Multipole alignment in the large-scale distribution of spin direction of spiral galaxies

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Abstract

Previous observations have suggested non-random distribution of spin directions of galaxies at scales far larger than the size of a supercluster. Here I use $\sim 1.7 \cdot 10^5$ spiral galaxies from SDSS and $3.3 \cdot 10^4$ spiral galaxies from Pan-STARRS to analyze the distribution of galaxy spin patterns of spiral galaxies as observed from Earth. The analysis shows in both SDSS and Pan-STARRS that the distribution of galaxy spin directions forms a non-random pattern, and can be fitted to a dipole axis in probability much higher than mere chance. These observations agree with previous findings, but are based on more data and two different telescopes. The analysis also shows that the distribution of galaxy spin directions fits a large-scale multipole alignment, with best fit to quadrupole alignment with probability of $\sim 6.9\sigma$ to have such distribution by chance. Comparison of two separate datasets from SDSS and Pan-STARRS such that the galaxies in both datasets have similar redshift distribution provides nearly identical quadrupole patterns.

1 Introduction

Because the spin direction of a spiral galaxy depends on the perspective of the observer, the distribution of the spin directions of spiral galaxies is expected to be randomly distributed in the sky to an Earth-based observer. However, several previous studies showed evidence of non-random patterns of the distribution of spin directions of spiral galaxies [25, 37, 38, 39, 41, 40, 23, 24, 42, 43].

First experiments were done with manually annotated galaxies [18, 22, 25], and showed evidence of asymmetry between the number of galaxies with opposite spin directions. However, manual annotation of galaxies is impractical for analyzing very large datasets of galaxies, and can also be biased by the human perception [22, 14]. The ability to automate the galaxy annotation led to far larger datasets, that are less vulnerable to human bias due to the machine-based nature of the annotation. Automatically annotated datasets of galaxy images showed clear and statistically significant asymmetry between clockwise and counterclockwise galaxies in Sloan Digital Sky Survey [39, 41, 43]. While the first experiments were based on SDSS alone, more recent work using several telescopes showed very good agreement between SDSS and data collected by other telescopes such as Pan-STARRS [40], and Hubble Space Telescope [42]. Other experiments used smaller manually annotated datasets to show patterns of spin directions of galaxies [44], including galaxies that are too far from each other to have gravitational interactions [24]. Alignment of spin directions has also been shown with quasars [17].

Although the observations might be difficult to explain without violating the basic cosmological foundations, explanations to the observations that do not necessarily require the violation of the foundational cosmology have been proposed [46, 4]. Here I use a large dataset of $\sim 1.7 \cdot 10^5$ SDSS galaxies that were annotated automatically by their spin directions to show a possible multipole alignment of the distribution of galaxy spin directions. The patterns identified in SDSS galaxies are also compared to the patterns of galaxy spin directions in a completely separate dataset of Pan-STARRS galaxies.

2 Data

Data from two different digital sky surveys were used in this experiment, to allow a comparison be-
between data collected by different telescopes and reduce the probability that the results are driven by an unknown instrumental flaw in a certain telescope system. The first dataset is $\sim 1.7 \cdot 10^5$ spiral galaxies from SDSS annotated by their spin directions, and it is the same dataset used in [39, 41, 40, 43]. The galaxies are spiral galaxies taken from the catalog of $\sim 3 \cdot 10^6$ SDSS galaxies classified automatically into spiral and elliptical galaxies [21]. These galaxies are relatively bright and large, with $i$ magnitude $< 18$ and Petrosian radius larger than 5.5". The 740,908 galaxies identified as spiral galaxies were used, while the galaxies that were identified as elliptical galaxies were removed from the experiment.

In addition to the SDSS dataset, a separate dataset of Pan-STARRS galaxies was used to allow comparisons between the results produced by the two sky surveys. For that purpose, a dataset of 2,394,452 Pan-STARRS galaxies that were labeled by Pan-STARRS photometric pipeline as extended sources in all bands [45] was used.

The galaxy images from both datasets were retrieved using the Cutout service, which both SDSS and Pan-STARRS provide. The images were retrieved in the form of 120×120 JPG images. To ensure that the galaxy fits inside the image, if more than 25% of the pixels on the edge of the image had grayscale value greater than 125, the image was downsampled by 0.01" and downloaded again until the number of bright pixels on the edge of the frame was less than 25% of the total number of edge pixels [21].

After the images were downloaded, they were separated into galaxies with clockwise spin direction and galaxies with counterclockwise spin direction. That was done by using the Ganalyzer algorithm [34, 35], as was done in [36, 37, 15, 9, 38, 39, 41, 40]. In summary, Ganalyzer computes the radial intensity plot of each galaxy image, which is a simple transform of the raw galaxy image into an image of dimensionality of 360×35, such that the X axis is the polar angle (in degrees) and the Y axis is the radial distance (in percents of the galaxy radius). The value of the pixel at coordinates $(x, y)$ in the radial intensity plot is the median of the 5×5 pixels around $(O_x + \sin(\theta) \cdot r, O_y - \cos(\theta) \cdot r)$ in the galaxy image, such that $\theta$ is the polar angle and $r$ is the radial distance. The radial distance is measured in terms of percent of the radius of the galaxy.

![Figure 1: Original galaxy images (left), the radial intensity plots (middle), and the peaks detected in the radial intensity plots (right). The sign of the regression of the vertical lines of the peaks determines the curve of the arms of the galaxy, and therefore also the spin direction.](image)

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After the radial intensity plot is computed, peak detection is applied to identify groups of peaks across the horizontal lines of the radial intensity plot [34]. Since arm pixels are brighter than the sky background, the groups of peaks in the radial intensity plot are the arms of the galaxy. Connecting the peaks detected in different horizontal lines creates vertical lines that correspond to the curve of the arm. Therefore, a linear regression applied to the peaks can reflect the shape of the arm, and the sign of the regression coefficient indicates whether the galaxy has clockwise or counterclockwise spin direction. Figure 1 shows examples of original galaxy images, the transforms into radial intensity plots, and the peaks detected in the radial intensity plots. A through description of the algorithm as well as analysis of its performance can be found in [34], as well as in [15, 36].

To use galaxies which their spin direction can be determined, only galaxies that had at least 10 identifiable peaks in the radial intensity plot were used, and galaxies that did not have at least 10 peaks were ignored. Of the peaks that were detected, at least 75% were expected to be oriented towards the same direction. Galaxies that did not meet these criteria were rejected, and were not used in the analysis. Manual inspection of 200 galaxies with clockwise spin direction and 200 randomly selected galaxies with counterclockwise spin direction showed that 10 galaxies classified as clockwise and
An important feature of Ganalyzer is that it is a model-driven algorithm that follows defined rules that are driven by the features of the galaxy. As deep neural networks are commonly used for the task of image classification, these methods are based on complex and unintuitive data-driven rules that make it extremely difficult to understand how the classification is performed. Such methods can capture subtle biases in the training set or in the data collection process, and lead to unexplained bias or asymmetry that is difficult to understand due to the complex classification process.

Annotating the dataset of SDSS galaxies by their spin direction using Ganalyzer as described above provided a dataset of 88,273 galaxies with clockwise spin patterns and 86,075 galaxies with counterclockwise patterns. Assuming mere chance probability of 0.5 of a galaxy to be associated with one of the two possible spin directions, the probability to have such separation by chance can be computed using cumulative binomial distribution, such that the number of tests is 174,348 and the success probability is 0.5. The two-tailed probability to have 87,509 or more successes is \( P < 4 \cdot 10^{-9} \). Repeating the experiment after mirroring the galaxies led to identical results, which is expected due to the deterministic and symmetric nature of Ganalyzer.

Table 1 shows the number of SDSS galaxies in each 30° RA ranges.

| RA  | \( \Delta RA \) | # galaxies |
|-----|----------------|-----------|
| 0°-30° | -0.005 | 27,128 |
| 30°-60° | 0.068 | 18,023 |
| 60°-90° | -0.031 | 3,477 |
| 90°-120° | 0.011 | 5,302 |
| 120°-150° | 0.022 | 20,820 |
| 150°-180° | 0.005 | 19,585 |
| 180°-210° | 0.012 | 18,466 |
| 210°-240° | 0.021 | 18,984 |
| 240°-270° | -0.001 | 14,245 |
| 270°-300° | 0.019 | 873 |
| 300°-330° | -0.04 | 8,351 |
| 330°-360° | 0.016 | 19,184 |

The distribution of these galaxies and the difference between clockwise and counterclockwise galaxies in the different RA ranges is shown in Table 2.

| RA  | \( \Delta RA \) | # galaxies |
|-----|----------------|-----------|
| 0°-30° | -0.009 | 3,559 |
| 30°-60° | -0.031 | 2,676 |
| 60°-90° | -0.015 | 1,999 |
| 90°-120° | 0.041 | 3,473 |
| 120°-150° | 0.025 | 5,064 |
| 150°-180° | -0.022 | 5,195 |
| 180°-210° | -0.001 | 4,088 |
| 210°-240° | 0.023 | 1,874 |
| 240°-270° | 0.013 | 429 |
| 270°-300° | 0.082 | 1,074 |
| 300°-330° | -0.024 | 2,799 |

Table 2: The number of galaxies and the asymmetry between clockwise and counterclockwise galaxies in different RA ranges in Pan-STARRS.

13 galaxies classified as counterclockwise did not have identifiable spin patterns, but none of these galaxies was misclassified.

The application of Ganalyzer to the Pan-STARRS galaxies provided a dataset of 33,028, of which 16,508 had clockwise spin direction and 16,520 had counterclockwise spin. Figure 3 shows the distribution of the Petrosian radius measure in the r band and the r Kron magnitude of the galaxies. The redshift distribution of the Pan-STARRS galaxies is shown in Figure 4. The redshift distribution is important for making a comparison between the Pan-STARRS and SDSS data, and will be used in Section 3. In the case of Pan-STARRS, Ganalyzer was applied to all galaxies that met the criteria described above, and not just to galaxies identified as spiral as was done in SDSS, since no catalog of Pan-STARRS spiral galaxies exists yet. Therefore, the number of Pan-STARRS galaxies with identifiable spin directions is much smaller relative to the size of the initial dataset of Pan-STARRS galaxies.

The distribution of these galaxies and the difference between clockwise and counterclockwise galaxies in the different RA ranges is shown in Table 2. The table also shows the asymmetry in each 30° RA range measured by \( \frac{c_{cw} - c_{ccw}}{c_{cw} + c_{ccw}} \). Consistency between the asymmetries in Tables 1 and 2 is not expected, due to differences in the declination and redshift of the galaxies, as will be discussed in Section 3.
3 Results

To test for the existence of an axis of asymmetry in the distribution of galaxy spin directions, for each possible \((\alpha, \delta)\) combination the \(\cos(\phi)\) of the galaxies were fitted using \(\chi^2\) to \(d \cdot |\cos(\phi)|\), such that \(\phi\) is the angular distance between \((\alpha, \delta)\) and the galaxy, and \(d\) is the spin direction of the galaxy (1 clockwise and -1 counterclockwise). To deduce the statistical significance of the axis, each galaxy was assigned a random number within \([-1,1]\), and the \(\chi^2\) of fitting the \(\cos(\phi)\) of the galaxies to \(d \cdot |\cos(\phi)|\) was computed such that \(d\) was the randomly assigned spin direction (1 or -1). The \(\chi^2\) was computed 1000 times for each \((\alpha, \delta)\). The mean and standard deviation of the 1000 runs were computed for each \((\alpha, \delta)\) combination. Then, the mean \(\chi^2\) computed with the random spin patterns was compared to the \(\chi^2\) computed with the actual spin directions of the galaxies. The \(\sigma\) difference between the mean \(\chi^2\) of the random spin directions and the \(\chi^2\) of the actual spin directions is the statistical probability of a dipole axis at \((\alpha, \delta)\).

Figure 5 shows the \(\sigma\) of the axis of spin direction asymmetry of all possible \((\alpha, \delta)\) combinations. The most likely axis was identified at \((\alpha = 88^\circ, \delta = 36^\circ)\), with \(\sigma\) of \(\sim 4.34\) \(P < 0.000014\). The 1\(\sigma\) error of the right ascension of the axis is \((62^\circ, 124^\circ)\), and the error range of the declination is \((7^\circ, 69^\circ)\).

Figure 6 shows the probability of an axis when the spin directions of the galaxies are determined randomly. The random spin directions show no statistically significant pattern, and the maximum probability of the axis is 1.04\(\sigma\). The much lower statistical significance indicates that the asymmetry profile is not driven by certain statistical noise.

Previous observations in the context of CMB anisotropy as observed by COBE, WMAP, and Planck showed evidence of quadrupole alignment. Figure 7 shows the \(\chi^2\) of fitting the galaxies to cosine 2\(\phi\) dependence in each possible \((\alpha, \delta)\) combinations. The axis with the highest probability of 6.88\(\sigma\) was identified at \((\alpha = 333^\circ, \delta = 56^\circ)\). The 1\(\sigma\) error range of the RA is \((292^\circ, 7^\circ)\), and on the declination the error range is \((36^\circ, 81^\circ)\). The other axis peaks at \((212^\circ, 17^\circ)\). Repeating the same experiment when the galaxies are assigned with random spin directions is shown in Figure 8 exhibiting no statistically significant pattern with maximum probability of 1.18\(\sigma\).

An attempt to fit the galaxy spin directions to octopole alignment is displayed in Figure 9. The most likely axis is identified at \((\alpha = 11^\circ, \delta = -22^\circ)\) with probability of 6.41\(\sigma\).

The patterns of spin direction asymmetry identified by SDSS was compared to the asymmetries identified with the dataset of Pan-STARRS galaxies described in Section 2. Figure 10 shows the probability (in \(\sigma\)) of a dipole axis to happen by chance in each possible \((\alpha, \delta)\) combination. The most likely axis was identified at \((49^\circ, -3^\circ)\), with \(\sigma = 1.86\). The 1\(\sigma\) error range is \((3^\circ, 112^\circ)\) on the right ascension and \((-81^\circ, 52^\circ)\) on the declination. The figure shows some differences between the large-scale patterns of spin direction asymmetry identified in Pan-STARRS and the patterns identified in SDSS as shown by Figure 5 although the differences are well within 1\(\sigma\) error.

The experiments described above with SDSS data showed that the probability of quadrupole alignment of the galaxy spin directions is much higher than the probability of a dipole alignment. Figure 11 shows the \(\sigma\) probability of quadrupole axis in each possible \((\alpha, \delta)\) combination. The most
likely axes are at (198°, 9°) and (305°, 40°), with σ of 1.65. These locations are very close to the quadrupole axis identified with the SDSS galaxies.

To further compare the large-scale alignment of galaxy spin patterns in SDSS and Pan-STARRS, another dataset of SDSS galaxies was prepared such that the redshift distribution of the galaxies in both datasets was similar. That was done by selecting SDSS galaxies with redshift such that the redshift distribution of the galaxies follows the redshift distribution of Pan-STARRS as shown in Figure 4. SDSS DR14 had spectra for 63,693 galaxies, and 38,998 of these galaxies were selected such that the redshift distribution of the galaxies was similar to the redshift distribution of the galaxies in Pan-STARRS as shown in Figure 4. Table 2 shows the number of galaxies and asymmetry between clockwise and counterclockwise galaxies in each RA range. As the table shows, the asymmetry in the different redshift ranges is more similar to the asymmetry shown in the same RA ranges in Table 2 with Pearson correlation between the asymmetries in the two sky surveys of ∼0.55 (P ≃ 0.05). The σ of quadrupole alignment in the spin directions of these galaxies is shown in Figure 12.

Although the two datasets were collected independently by two different telescopes, both datasets show very similar patterns of quadrupole alignment of the spin directions of the galaxies. The probability of the axis is ∼ 1.81σ and ∼ 1.66σ for the SDSS data and Pan-STARRS data, respectively. Due to the overlap in the footprint of the two telescopes it is expected that some galaxies would be included in both datasets. The number of galaxies included in both the SDSS and the Pan-STARRS datasets is 4,426. Excluding those galaxies such that the
two datasets are completely orthogonal has minor impacts on the distribution of the galaxies, and the graph practically does not change when these galaxies are excluded.

4 Conclusion

The distribution of galaxy spin directions in SDSS and Pan-STARRS shows patterns in the asymmetry between galaxies with opposite spin directions. Assuming that the asymmetry observed by the two telescopes reflects the real sky rather than a flaw in the telescope systems, the observation can be considered as evidence for large-scale anisotropy. The highest probability was achieved when fitting the distribution of galaxy spin directions to quadrupole, with probability greater than 6σ. Assigning the galaxies with random spin directions provides no statistically significant patterns.

The method used to annotate the galaxies is a deterministic model-driven algorithm that follows defined rules. It is not based on complex data-driven non-intuitive rules determined during the training process of a deep neural networks, which are very difficult to understand and can capture background noise or subtle biases in the training set. Using randomly assigned spin patterns leads to no statistically significant patterns in the data. Using mirrored images of the galaxies expectedly flips the numbers of clockwise and counterclockwise galaxies, providing also experimental evidence that the algorithm is symmetric. The observation that the asymmetry changes with the direction of observation also shows that a bias in the algorithm is unlikely, since a bias in the annotation algorithm is expected to be consistent in all directions of observation.

The analysis is based on data acquired by the Sloan Digital Sky Survey and Pan-STARRS, and under the assumption that these telescopes and their photometric pipelines are not biased in some unexplained manner that leads to differences between galaxies based on their spin direction. It is
The observations reported in this paper agree with previous observations that show asymmetry between galaxies with opposite spin directions [25, 36, 37, 15, 38, 39, 41, 40, 42, 43], or patterns between spin directions of galaxies that are too far to have gravitational interactions [24]. Cosmological-scale anisotropy was also observed through short gamma ray bursts, providing evidence of non-uniform distribution that could violate the isotropy assumption of the cosmological principle [26]. Although long gamma ray bursts show no statistically significant anisotropy [1]. Luminosity-temperature ratio of 313 galaxy clusters also showed violation of the isotropy assumption [27].

Cosmic Microwave Background (CMB) data also shows evidence of possible cosmological-scale polarization [2, 16, 8, 3, 10], and was fitted to quadrupole alignment [7, 13, 17]. These observations led to theories that shift from the standard cosmological models [11, 32, 33, 31, 20, 5]. Since the spin patterns of a galaxy as visible from Earth is also an indication of the actual spin direction of the galaxy [19], the large-scale patterns in the distribution of the spin directions can be an indication of a rotating universe [12, 20, 30, 6]. Other explanations that do not violate the basic cosmological assumptions have also been proposed, such as possible primordial subtle chiral violation exhibited in the current epoch by the asymmetry of the distribution of galaxy spin directions [46], or to parity-breaking gravitational waves [4]. As future space-based telescopes such as Euclid and ground-based
telescopes such as the Vera Rubin Telescope will allow much more powerful data collection, the asymmetry of the distribution of the spin directions of spiral galaxies can be studied in higher resolution to provide more accurate profiling.

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