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ASTRONOMY AND ASTROPHYSICS

Substructures and galaxy orientations in clusters

I. The cluster Abell 754

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Abstract. We present a general description of the rich cluster of galaxies Abell 754, including a discussion of some aspects concerning its evolution, and present an analysis of the orientations of the galaxies in the cluster region. Previous studies from X–ray data and galaxy distributions have provided evidence for pronounced subclustering in this cluster. In this light, our aim has been to examine non-random effects in the galaxy orientations in rich clusters with particular regard to the presence of subclustering. Our results do provide evidence for non-random alignment of the galaxies in Abell 754 and confirm the presence of subclustering within this cluster. We intend to continue our investigations by studying, in a similar manner, other clusters the results for which will be published in due course.

Key words: methods: statistical – galaxies: clusters: general – galaxies: clusters: individual: A 754

1. Introduction

The results of simulations of the evolution of cosmic structures in the face of various cosmological scenarios predict different distributions for the angular momenta of galaxies, i.e. of the galaxy orientations, which are represented as different forms for the alignment of galaxies within structures (clusters and superclusters).

In the framework of the major classical evolutionary scenarios (Shandarin 1974; Wesson 1982; Silk & Efstathiou 1983) – where the galaxy clusters are formed by random clumping of uniformly distributed galaxies – we expect to find a random distribution of the rotational axes. This situation is predicted in the hierarchical clustering picture of, for example, Dekel (1985).

On the other hand we expect to find coherence in the alignments of galaxy orientations in the case of fragmentation scenarios. For the latter there are two main theories. Firstly, according to Ozernoy (1978) and Efstathiou & Silk (1983) the ”turbulence” model will lead to a situation where the rotation axes of galaxies tend to be perpendicular to the major plane of the large scale structure (supercluster). Galaxy planes and the planes of the superclusters should be coherently aligned. In the second model (Shandarin 1974a,b; Doroshkevich et al. 1978) – where the galaxies originate from ”adiabatic fluctuations” – there occurs an alignment between galaxy rotation axes and the orientations of the corresponding larger cosmic structures in that galaxy planes and the planes of the superclusters are arranged perpendicular to each other. A third possibility – the recently proposed ”hedgehog model” – predicts a tendency for galaxy rotation axes to be directed towards the centre of the supercluster.

Thus, the study of galaxy orientations has the potential for yielding important information with respect to the formation and evolution of cosmic structures. Unfortunately, the practical applicability of tests for searching for galaxy alignments is difficult due to observational problems and line-of-sight superpositions of galaxies separated over large distances.

Results from most of the previous studies (Thompson 1981; Jaaniste & Saar 1978; Gregory 1981; MacGillivray 1982a,b, 1985; Flin & God owski 1986; God owski 1993; Flin 1995; Parnowski et al. 1994) have shown that there are coherent alignments of galaxy orientations in some clusters and superclusters. However in some papers e.g. Bukhari (1998) no alignment of galaxies in clusters has found. The question of whether the alignments seen within larger structures are due to global effects connected with the supercluster as a whole or to a conglomeration of galaxy alignments from individual constituent ”subunits” (i.e. clusters) needs to be addressed. This question has been, in the main, neglected. However, recently a series of papers (MacGillivray 1982a,b; Struble 1987, 1990; van Kampen 1990; Trevese et al. 1992; Han et al. 1995; Salvator–Sole & Solanes 1993) has gone some way towards furthering our understanding.

In this regard, also, the investigation of galaxy orientations in ”subclusters” of rich galaxy systems may provide further important information, especially concerning cluster evolution. This present paper is the first one to date to deal with the question of possible alignments of galaxy planes within clusters which have obvious subclustering.

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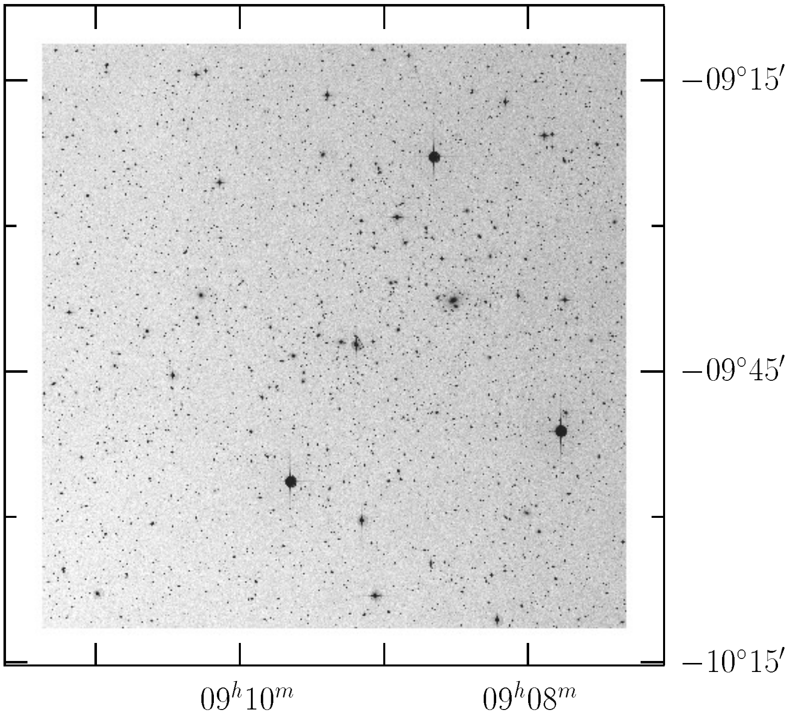

Fig. 1. The field of the galaxy cluster Abell 754

2. Method for analysing the orientations

Up to now there have been two main methods for studying the orientations of galaxy rotation axes. The first (Hawley & Peebles 1975; H–P) undertakes the analysis of the observed position angles on the sky of the major axes of the galaxy images. However, this angle can yield reliable information with respect to the galaxy planes only for galaxies seen edge–on. Consequently, all galaxies seen face–on or nearly face–on are excluded from the analysis.

The second approach, proposed originally by Jaaniste & Saar (1978; J–S), takes into account not only the position angles of galaxies but also the inclinations of the galaxy planes relative to the line of sight to the observer. This inclination, however, is not uniquely defined; it represents the orientation of the normal vector to one of the two possible orientations of the plane of the galaxy under consideration. Flin & Godlowski (1986) corrected the method of Jaaniste & Saar (1978) for inconsistencies and developed a method for analysing the distribution of these normal vectors. With the help of the latter's method it is possible to use galaxies of all possible orientations – including also "face–on" galaxies – for such an investigation. Flin and Godlowski's method is able to compute two angles to describe the orientation of the normal to the galaxy plane (which is mostly accepted to be the rotation axis) with respect to the plane of the cluster or supercluster: 1) The angle δ between the normal to the galaxy plane and the plane of the cluster or supercluster and 2) the angle η between the projection of the normal to the galaxy plane on the plane of the corresponding cluster– or supercluster structure and the direction toward the structure centre. Finally it is possible to analyse the distributions of these angles by means of statistical methods to find any non-random trends.

In principle, it is possible to examine the orientations of galaxies (i.e. the angular momenta) with respect to different coordinate systems (e.g. the coordinate system defined by the parent entity). In a previous paper, God owski (1992) analysed the distribution of angular momenta of galaxies with respect to the plane of the Local Supercluster (LSC). This reflects the situation referred to above where the alignment of galaxy orientations in a supercluster is determined by the general structure of the supercluster. However, there is no reason *a priori* not to consider the smaller structures (i.e. clusters or subclusters) as being the parent system. In such a situation we should expect that galaxy alignments in clusters are connected with the cluster (or subcluster) main plane instead of with regard to the supercluster plane.

Therefore, in principle we should consider other possibilities and look for the presence of different alignments of galaxy orientations in clusters in relation to different main planes. Bimodal distributions of orientations as found by Gregory et al. (1981), if detected, could support the presence of substructures. On the other hand, the absence of such bimodal or multimodal distributions cannot exclude definitely the existence of subclusters of galaxies.

As a first step, we transform the coordinates and position angles of galaxies to a new coordinate system based on the cluster or subcluster main plane. The position angle of the cluster is determined in a straightforward way by a least–squares method, taking as variables the coordinates of the galaxies. We fit the orthogonal regression line based on the minimum distance of the observed points from the regression line. The angle between the direction to the north pole of the coordinate system and the regression line is, in such a situation, the position angle of the cluster.

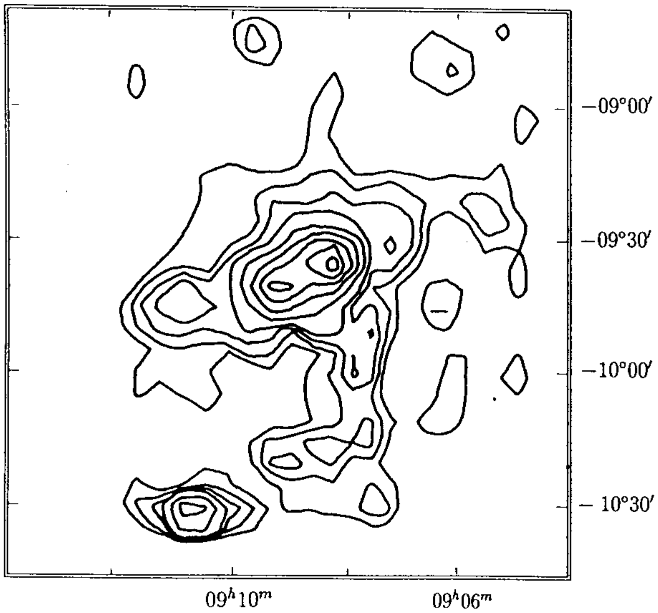

Fig. 2. The distribution of galaxies in the field of Abell 754 according to the investigation of Baier & MacGillivray (1994b)

The computation of the inclination angle (or pole direction) is not quite so straightforward. Ideally, the method requires fitting of the cluster reference plane for two cluster poles derived by assuming it to be an oblate spheroid with flatness ratio of some "standard" value (e.g. q=0.2). One should remember that such an approximation is acceptable for galaxies even if we do not have information about the morphological type of a particular galaxy. However, the application of such a procedure to clusters of galaxies could introduce gross errors (we have insufficient knowledge yet of the "true" shapes of rich clusters). Therefore, this method can only be used as a crude approximation.

Alternatively, if we knew the distances to the galaxies, we could fit their distribution in 3-D space by a "covariance" ellipse. Then, from the parameters of that ellipse we determine the axial ratio of the cluster q, or even directly the direction in space of the three axes of the ellipse. However, such an investigation is not possible in our case because we do not know the true distance of particular galaxies or, at least, radial velocities for the galaxies in our sample.

In the face of these difficulties, the approach we have adopted in our work is to assume clusters are oblate spheroids and to vary the possible pole direction of the cluster around the whole celestial sphere. Subsequently we analyse for possible alignments in all artificial coordinate systems.

In our approach, for a detailed analysis of galaxy alignments inside clusters we use the statistical parameter provided by the Fourier test, Δ_{11}, (Flin & God owski1986; God owski 1993, 1994) describing the preferential orientation of galaxian axes with respect to the cluster reference frame. For all clusters under examination, and subclusters, we map the ratio of Δ_{11} divided by its formal error $\sigma(\Delta_{11})$ as the cluster pole direction is moved around the entire celestial sphere. The resulting maps are analysed for correlations of the $\Delta_{11}/\sigma(\Delta_{11})$ extreme values (maxima or minima) with direction from the cluster centre to the derived cluster poles, and our line of sight. However, the interpretation is confused by galaxy superpositions along the line of sight. According to God owski & Ostrowski (1998) such effects mask to a high degree existing preferential orientations of galaxies in the cluster. Nonetheless, the comparison of such maps can give us important information concerning possible subclustering. Most importantly we may expect different directions of alignments in the presence of various subclusters. Hence, in our map we should find compact "structures" for possible maxima of the $\Delta_{11}/\sigma(\Delta_{11})$ value. The appearence of such structures is an important indicator for the presence of subclustering.

3. General description of the cluster Abell 754

The galaxy cluster Abell 754 is a very complex object, as can be seen from Fig. 1. Its structure was first studied by Baier and Mai (1979) and by Geller and Beers (1982). From these investigations the cluster was characterised as flat or double. A recent study by Baier (1997) (Figs. 2 and 3) found an even more complex structure for the cluster. A similar overall orientation of the cluster as found by other authors, e.g., $\Theta_{\rm orien} = 100^o$ (Fabricant et al. 1986), $\Theta_{\rm orien} = 110^o$ (West 1989), is seen if we connect the main structures by a straight line. However, there is further structure in the outskirts of the cluster. Moreover, there appears to be a connection to the cluster Abell 761 at $\alpha = 09^h\ 10^m\ 40^s$, $\delta = -10^o\ 33^{'}$ to the south.

There is an interesting possibility of an alignment between the orientations of the central dominant galaxy (CDG) and the cluster itself ($\Theta_{\rm orien} = 105^o$). However, a more detailed examination of the structure reveals a very strange behaviour for this double cluster.

There are two quite distinct subclusters in the central region of the field: firstly a western subcluster with a high galaxy density, with a CDG and with a small amount of X-ray emitting gas; secondly, the eastern subcluster has a high percentage of X-ray emitting gas but with no dominant galaxy. The temperatures of the western and the eastern components are $kT = 13.0 \pm 3.4$ keV and $kT = 3.2 \pm 1.7$ keV, respectively (Henriksen 1993; Henry and Briel 1995). We support the conclusion by Slezak *et al.* that analyses of global orientations of clusters very often do not appear to make any sense. The alignment between the CDG and the overall cluster structure seems to be purely coincidental. Moreover, there is a difference of 380 km s^{-1} (Dressler and Shectmann 1988a,b) or 20 km s^{-1} (Fabricant et al. 1986) between the two cluster components. The velocity offset between v_r of the CDG and $< v_r >$ of the western component is more than 500 km s^{-1}.

The projected masses of the western and of the eastern cluster components are M_W = 1.3 $\cdot$ 10^{14} $M_\odot$ (within 0.32 Mpc, H_0 = 100 km s^{-1} Mpc^{-1}) and M_E = 2.9 $\cdot$ 10^{14} $M_\odot$ (within 0.34 Mpc). Therefore the western component is twice as massive as the eastern component.

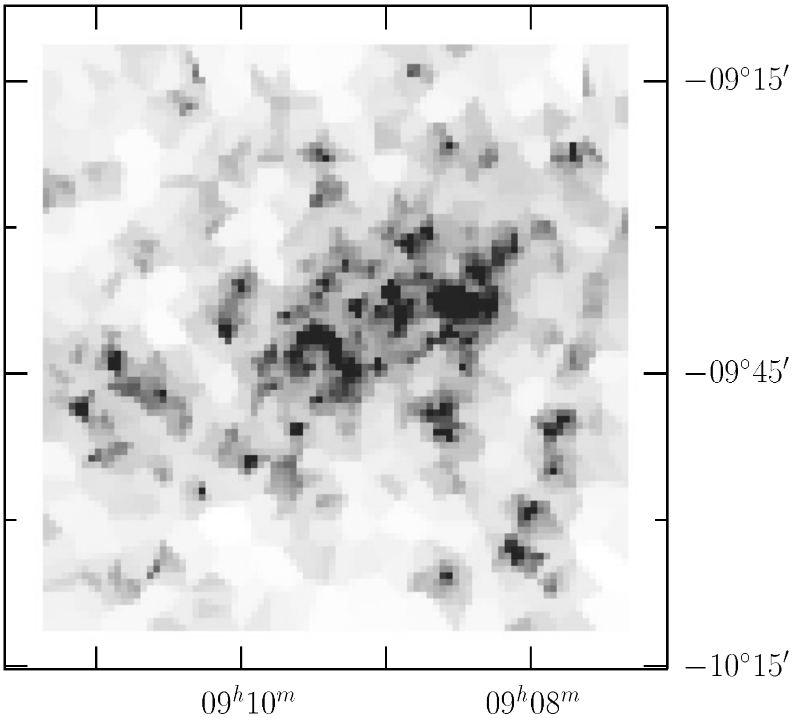

Fig. 3. The distribution of galaxies in the field of the cluster Abell 754 according to Baier et al. (1996b, Voronoi–distribution)

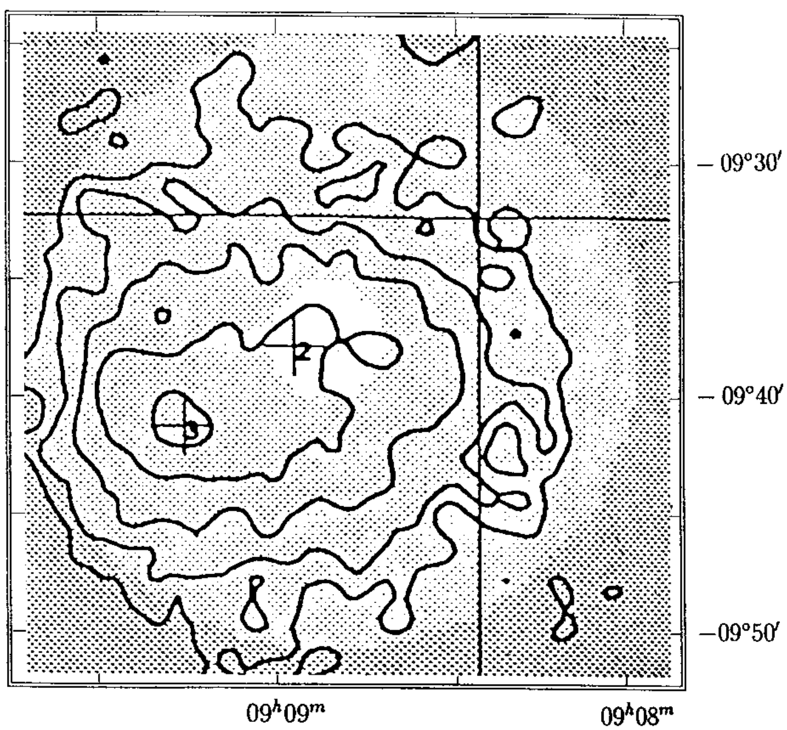

Fig. 4. The X-ray distribution of the cluster Abell 754 according to Harris et al. (1990)

As we can see from a comparison between the maps of the X-ray distribution by Harris et al. (1990), see Fig. 4, and by Slezak et al. (1994, Fig. 5) as well as from the distribution of the galaxies (Figs. 2 and 3) the CDG is located in a region with the highest galaxy number-density but with a rather low X-ray surface brightness. The main X-ray center of the cluster is associated with the eastern subcluster. Twisting of the X-ray orientation is visible in the X-ray map from $\Theta_{\rm orien} = 30^o$ in the eastern region to $\Theta_{\rm orien} = 105^o$ in the western region. It is evident that there is no physical connection between the complex eastern X-ray structure and the small X-ray region E (Fig. 5) which seems to be associated with the CDG.

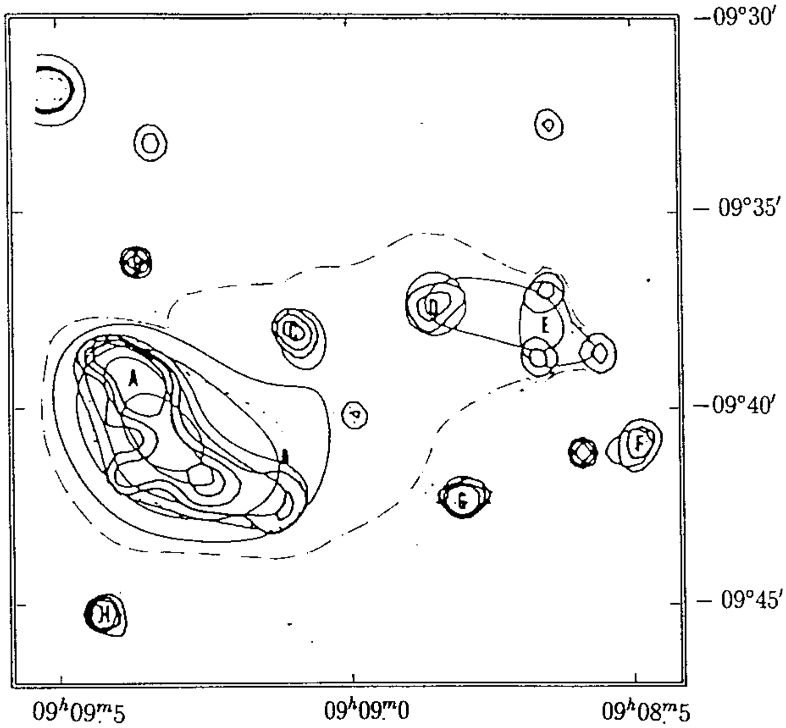

Fig. 5. The X-ray distribution of the cluster Abell 754 according to Slezak et al. (1994)

4. Remarks pertaining to the evolution of the cluster

The situation in the case of the cluster Abell 754 supports the assumption that there is no connection between the central dominant galaxy and the cooling flow. The relative weak accretion rate of $\dot{M} = 6M_{\odot}/yr$ (Godon et al. 1994) or $\dot{M} = 52M_{\odot}/yr$ (Edge & Stewart 1991a) is associated with the eastern cluster in particular. Moreover, the antisegregation of the galaxy luminosities in the western cluster component (Fabricant et al. 1986) could be interpreted as favouring the "cannibalism" scenario for the evolution of the dominant galaxy.

It is possible that the two subclusters are in the process of merging, as suggested by some studies (Ulmer *et al.* 1992; Roettiger *et al.* 1993; Henry and Briel 1995; Zabludoff and Zaritsky 1995). In such a case, we would expect the dominant galaxy to move to the centre of the common cluster potential. Perhaps this type of evolution can also lead to a higher accretion rate.

An alternative possibility – that the two subclusters actually passed completely through each other in the past – seems to be unlikely because of the temperature distribution. Some authors (e.g. Roettiger et al. 1995) consider the projected connecting line between the two particular clusters with orientation of $\theta_{orien} \sim 105°$ as the impact direction between them and explain the orientation of the eastern component ($\theta_{orien} \sim 30°$) as lengthening of the gas distribution (Fig. 5) perpendicular to the direction of the collision. Such lengthening is predicted by the simulations of Roettiger et al. (1993). In such a situation we should expect a rather high temperature for the gas in this eastern cluster component. This scheme, however, is in contradiction to the low gas temperature measured by Henry & Briel (1995).

A further argument against the latter explanation for the lengthening of the eastern component from SW to NE (perpendicular to the assumed collision direction) is the fact that the distribution of galaxies within this subcluster displays a corresponding elongated configuration, as can be seen in Fig. 3 taken from Baier (1997). We conclude that both components of the subcluster – galaxies and gas – appear to follow the same gravitational potential. Unfortunately, this last assumption is in contradiction to the result found by Zabludoff & Zaritsky (1995). According to their result, presented in Fig. 6, the maximum of the luminosity distribution of the eastern subcluster is located at the southern end of the elongated X-ray distribution.

Henriksen & Markewitch (1996) favoured a different concept with respect to the situation within this cluster. Like other authors, they found the highest temperature – more than 12 keV – in the northwestern subcluster. Furthermore, they found a temperature of T $\sim$ 9 keV (i.e. higher than the average cluster temperature) within an elongated region south of and parallel with the line connecting the two subclusters. They explained this temperature distribution by the suggestion that the two subclusters are moving around each other within an area perpendicular to the line of sight. According to this supposition, the eastern cluster should move to the south and the western cluster to the north. Such a situation corresponds to the simulations by Evrard et al. (1996). These simulations also predict the temperature distribution found by Henriksen & Markewitch (1996).

Perhaps this latter suggestion can explain the continuous "twisting" of the X-ray orientation from $\theta_{orien} \sim 30°$ in the eastern region to $\theta_{orien} \sim 105°$ in the western, as well as the very small velocity difference between both subclusters, after Fabricant et al. (1986). Of course, this is in contradiction

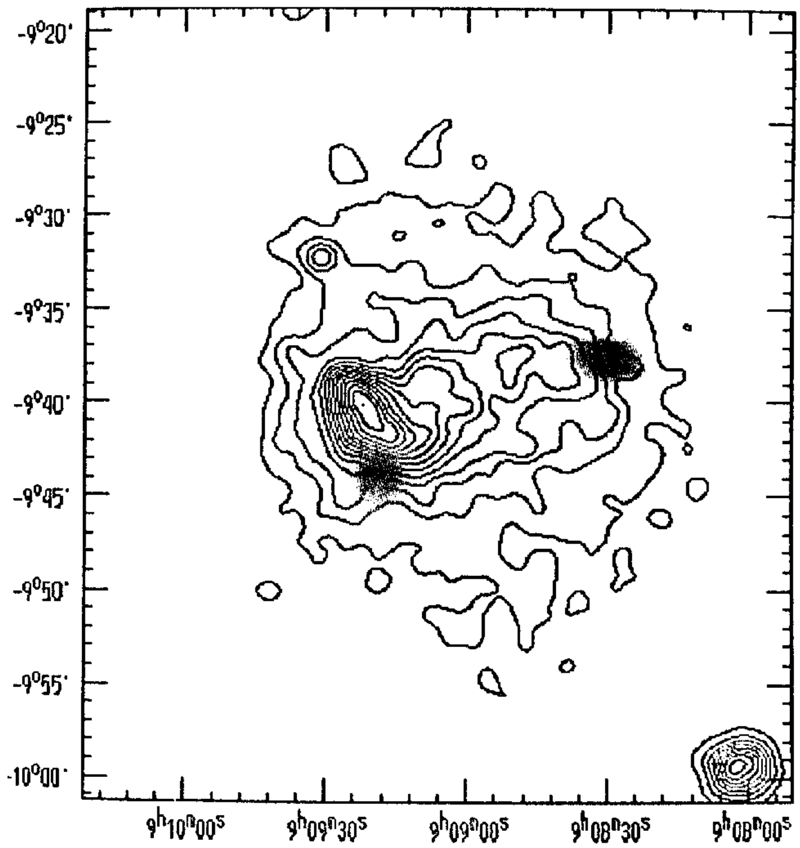

Fig. 6. The distribution of X-ray emission and optical luminosity for the cluster Abell 754 according to Zabludoff & Zaritsky (1995)

Table 1. Test for isotropy of the distribution of position angles of galaxies in the cluster A754

	subcluster number	N	χ^2	C	$P(\Delta_1)$	$P(\Delta_2)$	Δ_{11}	σ	W_a	σ
	all	491	136.1	72.54	.000	.082	0.506	.064	−.316	.045
P	A	330	99.8	48.98	.000	.129	0.544	.078	−.339	.055
	B	161	68.2	17.88	.000	.254	0.427	.111	−.267	.079
	2	97	60.0	17.31	.000	.742	0.447	.144	−.278	.102
	3	116	67.7	4.72	.000	.931	0.520	.131	−.328	.093

with the large velocity difference of 380 kms^{-1} between both subclusters found by Dressler & Shectmann (1988b) and to the large velocity difference between the cD–galaxy and the western subcluster (more than 500 kms^{-1} according to Fabricant et al. 1986). One possibility is that this western subcluster consists in fact of two parts, i.e. a rich cluster and a poor cluster or galaxy group containing the dominant galaxy.

5. Analysis of the galaxy orientations

We have analysed a sample of 927 galaxies in the field of the cluster. The data were taken from the *COSMOS/UKST Southern Sky Object Catalogue* (Yentis *et. al* 1991), which is a catalogue of stars and galaxies derived from glass copies of the Southern Sky SERC J sky survey. Initially, all galaxies down to a limiting magnitude of B=20.0 were selected. Subsequently, however, in order to reduce contamination of our results due to foreground and background objects, we have eliminated galaxies outside a region selected on the basis of galaxy surface density. The galaxies retained for our analysis are thus shown in Fig. 7.

The cluster area was subsequently split into different parts according to the constituent sub-components. To help identify these regions the reader is referred to Fig. 2. At first glance, the galaxy distribution in the cluster region may be characterised by two elongated main structures with different orientations. The first elongated structure has an orientation of $\Theta \sim 117^o$ and contains the four substructures with their centres at $\alpha = 09^h\, 11^m\, 00^s$, $\delta =$ –09^o 45$'$ (substructure 1), $\alpha = 09^h\, 09^m\, 36^s$, $\delta =$ –09^o 43$'$ (substructure 2), $\alpha = 09^h\, 08^m\, 31^s$, $\delta =$ –09^o 37$'$ (substructure 3) and $\alpha = 09^h\, 07^m\, 10^s$, $\delta =$ –09^o 30$'$ (substructure 4), respectively. This first elongated structure would appear to represent the main body of the cluster. To the south of this main part there is a second elongated structure, i.e. the bridge to the cluster Abell 761 (with coordinates $\alpha = 09^h\, 10^m\, 40^s$, $\delta =$ –10^o 33$'$ and with an orientation of $\Theta \sim 158^o$).

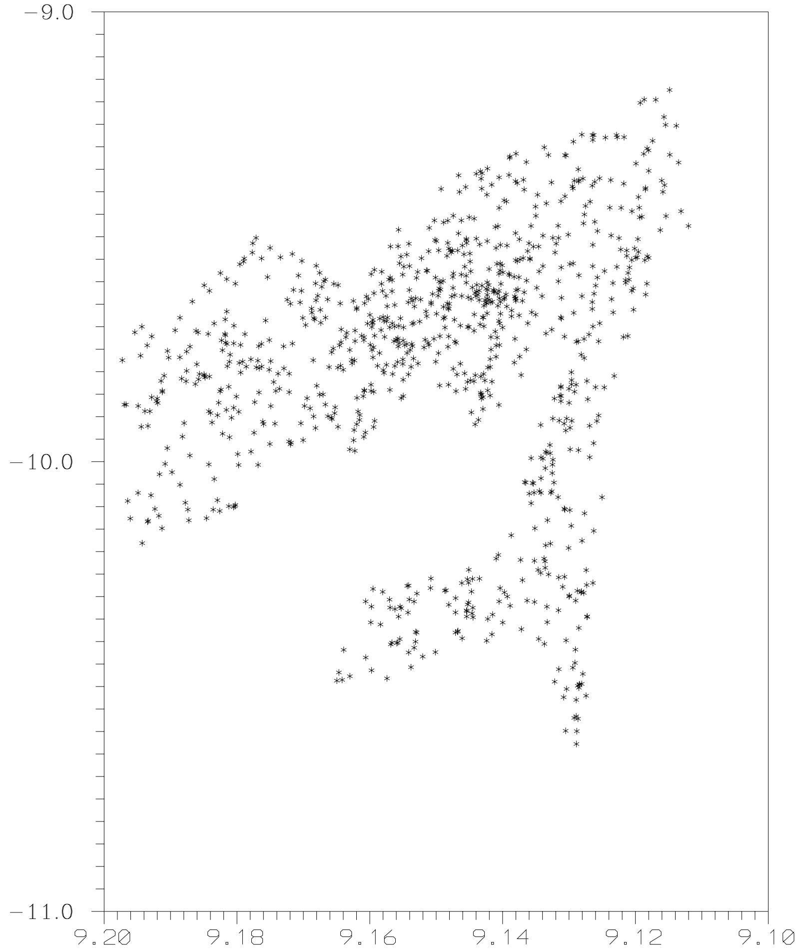

Fig. 7. The distribution of galaxies in the cluster field (above a surface density level) from the Edinburgh–database in α and δ for the epoch 2000.0

For our investigation we consider the following division of the components: region A with the substructures 1, 2 and 3, respectively and region B containing the substructure 4 and the bridge to the south. The two substructures 2 and 3 are normally considered to be the main members of the cluster Abell 754. However, the true physical interconnection between all of these different components must remain open to question because of the complex cluster structure.

We find 491 galaxies with axial ratios less then 0.3 in both regions A and B and have analysed the distribution of the position angles for these galaxies in the whole cluster and in the regions A, B, 2 and 3, respectively. Areas 1 and 4 were not investigated because of the small number of galaxies in these two areas.

The result of this investigation is given in Table 1 and Fig. 8. From our results we see a rather strong alignment of position angles in the cluster as a whole and within the subclusters. From all three powerful statistical tests used (and described in the appendix) we can reject the possibility of a random distribution of the position angles. The maximum in the distribution of the position angles is at $\Theta \sim 15^o$ both for the cluster as a whole (Fig. 8) and for particular subclusters. From this result we conclude that the galaxy planes are preferentially aligned perpendicular to the cluster main plane. Jaaniste & Saar (1978), Flin & God owski (1986), and God owski (1993, 1994) found a similar result from investigation of the normals to the galaxy planes. This result was confirmed by Parnowsky (1994).

We do not find any clear evidence that the distributions of position angles of galaxies in the two subclusters have different shapes or different positions for the maxima. However, from the

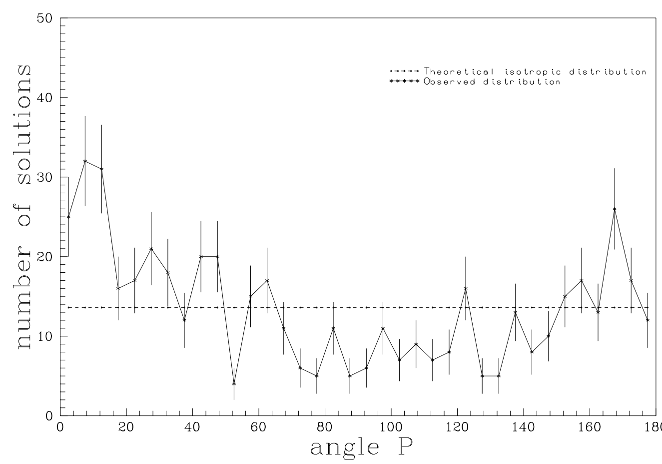

Fig. 8. The distribution of the position angles of galaxies in the whole cluster field

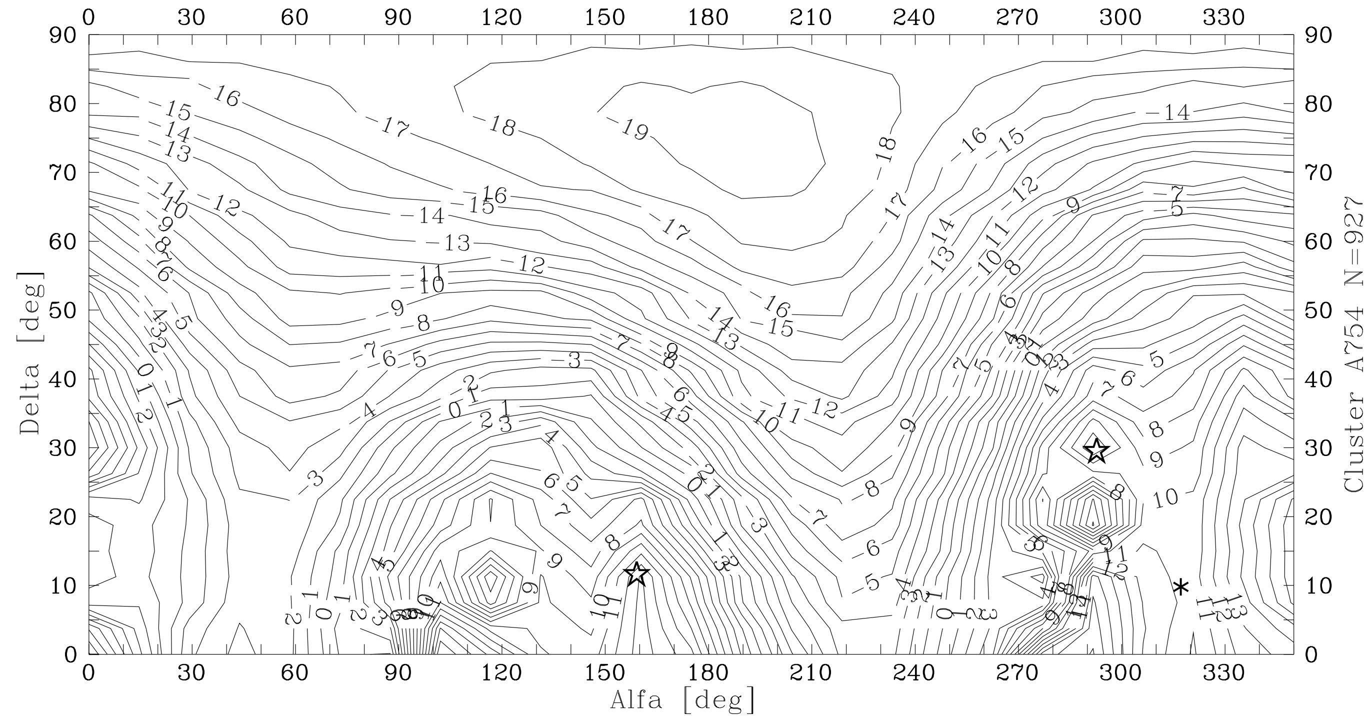

Fig. 9. The map of $\Delta_{11}/\sigma(\Delta_{11})$ presented in α,δ coordinates. In the map we show the important directions of the line of sight from the earth and the possible direction of the cluster pole with the assumption of a true ellipticity of 0.2.

Fourier test, taking into account only the highest Fourier mode i.e. when

$$N_k = N_{0,k}(1 + \Delta_{12}\cos 4\theta_k + \Delta_{22}\sin 4\theta_k)\ ,$$

(see God owski (1994) for a detailed explanation) we find a weak anisotropy (i.e. an 8 % probability that the distribution is random). This result could be an indication of a more complicated bimodal distribution similar to the result of Gregory et al (1981). Such a bimodal distribution can be explained by the influence of various substructures. However, the effect is very weak. Moreover, we were not able to find a definite correlation between substructures and different alignments. Thus, this interpretation should be treated with caution.

Next, we use the method orginaly proposed by Jaaniste & Saar (1978). There is here a large difference between the number of galaxies in the whole cluster area and the number of galaxies with axial ratio less than 0.3. It is not clear whether this is due to a general excess of ”round” galaxies in the cluster or is due mainly to effects of seeing on the photographic plates.

We have mapped the ratio of Δ_{11} divided by its formal error $\sigma(\Delta_{11})$ for different possible cluster pole directions on the celestial sphere, shown in Fig. 9. In the resulting map we have looked for any possible correlations between the extreme values of $\Delta_{11}/\sigma(\Delta_{11})$ and different directions. There is a correlation between the maximum of this ratio and the direction of the line of sight to the cluster. One very important observation is that this maximum has a highly compact nature, which is possibly an indication of the fact that there is substructure with a different type of alignment.

In one area of Fig. 9 we see a strong negative minimum. This result indicates that there is a very strong deficiency of galaxies with rotation axes in that direction. This is clear confirmation for a real general alignment within this cluster. Unfortunately, we have no information regarding the morphological types of galaxies in our data. Therefore, we are unable to investigate the question of alignments according to different morphological types.

6. Conclusion

From optical and X-ray observations of the cluster Abell 754 we conclude it has a very complex structure. Furthermore, we find strong evidence that the position angles of galaxies in the cluster are aligned, in the sense that galaxy major planes tend to be perpendicular to the direction of the position angle of the major axis of the cluster. Consequently, this means that the angular momenta of the galaxies are preferentially aligned parallel with the cluster plane. From analysis of the distribution of the position angles of galaxies we, moreover, find some evidence for possible subclustering inside the cluster as a whole. This result is confirmed by the investigation of the distribution of the normals to the galaxian planes.

Appendix A: the statistical methods applied to the data

To check the distribution of galaxy orientation angles (δ, η) we applied statistical tests originally introduced by Hawley & Peebles (1975) and described in detail by God owski (1993, 1994).

Below, a short summary is presented of the tests used in this paper: the χ^2-test, the Fourier test and the auto correlation test.

Let N denote the total number of galaxies in a cluster under consideration, N_k - the number of galaxies with orientations within the k-th angular bin – one of $n = 36$ bins (as a check we repeated derivations for different values of n but no significant differences was apparent), N_0 - the mean number of galaxies per bin and, finally, $N_{0,k}$ - the expected number of galaxies in the k-th bin. The χ^2-test of the distribution involves the value (the critical value 0.95 for 35 degrees of freedom being 49.8)

$$\chi^2 = \sum_{k=1}^{n} \frac{(N_k - N_{0,k})^2}{N_{0,k}} . \quad \text{(A1)}$$

This is minimised in model fitting, with the use of a model distribution provided by $N_{0,k}$. In the Fourier test involving the first Fourier mode only, the actual distribution N_k is approximated as

$$N_k = N_{0,k}(1 + \Delta_{11} \cos 2\theta_k + \Delta_{21} \sin 2\theta_k) . \quad \text{(A2)}$$

The coefficients Δ_{i1} $(i = 1, 2)$ are given as:

$$\Delta_{11} = \frac{\sum_{k=1}^{n}(N_k - N_{0,k}) \cos 2\theta_k}{\sum_{k=1}^{n} N_{0,k} \cos^2 2\theta_k} , \quad \text{(A3)}$$

$$\Delta_{21} = \frac{\sum_{k=1}^{n}(N_k - N_{0,k}) \sin 2\theta_k}{\sum_{k=1}^{n} N_{0,k} \sin^2 2\theta_k} , \quad \text{(A4)}$$

with the standard deviation

$$\sigma(\Delta_{11}) = \left(\sum_{k=1}^{n} N_{0,k} \cos^2 2\theta_k\right)^{-1/2} = \left(\frac{2}{nN_0}\right)^{1/2} ,$$

$$\sigma(\Delta_{21}) = \left(\sum_{k=1}^{n} N_{0,k} \sin^2 2\theta_k\right)^{-1/2} = \left(\frac{2}{nN_0}\right)^{1/2} . \quad \text{(A5)}$$

The probability that the amplitude

$$\Delta_1 = \left(\Delta_{11}^2 + \Delta_{21}^2\right)^{1/2} , \quad \text{(A6)}$$

is greater than a certain chosen value is given by the formula:

$$P(> \Delta_1) = \exp\left(-\frac{n}{4} N_0 \Delta_1^2\right) , \quad \text{(A7)}$$

while the standard deviation of this amplitude is

$$\sigma(\Delta_1) = \left(\frac{2}{nN_0}\right)^{1/2} . \quad \text{(A8)}$$

From the value of Δ_{11} one can deduce the direction of the departure from isotropy. If $\Delta_{11} < 0$, then, for $\theta \equiv \delta + \pi/2$, an excess of galaxies with rotation axes parallel to the cluster plane is present. For $\Delta_{11} > 0$ the rotation axes tend to be perpendicular to the cluster plane.

The auto correlation test quantifies the correlations between the galaxy numbers in adjoining angular bins. The correlation function is defined as

$$C = \sum_{k=1}^{n} \frac{(N_k - N_{0,k})(N_{k+1} - N_{0,k+1})}{[N_{0,k} N_{0,k+1}]^{1/2}} . \quad \text{(A9)}$$

In the case of an isotropic distribution, $C = 0$ with standard deviation

$$\sigma(C) = n^{1/2} . \quad \text{(A10)}$$

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