A&A 425, 871–879 (2004)
DOI: 10.1051/0004-6361:20041228

Astronomy & Astrophysics

Spin vector orientations of galaxies in eight Abell clusters of BM type I

B. Aryal and W. Saurer

Institut für Astrophysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
e-mail: [binil.aryal; walter.saurer]@uibk.ac.at

Received 5 May 2004 / Accepted 16 June 2004

Abstract. We present an analysis of the spatial orientations of 1231 galaxies in 8 Abell clusters of BM type I (type I in the Bautz-Morgan system). Our aim is to examine non-random effects in galaxy orientations in the clusters containing centrally located cD galaxies. We used the "position angle-inclination" method to find the polar and azimuthal angles of the galaxy rotation axes. To analyse the distribution of the polar and azimuthal angle of the galaxy rotation axes and to check for anisotropy or isotropy we have carried out three statistical tests: chi-square, Fourier, and auto correlation. We assumed a spatially isotropic distribution to examine non-random effects. It is found that the spin vector orientations of the galaxies in the clusters Abell 42, Abell 1775, Abell 3558 and Abell 3560 tend to lie parallel to the local supercluster plane. The spin vector projections of galaxies in the clusters Abell 42 and Abell 1775 tend to be oriented perpendicular to the Virgo cluster center whereas the clusters Abell 3558 and Abell 3562 tend to point towards the Virgo cluster center. No preferred orientation is noticed in the clusters Abell 401, Abell 2199 and Abell 3556.

Key words. galaxies: evolution – galaxies: formation – galaxies: statistics – galaxies: clusters: general – astronomical data bases: miscellaneous

1. Introduction

Galaxy clusters are gravitationally bound markers of the large scale structure of the universe. To understand the evolution of these largest aggregates it is essential to know when and how galaxy clusters have formed and how their structure and constituents change with time. The spatial orientation of spin vectors (hereafter SVs) of galaxies can be an indicator of the initial conditions when galaxies and clusters formed, provided the angular momenta of the galaxies have not been altered too much since their formation. Contemporary theories advocate three different predictions concerning the spatial orientation of SVs of galaxies. First, the "pancake model" (see, e.g., Doroshkevich 1973; Shandarin 1974; Doroshkevich & Shandarin 1978) predicts that SVs of galaxies tend to lie within the cluster plane. Second, according to the "hierarchy model" (see, e.g., Peebles 1969) the directions of the SVs should be distributed randomly. Third, the "primordial vorticity theory" (see, e.g., Ozernoy 1978) predicts that the SVs of galaxies are distributed primarily perpendicular to the cluster plane. There are two camps in the field of galaxy orientation studies: one of these is searching for nonrandomness of the orientations of galaxies in the Local Supercluster (hereafter LSC) plane (e.g., Reinhardt & Roberts 1972; Jaaniste & Saar 1978, hereafter JS; MacGillivray et al. 1982; Kapranidis & Sullivan 1983; MacGillivray & Dodd 1985a,b; Flin & Godlowski 1986, hereafter FG; Kashikawa & Okamura 1992, hereafter KO; Godlowski 1993, hereafter Go93; Godlowski 1994; Yuan et al. 1997; Hu et al. 1998). The other research direction is the investigation of the orientations of galaxies in other clusters (e.g., Hawley & Peebles 1975; Thompson 1976; MacGillivray et al. 1982; Helou & Salpeter 1982; Djorgovski 1983, 1987; Hoffman et al. 1989; Trevese et al. 1992; Hu et al. 1995; Wu et al. 1997; Godlowski et al. 1998, 1999; Baier et al. 2003), particularly in the well studied Virgo cluster (e.g., Hawley & Peebles 1975; Thompson 1976; MacGillivray et al. 1982; Helou & Salpeter 1982; Djorgovski 1987; Hoffman et al. 1989; Hu et al. 1995) and Coma cluster (e.g., Hawley & Peebles 1975; Thompson 1976; Djorgovski 1987; Wu et al. 1997; Flin 2001).

However, the situation is not clear up to now. Different authors have drawn different conclusions. A few authors concluded that the SVs of galaxies tend to lie in the LSC (or parent cluster) plane (e.g., JS; FG; Go93; Godlowski 1994), others showed that the SVs of galaxies tend to be oriented perpendicular to the LSC plane (e.g., Reinhardt & Roberts 1972; MacGillivray et al. 1982). KO noticed a bimodal tendency, that is, galaxies near the LSC plane tend to have their SVs parallel to the LSC plane, while those off the LSC plane have their SVs perpendicular to it. Bukhari & Lawrence (2003) found a random distribution. Morphological dependence of the orientations of disk galaxies has been found for the LSC bright field galaxies (Hu et al. 1998) and in the Coma cluster (Wu et al. 1997). Go93 reached the conclusion that the orientations of nearly face-on and edge-on galaxies are different. These inconsistencies are probably due to different methods and selection criteria applied by different authors.

Interestingly, Godlowski et al. (1998) and Baier et al. (2003) used similar selection criteria and methods but found an opposite result for the clusters Abell 754 and Abell 14. Godlowski et al. (1998) found that the angular momenta of the galaxies in the cluster Abell 754 are preferentially aligned parallel with the cluster plane. Baier et al. (2003) noticed an opposite alignment in the cluster Abell 14. This result could be a sign of the existence of different types of galaxy alignment in the clusters as suggested by Baier et al.

In the beginning, the statistical analysis of the position angles (hereafter PA) and the axial ratio distributions was the most popular method and was widely used in this field of study (e.g., Reinhardt & Roberts 1972; JS; MacGillivray et al. 1982). Later, JS and FG introduced the "PA-inclination" method. In this method, two-dimensionally measured parameters are converted into three-dimensional SVs of galaxies.

A cluster containing a centrally located cD galaxy is termed type I in the Bautz-Morgan system (Bautz & Morgan 1970, hereafter BM). In this paper we analyse the spatial orientations of SVs of 1231 galaxies in 8 Abell clusters of BM type I. The early-type clusters (BM type I) are in fact the most evolved systems and the late type the least evolved. These clusters have systematically higher X-ray luminosities than later types (Ledlow et al. 2003). In a large fraction of these clusters cooling flows are found because of the presence of a cD galaxy and a correspondingly deeper gravitational potential (McHardy 1978). These clusters are dynamically very active. They are still in the process of formation from their parent clusters or vice versa. We intend to study the alignment effects in BM type I clusters including the core of the Shapley Concentration. The investigated clusters include Abell 42, Abell 401, Abell 1775, Abell 2199, Abell 3560 and the core of the Shapley concentration (Abell 3558, Abell 3562 and Abell 3556).

We expect to test the following: (1) do the galaxies in the BM type I cluster show a significant alignment? (2) Is there any correlation between the alignments of cluster galaxies in two and three-dimensional analysis? (3) Does orientation change with radial velocity (hereafter RV) of the cluster? And finally, (4) what can we say about the origin of angular momenta from this study?

This paper is organized as follows: in Sect. 2 we describe the sample used and the method of data reduction. In Sect. 3 we describe the methods, statistical tools and the selection effects. Finally, a discussion of the statistical results and the conclusions are presented in Sects. 4 and 5.

2. The sample

A cluster had to fulfill the following selection criteria in order to be selected: (1) the morphology of the cluster should be "type I" in the BM system; (2) the clusters had to have an Abell richness ≥1; (3) the clusters had to fall outside the galactic plane; (4) the RVs of the clusters should be known; and (5) the number of galaxies in the cluster should be >100. There were 35 (0.9%) clusters in the ACO (Abell et al. 1989) catalogue fulfilling the selection criteria. We inspected all these clusters on the film copies (red sensitive ESO/POSS II) with the aid of a binocular microscope, and selected eight of them. The reasons for the selection were: (1) the galaxies in these clusters were not too faint and it was relatively easier to determine diameters and PAs of many galaxies with relatively great accuracy; and (2) the Galactic contamination in and around the clusters was minimum.

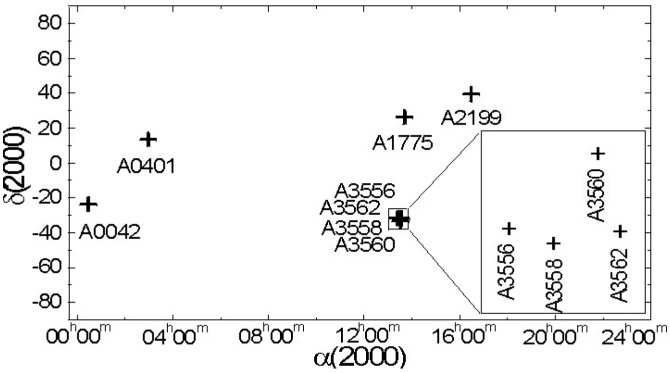

Fig. 1. Distribution of 8 Abell clusters in the equatorial coordinate system. The clusters Abell 3558 and Abell 3556 overlap on the film copy.

Table 1. A list of the investigated Abell clusters.

Abell	α(2000)	δ(2000)	RV (km s^{-1})	m_{10}	$N_{\rm T}$	N
0042	00$^{\rm h}$28$^{\rm m}$36$\fs$5	−23°36′23″	32 587	17.1	155	127
0401	02$^{\rm h}$58$^{\rm m}$56$\fs$9	+13°34′56″	22 424	15.6	171	140
1775	13$^{\rm h}$41$^{\rm m}$55$\fs$6	+26°21′53″	20 866	15.7	140	112
2199	16$^{\rm h}$28$^{\rm m}$37$\fs$0	+39°31′28″	9156	13.9	109	91
3556	13$^{\rm h}$24$^{\rm m}$06$\fs$2	−31°39′38″	14 360	16.4	157	130
3558	13$^{\rm h}$27$^{\rm m}$54$\fs$0	−31°29′00″	14 390	15.1	347	296
3560	13$^{\rm h}$31$^{\rm m}$50$\fs$5	−33°13′25″	14 660	15.1	143	122
3562	13$^{\rm h}$33$^{\rm m}$31$\fs$8	−31°40′23″	16 632	15.5	256	213

m_{10}: red magnitude of the tenth brightest cluster member.
$N_{\rm T}$: total number of galaxies investigated in the cluster region.
N: total number of galaxies with known position angle.

A list of the investigated Abell clusters is given in Table 1. The data given in the second, third, fourth and fifth column (α(2000), δ(2000), RV and the red magnitude of the tenth brightest cluster member, m_{10}) in Table 1 are taken from the ACO catalogue.

The coordinates of the cluster centers were used to locate the clusters on the films. The cluster morphology was studied on the films and compared with the given BM type. A circular survey area was defined using a radius $R = 90''(1 + z)^2/z$ (Thompson 1976). Here z represents the redshift of the cluster. The apparent distribution of galaxies in and around the cluster was carefully studied. We noticed that the BM type I and I-II clusters had well defined centers. They were less elongated. The elongated or L-type clusters were either of type II-III or III. It was relatively easy to define the cluster region for type I.

The search for galaxies and the measurements of PAs and major and minor diameters (a, b) were carried out visually by one of the authors (to maintain homogeneity) with the aid of a binocular microscope (25-fold magnification) on red sensitive ESO film-copies ($\lambda_{\rm eff} \approx 6400$ Å) having a limiting magnitude of $m_{\rm lim} = 20^{\rm m}$. A transparent scale with units of one tenth of a millimetre was used to measure the diameters. A protractor of 15 cm radius and a transparent glass with a thin line were used to measure the PA. The positions of the galaxies were measured on Digitized Survey (DSS) images with the help of the software ESO/ECF/CADC (Association of Universities for Research in Astronomy, Inc.) version 1.3.

The positions of galaxies in the 8 Abell clusters are shown in Fig. 2. The galaxies with known PAs are represented by a plus (+) and those with unknown PAs by a hollow triangle (△). The numbers of galaxies with known and unknown PAs are given in the last 2 columns. A cD galaxy resides at the center of the circle shown in Fig. 2.

The number of background galaxies in the cluster region was estimated. The estimation was based on the area distribution of background galaxies around the cluster region. To this end, the number of background galaxies per unit area around the cluster region is calculated and divided by the number of galaxies per unit area in the cluster region. It is estimated that the background contamination of galaxies in the investigated cluster region is 7–15%.

The foreground field galaxies in the investigated cluster region were identified with the help of the Uppsala General Catalogue of Galaxies (Nilson 1973, hereafter UGC), the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991), the ESO/Uppsala Survey of the ESO (B) Atlas (Lauberts 1982, hereafter ESO), the Morphological Galaxy Catalogue (Vorontsov-Vel'Yaminov et al. 1962–74, hereafter MGC) and the Southern Galaxy Catalogue (Corwin et al. 1985). These field galaxies have been removed from the database.

3. Method of analysis

3.1. Spin vector orientation

We follow the usual method (see, e.g., FG) to derive spatial orientations of SVs of galaxies. The three-dimensional orientation of the SV of a galaxy is characterized by two angles: the polar angle (θ) between the galactic SV and a reference plane, and the azimuthal angle (ϕ) between the projection of a galactic SV on this reference plane and the X-axis within this plane. When using the LSC as reference, θ and ϕ can be obtained from measurable quantities as follows:

$$\sin\theta = -\cos i \sin B \pm \sin i \sin P \cos B \qquad (1)$$

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

where i is the inclination angle, estimated with Holmberg's (1946) formula: $\cos^2 i = [(b/a)^2 – 0.2^2]/(1–0.2^2)$ with b/a the measured axial ratio. L, B and P represent the supergalactic longitude, latitude and position angle, respectively.

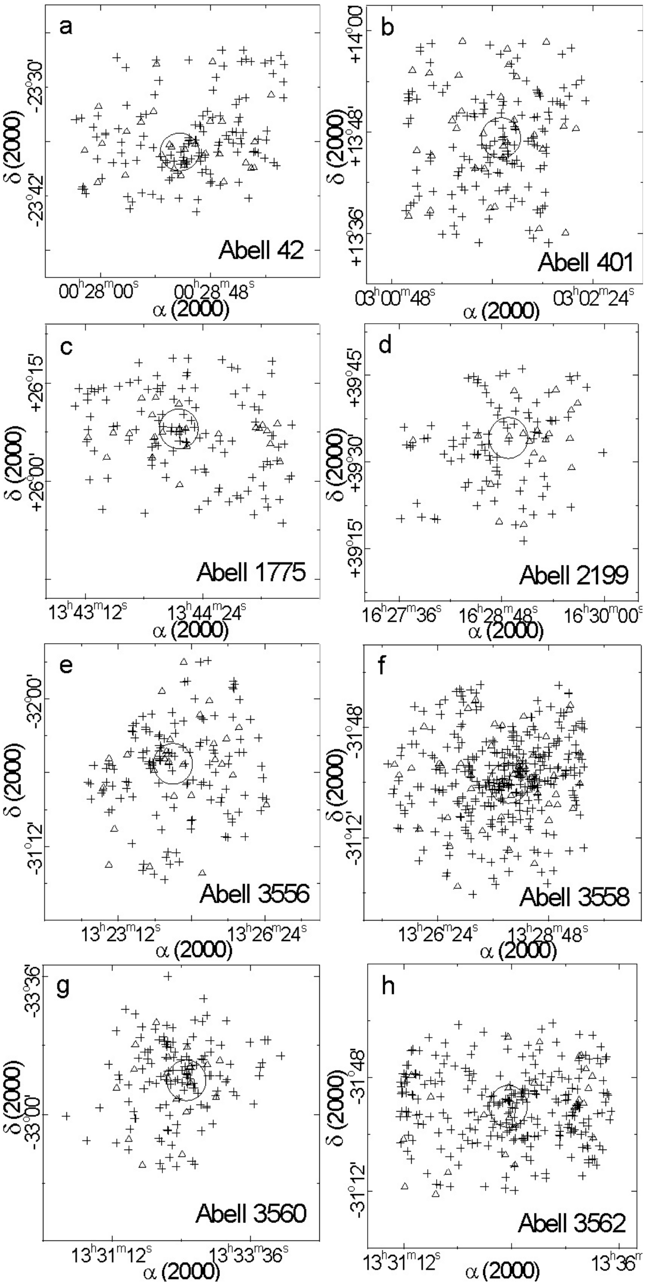

Fig. 2. Distribution of galaxies in the clusters Abell 42 **a)**, Abell 401 **b)**, Abell 1775 **c)**, Abell 2199 **d)**, Abell 3556 **e)**, Abell 3558 **f)**, Abell 3560 **g)** and Abell 3562 **h)**. A plus (+) sign represents a galaxy with known PA. The PA is not known for the galaxies represented by a hollow triangle (△). A cD galaxy is at the center of the circle in each figure.

There is no information from which we can define a physically based reference frame for the selected Abell clusters. The reference plane is complex in these clusters. So, we use the LSC plane as a reference for the analysis.

To calculate the SV orientation (θ, ϕ) of a given disk galaxy, the measured quantities α, δ, PA (equatorial system) have to be transformed to the supergalactic variables L, B, P. We adopt the supergalactic coordinate system as defined by Tammann & Sandage (1976): (1) the equatorial coordinates of the supergalactic pole are $\alpha = 28.^\circ 5$, $\delta = +16^\circ$; and (2) the meridian of the supergalactic system is selected to pass through the center of the Virgo cluster, having $\alpha = 186.^{\circ}25$, $\delta = +13.^{\circ}10$. In the supergalactic coordinate system the Virgo center is near to the supergalactic X-axis (SGX): $L = 0^{\circ}$, $B = -3.^{\circ}19$.

Note that for a given value of i the expressions (1) and (2) give two solutions for both θ and ϕ and hence 4 solutions for the angular momentum vector of a galaxy. However, for a large sample of galaxies it is hardly possible to determine – for each galaxy – which is the physically correct one. For the statistical analysis we have taken into account each of these possibilities independently, as usual.

We assume a spatial isotropic distribution of SVs of galaxies as a theoretical reference. This spatial reference distribution will give further reference distributions for the angles θ and ϕ. As a next step, our observations are compared with these isotropic distribution curves in both θ and ϕ. For this comparison we use three different statistical tests: chi-square, Fourier, and auto correlation. For a detailed description of these tests see Go93.

3.2. Statistics

The chi-square probability function $P(>\chi^2)$ estimates the goodness of the fit: the observed distribution is more consistent with the isotropic distribution when $P(>\chi^2)$ is large. We set $P(>\chi^2) = 0.050$ as the critical value to discriminate isotropy from anisotropy, this corresponds to a deviation from isotropy at the 2σ level.

If the deviation from isotropy is only slowly varying with θ or ϕ, the Fourier test can be applied. In this case the first order Fourier coefficient Δ_{11}, determines the preferred orientation of SVs of galaxies with respect to the reference plane. For the θ-distribution, a negative (positive) value of Δ_{11} indicates that the SVs of galaxies tend to lie parallel (be perpendicular) to the LSC plane. In the ϕ-distribution, $\Delta_{11} > 0$ means that the projections of SVs tend to point towards the LSC center. The first order Fourier probablity function $P(>\Delta_1)$ estimates whether (smaller value of $P(>\Delta_1)$) or not (higher value of $P(>\Delta_1)$) a pronounced preferred orientation occurs in the sample.

For the auto correlation test we use the correlation function C as defined in Go93. For an isotropic distribution we expect $C \rightarrow 0$. The critical limit is the standard deviation of the correlation coefficient C.

In all three statistical tests the bin size was chosen to be 10° for equatorial PAs, θ and ϕ-distributions. The ranges for the angles θ and ϕ are 0° to 180° (for $\theta+\phi/2$) and −90° to +90° (for ϕ), respectively. However, the range of the polar angle was reduced to 0° to 90° by taking its absolute value (control test, FG 1986) and using this range in the histogram of the θ-distribution. The polynomials of the expected distributions were used to fix the degrees of freedom in the chi-square test. The statistically poor bins (number of solution < 5) are omitted in the analysis. The conditions for anisotropy are the following: the chi-square probability $P(>\chi^2) < 0.050$, correlation coefficient $C/\sigma(C) > 1$, first order Fourier coefficient $\Delta_{11}/\sigma(\Delta_{11}) > 1$ and the first order Fourier probability $P(>\Delta_1) > 0.150$ as used by Go93.

3.3. Selection effects and the error

As was shown by Aryal & Saurer (2000) (hereafter AS), any selection criteria imposed on the data may cause severe changes in the shapes of the expected isotropic distribution curves. Inhomogenous distribution of positions of galaxies and the lack of our knowledge of PAs of nearly face-on galaxies are the main selection effects. Because our galaxy samples are taken from various but limited regions of the sky it is of importance to remove both the positional and the inclination effect. To do this we use the method described by AS. In their method, a true spatial distribution of the galaxy rotation axis is assumed to be isotropic. Then, due to the projection effects, i can be distributed $\propto \sin i$, B can be distributed $\propto \cos B$, the variables L and P can be distributed randomly, and formulae (1) and (2) can be used to calculate the corresponding values of θ and ϕ. The isotropic distribution curves are based on calculations including 1×10^5 virtual galaxies. These isotropic distribution curves in θ (solid lines in Fig. 4) and ϕ (solid lines in Fig. 5) are compared with the observations.

To remove the Holmberg effect we adopt the method of Fouque & Paturel (1985) to convert the measured diameters to standard photometric diameters. For this aim we measured the diameters of 215 galaxies for which diameters were given in the catalogue and compared those values with the measurements. The ratio of the measured and given diameters is found to be 1.05 to 1.11 (5–11% larger). We used an additive constant for the ESO, UGC and MGC catalogues to reduce the visual diameters of galaxies to photometric ones. We found that our data need an additive constant $0.'18$ to the visual diameters to put them on the photometric system.

Both θ and ϕ are assigned to be functions of B, L, i and P. The errors in the coordinates and PAs were determined by comparing the measured values with known values in the catalogues (UGC, ESO & MGC) and the errors turned out to be less than $10'$ and $\pm 10^{\circ}$, respectively. The error in major and minor diameters, mainly due to a limited step size, was estimated to be $4.5'$. Using the standard tool of error propagation, the errors in i, θ, and ϕ can be estimated to be 7°, 13°and 18°, respectively.

4. Results

We first give the results of two-dimensional analysis (equatorial PA-distribution) and later discuss its significance in three-dimentional analysis (θ and ϕ-distribution).

4.1. Anisotropy in the position angle distribution

Here we analyse the distribution of the PAs (i.e., the PA of the major diameter) of galaxies instead of the rotation axes. The rotation axis is perpendicular to the galactic plane. Thus, the conditions for anisotropy are the same as for the θ and ϕ-distributions. Only the sign of Δ_{11} is opposite: $\Delta_{11} < 0$ indicates an excess of galaxies with the galactic plane parallel to the equatorial plane.

Table 2. Statistics of the PA-distribution of galaxies in eight Abell clusters.

Abell	$P(>\chi^2)$	$C/C(\sigma)$	$\Delta_{11}/\sigma(\Delta_{11})$	$P(>\Delta_1)$
0042	0.052	−0.8	−1.6	0.046
0401	0.998	+0.0	+0.7	0.761
1775	0.998	+0.4	+0.2	0.579
2199	0.578	+0.3	−1.1	0.447
3556	0.999	−0.3	+0.2	0.964
3558	0.002	−1.8	−1.6	0.142
3560	0.999	−0.1	−0.4	0.909
3562	0.940	−0.8	+0.4	0.678

Statistical parameters for the PA-distribution of the cluster galaxies are given in Table 2. Figure 3 shows the PA-distribution of galaxies in the investigated cluster.

All three statistical tests show anisotropy only in Abell 3558, the core of the Shapley Concentration. Humps at 5°, 45°, 75°, 85°, 125° and 175° can be seen in Fig. 3f. The humps in the middle (45°, 75°, 85° and 125°) lead to a negative Δ_{11} value at the $\sim 2\sigma$ level, suggesting that the galactic planes of the galaxies in this cluster tend to lie parallel to the equatorial plane. In other words, the rotation axes of the galaxies tend to be oriented perpendicular to the equatorial plane.

Abell 42 shows isotropy in the chi-square and auto-correlation tests but anisotropy in the Fourier test. This ambiguous result in the Fourier test is found to be due to the poor statistics. Indeed, for this sample, we have found isotropy in all three tests when the bin size is doubled (i.e., 20°). Abell 401, Abell 1775, Abell 2199, Abell 3556, Abell 3560 and Abell 3562 show isotropy in all three statistics. No preferred alignment is noticed in these clusters.

To understand the evolution scenario of a cluster, a good knowledge of its reference system is needed. van Kampen & Rhee (1990) studied the nature of the distribution of PAs for the 10–20 brightest galaxies in a sample of rich Abell clusters to estimate the cluster PA. They studied the clusters Abell 401, Abell 1775 and Abell 2199 and estimated their PAs ~ 30°, ~120°, and ~50°, respectively (van Kampen & Rhee 1990). We studied the PA-distributions of galaxies in these clusters with respect to their cluster PA. No preferred alignment is noticed. Isotropy is found in all three clusters. Hence, Abell 401, Abell 1775 and Abell 2199 show isotropy with respect to the cluster PA as well as to the equatorial plane. We compare our results of two-dimensional analysis (PA distribution) and three-dimensional analysis (θ and ϕ distribution) in Sect. 4.3.

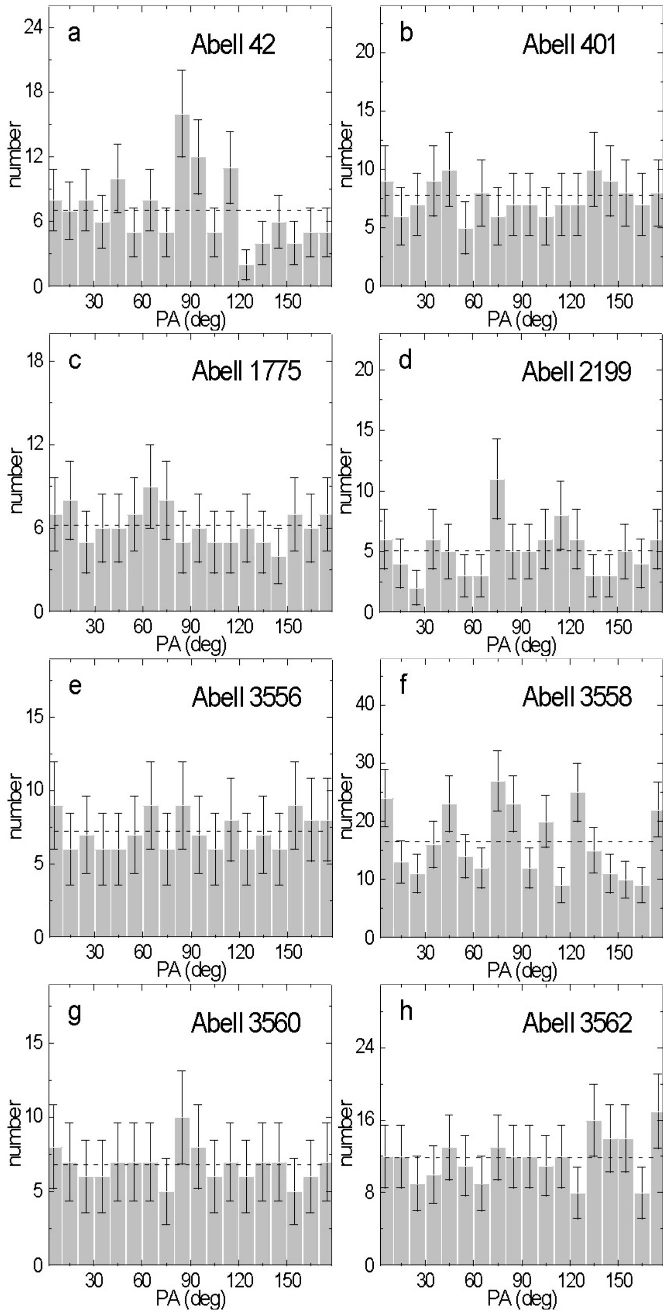

Fig. 3. The equatorial PA distributions of galaxies in Abell 42 **a)**, Abell 401 **b)**, Abell 1775 **c)**, Abell 2199 **d)**, Abell 3556 **e)**, Abell 3558 **f)**, Abell 3560 **g)** and Abell 3562 **h)**. The dashed line represents the expected distributions. The observed counts with statistical $\pm 1\sigma$ error bars are shown. PA = 0° or 180° corresponds to the galactic rotation axes lying in the equatorial plane.

4.2. Anisotropy in the polar angle distribution

Table 3 gives the statistical parameters for the polar angle (θ) distribution of the cluster galaxies.

Figure 4 shows the the polar angle distribution of galaxies in the 8 Abell clusters with respect to the LSC plane: $\theta = 0°$ and 90° correspond to the galactic SV and tend to lie parallel and perpendicular to the LSC plane, respectively. The shapes of the expected isotropic θ-distribution curves (solid lines in Fig. 4) are different in different Abell clusters because of the selection effects concerning positions and inclination angles, as explained by AS (2000). A common feature can be seen in the expected isotropic θ-distribution curves in Fig. 4: a smooth dip at small angles. This deviation from the cosine curve (dashed lines in Fig. 4) is due to the selection effect concerning nearly face-on galaxies. We noticed that the error in θ (13°) may shift the observed value by one bin, but it could not alter the statistical result as a whole.

Table 3. Statistics of the polar angle distribution of galaxies in eight Abell clusters.

Abell	$P(>\chi^2)$	$C/C(\sigma)$	$\Delta_{11}/\sigma(\Delta_{11})$	$P(>\Delta_1)$
0042	0.001	+2.0	−2.8	0.012
0401	0.983	−0.4	−0.8	0.289
1775	0.010	+2.8	−2.4	0.013
2199	0.546	+0.1	+0.8	0.254
3556	0.929	−0.3	+0.0	0.998
3558	0.001	+1.7	−2.5	0.024
3560	0.017	+2.5	−3.8	0.000
3562	0.615	−0.1	+0.1	0.992

In the polar angle distribution, four clusters, Abell 42, Abell 1775, Abell 3558, and Abell 3560 show anisotropy (Table 3). All three statistical tests show anisotropy in these clusters. Humps and dips can be seen in Figs. 4a,c,f and g. It should be noted that the humps at smaller angles (<45°) and the dips at larger angles (>45°) lead to a negative Δ_{11} value, suggesting that the SVs of galaxies tend to lie parallel to the LSC plane.

In the θ-distribution of the galaxies in Abell 42, the humps at 35° and 45° and dips at 55° and 65° lead to a negative Δ_{11} value (~3σ) revealing that the SVs of galaxies in Abell 42 tend to lie parallel to the LSC plane (Fig. 4a).

Two humps at 15° (2.5σ) and 25° (1.5σ) can be seen in the θ-distribution of the galaxies in Abell 1775 (Fig. 4c). The Δ_{11} is found to be negative (2σ), which suggests that the SVs of galaxies in this cluster tend to lie parallel to the LSC plane.

A similar tendency is shown by the galaxies in Abell 3558 and Abell 3560: their SVs tend to lie parallel to the LSC plane. In both clusters a hump at 5° and dips at 65° and 75° can be seen from Figs. 4f,g.

All three statistical tests show isotropy in the θ-distribution of the galaxies in Abell 401, Abell 2199, Abell 3556 and Abell 3562 (Table 3). In these clusters, Δ_{11} is within its error limit. No hump or dip can be seen in Figs. 4b and 4e. The small dips in Figs. 4d and 4h were not enough to make the statistical result anisotropy. In Figs. 4b,d,e and h, the expected isotropic distribution (solid line) almost fits the observed distribution (solid dots with statistical $\pm 1\sigma$ error bars).

Thus, four clusters show isotropy and four anisotropy in the polar angle distribution. The SVs of the galaxies in Abell 42, Abell 1775, Abell 3558 and Abell 3560 tend to lie parallel to the LSC plane. No preferred alignment of SVs of galaxies in Abell 401, Abell 2199, Abell 3556 and Abell 3562 is noticed.

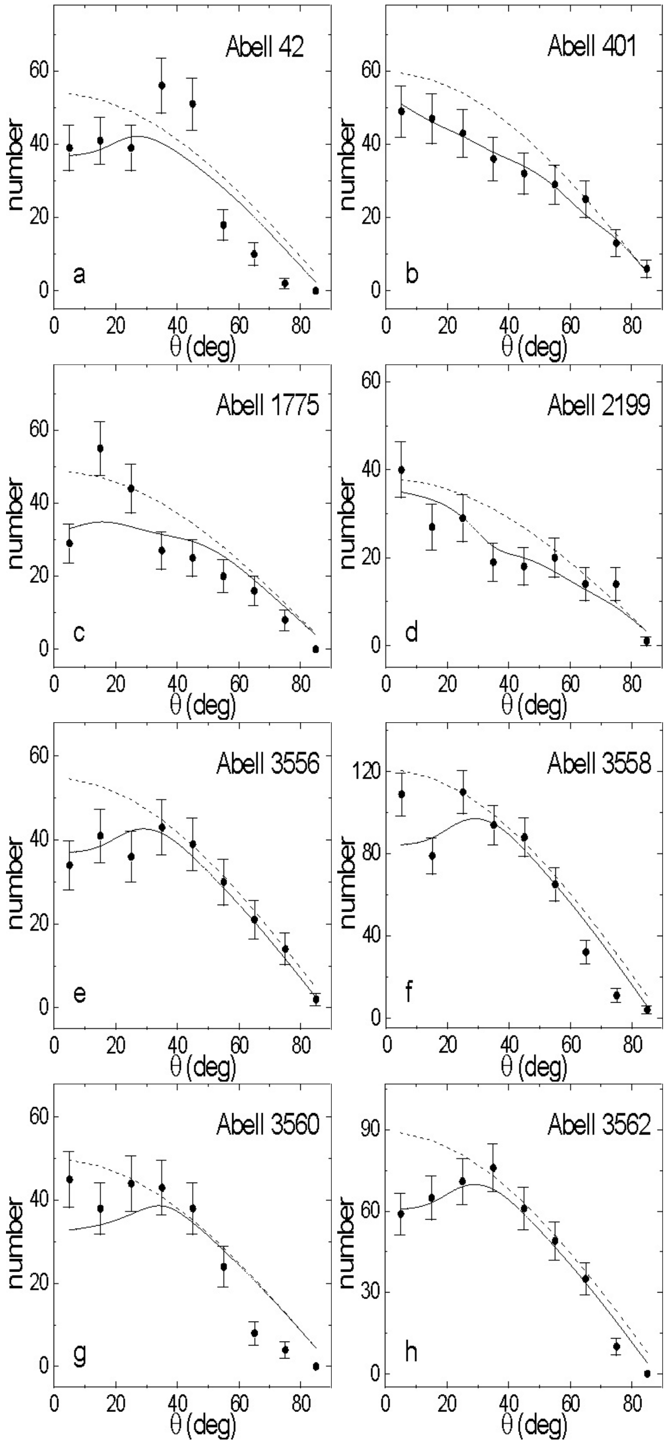

Fig. 4. The polar angle (θ) distribution of galaxies in Abell 42 **a)**, Abell 401 **b)**, Abell 1775 **c)**, Abell 2199 **d)**, Abell 3556 **e)**, Abell 3558 **f)**, Abell 3560 **g)** and Abell 3562 **h)**. The solid line represents the expected isotropic distributions; the dashed lines give the cosine, for comparison. The observed counts with statistical $\pm 1\sigma$ error bars are shown. $\theta = 0°$ corresponds to the galactic SV lying in the LSC plane. Anisotropy can be seen in Abell 42 **a)**, Abell 1775 **c)**, Abell 3558 **f)** and Abell 3560 **g)**.

4.3. Anisotropy in the azimuthal angle distribution

Statistical parameters for the azimuthal angle (ϕ) distribution of the cluster galaxies are given in Table 4.

Figure 5 shows the distribution of the SV projections (ϕ) of galaxies in 8 Abell clusters with respect to the LSC center (or the Virgo cluster center). In the figures, $\phi = 0°$ means the direction towards the Virgo cluster center. Selection effects make the shape of the expected isotropic ϕ-distribution curves rather complex (solid lines in Fig. 5). We ran simulations to examine the possible effects on the results of the three statistical tests of the errors in ϕ(18°). It turned out that the chi-square and auto

Table 4. Statistics of the azimuthal angle distribution of galaxies in eight Abell clusters.

Abell	$P(>\chi^2)$	$C/C(\sigma)$	$\Delta_{11}/\sigma(\Delta_{11})$	$P(>\Delta_1)$
0042	0.000	+7.5	−6.1	0.000
0401	0.611	−0.1	+0.8	0.698
1775	0.000	+8.2	−6.5	0.000
2199	0.341	+0.1	+1.3	0.179
3556	0.658	−0.7	+1.1	0.223
3558	0.006	+2.8	+1.8	0.065
3560	0.142	−0.2	+0.6	0.812
3562	0.029	+2.6	+1.8	0.043

correlation test could be affected but the Fourier tests remains unchanged. Thence we regard the Fourier test as more reliable.

Four clusters, Abell 42, Abell 1775, Abell 3558, and Abell 3562 show anisotropy in the ϕ-distribution. All three statistical tests show anisotropy in these clusters (Table 4).

In the ϕ-distribution, the Δ_{11} value would be negative for ϕ when the humps are at −90° to −50° (first 4 bins) and at 50° to 90° (last 4 bins), and the dips at −50° to +50° (ten bins at the middle). Abell 42 show humps at −45° and −55° and dips at 5°, 15° and 25°, leading to a negative Δ_{11} value at 6σ level (Fig. 5a). The negative Δ_{11} value suggests that the SV projections of galaxies in the cluster Abell 42 tend to be directed perpendicular to the Virgo cluster center. The cluster Abell 1775 shows a similar tendency: SV projections tend to be directed perpendicular to the LSC center (Fig. 5c).

The Δ_{11} value would be positive for ϕ when the dips are at −90° to −50° (first 4 bins) and at 50° to 90° (last 4 bins), and the humps at −50° to +50° (ten bins at the middle) in the ϕ-distribution. Abell 3558 show dips at −45° and humps at −5° and 15°, leading to a positive Δ_{11} value at $\sim 2\sigma$ level (Fig. 5f). The positive Δ_{11} value suggests the SV projections of galaxies in Abell 3558 tend to point towards the Virgo cluster center. Abell 3562 shows a similar tendency.

All three statistical tests show isotropy in the ϕ-distributions of the galaxies in Abell 401, Abell 2199, Abell 3556 and Abell 3560 (Table 4).

Thus, four clusters show isotropy and four anisotropy in the azimuthal angle distribution. The SVs projections of the galaxies in Abell 42 and Abell 1775 tend to be directed perpendicular to the Virgo cluster center whereas Abell 3558 and Abell 3562 tend to point towards the Virgo cluster center. The distributions of SV projections of galaxies in Abell 401, Abell 2199, Abell 3556 and Abell 3560 are found to be random.

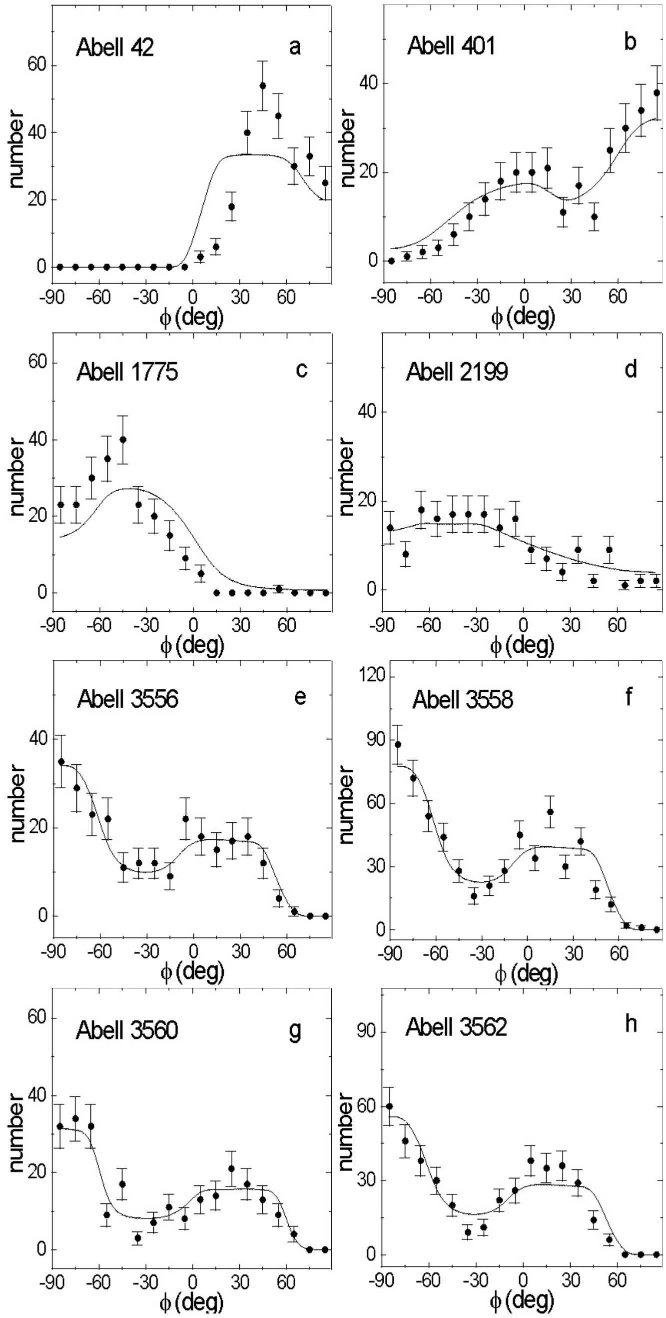

Fig. 5. The azimuthal angle (ϕ) distribution of galaxies in Abell 42 **a)**, Abell 401 **b)**, Abell 1775 **c)**, Abell 2199 **d)**, Abell 3556 **e)**, Abell 3558 **f)**, Abell 3560 **g)** and Abell 3562 **h)**. ϕ = 0° means the direction to the LSC center or the Virgo cluster center. Anisotropy can be seen in Abell 42 **a)**, Abell 1775 **c)**, Abell 3558 **f)** and Abell 3562 **h)**. Symbols as in Fig. 4.

4.4. Discussion

Abell 3558 shows anisotropy in the two-dimensional (equatorial PA-distribution) analysis whereas 4 clusters including Abell 3558 show anisotropy in the three-dimensional analysis (θ and ϕ-distributions). The clusters which showed strong isotropy in the two-dimensional analysis showed similar results in the three-dimensionl analysis. Thus, the projection effects in the two dimensional study can be remarkably reduced in the three-dimensional analysis.

The PA-distribution of 126 galaxies in Abell 2199 was studied by Thompson (1976). The chi-square probability $P(>\chi^2)$ was 48% in his calculation suggesting no significant alignment. Our result is similar to that result obtained by Thompson (1976) in the PA-distribution. We found 58% probability in the chi-square test (Table 2). In addition, we noticed isotropy in θ and ϕ-distributions (Tables 3 and 4). Therefore no preferred alignment is found for Abell 2199 in both two and three-dimensional analysis. The only cluster in which Thompson (1976) found a significant preference in the PA-distribution was Abell 2197.

The core of the Shapley Concentration is dynamically very active; the main cluster Abell 3558 appears to be interacting with the other clusters Abell 3562 and Abell 3556 (Bardelli et al. 1994). In our study, the galaxies in the main cluster Abell 3558 show anisotropy whereas Abell 3556 shows isotropy in both the two- (equatorial PA-distribution) and three-dimensional (polar and azimuthal angle distribution) analysis. Abell 3562 show anisotropy in azimuthal angle distribution but isotropy in polar angle distribution. Different galaxy alignments are found in these clusters. In a substructure analysis Bardelli et al. (1998) briefly discussed the core of the Shapley concentration and suggested that the core complex is the result of a series of incoherent group-group and cluster-group mergings. Bardelli et al. (1998) studied the fraction of blue galaxies in the whole substructure and found that the bluest group is located between Abell 3558 and Abell 3562, i.e., in the expected position for the scenario of cluster-cluster collision. In this region, preferred alignments are noticed. Metcalfe et al. (1994) suggested that there may already have been an encounter between Abell 3558 and Abell 3562. Anisotropic orientations in these clusters might be due to cluster-cluster collisions in the past. We separately study the alignments of 164 galaxies in the subclusters SC 1329-312 & SC 1327-313 between the main cluster Abell 3558 and Abell 3562 and found weak anisotropy. This supports the collision scenario.

In the polar angle distribution, no clusters showed Δ_{11} values positive at $>1\sigma$ level, ruling out the possibility that the SVs of galaxies in BM type I clusters tend to lie perpendicular to the LSC plane. We suspect that the BM type I cluster galaxies might have preferred alignments with respect to a suitable reference frame. This result should be tested in the future.

The RVs of 8 selected clusters in our sample range from $\sim$9000 to $\sim$32 000 km s^{-1}. Two clusters (66.7%) that have RVs > 22 000 km s^{-1} show anisotropy and the cluster has RV < 10 000 km s^{-1} (100%) shows isotropy. Thompson (1976) analysed 6 Abell clusters with RV < 10 000 km s^{-1} and found isotropy in 5 (83%) of them. We suspect that the orientations of galaxies in the distant clusters might be different from those in nearby clusters with respect to the LSC plane.

We ran simulations to observe the changes in the results when the LSC plane is rotated by an angle η. Our results for 8 BM type I Abell clusters remain the same when $-25° \leq \eta \leq +25°$. This indicates that these clusters support the pancake model if the reference plane of the clusters does not deviate by more than $\pm 25°$ from that of the LSC plane. The anisotropic result for the core of the Shapley Concentration (Abell 3558 and Abell 3562) remains unchanged when $-50° \leq \eta \leq +50°$. Our next goal is to understand the relation between the physical reference system of our clusters and the LSC system.

5. Conclusion

The core of the Shapley Concentration, Abell 3558, shows anisotropy in both two- and three-dimensional analysis. The spin vector orientations of galaxies in Abell 3558 tend to lie parallel to the LSC plane and their SV projections tend to point towards the Virgo cluster center. Abell 3562 shows a similar orientation in the azimuthal angle distribution. No preferred orientation is noticed in Abell 3556. Thus, different alignments are found in the Shapley Concentration.

The spatial orientations of galaxies in Abell 42 and Abell 1775 tend to lie parallel to the LSC plane and their SV projections tend to be directed perpendicular to the Virgo cluster center. Abell 3560 shows a similar orientation in the polar angle distribution. Abell 401 and Abell 2199 show isotropy similar to that of Abell 3556. Hence, the clusters of BM type I show different alignments.

We intend to study the spin vector orientations of galaxies in the elongated or L-type clusters (BM type II-III or III) in the future.

Acknowledgements. B. Aryal acknowledges the Oesterr. Akad. Austauschdienst (OeAD), Austria, for providing a scholarship, and Tribhuvan University, Kathmandu, Nepal, for the study leave. We thank R. Weinberger for his helpful advice regarding the manuscript.

References

Abell, G. O., Corwin, H. G., & Olowin, R. P. 1989, ApJS, 70, 1
Aryal, B., & Saurer, W. 2000, A&A, 364, L97 (AS)
Baier, F. W., Godlowski, W., & MacGillivray, H. T. 2003, Ap&SS, 403, 847
Bardelli, S., Zucca, E., Vettolani, G., et al. 1994, MNRAS, 267, 665
Bardelli, S., Pisani, A., Ramella, M., Zucca, E., & Zamoreni, G. 1998, MNRAS, 300, 589
Bautz, L. P., & Morgan, W. W. 1970, ApJ, 162, L149
Bukhari, F. A., & Lawrence, E. C. 2003, A&A, 283, 173
Corwin, H. G., de Vaucouleurs, A., & de Vaucouleurs, G. 1985, Univ. Texas Monogr. Astron., 4, 1
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., et al. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer-Verlag)
Djorgovski, S. 1983, ApJ, 274, L7
Djorgovski, S. 1987, in Nearly Normal Galaxies, ed. S. M. Faber (New York: Springer), 227
Doroshkevich, A. G. 1973, ApJ, 14, L11
Doroshkevich, A. G., & Shandarin, S. F. 1978, MNRAS, 184, 643
Flin, P. 2001, MNRAS, 325, 49
Flin, P., & Godlowski, W. 1986, MNRAS, 222, 525 (FG)
Fouque, P., & Paturel, G. 1985, A&A, 150, 192
Godlowski, W. 1993 MNRAS, 265, 874 (Go93)
Godlowski, W. 1994 MNRAS, 271, 19
Godlowski, W., Baier, F. W., & MacGillivray, H. T. 1998, A&A, 339, 709
Godlowski, W., & Ostrosky, M. 1999, MNRAS, 303, 50
Hawley, D. L., & Peebles, P. J. E. 1975, AJ, 80, 477
Helou, G., & Salpeter, E. E. 1982, ApJ, 252, 75
Hoffman, G. L., Lewis, B. M., Helou, G., et al. 1989, ApJS, 69, 65
Holmberg, E. 1946, Medd. Lund. Astron. Obs., Ser VI, No. 117
Hu, F. X., Wu, G. X., Su, H. J., & Liu, Y. Z. 1995, A&A, 302, 45
Hu, F. X., Yuan, Q. R., Su, H. J., Wu, G. X., & Liu, Y. Z. 1998, ApJ, 495, 179
Jaaniste, J., & Saar, E. 1978, in The Large Scale Structure of the Universe, ed. M. S. Longair, & J. Einasto (Dordrecht: Reidel), Proc. IAU Symp., 79, 448 (JS)
Kapranidis, N., & Sullivan, W. T. 1983, A&A, 118, 33

Kashikawa, N., & Okamura, S. 1992, PASJ, 44, 493 (KO)
Lauberts, A. 1982, ESO/Uppsala Survey of the ESO B Atlas. ESO, Garching bei Muenchen
Ledlow, M. J., Voges, W., Owen, F. N., & Burns, J. O. 2003, AJ, 126, 2740
MacGillivray, H. T., & Dodd, R. J. 1985a, A&A, 145, 269
MacGillivray, H. T., & Dodd, R. J. 1985b, in ESO Workshop on Virgo Cluster 1984, ESO, ed. B. Binggeli B., Garching bei Mnchen, 217
MacGillivray, H. T., McNally, B. V., Corwin, H. G., & Dodd, R. J. 1982, MNRAS, 198, 605
McHardy, I. 1978, MNRAS, 184, 783
Metcalfe, N., Godwin, J. G., & Peach, J. V. 1994, MNRAS, 267, 431
Nilson, P. 1973, Uppsala General Catalogue of Galaxies, Nova Acta Uppsala University, Ser. V.A., 1 (UGC)
Ozernoy, L. M. 1978, in The Large Scale Structure of the Universe, ed. M. S. Longair, & J. Einasto (Dordrecht: Reidel), Proc. IAU Symp., 79, 427
Peebles, P. J. E. 1969, ApJ, 155, 393
Reinhardt, M., & Roberts, M. S. 1972, ApJ, 201, L12
Shandarin, S. F. 1974, Astr. Zh 51, 667 (in Russian), Soviet Astron, 18, 392 (in English)
Tammann, G. A., & Sandage, A. 1976, ApJ, 207, L1
Thompson, L. A. 1976, ApJ, 209, 22
Trevese, D., Cirimele, G., & Flin, P. 1992 AJ, 104, 935
Tully, R. B. 1988, Nearby Galaxy Catalog (Cambridge: Cambridge Univ. press)
van Kampen, E., & Rhee, G. F. R. N. 1990, A&A, 237, 283
Vorontsov-Vel, Y. B. A., Krasnogorskaya, A. A., & Arkhipova, V. P. 1962–74, in Morphological Catalogue of Galaxies (Part I-V), Trudy Gosud. Astron. Inst. Shternberga (MGC)
Wu, G. X., Hu, F. X., Su, H. J., & Liu, Y. Z. 1997, A&A, 323, 317
Yuan, Q. R., Hu, F. X., Su, H. J., & Huang, K. L. 1997, AJ, 114, 1308