Spin Parity of Spiral Galaxies. III. Dipole Analysis of the Distribution of SDSS Spirals with 3D Random Walk Simulations

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Abstract
Observation has not yet determined whether the distribution of spin vectors of galaxies is truly random. It is unclear whether there is any large-scale symmetry-breaking in the distribution of the vorticity field in the universe. Here, we present a formulation to evaluate the dipole component $D_{\max}$ of the observed spin distribution, whose statistical significance $\sigma_D$ can be calibrated by the expected amplitude for 3D random walk (random flight) simulations. We apply this formulation to evaluate the dipole component in the distribution of Sloan Digital Sky Survey (SDSS) spirals. Shamir published a catalog of spiral galaxies from the SDSS DR8, classifying them with his pattern recognition tool into clockwise and counterclockwise (Z-spiral and S-spiral, respectively). He found significant photometric asymmetry in their distribution. We have confirmed that this sample provides dipole asymmetry up to a level of $\sigma_D = 4.00$. However, we also found that the catalog contains a significant number of multiple entries of the same galaxies. After removing the duplicated entries, the number of samples shrunk considerably to 45%. The actual dipole asymmetry observed for the “cleaned” catalog is quite modest, $\sigma_D = 0.29$. We conclude that SDSS data alone do not support the presence of a large-scale symmetry-breaking in the spin vector distribution of galaxies in the local universe. The data are compatible with a random distribution.

Unified Astronomy Thesaurus concepts: Cosmic anisotropy (316); Spiral galaxies (1560); Galaxy formation (595); Catalogs (205); Galaxy rotation (618)

1. Introduction

For many decades, investigation of the formation and evolution of galaxies has been a primary subject of astrophysics. Semianalytic simulations of structure formation in the Λ cold dark matter (ΛCDM) model of the universe to reproduce clustering and merging of galaxies provide the current standard picture of galaxy formation (White & Rees 1978; Steinmetz & Navarro 2002). Ferreira (2020) suggests that ultralight dark matter may reconcile certain remaining problems that the standard models fail to explain. Recent high spatial resolution simulations enable tracking of the formation of the spiral structure of individual galaxies (Robertson et al. 2004; Agertz et al. 2011; Ceverino et al. 2017; Shimizu et al. 2019).

On the other hand, there are other classical models of galaxy formation, such as the primordial whirl scenario (von Weizsaecker 1955), the pancake shock scenario (Peebles 1969; Zeldovich 1970), and the tidal torque scenario (White 1984). Each provides naïve inference regarding the statistical distribution of the spin vectors of galaxies.

If the spin vectors of individual galaxies were produced by splitting of large-scale primordial whirls, there would be some remaining coherent spin alignment parallel to the primordial whirl vectors, producing an observable dipole anisotropy. If the galaxies were formed mainly at the equatorial planes of primordial collapsing pancakes, spin vectors can mostly be expected to be parallel to the equatorial planes, possibly producing a quadrupole anisotropy seen from the observer located within a cluster of galaxies.

If an individual galaxy started spinning owing to the tidal torque from a galactic cluster mass assembly, the galaxy’s spin vector should initially be perpendicular to the line joining the galaxy and the center of gravity of the cluster mass assembly. Such an initial correlation would, however, be diluted soon by orbital mixing.

Figure 1 illustrates potential anisotropy that might be induced from different galactic formation scenarios (Sugai & Iye 1995). While the orbital mixing and merging of galaxies could wipe out these initial spin vector anisotropy, if any, observational verification of any symmetry-breaking in the distribution of spin vectors would be a significant evidence.

There were hot debates in the middle of the last century over whether the spiral structure of galaxies winds in a trailing way or in a leading way. It has been generally believed that the spiral structure of galaxies is in general “trailing” rather than “leading.” Iye et al. (2019) found corroborative evidence from their survey of 146 spiral galaxies that all spiral structure in these galaxies is indeed “trailing.” This confirmation provides a basis for us to use the spiral winding direction projected on the sky, either S-wise spirals or Z-wise spirals, to judge the sign of the line-of-sight component $\Omega_d$ of a galaxy’s spin vector. This determines whether the spin vector is pointing away from or toward us.

Borchkhadze & Kogoshvili (1976) pointed out the number dominance of “S” spirals over “reverse S” spirals, hereafter referred to as Z-spirals in the present paper, in the 7563 galaxies sampled from the Abastumani catalog of Bright Galaxies. MacGillivray & Dodd (1985) found a similar trend and a marginal dependence on the supergalactic hemisphere. Iye & Sugai (1991) and Sugai & Iye (1995) used S/Z parity information on spiral galaxies to study the distribution of spin angular momentum vectors in the assembly of galaxies. However, the data sets available at that time were not large enough.

The Galaxy Zoo 1 catalog, a morphological classification of Sloan Digital Sky Survey (SDSS) galaxies, was compiled by a public poll. It showed a similar predominance of S-spirals as...
previous studies, but Hayes et al. (2017) interpreted this as being due to human selection bias rather than a human chirality bias or physical reality.

Shamir (2017a) published tables of 82,244 clockwise (Z-spiral) and 80,272 counterclockwise (S-spiral) galaxies by using his GalaxAyer algorithm (Shamir 2011a, 2011b) for a data set of 740,908 galaxies classified as spiral galaxies from three million SDSS Data Release 8 galaxies (Kuminski & Shamir 2016). The statistics show overdominance of Z-spirals from a random distribution at 3.46σ. Shamir (2017b) reported finding a significant “photometric anisotropy” such that the mean magnitudes of S/Z-spirals behave differently depending on their R.A. with a possible asymmetry axis at (α = 172°, δ = +50°) in J2000. This axis corresponds to the direction (l = 152°, b = +62°) near the galactic pole (b = +90°). Note that Shamir’s catalog shows dominance of Z-spirals instead of the S-spiral dominance reported by previous works.

In the present paper, we develop a formulation to analyze the dipole anisotropy of S/Z spin distribution of galaxies and apply this formulation to reanalyze Shamir’s SDSS catalog.

2. Formulation of Dipole Analysis

2.1. Dipole Component of Spin Distribution

Number statistics can be used to study the S/Z number asymmetry from equipartition. The significance level of the number asymmetry is given by

\[ \sigma_N = \left| N(S) - N(Z) \right| / \sqrt{N(S) + N(Z)} . \]  

Another option is to look for any statistically significant dipole in the spatial distribution of S/Z-spirals.

Let \( \Omega(l', b', d') = (\Omega_l, \Omega_b, \Omega_d) \) be the spin vector of the \( i \)th galaxy with galactic longitude \( l' \), galactic latitude \( b' \), and distance \( d' \). The distance \( d' \) to the galaxy can be approximated for the nearby universe by \( d' = cz' / H_0 \), where \( c \) is the speed of light, \( z' \) is the spectroscopic/photometric redshift of the \( i \)th galaxy, and \( H_0 \) is the Hubble constant.

Measuring the 3D vector \( \Omega \) is nontrivial, but one can easily judge the sign \( h' \) of \( \Omega_d \). This can be done by examining the spiral winding sense to see if it is S-wise (\( h' = -1 \)) or Z-wise (\( h' = +1 \)), since all spiral galaxies can be safely assumed to be trailing (Iye et al. 2019, Paper I). The net effect of misidentifying S-spirals versus Z-spirals and the improbable presence of leading spiral arms would be the reduction of the dipole strength, should it exist. For simplicity, hereafter we assume that all the \( \Omega \) have a unit length, namely, \( \Omega_d = h' \).

By compiling the spin parity, \( h' = \pm 1 \), together with the coordinates of spiral galaxies from image archives such as SDSS, Pan-STARRS1, ESO-DR2, DES, Subaru HSC, and others, we estimate that one can produce a spin parity catalog of up to a million spiral galaxies in the 3D volume within 1 Gpc of the Earth. We are developing an analysis scheme to probe any partial volume within this volume, not necessarily centered on the Earth. This will be discussed in a forthcoming paper. For the moment, however, we consider a local volume centered on the Earth.

To analyze the spin vector distribution in terms of spherical harmonics expansion, one can first examine on its dipole component \( Y_0^1 \), quadrupole component \( Y_2^0 \), and higher components.

If we define a unit vector to a fiducial pole \( P(l_p, b_p) \), one can calculate the inner product

\[ D(l_p, b_p) = \sum_{i=1}^{N} h_i \Omega \cdot P / N = \sum_{i=1}^{N} h_i \cos \theta'_i / N, \]  

where the angle \( \theta'_i \) is the angle between the direction of the \( i \)th galaxy and the direction of the fiducial pole vector \( P \). By determining the direction of the vector \( P \) for which the amplitude \( D_{\text{max}} = |D(l_p, b_p)| \) takes the largest value, one can derive the dipole vector \( D_{\text{max}} \) of the observed distribution.

In fact, \( D_{\text{max}} \) can be obtained simply by calculating a vector \( G \), which is the vector sum of the unit radial vectors pointing to the direction of the \( i \)th galaxy multiplied by the helicity \( h_i \). The inner product of \( G \) with \( P \) takes the maximum value when \( P \) is pointing parallel to \( G \), and then \( D_{\text{max}} \) is \( ||G/N|| \).

2.2. Perfect Dipole Distribution

We assume an extreme case of perfect dipole segregation, where all S-spirals are in the northern hemisphere and all Z-spirals are in the southern hemisphere as shown in Figure 2(a). The weight factor \( \cos \theta' \) of Equation (2) shows that the galaxies toward the dipole axis with small \( \theta' \) add to \( D_{\text{max}} \) while those near the equator with \( \theta' \sim \pi/2 \) reduce \( D_{\text{max}} \). It is easy to see by integration that the expected mean amplitude \( D_{\text{max}}^\text{perfect} \) of all sky sampling is 0.5. Perfect but random dipole distribution produces fluctuation around this expected mean amplitude of 0.5. Monte Carlo simulation shows that the associated standard deviation from this mean amplitude for perfect random dipole distributions is \( \sim 0.3 / \sqrt{N} \).

2.3. Effect of Nonuniform Sky Coverage for a Perfect Dipole Distribution

Although the currently available data from imaging surveys are growing rapidly, the data do not yet fill the entire sky uniformly. There may be observational biases that affect
evaluation of S/Z number asymmetry and/or the evaluation of the observed dipole vector in the S/Z distribution. Let us examine the effect of nonuniform sky coverage for the perfect dipole distribution case mentioned in the previous subsection.

When the sky sampling is limited to a certain narrow cone direction, the dipole amplitude can take any value in the range $0 \leq D_{\text{max}} \leq 1$ depending on the direction to the sample. The largest amplitude $D_{\text{max}} = 1$ is obtained when the sampling is toward the pole, $\theta = 0$ or $\pi$, and the lowest amplitude $D_{\text{max}} = 0$ is observed toward the equator $\theta = \pi/2$. Therefore, depending on the direction of the biased small sky sampling, the resulting $D_{\text{max}}$ can be larger or smaller than the whole sky sampling.

Consider a nonuniform sampling of the complete dipole distribution covering only the northern hemisphere as shown in Figure 2(b). There would be a conspicuous number count asymmetry. However, the dipole strength observed would be equal to that of the whole sky sampling. If the sampling were limited to the eastern hemisphere as shown in Figure 2(c), there would be no number asymmetry. The dipole amplitude, again, would be equal to that of full sky sampling.

The number asymmetry and the dipole amplitude thus provide complementary information to analyze large-scale symmetry-breaking in the spin distribution of galaxy ensembles.

2.4. Random Flight Simulation for an Isotropic Distribution

For a uniformly randomly distributed set of $N$ vectors with $\Omega^2$, the resultant vector sum $D_{\text{max}}$ will have an isotropic distribution with nonzero amplitude, unless the summation has incidentally completely canceled $D_{\text{max}}$.

As $D_{\text{max}}$ can be calculated by $\|G/N\|$, our problem is equivalent to a well-studied mathematical problem, 3D random walk (random flight). Namely, it is equivalent to finding the distribution of distance to the final point vector $v$ of a particle that starts from the origin and takes $N$ steps of a 3D random walk. One can evaluate the mean length of $D_{\text{max}}$ and the standard deviation around the mean amplitude as a function of $N$.

Chandrasekhar (1943) established that the probability density function $W(R)$ of the final displacement vector $v$ of random flights for a large $N$ will be a 3D Gaussian distribution.

$$W(v) \propto \frac{1}{(2\pi N)^{3/2}} \exp \left( -\frac{1}{2N} \langle v^2 \rangle_{Av} \right),$$

where $\langle v^2 \rangle_{Av}$ is the expected mean square displacement, which is in our case $\langle v^2 \rangle_{Av} = 1$.

The distribution of $D_{\text{max}}$, therefore, follows the chi-squared distribution for three degrees of freedom. The distribution of $D_{\text{max}}$, hence, follows the chi distribution, a square root of chi-squared distribution. The expected mean amplitude $\overline{D}_{\text{max}}$ is

$$\overline{D}_{\text{max}} = \sqrt{\frac{\Gamma(2)}{3N\Gamma(3/2)}} \sim \frac{\sqrt{2}}{\sqrt{3\pi N}} \overline{D}_{\text{max}} = \sqrt{\frac{\Gamma(2)}{3N\Gamma(3/2)}} \sim \frac{\sqrt{2}}{\sqrt{3\pi N}}.$$

The associated standard deviation from this expected mean distance is given by

$$\text{Stdev} = \sqrt{\frac{2 \Gamma(3/2) \Gamma(5/2) - \Gamma(2)^2}{3\Gamma(3/2)^2N}} \sim \frac{\sqrt{\frac{3\pi - 8}{\sqrt{3\pi N}}} - 0.389}{\sqrt{N}}.$$

We can use these formulae to evaluate the statistical significance $\sigma_D$ of the observed spin dipole strength $D_{\text{max}}$ in any ensemble of spiral galaxies using

$$\sigma_D \sim (D_{\text{max}} \sqrt{N} - 0.921)/0.389.$$  

2.5. Detectability of Dipole Component

Consider an ensemble of galaxies where a perfect dipole system and a uniform random system are mixed with fractions $p$ and $1-p$, respectively. The observed dipole vector $D_{\text{max}}$ would be, on average, a vector sum of $D_{\text{max}}$ with an amplitude $0.5p$ and a random vector with an amplitude $(1-p) \times 0.921/\sqrt{N}$ in an arbitrary direction. To discern the intrinsic dipole from the random dipole with a statistical significance of $\sigma$, the following relation is required:

$$0.5p \leq (s+1) \times 0.921(1-p)/\sqrt{N}.$$  

This implies

$$N \geq \left( \frac{0.921(1-p)(1+s)}{0.5p} \right)^2.$$  

Equation (8) indicates that between one hundred thousand or one million spirals are necessary to detect a 3% or 1% residual inherent dipole system at 5$\sigma$ confidence level, respectively.

Real data are not always obtained uniformly. The quantitative discussion of the nonuniform sampling of a random distribution in the general case is not straightforward. We examine, however, the actual S/Z data of SDSS spirals in the next section and compare the observed dipole amplitude with those expected from simulated random distributions.

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* E. W. Weisstein, “Chi Distribution,” from MathWorld—A Wolfram Web Resource, https://mathworld.wolfram.com/ChiDistribution.html.
3. Application to the S/Z Distribution of SDSS Spiral Galaxies

3.1. Reanalysis of Shamir’s Spin Catalog

To apply our formulation of dipole anisotropy to real data, we studied two samples using Shamir’s catalog based on SDSS photometric data (Shamir 2017a). The first sample retains all 162,516 spirals from the original catalog. The original sample shows an S/Z dipole signal of $D_{\text{max}} = 0.0225$ with its axis pointing toward $(l, b) = (189^\circ, +15^\circ)$. This axis coincides with that reported in Shamir (2020a), $(\alpha = 88^\circ, \delta = +36^\circ)$, which is $(l = 175^\circ, b = +5^\circ)$ for an SDSS sample supplemented by 33,028 Pan-STARRS spirals, showing the mean amplitude of $\sigma = 0.00105$, as shown in Table 1. The observed dipole signal for the entire cleaned sample set has a standard deviation from the mean amplitude. The observed dipole (red circle) for this volume-limited sample is 4.00° away from the expected mean amplitude.

The second sample we studied is a volume-limited sample retaining 111,867 spirals with measured redshift (Paul et al. 2018) in the range $0.01 \leq z \leq 0.1$. To avoid any possible effect of local peculiar motions, 162 nearby spirals at $z \leq 0.01$ were removed from this volume-limited sample. This sample shows a stronger S/Z dipole signal $D_{\text{max}} = 0.00773$ with its axis pointing toward $(l, b) = (138^\circ, -38^\circ)$.

The $D_{\text{max}}$ value observed for this sample, together with that of 50,000 simulated mock samples, is shown in Figure 3. The observed $D_{\text{max}}$ from the original catalog, therefore, has an amplitude that is larger than the mean amplitude by $\sigma = 0.00225$, as shown in Table 1. The observed dipole for the entire cleaned sample set has a standard deviation from the mean amplitude.

A total of 106 spirals had contradicting S/Z classification among the duplicated entries. We rectified these contradictions by assigning a spin parity via visual inspection in some cases. In other cases, where the voting was significantly split, we adhered to the outcome of majority voting.

After removing the duplicated entries, the number of spiral galaxies is reduced to 72,888, that is, 45% of the original number. The number of spirals in the volume-limited sample range $0.01 \leq z \leq 0.1$ is 48,089 (23,819 S-spirals and 24,270 Z-spirals), 43% of the 111,867 counted in the original catalog. The measured amplitudes for these “cleaned” samples with and without the volume limitation are summarized in Table 1. The observed dipole for the entire cleaned sample set has $D_{\text{max}} = 0.00535$ with its axis pointing toward $(l, b) = (192^\circ, +79^\circ)$. Fifty thousand random mock simulations for the cleaned sample show a mean amplitude $D_{\text{max}} = 0.00336$ and a standard deviation $\sigma = 0.00154$. Therefore, the observed

3.2. Analysis of New Cleaned Catalog

Upon reexamining the original catalog, we found significant duplication of entries in its tables. Apparently, Shamir (2017a) used PhotoObjAll to search the SDSS catalog. According to the Table Description of DR8, the view of PhotoPrimary, instead of PhotoObjAll, should be used to avoid duplicate detections. PhotoObjAll returns every entry from the searched images without checking for duplication of the same object.

In fact, 34,198 spiral galaxies were found to have multiple entries with their coordinates within 3 arcsec distance of each other. For instance, one of the galaxies in his catalog, SDSS J031945.63-000437.9 (objd = 1237666300555427954) at $z = 0.037$, has 89 separate entries. We confirmed by visual inspection that all of them are the same galaxy.

A total of 106 spirals had contradicting S/Z classification among the duplicated entries. We rectified these contradictions by assigning a spin parity via visual inspection in some cases. In other cases, where the voting was significantly split, we adhered to the outcome of majority voting.

After removing the duplicated entries, the number of spiral galaxies is reduced to 72,888, that is, 45% of the original number. The number of spirals in the volume-limited sample range $0.01 \leq z \leq 0.1$ is 48,089 (23,819 S-spirals and 24,270 Z-spirals), 43% of the 111,867 counted in the original catalog. The observed dipole for the entire cleaned sample set has $D_{\text{max}} = 0.00535$ with its axis pointing toward $(l, b) = (192^\circ, +79^\circ)$. Fifty thousand random mock simulations for the cleaned sample show a mean amplitude $D_{\text{max}} = 0.00336$ and a standard deviation $\sigma = 0.00154$. Therefore, the observed

Table 1: Observed Dipole Asymmetry in the Spin Distribution of SDSS Galaxies

| Sample   | Redshift Range | N   | N(S) | N(Z) | $\sigma_D$ | $D_{\text{max}}$ | N   | N(S) | N(Z) | $\sigma_D$ | $D_{\text{max}}$ | N   | N(S) | N(Z) | $\sigma_D$ | $D_{\text{max}}$ |
|----------|----------------|-----|------|------|------------|-----------------|-----|------|------|------------|-----------------|-----|------|------|------------|-----------------|
| Original | All            | 162,516 | 80,272 | 82,244 | 4.89       | 0.00489         | 189 | +15 | 0.00225 | 2.52        | 2.70             |     |       |      |            |                  |
| Original | $0.01 \leq z \leq 0.1$ | 111,867 | 54,870 | 56,997 | 6.36       | 0.00773         | 138 | +79 | 0.00271 | 4.00        | 4.28             |     |       |      |            |                  |
| Cleaned  | All            | 72,888 | 36,191 | 36,697 | 1.87       | 0.00535         | 192 | +79 | 0.00336 | 1.29        | 1.34             |     |       |      |            |                  |
| Cleaned  | $0.01 \leq z \leq 0.1$ | 48,089 | 23,819 | 24,270 | 2.06       | 0.00468         | 106 | +57 | 0.00414 | 0.29        | 0.27             |     |       |      |            |                  |

Note. Column (6) is the number asymmetry significance level. Columns (7)–(9) show the observed amplitude and the direction of the dipole $D_{\text{max}}$, while columns (10) and (11) show the standard deviation from the mean value, respectively. Column (12) is the observed significance level of $D_{\text{max}}$. Column (13) is the expected significance level for an isotropic random distribution as given by Equation (6).
dipole deviates from the expected mean strength only at a level of \( \sigma_D = 1.29 \). Number dominance of Z-spirals over S-spirals is also only at the \( \sigma_N = 1.87 \) level.

The observed dipole for the cleaned sample limited to the redshift range \( 0.01 \leq z \leq 0.1 \) is \( D_{\text{max}} = 0.00468 \) with its axis pointing toward \((l, b) = (106^\circ, +57^\circ)\). Results of 50,000 random mock simulations for the cleaned sample show a mean amplitude \( D_{\text{max}} = 0.00414 \) and a standard deviation \( \sigma = 0.00188 \), as shown in Figure 4.

Therefore, the observed dipole deviates from the expected mean strength only at the \( \sigma_D = 0.29 \) level. Column (13) of Table 1, obtained from Equation (6) for uniform sampling, is not necessarily correct for nonuniform sampling. However, the fact that column (13) shows values close to the values in column (12), obtained from actual sampling, suggests their relevance. Finally, the number dominance of Z-spirals over S-spirals is also only at the \( \sigma_N = 2.06 \) level.

Comparison of Figures 3 and 4 clearly shows that the apparent pseudo dipole signal observed in Figure 3 came from massively duplicated data in the original catalog. As a final remark, Longo (2011) made a similar analysis of his sample of 15,158 spirals with \( z \leq 0.085 \) from SDSS DR6. He used the terms left-handed (S-spiral in the present paper) and right-handed (Z-spiral). He found a dipole asymmetry by plotting the distribution of \( A = (Z - S)/(Z + S) \). The dipole strength under his definition was \( -0.0408 \pm 0.011 \), found with an axis pointing at \((l, b) = (52^\circ, +68^\circ)\) at 5.6\( \sigma \). The relation of his study to the current work has yet to be investigated.

4. Conclusion

We present a formulation to quantify the observed dipole amplitude \( D_{\text{max}} \) of the S/Z spin parity distribution of spirals in an ensemble of galaxies. We show that the statistical significance \( \sigma_D \) of this quantity can be calibrated with that expected from 3D random flight simulations.

Notably, we found that the S/Z spin catalog published by Shamir (2017a) contains a significant amount of duplicated data, which at least partly caused the increased level of dipole asymmetry that we observed. After removing the duplicated entries from the catalog, we found that the distribution is compatible with random distribution. We conclude that the SDSS sample of spiral galaxies does not show large-scale anisotropy in the spin distribution of galaxies as was suggested by Shamir (2017a). Recently, Shamir (2020b) studied another data set based on spectroscopic samples to detect a significant dipole signal. Previously, Shamir (2012) also presented that a data set based on SDSS SpecObj shows a significant dipole signal, while the direction of the axis is different. The different results from the different data sets will be investigated elsewhere.

The current authors are compiling a large coherent data set of spiral winding evaluation as derived from several modern large image data sets, including SDSS (Aguado et al. 2018), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS1; Chambers et al. 2016), the Hyper Suprime-Cam (HSC; Miyazaki et al. 2018) of Subaru Telescope, and the Dark Energy Survey (Abbott et al. 2018) by deep learning algorithm. Tedaki et al. (2020) developed a deep learning algorithm to judge S/Z winding of 76,635 spiral galaxies from the Hyper Suprime-Cam Subaru Strategic Program Data Release 2 data set (HSC SSP DR2; Aihara et al. 2019) sample, with a further objective to generate a galactic spin data catalog.

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Figure 3. As Figure 2, for a “cleaned” sample of 48,089 spirals, removing multiple entries in the original catalog.

Figure 4. Same as Figure 3, but for a “cleaned” sample of 48,089 spirals, removing multiple entries in the original catalog.
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