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Spatial orientation of spin vectors of SDSS DR16 galaxies at $0.18 < z < 0.21$ in u-magnitude dependence

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Abstract

This paper presents a scientific study of the spatial orientation of spin vectors of 1233 SDSS DR16 (Sloan Digital Sky Survey Data Release 16) galaxies within the redshift range of 0.18 to 0.21 using the u-band data. This study analyzed a total of 1233 galaxy samples to provide new insights into the formation and evolution of galaxies and help interpret observational data. This study also applied the method proposed by Flin & Godlowski to understand the angular momentum alignment of galaxies, enabling the transformation of two-dimensional projected images into three-dimensional spin vector components: specifically, polar (θ) and azimuthal (ϕ) angles. Through the chi-square, auto-correlation, and Fourier analysis statistical tests, we concluded that the SDSS DR16 data of 1233 galaxies strongly support anisotropies in the polar angle distribution and point toward mild anisotropies in the azimuthal angle distribution, supporting the Pancake model of the galaxy evolution theory. These findings suggest the presence of large-scale or environmental influences on the spin vector orientations of the galaxy at the examined redshift limit.

Keywords
SDSS DR16, galaxy, anisotropy, u-band, angular momentum vectors.

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1 Introduction

The universe exhibits intricate patterns of cosmic structure, and galaxies are the fundamental units in this masterpiece. These gravitationally bound systems of stars, gas, dust, and dark matter are not scattered haphazardly; instead, they exist as hierarchical structures ranging from tight groups to vast Superclusters [1]. Having knowledge of their directions in space, i.e., the relative positions of their angular momentum vectors, holds the key to understanding primordial conditions, dark matter evolution, and the validity of cosmological principles. The cosmos we inhabit is expanding at an ever-accelerating rate, and its dominant ingredients are hydrogen and helium, sprinkled with only trace amounts of the heavier elements synthesized in stellar furnaces. The prevailing theoretical paradigm holds that these majestic structures are the end-product of the gravitational amplification of minute primordial density ripples. According to the standard narrative, the Universe emerged from an extraordinarily hot and almost perfectly homogeneous phase. During an early epoch of cosmic inflation [2], quantum fluctuations were stretched to macroscopic scales and their amplitudes were inflated to seed the later hierarchy of structure.

Once radiation ceased to dominate the cosmic energy budget, the self-gravity of over-dense regions halted their expansion, causing them to turn around and collapse into gravitationally bound systems. The statistical history of these interactions may be interpreted using the two-point correlation function, which maps the dependence of the strength of clustering on the observable properties of galaxies (such as luminosity, color, and stellar mass), and how that clustering changes with cosmic time, via redshift. Redshift is a complicated quantity, and has three component contributors: a component due to the expansion of space itself (cosmological redshift), a component due to relative motion between observer and source (Doppler redshift), and a component due to loss of energy of the photon as it climbs out of gravitational potential (gravitational redshift). Therefore the observed redshift of any extragalactic source is a linear combination of all three components. A complete understanding of the processes of galaxy formation and evolution is one of the most important and most difficult problems in modern astrophysics.

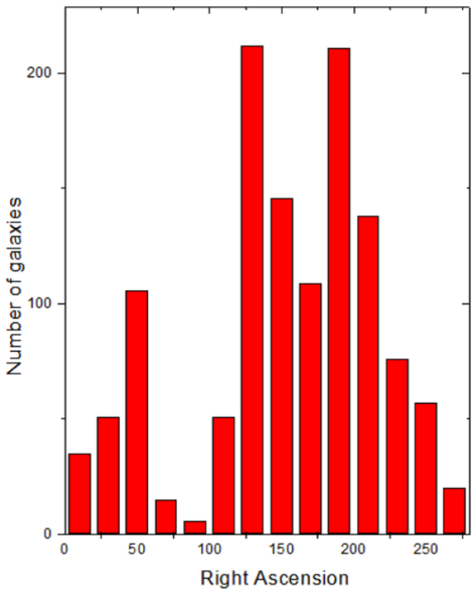
In recent decades, high-quality observational data, now abundant thanks to massive telescopes, has repeatedly challenged and overturned even the most entrenched theoretical ideas. The observed pattern of large-scale structure depends on global cosmological parameters and the astrophysical processes that govern galaxy formation and evolution. Careful measurements of galaxy clustering permit astronomers to estimate the mass of dark-matter haloes that lie beneath the galaxies, to connect high-redshift progenitors with their low-redshift descendants, and to make joint constraints on both cosmological parameters and the physics of galaxy evolution. In the extreme, gas-rich early Universe, galaxies were formed rapidly through many cases of repeated accretion of smaller galaxies and merging. A number of studies have directly addressed how galaxy magnitude influences orientation patterns. Hawley and Peebles in 1975 [3] explained the galaxy orientation studying method by independently examining the ob- served position angle and axial ratio distribution. In addition, they provide the Fourier method for analyzing the position angle histogram. Aryal and Saurer in 2001 [4] created a method for minimizing the selection effect through numerical simulation. To examine galactic orientation, numerical simulation and the position angle-inclination approach are applied. Malla et al. [5–8] reported random orientations supporting hierarchical formation models in specific Superclusters at similar redshift ranges). These findings suggest that environmental factors might play a significant role in determining orientation patterns. Most studies have focused on either lower redshift ranges ($z < 0.15$) or higher redshift ranges ($z > 0.25$), with limited investigation specifically in the 0.18-0.21 range. This research aims to address these gaps by conducting a systematic study of the spatial orientation of SDSS galaxies within the redshift range of 0.18 to 0.21 using u-band data. With a specific focus on the redshift range of 0.18 to 0.21, this paper examines the spin vector orientations of the galaxies, contributing to the development on the understanding of galaxy formation and evolution processes as seen through the u-band.

2 Database and methods

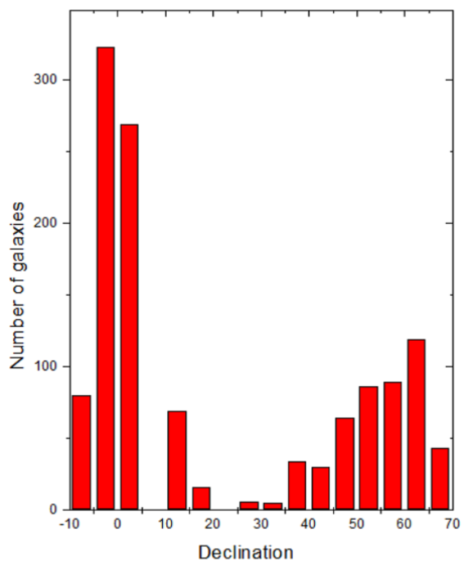
The research utilized data from the Sloan Digital Sky Survey (SDSS), specifically the Data Release 16 (DR16) [9]. The dataset was accessed using the SQL search of the DR16 database.

```
SELECT TOP 3000
p.objid,p.ra,p.dec,p.u,p.g,p.r,p.i,p.z,
p.run, p.rerun, p.camcol, p.field, s.specobjid,
s.class, s.z as redshift,
s.plate, s.mjd, s.fiberid,me1_u, me2_u
FROM PhotoObj AS p
JOIN SpecObj AS s ON s.bestobjid = p.objid
WHERE
p.i BETWEEN θ AND 30.0
AND s.z BETWEEN 0.18 AND 0.21
```

The sample data of SDSS DR16 galaxies are shown in appendix A. This dataset provides comprehensive spectroscopic and photometric data for millions of celestial objects and is ideal for this study due to its extensive coverage, high-resolution imaging, and consistent data quality. Our sample was selected from the top 3000 objects within the redshift range of $0.18 < z < 0.21$. The sample was further filtered for galaxies only, and then the galaxies' parameters were treated with mathematical operations where the irrelevant data or errors were erased, which gave us the final number of galaxies, i.e., 1233. Then, the galaxies were divided into multiple bins to study the spatial orientation of spin vectors of galaxies. For all bins in the distributions of the parameters α, δ, P and i, we find the corresponding number of galaxies in 10^7 virtual galaxies, shown in Figures 1(a,b) and 2(a,b). These numbers are used to make input file the expected distribution for the sample by running simulation in MATLAB 7.6.0. These histograms represent the number of observed galaxies.



(a)

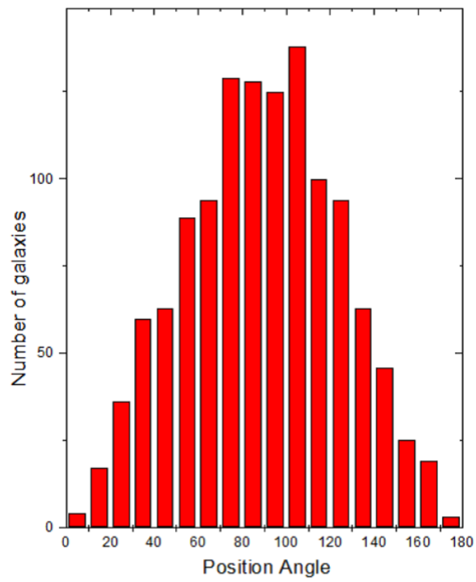


(b)

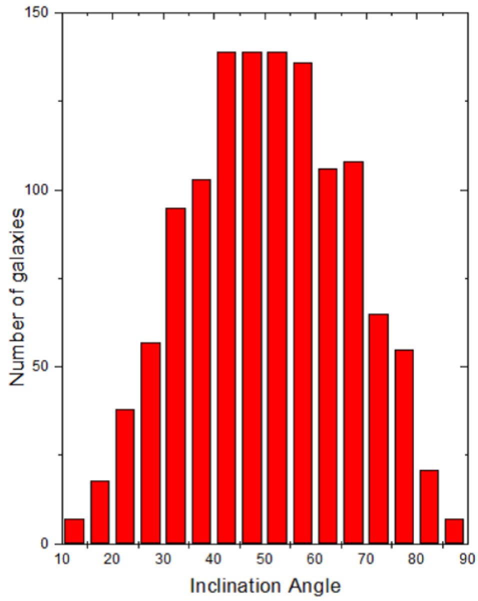
Figure 1: Distribution of the (a) right ascension and (b) declination values of 1233 SDSS DR16 galaxies.

2.0.1 Redshift distribution

Figures 3 and 4shows the redshift of 1233 galaxies in the 3D plane and contour map, respectively. Both visualizations are anchored to the same three observables: right ascension, declination, and spectroscopic redshift. Both figures show some galaxies merged at the lower redshift. This distribution reveals that the galaxies are not equally distributed, as shown in the figures. We can see a fair amount of galaxies are merged in the region of right ascension between 125° to 225° and declination angle between $-5°$ to 5°.



(a)



(b)

Figure 2: Distribution of the (a) position and (b) inclination angles of 1233 SDSS DR16 galaxies.

2.1 Transformation from 2D to 3D

The primary data we got includes right ascension, declination, major axis, minor axis, and position angle in two dimensions. Nevertheless, a complete description of the spin-vector orientation demands three spatial dimensions. To transform the two-dimensional data into 3-D, we adopt the 'PA-inclination' technique introduced by Flin and Godlowski [10]. The requisite equations for transformations are

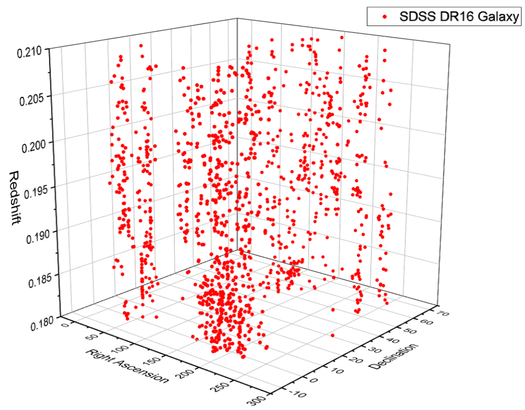


Figure 3: 3D scattering show casing the distribution of 1233 SDSS DR16 galaxies in the sky.

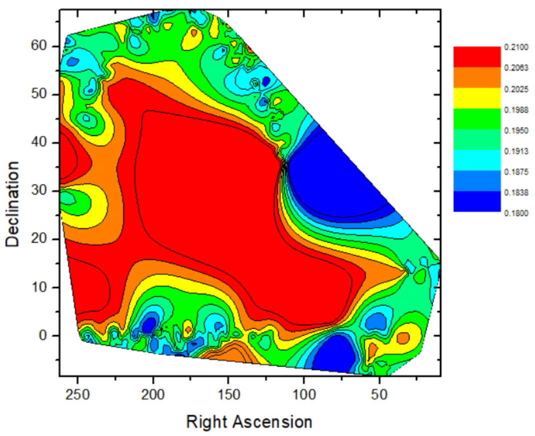


Figure 4: Contour map of the distribution of 1233 SDSS DR16 galaxies in the sky.

$$\sin\theta = -cosi\ sin\delta\ \pm\ sini\ sinP\ cos\delta \quad (1)$$

$$\sin\phi = (\cos\theta)^{-1}\left[-\cos i\ \cos\delta\ \sin\alpha + \sin i\left(\mp\sin P\ \sin\delta\ \sin\alpha \mp \cos P\ \cos\alpha\right)\right] \quad (2)$$

The inclination angle is derived via Holmberg formula [9]

$$cos^2 i = \frac{(q^2 - q^{2*})}{(1 - q^{2*})} \quad (3)$$

Here, $q = b/a$ is axial ratio and q* is galaxy's intrinsic flatness. For cases where a galaxy's morphology is oblate spheroid, Holmberg in 1946 suggested using a value of $q^* = 0.20$ [11].

2.1.1 Statistics used

When the images of galaxy clusters are observed, it is difficult to distinguish any obvious alignments between them. So, in order to check the preferred alignments, statistical analyses are carried out. For the analysis purpose in this study, we adapted the chi–square test, auto–correlation, and the Fourier tests. The galaxies alignments are investigated using the statistical tests of the polar angle (θ) and azimuthal angle (ϕ) distributions resulting from the Godlowskian transformation [10]. MICROSOFT EXCEL 2009, ORIGIN (version 5.0 and 8.0), and MATLAB 7.0 were the computer programs used in these computations.

2.1.2 Chi-square test

The chi-square test fundamentally involves a comparison of two frequency distributions: the observed frequencies from the data and the expected frequencies derived from the assumption of no association. From this comparison, the test generates a chi-square statistic, which directly measures the divergence between the actual outcomes and the expected outcomes. Mathematically, it is defined by

$$\chi^2_\nu = \chi^2/\nu \quad (4)$$

$$\chi^2 = \sum \frac{(N_{oi} - N_{ei})^2}{N_{ei}} \quad (5)$$

where ν represents the degrees of freedom, which must be a positive integer. The summation is performed from 1 to n, with n being the total number of bins or categories. In this context, N_{oi} and N_{ei} refer to the observed and expected isotropic distributions, respectively.

2.1.3 Auto-correlation test

The auto-correlation test is a statistical method used to analyze a series of observations ordered by time or space. It functions as a mathematical tool for identifying and quantifying repeating patterns and the strength of a linear relationship between two variables. When correctly applied, the test's value will fall within the closed interval of $[-1, 1]$. The correlation function is

$$C = \sum_{1}^{n} \frac{(N_k - N_{0k})(N_{k+1} - N_{0k+1})}{(N_{0k}N_{0k+1})^{1/2}} \quad (6)$$

$$\sigma(\Delta_1) = n^{1/2} \quad (7)$$

In an isotropic distribution, correlation vanishes. So we expect to have $C \to 0$ for their systems which obeys cosmological principle.

2.1.4 Fourier test

The Fourier series can be referred to as an infinite series of sine and cosines that define periodic functions, whether they are continuous or not. It is a statistical test used to test the deviation from isotropy, in cases where the deviation only varies with angles (over here θ and ϕ). The quantity of solutions in the kth bin is represented by N_k, while N_0 is the average number of solutions per bin. N_{0k} is the anticipated number of solutions in the kth bin. Then the Fourier series is expressed as follows

$$\sigma(\Delta_{11}) = \left(\sum_{k=1}^{n} N_{0k}\cos^2 2\theta_k\right)^{-1/2}, \quad \sigma(\Delta_{21}) = \left(\sum_{k=1}^{n} N_{0k}\sin^2 2\theta_k\right)^{-1/2}. \tag{8}$$

$$\Delta_1 = \left(\Delta_{11}^2 + \Delta_{21}^2\right)^{1/2} \tag{9}$$

$$P(>\Delta_1) = \exp\left(-\frac{n}{4}N_0\Delta_1^2\right) \tag{10}$$

With standard deviation

$$\sigma(\Delta_1) = \left(\frac{2}{nN_0}\right)^{1/2} \tag{11}$$

The Fourier coefficient Δ_{11} is considered highly significant as it signifies the direction of departure from isotropy.

3 Results and discussion

The analysis begins by examining the distribution of polar(θ) and azimuthal (ϕ) angles for the spin vectors of 1233 galaxies from the SDSS DR16 catalog (Appendix A).The primary motive is to study any non-random effects on the space orientation of galaxy spin vectors relative to the equatorial coordinate system. We have used four statistical parameters to investigate any deviation from an isotropic distribution. According to Godlowski [12], these parameters can indicate an anisotropic nature in spin vectors if their values exceed specific thresholds. Specifically, an anisotropic distribution is suggested if the chi-square probability $P(>\chi^2) < 0.050$, the auto-correlation coefficient $C/C(\sigma) > 1.0$, the absolute value of the first-order Fourier coefficient $\Delta_{11}/\sigma(\Delta_{11}) > 1.5$, and the first-order Fourier probability $P(>\Delta_1) < 0.15$. Beyond the statistical tests, we also examined the graphical representation of the polar and azimuthal angle distributions. The total number of galaxies in this work is 1233.The paper proceeds by calculating the solutions for θ and ϕ for each galaxy twice. Therefore, there are 2466 solutions altogether and Figure 5 represents θ distribution of galaxies.

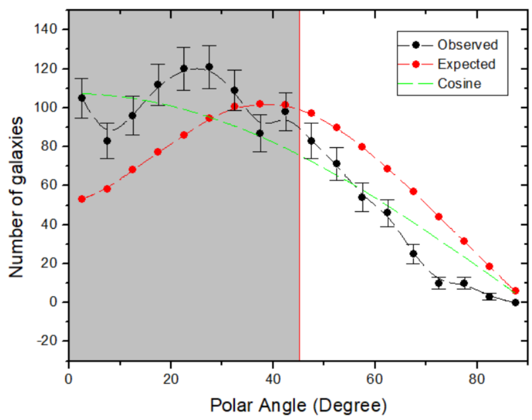


Figure 5: The polar angle (θ) distribution of 1233 SDSS DR16 galaxies. The solid circle with a line symbolizes the expected distributions. The dashed lines symbolize the cosine distributions. The observed distribution is symbolized by a solid circle with $\pm 1\sigma$ error bars..

In the shaded region ($\theta < 45°$), multiple humps are observed between $\theta \approx 17°$ and $33°$, where the observed galaxy counts exceed the expected counts. This suggests a preference for spin vector orientations parallel to the equatorial coordinate system. In contrast, in the unshaded region ($\theta > 45°$), a significant dip is noted particularly in the range $\theta \approx 60°$ to $80°$, showcasing the fall of observed values way below the simulated expected distribution. This indicates a deficiency of galaxies with spin vectors oriented perpendicular to the equatorial plane. The deviation from both the expected and cosine curves, particularly at higher θ, reinforces the presence of anisotropy in the polar angle distribution.

Similarly, within the shaded region, noticeable humps appear between $\phi \approx -45°$ and $\phi \approx -10°$ and also near $\phi = 5°$ and $\phi = 25°$, where the observed number of galaxies significantly exceeds the expected values, Figure 6. This suggests a preferred alignment of galaxy spin vectors within this central azimuthal range. Conversely, the outer regions ($|\phi| > 45°$) display a marked decline in the observed number of galaxies compared to the expected values, pointing toward a deficiency in orientations that deviate far from the equatorial axis.

Overall, the presence of such significant deviations from isotropic expectations in both the polar and azimuthal angle distributions strongly supports the anisotropy in the spatial orientation of galaxy spin vectors at this redshift. These findings may reflect the influence of large-scale cosmic structures, local environmental effects, or evolutionary processes on galaxy angular momentum orientation.

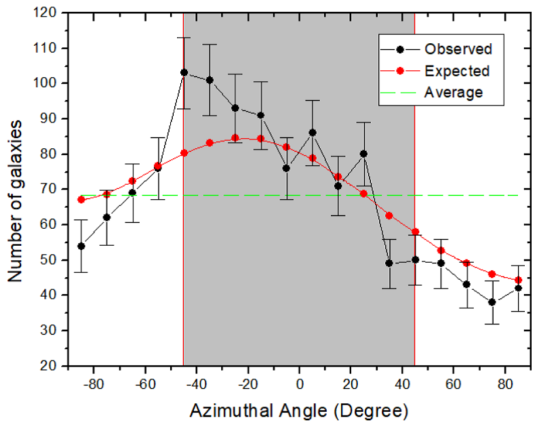


Figure 6: The azimuthal angle (ϕ) distribution of 1233 SDSS DR16 galaxies. The solid circle with a line symbolizes the expected distributions. The dashed lines symbolize the average distributions. The observed distribution is symbolized by solid circle with $\pm 1\sigma$ error bars.

The statistics of θ and ϕ angle distributions of 1233 SDSS DR16 galaxies are displayed in Table 1. Analysis of the polar angle distribution yields a χ^2 probability P($> \chi^2$) of 0.000, a value below the standard 0.05 significance threshold. This extremely small p-value constitutes compelling evidence against the null hypothesis of isotropy, indicating a statistically significant anisotropy in the angular pattern.

Table 1: Statistics of the polar (θ) angle and azimuthal (ϕ) angle distributions of SDSS DR16 galaxies

Statistics	**Polar angle** (θ)	**Azimuthal angle** (ϕ)
$P(> \chi^2)$	0.000	0.108
$C/C(\sigma)$	39.130	2.128
$\Delta_{11}/\sigma(\Delta_{11})$	13.394	2.174
$P(> \Delta_1)$	0.000	0.003

The auto-correlation coefficient $C/C(\sigma)$ is found to be 39.130, which is significantly greater than the 1σ threshold, indicating a high degree of non-randomness and strong correlation in the distribution of polar angles. This suggests a pattern or alignment in the orientation of spin vectors rather than a random (isotropic) distribution. Similarly, from the statistical tests, the first-order Fourier coefficient of θ, $\Delta_{11}/\sigma(\Delta_{11})$, resulted at 13.394, signaling a significant deviation from isotropy at the 1.5σ limit. The corresponding first-order Fourier probability P($< \Delta_1$) is 0.000, further reinforcing the presence of anisotropy.

In parallel, the P($> \chi^2$) applied to the azimuthal angle distribution yields a p-value of 0.108, comfortably exceeding the 0.05 significance threshold. Consequently, the data provide no compelling evidence for a departure from isotropy in the azimuthal component. However, other statistical measures point to mild anisotropy. The auto-correlation coefficient $C/C(\sigma)$ is obtained to be 2.128, which slightly exceeds the 1σ level, indicating a weak correlation that might point toward underlying alignment tendencies.

Furthermore, the first-order Fourier coefficient, expressed in units of its uncertainty as $\Delta_{11}/\sigma(\Delta_{11})$, is measured to be 2.174, which is above the standard 1.5σ threshold, suggesting a notable an isotropy in the ϕ-distribution. The corresponding Fourier probability P($< \Delta_1$) is 0.003, which is lower than the 0.15 cut off, again indicating significant deviation from isotropy. These statistics once again suggests that the spatial orientation of the spin vector of the galaxies aligns with the Pancake model of galaxy evolution. Therefore, while the chi-square test alone might suggest weak or marginal isotropy, the auto-correlation and first-order Fourier tests clearly indicate mild anisotropy in the azimuthal angle distribution. The positive first-order Fourier coefficient of ϕ statistics affirms that, on average, the spin axes of galaxies point radially out ward from the origin of the equatorial coordinate system rather than exhibiting a random or tangential orientation. Finally, the statistical analysis strongly supports anisotropy in the polar angle distribution and points toward mild anisotropy in the azimuthal angle distribution, aligning with the Pancake model of galaxy evolution [13]. These findings reinforce the graphical interpretations discussed earlier and suggest the presence of large-scale or environmental influences on the spin vector orientations of galaxies at the examined redshift range.

4 Conclusion

In this study, we investigated the spatial orientation of spin vectors of SDSS DR16 galaxies within the redshift range $0.18 < z < 0.21$ using u-band data. A total of 1233 galaxies were analyzed to understand their angular momentum alignment by applying the method proposed by Flin & Godlowski, which enables the transformation of two-dimensional projected images in to three-dimensional spin vector components: specifically, polar (θ) and azimuthal (ϕ) angles. To establish the expected isotropic behavior, we performed a simulation of 10^7 virtual galaxies following the approach outlined by previous researchers. We then employed three statistical tests: chi-square, auto-correlation, and Fourier analysis, to compare the observed and expected distributions. The results of the statistical tests for the polar angle distribution show compelling evidence of strong anisotropy. Specifically, the extremely low ($P(>\chi^2) = 1.21 \times 10^{-35}$), high ($C/C(\sigma) = 39.13$), and significant ($\Delta_{11}/\sigma(\Delta_{11}) = 13.394$ with $P(<\Delta_1) = 0.000$) all indicate that the spin vectors of galaxies are not randomly distributed, but preferred a parallel alignment (Pancake model) with respect to the equatorial coordinate system. In contrast, the azimuthal angle distribution reveals mild anisotropy. The chi-square probability ($P(>\chi^2) = 0.108$) suggests near isotropy, but the elevated values of $C/C(\sigma) = 2.128$ and $\Delta_{11}/\sigma(\Delta_{11}) = 2.174$ with a low Fourier probability of $P(>\Delta_1) = 0.003$ suggest a subtle preferred orientation, possibly influenced by large-scale structure or local interactions. As our findings show clear evidence of anisotropic behavior, supporting the Pancake model of the galaxy evolution, this points to the influence of environmental effects and cosmic web structures in governing galaxy spin orientation at intermediate redshifts. These results partially challenge the predictions of hierarchical galaxy formation models, indicating that spin alignment may be preserved across cosmic time scales or influenced by anisotropic large-scale environments. The presence of humps and dips in the angular distributions further supports the role of local and global influences on galactic spin vector orientation.

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Conflicts of interest

The authors declare that there are no conflicts of interest associated with the publication of this research paper.

Author's contribution

JRM:

Please provide authors contributions

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Appendix A

Table 2: Astronomical data used in the analysis.

objid	ra	dec	u	field	specobjid	class	redshift	me1_u	me2_u
1.238E+18	29.565726	13.880396	20.38646	157	5.243E+18	GALAXY	0.1911034	-0.0453845	0.5184176
1.238E+18	31.362606	13.565602	20.77159	168	4.82E+17	GALAXY	0.2073895	0.2519918	-0.1586332
1.238E+18	31.646050	13.516190	21.01062	170	4.808E+17	GALAXY	0.2075610	-0.1891265	-0.3964669
1.238E+18	31.628964	13.502324	26.39404	170	4.82E+17	GALAXY	0.2061218	-0.6208656	0.1447500
1.238E+18	32.837047	13.335819	20.69788	178	4.819E+17	GALAXY	0.2072662	-0.6547608	-0.5282718
1.238E+18	10.180825	15.471200	21.46009	31	6.977E+18	GALAXY	0.1948879	-0.2717016	-0.6113532
1.238E+18	10.283697	15.425328	21.24801	32	4.708E+17	GALAXY	0.1958842	-0.6463969	0.1531881
1.238E+18	10.899237	15.353092	21.03381	36	4.708E+17	GALAXY	0.1896938	-0.5632824	0.6339843
1.238E+18	12.144328	15.384978	20.07882	44	4.719E+17	GALAXY	0.1918032	-0.2970847	-0.0241535
1.238E+18	12.397597	15.391888	22.82201	45	4.719E+17	GALAXY	0.1876189	-0.7900101	0.1051302
1.238E+18	13.027159	15.360477	21.38843	49	4.73E+17	GALAXY	0.1808917	0.3178658	-0.9060206
1.238E+18	13.062014	15.325826	21.11855	49	4.73E+17	GALAXY	0.2063197	0.0510754	-0.5468866
1.238E+18	13.132634	15.482425	20.31611	50	4.73E+17	GALAXY	0.1824711	0.0071439	-0.3101091
1.238E+18	14.071788	15.447712	20.59720	56	4.73E+17	GALAXY	0.2017968	-0.1043268	-0.3126958
1.238E+18	14.172572	15.255065	21.46246	57	4.73E+17	GALAXY	0.2028262	0.1885099	0.3298785
1.238E+18	14.213840	15.296963	22.25091	57	6.422E+18	GALAXY	0.2034016	0.5637088	-0.5751076
1.238E+18	14.294699	15.300290	21.14726	57	4.741E+17	GALAXY	0.2025277	-0.0037714	0.3221334
1.238E+18	14.325174	15.401521	20.87947	58	4.73E+17	GALAXY	0.2024597	0.5501190	-0.3077659
1.238E+18	15.557896	15.228352	22.24890	66	6.422E+18	GALAXY	0.1824115	-0.0994637	0.4713173