxy plane. At present, this problem is very difficult to solve. We will address this problem in the future. For simplicity, a true spatial distribution of the galaxy rotation axis is assumed to be isotropic. Then, due to the projection effects, i can be distributed $\propto sin\ i$, latitude can be distributed $\propto cos\ B$, the variables longitude (L) and PA can be distributed randomly, and formulae (1) and (2) can be used to simulate (numerically) the corresponding distribution of θ and ϕ. The isotropic distribution curves are based on simulations including 10^6 virtual galaxies. The simulation procedure is described in Aryal & Saurer (2004). We perform numerical simulations with respect to all three reference systems (ECS, GCS and SCS). Fig. 3 shows the expected isotropic distribution of ZOA galaxies for polar (a) and azimuthal (b) angles with respect to ECS (solid line), GCS (dash line) and SCS (dash-dot line), respectively. For a comparison, cosine distribution (dot line) is shown. The expected isotropic distribution is cosine in θ and average
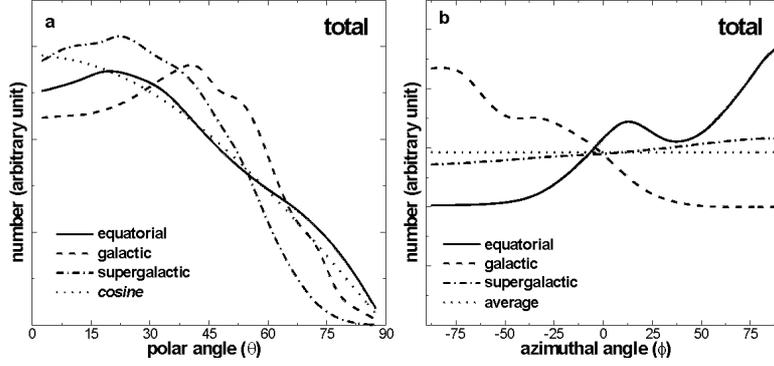
Figure 3. The expected polar (θ) (a) and azimuthal angle (ϕ) distribution (b) of ZOA galaxies with respect to equatorial, Galactic and supergalactic coordinate systems, respectively. The dotted line represents expected distribution when there are no selections on inclination angle and positions.

in ϕ when there are no selections on inclination angles and positions. We use these expected isotropic distributions for the comparison with the observed distribution.

3.3 Statistical tests

Our observed distributions are compared with expected isotropic distribution curves in θ and ϕ. For this comparison we applied Fourier (Hawley & Peebles 1975; Godłowski 1993, 1994; Godłowski & Ostrowski 1999; Aryal 2011; Godłowski 2011), Kolmogorov-Smirnov (K-S) (Stephens 1970; Press et al. 1992; Kanji 1995) and Kuiper-V (Kuiper 1962; Stephens 1970) tests. We do not describe these statistical tests here. These tests are described in the appendix of Aryal et al. (2007). These tests are a proper method in our case, because θ and ϕ are independent data. The significance level is chosen to be 95%, the null hypothesis is established to be an equidistribution for the θ and ϕ. As null hypothesis a spatial isotropy of the angular momentum vector was chosen. In cases of too small sample size only the K-S and Kuiper-V tests are meaningful. The conditions for anisotropy are the following: K-S = 1, Kuiper-V = 1, first order Fourier coefficient $\Delta_{11}/\sigma(\Delta_{11})>1$ and the first order Fourier probability $P(>\Delta_1)<0.150$.

4. Results

The ranges for the angles θ and ϕ are 0° to 90° and –90° to +90°, respectively. The bin size was chosen to be 10° for polar angle (θ) and 20° for azimuthal (ϕ) angle distributions in the Fourier test. Table 1 lists the values of the statistical parameters for θ and ϕ distributions of ZOA galaxies with respect to ECS, GCS and SCS. Fig. 4 shows the polar (θ) and azimuthal (ϕ) angle distributions of the SVs of galaxies with respect to ECS, GCS and SCS, respectively. We assume weak anisotropy if K-S and Kuiper-V tests do not agree and $1<\Delta_{11}/\sigma(\Delta_{11})\leq1.5$.

Table 1. Statistics of the θ and ϕ distributions. The first column shows the reference systems: equatorial (ECS), Galactic (GCS) and supergalactic (SCS). The next two columns lists the results of Kolmogorov-Smirnov (K-S) and Kuiper-V (KV) tests. In these tests, "0" denotes that the null hypothesis (isotropy) can not be rejected at the chosen significance level, "1" designates that the null hypothesis can be rejected (anisotropy). The last two columns give the first order Fourier coefficient $\Delta_{11}/\sigma(\Delta_{11})$ and first order Fourier probability $P(> \Delta_1)$. The next four columns repeats the columns 2-5.

Abell		θ				ϕ		
	K-S	KV	Δ_{11}/σ	$P(> \Delta_1)$	K-S	KV	Δ_{11}/σ	$P(> \Delta_1)$
ECS	1	1	+2.0	0.115	0	0	+0.9	0.736
GCS	1	0	+1.0	0.260	1	1	+2.4	0.150
SCS	1	1	−3.2	0.045	1	1	−1.6	0.136

Fig 4a shows polar angle distribution of ZOA galaxies with respect to the ECS. All three statistical tests suggest anisotropy. The value of first order Fourier probability ($P(> \Delta_1)$) is found to be less than <15%, suggesting anisotropy. The symbol "1" in K-S and Kuiper-V tests indicates that the null hypothesis (isotropy and homogeneous) can be rejected. The value of $\Delta_{11}/\sigma(\Delta_{11})$ is found to be positive at 2σ level, suggesting that the SVs of galaxies tend to lie in the equatorial plane. Two humps at 5° (1.5σ) and 15° (1.5σ) support this result. With respect to GCS, we found a mixed result: isotropy in the Fourier and Kuiper-V tests whereas anisotropy in the K-S test. In the histogram, humps at the middle (25°-45°) can be seen (Fig. 4b). These humps are compensated by the dip at smaller and larger angles, suggesting isotropy. Thus, no preferred alignments of SVs of galaxies in the ZOA is found when analyzed with respect to the GCS. We found anisotropy when analyzing with respect to the SCS. Humps at larger angles (55°, 65° and 75°) at 1.5σ level can be seen (Fig. 4c). Because of these humps, the value of $\Delta_{11}/\sigma(\Delta_{11})$ is found to be negative at $> 3\sigma$ level, suggesting that the SVs of galaxies tend to be oriented perpendicular to the Local Supercluster plane. Other statistical tests support this result. Thus, it is interesting that the SV orientation of ZOA galaxies support hierarchy model when analysing with respect to GCS whereas it supports pancake model (primordial vorticity model) when analyzing with respect to SCS (ECS). These inconsistencies in the preferred alignments strongly suggest the need of true physical reference system for ZOA galaxies.

In the ϕ distribution, value of $\Delta_{11}/\sigma(\Delta_{11})$ is found to be less than 1σ limit when analyzing with respect to the ECS. No significant humps or dips can be seen (Fig. 4d). All three statistical tests suggest isotropy (Table 1). Thus, no preferred alignments of the SV projections of ZOA galaxies with respect to ECS is noticed. Two humps (−20°, 0°) at the middle of the histogram can be seen in Fig. 4e. Humps in the region −50° to +50° and the dips at −90° to −50° (first 2 bins) and at 50° to 90° (last 2 bins) turn the Δ_{11} value positive in the ϕ distribution. A positive Δ_{11} suggests that the projections of SVs of galaxies tend to point towards the Galactic center. All three statistical tests support this result. In SCS, anisotropy is found in all three statistical tests (Table 1). The Δ_{11} value is found to be $> 1.5\sigma$ error limit, suggesting a preferred alignment. The
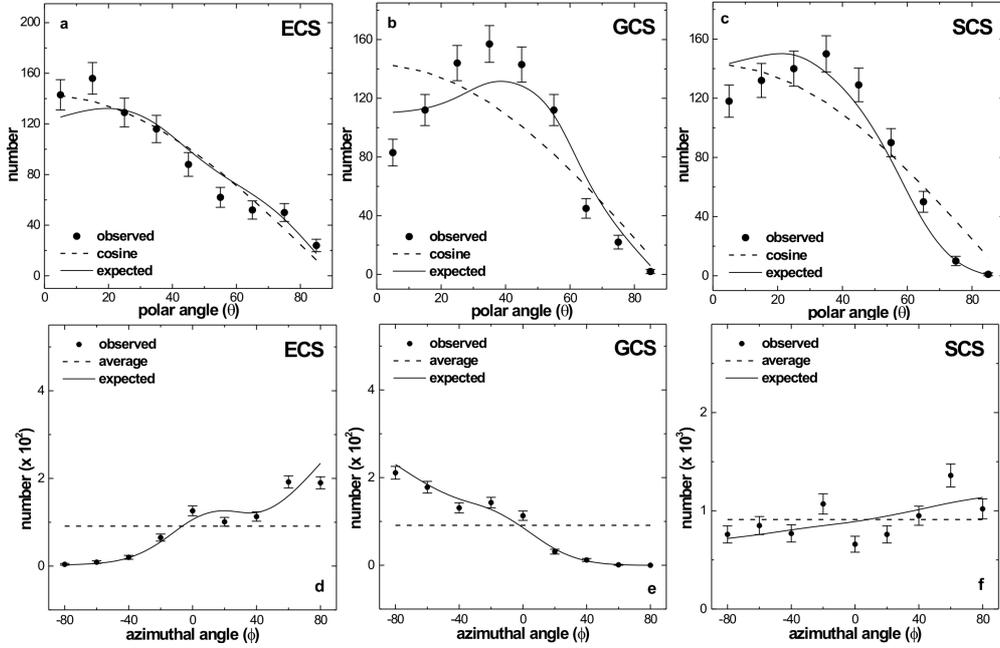
Figure 4. The polar (θ) and azimuthal (ϕ) angle distributions of ZOA galaxies with respect to equatorial (ECS), Galactic (GCS) and supergalactic (SCS) coordinate system. The solid line represents the expected isotropic distributions. The cosine distribution (dashed) is shown for the comparison. The statistical error ($\pm 1\sigma$) bars are shown for the observed counts. $\theta = 0°$ (90°) corresponds to the galactic angular momentum vector tends to lie parallel (perpendicular) the reference plane. $\phi = 0°$ means the direction to the centre of the reference coordinate system.

SV projections of ZOA galaxies is found to be oriented perpendicular with respect to the LSC center. A significant hump at +60° (2σ) supports this result (Fig. 4f).

The ZOA galaxies showed anisotropy in both θ and ϕ distributions when analyzing with respect to the SCS. In other two systems (ECS and GCS), either θ or ϕ distribution showed isotropy. It is difficult to explain the situation where SV orientation of galaxies showed isotropy and the distribution of their projections turned anisotropy or vice versa.

Aryal & Saurer (2005) studied the orientations of 1 433 galaxies found in the region $15^h48^m \leq \alpha(2000) \leq 19^h28^m$, $-68° \leq \delta(2000) \leq -62°$ with respect to equatorial coordinate system and noticed a random orientation of spin vectors of galaxies. Aryal, Kandel & Saurer (2006) reported orientations of 323 galaxies in the core of the Shapley concentration with respect to Galactic coordinate system. They noticed isotropy in both the two- and three-dimensional study when analyzing with respect to the Galactic coordinate system. Thus, these results support the hierarchy model (Peebles 1969), which predicts that the directions of the spin vectors are entirely random.

Aryal et al. (2007) noticed a systematic change in the galaxy alignments from early-type (BM I) to late-type (BM III) clusters. The spin vectors (SVs) of galaxies in the high radial velocity (RV) clusters are found to be oriented parallel with respect to the Local Supercluster (LCC) plane. The SV projections of galaxies showed a significant anisotropy in the high RV clusters. They studied 4 clusters (A0042, A1227, A1920, and A2142) that have RV > 30 000 km s^{-1}. All 4 clusters showed anisotropy in both the θ and ϕ distributions. The high RV cluster galaxies showed anisotropy in such a way that their SV orientations tend to lie parallel to the LSC plane. In the past and the present work, the common point is the reference coordinate system, i.e., supergalactic system. Therefore a relation between the orientation of cluster galaxies, LSC galaxies and the galaxies in the ZOA can be suspected. Probably, this could be connected with the fact that LSC plane roughly coincides with a plane with a larger concentration of galaxies at much more larger scales.

Aryal, Kafle & Saurer (2008) studied the RV dependence in 10 subsamples of 10 562 galaxies that have RV less than 5 000 km s^{-1}. They used supergalactic coordinate system as a physical reference system. The RV dependence is found to be significant for high RV galaxies than that of low RV galaxies in both the θ and ϕ distributions. Thus, the distant galaxies showed a significant preferred alignment.

5. Conclusions

We studied the spatial orientations of spin vector (SV) orientation of 410 Zone of Avoidance (ZOA) galaxies found in the region $20° \leq \ell \leq 80°$, $-10° \leq b \leq -5°$ on the first Palomar Observatory Sky Survey. We used the position angle - inclination method to find the three-dimensional rotation axes of galaxies. A spatially isotropic distribution is assumed to examine non-random effects. To check for anisotropy or isotropy we have carried out three statistical tests: Kolmogorov-Smirnov, Kuiper-V and the Fourier.

Interestingly, all three possible scenarios (pancake-, primordial vorticity- and hierarchy model) are observed when we studied preferred alignments with respect to equatorial, Galactic and supergalactic systems. The 'pancake model' predicts that SVs of galaxies tend to lie within the reference plane. According to the 'hierarchy model' the directions of the SVs should be distributed randomly. The 'primordial vorticity theory' advocates that the SVs of galaxies are distributed primarily perpendicular to the reference plane. We noticed that the SV orientation of ZOA galaxies tend to lie in the equatorial plane. These vectors are found to be oriented perpendicular to the Local Supercluster plane. A random alignment of SVs of galaxies is noticed with respect to the Galactic plane. The projections of SVs showed a mixed picture: tend to point towards the Galactic centre and tend to be oriented perpendicular towards the LSC centre. This result clearly hints the need of suitable reference system for the ZOA galaxies. The supergalactic coordinate system is found to be most suitable among three systems because we noticed anisotropy in both the SV distributions and the distribution of SV projections of galaxies. The issue of suitable physical reference system is critical while studying spatial orientation of galaxies

in a cluster or supercluster. We intend to work on this issue using the Sloan Digital Sky Survey (seventh data release) and Galaxy Zoo project data in the future.

Acknowledgments

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