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Orientation of the disk galaxies in the Coma cluster

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Abstract. The orientations of the spin vectors of 128 disk galaxies (66 S0 galaxies, 62 S and Irr galaxies) in the Coma cluster have been statistically studied. With respect to the expected isotropic distribution, the distribution of the spin vectors in the Coma cluster is shown to be anisotropic, in the sense that S0 galaxies tend to have their spin vectors parallel to the cluster plane, while the spin vectors of S and Irr galaxies tend to be parallel or perpendicular to the cluster plane. The excess orientation of the projection on the cluster plane of the spin vectors of all disk galaxies are around directions which deviate from the direction pointing to the cluster center by an angle of 30 degrees. Additionally, the projection on the cluster plane of the spin vectors of S and Irr galaxies also tend to point towards the cluster center. The results are discussed in the context of theories of the formation of galaxies and clusters of galaxies.

Key words: galaxies: clusters: Coma cluster – galaxies: general – galaxies: formation

1. Introduction

The origin of the angular momentum of galaxies is one of the questions that any theory on galaxy and cluster formation must answer. No present theories can explain perfectly how galaxies obtained their angular momenta. If the angular momenta of the galaxies have not been altered too much since their formation (Thompson 1976; Farouki & Shapiro 1981), the present orientation of the spin vectors (hereafter SVs) of the disk galaxies can be an indicator of the initial conditions when galaxy and cluster formed. An analysis of the orientation of SVs can teach us something about this formation process.

Many investigators have studied the orientation effects of galaxies and clusters (e.g. Djorgovski 1987, and the references therein), but the results are diverse, maybe due to various methods and sample criteria (Kashikawa & Okamura 1992, hereafter KO; Hu et al. 1995, hereafter HWSL). However, the evidence for alignments is accumulating.

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In a previous paper (HWSL), we confirmed the alignment of SVs of disk galaxies in the Virgo cluster, and we concluded that this alignment of SVs may be morphologically dependent. The Virgo cluster is an irregular cluster, its dynamical relaxation on a large scale has just begun. One may ask what is the situation in a more regular cluster, like the Coma cluster. Hawley and Peebles (1975) did not find any anisotropy in the distribution of position angles (hereafter PAs); however, they found a possible indication that PAs are preferentially aligned towards the center of the cluster. Thompson (1976) found no significant preference in the PAs distribution for the Coma cluster, but he also found a tendency for PAs to point toward the cluster center. Djorgovski (1983) reported a prominent effect of galaxies alignment with the Coma cluster itself. These three studies are all based on the examination of the distribution of PAs, as pointed out in KO and HWSL, the approach considering both the PA and axial ratio (Flin & Godlowski 1986, hereafter FG) is more appropriate to study this question. In the present paper, we use the same method as HWSL to examine the orientation effect of disk galaxies in the Coma cluster.

The sample and method are described in Sect. 2, the results are presented in Sect. 3, some discussions are made in Sect. 4.

2. The sample and the method

2.1. The sample

The data come from Kent and Gunn (1982, hereafter KG) and Doi et al. (1995, hereafter DFOT). In order to study the structure and dynamics of the Coma cluster, KG compiled a list of redshifts for galaxies in the Coma cluster. We choose one of their samples which is complete to $m_p \leq 15.7$ mag within a radius of 3° from the cluster center. The galaxies in this sample are believed to be members of the Coma cluster given their radial velocities and positions. DFOT presented a homogeneous photometry catalog for 450 galaxics with $B_{25.5} \leq 16$ mag located in the $9.°8 \times 9.°8$ region centred on NGC 4874. This catalog was produced using automated surface photometry software applied to five plates (Kodak IIa-O plus Schott 385 filter) taken at the Kiso observatory; it contains PAs, major and minor axes at the surface brightness level of 25.5 mag arcsec^{-2}.

It is generally assumed that the SV of disk galaxy is perpendicular to the galactic disk, as the disk is rotationally supported, so we confine our samples to disk galaxies. To study the orientation of SVs in the cluster of galaxies, we must know the position, PA, axis ratio of each member galaxy. Our database is compiled as follows, we first choose disk and non-classified galaxies in KG with $m_p \leq 15.6$ and within a radius of 3° from the cluster center, we adopt a radial velocity interval of 5400 km s^{-1}, from 4500 to 9900 km s^{-1} (Tifft & Gregory 1976) in the KG sample, and then we obtain the corresponding PA and axis ratio in the DFOT catalog. We use the morphological types presented in KG; intermediate types E/S0 have been assigned to S0, while S0/S can be correctly identified applying morphological types in the Catalogue of Principal Galaxies (Paturel et al. 1989; hereafter PGC). As to 32 galaxies without morphological types in KG, their PGC types are used: one galaxy is S0 and 17 galaxies are S or Irr. Thus, we get a database of 128 disk galaxies which is complete to $m_p \leq 15.6$ within a radius of 3° from the cluster center. From these galaxies, three statistical samples are formed: S0 sample (66 S0 galaxies), S sample (62 S and Irr galaxies), S+S0 sample (all 128 galaxies). The numbers of galaxies we selected from KG, DFOT and the numbers of galaxies used in each sample are listed in Table 1.

It is worthwhile pointing out that the PAs, major and minor axes taken from DFOT are obtained objectively from automatic measurements and are free from personal bias.

2.2. The method

We apply the same method as HWSL to study the orientation of SVs of disk galaxies in the Coma cluster; the details of the method were well described by FG and KO. We merely give a brief description. FG studied the orientation of SVs in the supergalactic coordinate system, where the SGX and SGY axes are in the Local Supercluster (LSC hereafter) plane, SGZ is the direction of the supergalactic north pole with coordinates α = 285.°5, δ = 16° (FG). In our case, we set the basic great circle 'meridian' passing through the Coma cluster center with coordinates $\alpha = 12^h 57.^m 18$, $\delta = 28°13'.8$ (KG), so the SGX axis points to the direction of the cluster center. The polar coordinates of the Coma cluster center in this supergalactic system are: SGL = 0, SGB = 6.°5. The direction of SV can be designated by two angles: θ and ϕ, θ is the angle between SV and SGX-SGY plane, ϕ is the angle between SGX-axis and the projection on SGX-SGY plane of SV. Based on the position, PA and axial ratio of each galaxy and assuming the intrinsic flatness of disk galaxies as 0.2, we can calculate the angles θ and ϕ of each member galaxy in the Coma cluster. Of course, we cannot determine which side of the minor axis is closer to us, and whether the SV is pointing to or away from us, so there are four possible solutions for each galaxy, we count all the four possibilities independently as KO and HWSL. The ranges of θ and ϕ are divided into n bins (n = 9 for θ, n = 18 for ϕ, n = 36 for area on the sky of supergalactic polar coordinates); we count the number of θ and ϕ in each bin to obtain the observational distribution of θ and ϕ. Applying χ^2-test and histograms of distribution, we evaluate how much the observational distribution deviates from the expected (isotropic) distribution.

The coordinate system mentioned above stems from the LSC, the Coma cluster does not belong to it. In spite of this, we can analyze the orientation of the SVs with respect to the LSC plane; the alignment of SVs will be reflected with respect to any fixed reference frame, if it does exist. The Coma cluster appears as an elliptic shape, the position angle of the cluster's major axis is 70° within a radius of 3° from the cluster center (Thompson & Gregory 1978). The angle between the SGX-SGY plane and the major axis of the cluster is 82°. Hence, the SGX-SGY plane is roughly perpendicular to the major axis of the cluster. Furthermore, Gregory and Tifft (1976) detected a rotation around the cluster's major axis. The plane parallel to SGX-SGY plane and passing through the center of the Coma cluster is roughly perpendicular to the major axis of the cluster; we tentatively regard this plane as the cluster plane. The orientation effect will be discussed with respect to this plane.

3. The results

3.1. χ^2-test

Using the χ^2-test, we can statistically examine whether the observational distribution deviate from the expected (isotropic) distribution, the quantity $P(>\chi^2_\nu)$ gives the probability that the observed χ^2_ν value is realized by the expected isotropic distribution. We set $P(>\chi^2_\nu)$ = 0.05 as the critical value to discriminate isotropy from anisotropy, it corresponds to the deviation from isotropy at 2σ-level.

The results of the χ^2-test to our samples are listed in Table 2. The bin size is 10 degrees for θ and ϕ, and 30×30 square degrees for the area in the supergalactic polar coordinates (SGL, SGB). Some values of $P(>\chi^2_\nu)$ in Table 2 are below the critical value, indicating a significant (more than 2σ) deviation from isotropy. So, the distribution of SVs in the Coma cluster is significantly anisotropic. This anisotropic distribution is shown by the deviation from isotropic distribution of the SV's azimuthal angle in the supergalactic coordinate system; the direction of SVs (area distribution) in the supergalactic coordinate system is also anisotropic. However, the distribution of the polar angles in the supergalactic coordinate system only shows marginal deviation from an isotropic distribution.

3.2. The distribution of θ

The histograms of the θ distribution are shown in Fig. 1 for S0, S, and S+S0 galaxies, the solid lines being the expected isotropic distribution, and the dots with $\pm 1\sigma$ statistical error bars being the observational distribution. The histograms show how much the θ distribution of each sample deviates from the expected distribution. It is easy to see that some humps superpose on the background of the isotropic distribution, implying an anisotropic distribution of θ. These humps can be classified into two types, one at small θ (10°–20°) and another at large θ (50°–60°).

Table 1. The numbers of galaxies in each catalogue

	Morphological type				Non-type in KG	Total
	E/S0	S0	S0/S	S+Irr		
Galaxies with 3° in KG	11	102	11	50	62	236
KG galaxies selected	6	55	11	39	32	143
KG galaxies with DFOT PA	6	54	11[a]	39	18[b]	128
S0 sample	6	54	5		1	66
S sample			6	39	17	62
S+S0 sample	6	54	11	39	18	128

[a] Five of them are S0, the other six are S or Irr.
[b] Among them, one is S0, 17 are S or Irr.

Table 2. The χ^2-test of the θ, ϕ and area distribution

Sample	Numbers	θ		ϕ		Area	
		χ^2_ν	$P(>\chi^2_\nu)$	χ^2_ν	$P(>\chi^2_\nu)$	χ^2_ν	$P(>\chi^2_\nu)$
S0	66	1.656	0.104	1.989	0.009	0.990	0.485
S	62	1.793	0.073	2.526	0.000	2.153	0.000
S0+S	128	1.371	0.203	3.330	0.000	1.638	0.010

The humps at small and large θ indicate SVs roughly parallel and roughly perpendicular to the cluster plane, respectively. As shown in Fig. 1, there is a small θ hump ($> 1\sigma$) for S0 galaxies, which indicates that there are more S0 galaxies laying their SVs parallel to the cluster plane. There are two humps, one small θ hump ($> 1\sigma$) and another large θ hump ($> 1\sigma$) for S and Irr galaxies, indicating SVs of these galaxics tend to be parallel or perpendicular to the cluster plane. As a whole, the Coma cluster merely shows small θ hump ($\sim 2\sigma$), in other words, disk galaxies in the Coma cluster preferentially have their SVs parallel to the cluster plane.

It is clear in Fig. 1 that the behavior of the distribution of S0 and S is different, implying that the result of morphological dependence for the distribution of SVs in the Virgo cluster reported in HWSL is also found in the Coma cluster.

3.3. The distribution of ϕ

The histograms of ϕ distribution are shown in Fig. 2 for all the three samples. An anisotropic distribution of ϕ is noticeable. The common features in these histograms are dips near ±90° and humps at different ϕ values.

The direction of ϕ = ±90° is perpendicular to the direction pointing to the cluster center ($\sim$ direction of SGX axis). As shown in Fig. 2a, there is one dip (6σ) near −90° and two humps (2σ) near ±30° for the ϕ distribution of S0 galaxies. It means that the projection on the cluster plane of the SVs of S0 galaxies avoid pointing to the directions perpendicular to the cluster center, the excess orientation of ϕ distribution are between directions pointing to and being perpendicular to the cluster center. The ϕ distribution of S and Irr galaxies is given in Fig. 2b, dips ($> 3\sigma$) are near ±90°, this is similar to the dip for S0 galaxies, however, apart from the humps ($> 1\sigma$) near ±30°, there is a hump ($> 1\sigma$) near ϕ = 0°, meaning the projection of SVs on the cluster plane of S and Irr galaxies also tend to point towards the cluster center. The ϕ distribution of all galaxies as a whole is shown in Fig. 2c, it is merely a summation of S and S0 samples.

Table 3. The area distribution

θ	ϕ						expected
	−75°	−45°	−15°	15°	45°	75°	
S0:							
−75°	0	1	1	1	0	1	1.47
−45°	1	3	2	6	3	2	4.03
−15°	2	7	10[a]	5	8	7	5.50
15°	8	10[a]	4	8	7	3	5.50
45°	4	5	6	5	7[a]	1	4.03
75°	1	1	0	0	1	1	1.47
S:							
−75°	0	0	0	1	1	1	1.38
−45°	0	5	10[b]	6	2	0	3.78
−15°	3	7	3	8[a]	10[a]	0	5.17
15°	1	8[a]	9[a]	5	6	3	5.17
45°	1	3	2	5	6	1	3.78
75°	1	3	6[a]	3	3	1	1.38
S0+S:							
−75°	0	1	1	2	1	2	2.86
−45°	1	8	12[a]	12[a]	5	2	7.81
−15°	5	14	13	13	18[a]	7	10.67
15°	9	18	13	13	13	6	10.67
45°	5	8	8	10	13[a]	2	7.81
75°	2	4	6[a]	3	4	2	2.86

[a] excess to expected number at more than 1σ level.
[b] excess to expected number at more than 2σ level.

The orientation effect shown by ϕ distribution is also different for S and S0 galaxies, since the location of the humps for S and S0 are different.

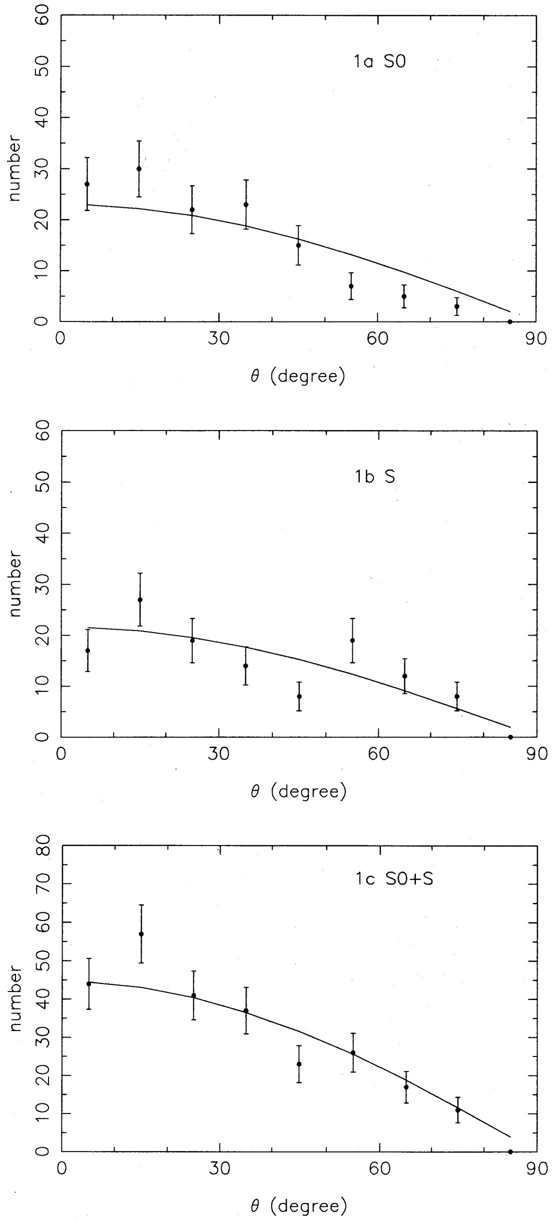

Fig. 1a–c. Histograms of the θ distributions. The solid line represent the expected isotropic distribution, dots with $\pm 1\sigma$ error bars represent the observed distribution. Histograms are for S0 galaxies **a**, S+Irr galaxies **b**, and all galaxies **c**

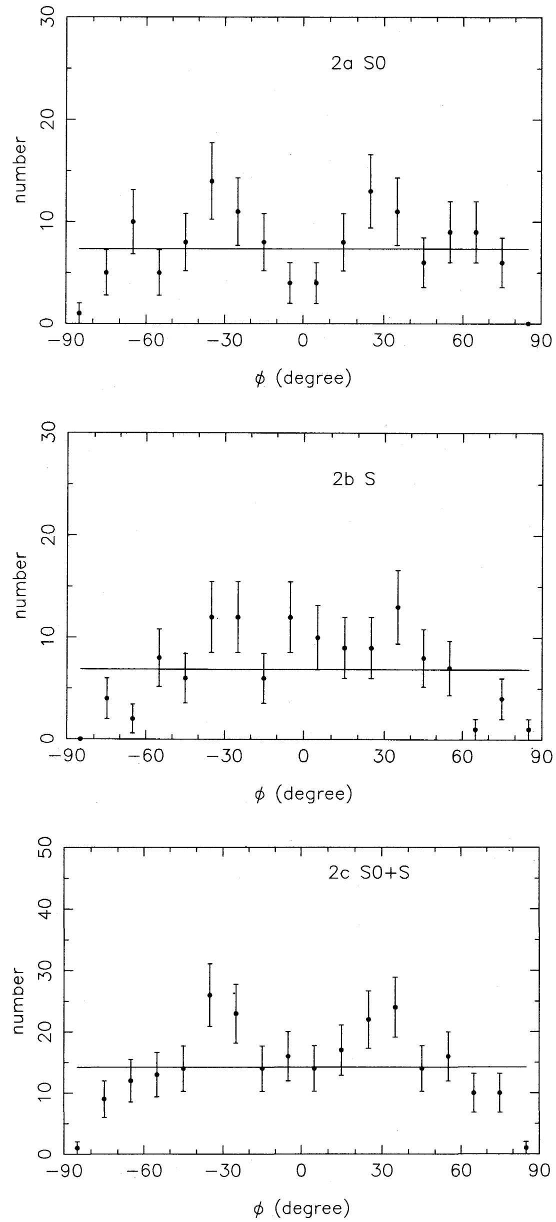

Fig. 2a–c. Histograms of the ϕ distributions. Symbols as for Fig. 1

3.4. The area distribution

We divide the half sky in the supergalactic polar coordinate system into 36 bins (another half are its mirror image), the bin size is 30 degrees square, the observational and expected distribution are shown in Table 3, the θ and ϕ in Table 3 correspond to the center of each bin. Similiar to the results of χ^2-test, an anisotropic distribution are also seen in Table 3. There are more galaxies than expected in some bins at more than 1σ-level, implying a marginal deviation from the expected distribution.

As shown in Table 3, the directions of excess orientation of SVs are different for S and S0 galaxies, also implying the morphologically dependent orientation effect.

4. Discussion

The interesting thing about θ distribution is the different behavior between S0 and S samples. KO explained the two humps in θ distribution histograms for galaxies in LSC by a $|SGZ|$ effect; the two θ humps correspond to different distance to the LSC plane, galaxies near LSC plane tend to lay their SVs parallel to the cluster plane, and the SVs of galaxies off the cluster plane tend to be perpendicular to the LSC plane. In our case, the average distance of galaxies from the cluster plane (tentatively defined with the average value of $|SGB - \overline{SGB}|$) is 0.59 degrees for S0 galaxies and 0.92 degrees for S and Irr galaxies, the average distance of galaxies corresponding to the small-θ hump in Fig. 1a, Fig. lb and to the large-θ hump in Fig. 1b are 0.67, 0.74 and 0.91 degrees, respectively. It seems that a $|SGZ|$ effect exists within a radius of 3° from the Coma center. If we only consider galaxies within a radins of 1.°3 from the cluster center, the average distances from the cluster plane of S0 and S galaxies are 0.37 and 0.44 degrees respectively, and the average distances of galaxies corresponding to the small-θ hump in Fig. 1a, Fig. 1b and to the large-θ hump in Fig. 1b are 0.46, 0.42, 0.50 degrees respectively; the $|SGZ|$ effect is less apparent than that mentioned above. We note that a large scale morphological segregation can be present in clusters (Dressler 1980; Giovanelli et al. 1986): the morphological segregation in the Coma cluster is obvious (e.g. KG). We conclude that the reported results of the orientation effect relating to the distance to the cluster or supercluster plane may be the result of morphological segregation and of an SV's morphologically dependent distribution; the SV morphological dependence may be more basic.

Considering the selection effect in HWSL and the difference of the reference frames between KO (their SGY axis points to the Virgo center) and ours, the patterns of the ϕ distribution in Fig. 2 are similar to that for the Virgo cluster, especially the Fig. 6(3a) of KO is very similar to our Fig. 2c. As mentioned in Sect. 1, the orientation of the SVs of disk galaxies may be the indicator of an early stage of the evolution of the cluster. Although some dynamical processes do exist in the post-formation epoch, the present ϕ distribution may be still the reflection of primordial effect, as is also illustrated by the similarity of the distribution of SVs of disk galaxies in Virgo and Coma. We think that the humps near $\pm 30°$ and hump near 0 in the ϕ distribution displayed in Fig. 2 may be the consequence of the alignment of SVs plus the elliptic shape of the cluster itself. A certain initial condition (such as a special configuration of collapse) determined the evolution process of the cluster, by which the shape of the cluster and the distribution of SVs of disk galaxies were also determined.

We notice that the orientation effect in the Coma cluster is essentially similar to that in the Virgo cluster (KO; HWSL), although the evolution stage of these two clusters are different. It seems that the evolution of the cluster cannot redistribute the angular momenta of member disk galaxies. The galactic density in the core of Coma is high enough for strong interaction between galaxies (Thompson 1976). Furthermore Thompson (1981) reported that a significantly large fraction of bar galaxies are present in the cluster core. If the barred galaxies in the Coma core are formed by Ostriker-Peebles-type bar instabilities (Ostriker & Peebles 1973), it seems that the strong interaction between galaxies in the cluster core might have destroyed the haloes of some disk galaxies, while the spins have not been altered too much. Hence, the halo of a disk galaxy cannot be a rotating continuation of the flatter disk: the halo and disk are not spin-coupling.

A morphologically-dependent orientation of SVs is confirmed here, and this effect might constitute a continuous sequence along the Hubble sequence for the Virgo cluster (HWSL). Dressler (1980) found a large scale morphological segregation in clusters, and Giovanelli et al. (1986) reported that morphological segregation was also found to vary within the range of the spiral type. This may suggest that the morphological segregation is associated with early condition of the formation of galaxy and cluster.

A bimodal PAs distribution was first reported by Adams et al. (1980); we also found that the distribution of SVs of S and Irr galaxies in the Coma is bimodal (i.e. preferably parallel or perpendicular to the cluster plane). It seems that the bimodal distribution of SVs is relative to the distance from the cluster plane, and this relationship may basically concern morphological segregation. This may be suggesting that there are two different mechanisms by which spiral galaxies obtain their angular momenta, these mechanisms being relative to the environment where galaxies or cluster of galaxies formed.

We next discuss our results with regard to the theories of galaxy and cluster formation. In this context, there are three main rival theories, the hierarechical clustering theory (Peebles 1969, 1974), the adiabatic fluctuations theory (generally called "pancake" model, Zeldovich 1978; Doroshkevich & Shandaxin 1978), and the primordial vorticity theory (Ozernoy 1978). No theory as it stands at present can completely explain our observational distribution of SVs, our results is not in agreement with the hierarchical and primordial theories at all. However, in spite of its failure to explain bimodal distribution of S sample and ϕ distribution of S0 sample, our result of θ distribution of S0 sample is in agreement with the pancake model, which predicts that SVs of galaxies tend to lie randomly in the cluster plane caused by the colliding shock waves. Pancake formation is due to compression on one direction, but this does not exclude less dramatic compression in other directions (Zeldovich 1978), which may be the cause of the elliptic shape of the cluster and the observational ϕ distribution of S0 sample in our case. There is now much observational evidence which indicates that clusters of galaxies contain a relaxed core and infalling surroundings outside the core vicinity, the formation of cluster being still an ongoing process (Maoz 1990). We cannot exclude the bimodal distribution of SVs of S and Irr galaxies may be due to a hybrid model.

5. Conclusion

We have statistically studied the orientation of the SVs of disk galaxies in the Coma cluster. The distribution of polar and azimuthal angles in the supergalactic coordinate system of SVs and the direction of SVs all deviate from the isotropic distribution. We conclude that the distribution of SVs is anisotropic, and this orientation effect is morphologically dependent. There are more S0 galaxies than expected tending to have their SVs parallel to the cluster plane, while the excess orientation of SVs are parallel or perpendicular to the cluster plane for S and Irr galaxies. The excess orientation of the projection on the cluster plane of all disk galaxies are around directions which deviate from the direction pointing to the cluster center by an angle of

30 degrees. Additionally, the projection on the cluster plane of S and Irr galaxies also tend to point to the cluster center. We deduce that the relationship between orientation effect and distance to the cluster or supercluster plane may be a consequence of morphological segregation and SV's morphologically dependent orientation.

Our results show properties of the galaxies which are more characteristic of the "pancake" model for the formation of galaxies than of the other models. However, to explain our results completely, a better theoretical understanding of the collapse process is required, and to check the results obtained here, a larger and deeper sample is necessary.

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