Discordant redshifts in compact groups

A. Iovino,¹ and P. Hickson,¹,²
¹Osservatorio Astronomico di Brera, Via Breira 28, I-20121 Milano, Italy
²Department of Geophysics and Astronomy, University of British Columbia, 2219 Main Mall, Vancouver, BC V6T 1Z4, Canada

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ABSTRACT
This paper addresses the long standing question of discordant redshifts in compact groups. We have used an homogenous catalogue of 173 compact groups selected by an automated procedure to objectively predict the fraction of discordant redshifts with high statistical accuracy, and then applied these results to the sample of 92 compact groups in Hickson’s revised catalogue. Our results confirm that projection effects alone can account for the high incidence of discordant redshifts in compact groups. We have also examined the spatial distribution of discordant galaxies in Hickson’s compact groups. Contrary to previous studies, we find that there is no evidence for central concentration of discordant galaxies.

Key words: galaxies – clustering: redshifts.

1 INTRODUCTION

Compact groups of galaxies pose a number of interesting questions for astronomers. The most long-standing and controversial is that of discordant redshifts. The difficulty began when the first two known compact groups, Stephan’s Quintet (Stephan 1877) and Seyfert’s Sextet (Seyfert 1948a,b), were both found to contain a galaxy whose redshift differed greatly from that of the other group members (Burbidge & Burbidge 1961). This surprising result was repeated with the discovery (Sargent 1968) of a discordant redshift in VV172 (Vorontsov-Vel’yaminov 1959), and in many more compact groups (Hickson et al. 1992).

Because of the seemingly high incidence of discordant redshifts, doubts have been expressed as to whether they can be explained by projection effects alone (Arp 1973, Sulentic 1984). Early attempts to answer this question have not been conclusive. From a study of ~ 200 galaxy quartets and triplets, Rose (1977) concluded that projection effects were responsible for the discrepant redshifts cases observed. However, his conclusion was based on a sample of galaxies with few measured velocities. Sulentic (1987) reached the opposite conclusion, based on counts of galaxies around Hickson’s (1982) sample of compact groups. However this work underestimated the probability of background contamination by requiring the discordant galaxy to be inside the group and not just outside (still making it an isolated and compact group). Hickson et al. (1988) computed separately probabilities for internal and external discordant redshifts. They concluded that the overall number of discordant redshifts was consistent with projection effects, but that there was (at the 98% level) an excess of internal discordant redshifts. Mendes de Oliveira (1995) reached a similar conclusion, using more complete redshift data, and suggested that the apparent concentration of discordant redshifts towards the centres of the groups might be due to weak gravitational lensing (see also Mendes de Oliveira & Giraud 1994).

These recent studies compare the number of discordant quintets with the number expected by chance, based on the number of accordant quartets in the catalogue and the surface density of field galaxies. Since the number of groups studied is small, the statistical significance is limited. Also, because the probability of a projected field galaxy increases with group area, one expects that that most discordant groups would be of low surface brightness. However, as several investigators have emphasized (Sulentic 1993, Arp 1995), this is not what is actually seen. A possible explanation for this discrepancy is that Hickson’s catalogue is not complete at low surface brightness (Hickson 1982, Prandoni et al. 1994). As a result, most low surface brightness groups (discordant or not) are not detected. Since previous analyses do not include this bias, the situation needs to be reexamined.

In this paper we address two separate questions: 1) is the number of discordant redshifts in compact groups consistent with projection effects, and 2) is there evidence for central concentration of discordant redshifts? We improve upon previous work by making use of a large homogenous catalogue of groups selected by an automated procedure (Iovino et al., 1996). This allows us to predict the fraction of discordant redshifts in an objective manner and with high statistical accuracy. These results are then applied to the Hickson catalogue of groups, which is 99% complete in redshift measurements. To improve statistics, we study both discordant quintets and discordant quartets in the catalogue. Our
analysis explicitly includes incompleteness effects, in both surface brightness and magnitude.

Our results confirm that projection alone can account for the high incidence of discordant redshifts in compact groups. Contrary to previous studies, we show that there is no evidence for central concentration of discordant galaxies.

2 ARE DISCORDANT GALAXIES CENTRALLY LOCATED?

Let us first consider the question of whether discordant galaxies (i.e., galaxies with velocity within 1000 km s$^{-1}$ of the median galaxy velocity of the group) fall preferentially closer to the centre of the group than do accordant galaxies, as has been suggested by previous work (Hammer & Nottale 1986, Mendes de Oliveira 1995). As previous studies have suggested that discordant galaxies are preferentially internal to the group, we consider the relative numbers of internal galaxies. An internal galaxy is one whose center is located inside the smallest circle which contains the centers of the other galaxies. For the 100 groups in Hickson’s (1982) catalogue, 44 galaxies are discordant and 391 galaxies are accordant, by the above definition. 43% of the discordant galaxies are internal and 54% of the accordant galaxies are internal. Clearly there is no preference for discordant galaxies to be internal.

We can also ask if the number of internal discordant galaxies is consistent with a random distribution of galaxies on the sky. For a set of $n$ galaxies randomly placed on a plane surface, the probability that any particular one of them will be internal is (from Appendix A)

$$P_n = \frac{(n-1)(n-2)}{n^2}.$$  \hspace{1cm} (1)

Multiplying this probability by the number of groups with one discordant redshift gives the predicted number of internal discordant redshift groups.

Table 1 lists data for the HCG groups. The columns are (1) Number of galaxies in the group (accordant plus discordant), (2) number of groups having one discordant galaxy (3) probability from Eq. (1), (4) predicted number of groups having one internal discordant galaxy, (5) observed number of groups having one internal discordant galaxy, (6) chance probability of finding at least that many discordant-redshift galaxies (from the binomial distribution).

From the table it is clear that the observations are in accord with the predictions of the random model. All differences are attributable to chance. From the consistent negative results of both these tests, we conclude that there is no evidence for central concentration of the discordant galaxies.

3 THE FREQUENCY OF PROJECTIONS

In order to analyze the frequency of discordant redshifts, we make use of both the SCG and HCG catalogues. The SCG catalogue employs selection criteria designed to match exactly those of the HCG catalogue (i.e., richness, compactness and isolation, Hickson 1982) and is obtained applying these selection criteria to a database of $\sim 1,000,000$ galaxies up to mag in $B_J \sim 19.5$, obtained through COSMOS scans of $\sim 200$ UKST $b_J$ plates (MacGillivray and Stobie 1984). However, because the SCG’s are found by a computer algorithm, they are not affected by any subjective or visual bias. That makes them ideal for estimating the probabilities of chance alignments. On the other hand, very few redshifts are available for this sample, so the actual numbers of discordant redshifts are not known. The HCG catalogue includes redshifts for almost all member galaxies. The observed numbers of discordant galaxies are therefore known, but biases such as the incompleteness of the catalogue at low surface brightness makes calculation of the probability of chance alignments uncertain.

Our technique, therefore, is the following: The SCG catalogue is used to determine the probabilities of chance alignments, and to study the factors which affect these probabilities. The results are then applied to the HCG catalogue, to see whether or not the observed frequencies of discordant redshifts are compatible with the projection hypothesis. Obviously this approach can only work if the probabilities calculated from the SCG are applicable to the HCG catalogue. In this section we discuss the method used to estimate the probabilities, and the factors affecting them. We find that the probability of a group being a chance alignment depends sensitively on the surface brightness of the group, and that other factors are much less important.

The probability $P$ that a triplet will form a discordant quartet due to chance projection of a field galaxy was determined by taking all the triplets in the SCG catalogue, without any surface brightness limit, and placing each of them at 100 random positions in the sky (i.e., giving them random coordinates within the area of the galaxy catalogue). The SCG search algorithm was then applied to see how many times a quartet was formed which satisfied the selection criteria. Since it is very unlikely that a random field galaxy will have the same redshift as the triplet, the ratio of the number of quartets found in this manner to the number of triplets times the number of random positions gives the probability.

Since the above method places the triplets at random locations with equal prior probability, it does not take into account galaxy clustering or large-scale structure. In order to examine the effects of clustering, a second series of runs was performed in which the results were weighted according to the average density of galaxies in the region where the triplet was placed. In this case, the prior probability of a triplet being found in a region of galaxy surface density $\rho$ was taken to be proportional to $\rho^3$ (because the probability of each galaxy in the triplet should be proportional to $\rho$, neglecting clustering within the triplets). For each position, a weight proportional to $\rho^3$ was computed. The final probability, denoted $\hat{P}$, is then the sum of the weights at successful locations (i.e. where a quartet was made) divided by the sum of all the weights, and is an upper limit to the true.

Table 1. Statistics of Internal Discordant Redshifts

| $n$ | $N_{\text{groups}}$ | $P_n$ | $N_{\text{pred}}$ | $N_{\text{obs}}$ | Prob |
|-----|------------------|-------|-------------------|------------------|------|
| 4   | 19               | 0.3750| 7.1250            | 6                | 0.78 |
| 5   | 6                | 0.4800| 2.8800            | 4                | 0.31 |
| 6   | 3                | 0.5556| 1.6667            | 0                | 1.00 |
| 7   | 0                | 0.6122| 0.0000            | 0                | —    |
| 8   | 1                | 0.6563| 0.6563            | 1                | 0.66 |

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probability, having considered independently the members of the triplets.

Similar runs were made in which the program checked for the formation of a quintet, by superposition of two field galaxies on a triplet. Also, the SCG quartets were moved to random positions to determine the probability of forming a quintet by superposition of one field galaxy on a quartet.

4 ANALYSIS

Using probabilities calculated from the SCG catalogue, we can now predict the numbers of discordant-redshift quartets and quintets in the HCG catalogue. Figure 1 shows the distribution with surface brightness of the SCG quartets and of the discordants quartets found by randomly positioning the SCG triplets. From the figure it is evident that the contamination rate increases as the surface brightness decreases. Because of this, the analysis is done separately in intervals of surface-brightness. This allow us to properly take into account the exact distribution in surface brightness of HCGs.

These unknown variables are not all independent, but, by virtue of their definition, are connected by the following relationships:

\begin{align}
    m_{31} &= q m_4 \\
    n_3 &= s n_4 \\
    q &= ps \\
    n_3 &= q n_4 / p
\end{align}

They are related to the observables through the probability distributions:

\begin{align}
    P(\hat{n}_3 | n_3) &= \frac{n_3^{\hat{n}_3}}{\hat{n}_3!} \exp(-n_3) \\
    P(\hat{n}_4 | n_4) &= \frac{n_4^{\hat{n}_4}}{\hat{n}_4!} \exp(-n_4) \\
    P(\hat{m}_4 | m_4) &= \frac{m_4^{\hat{m}_4}}{\hat{m}_4!} \exp(-m_4) \\
    P(\hat{m}_{31} | m_{31}, q) &= \left( \frac{\hat{m}_4}{\hat{m}_{31}} \right)^{\hat{m}_{31} q} (1 - q)^{\hat{m}_4 - \hat{m}_{31}}
\end{align}

Where the notation \( P(a|b, c, \ldots) \) means the probability of obtaining a given \( b, c, \ldots \). The first three equations are Poisson distributions, which are appropriate because the associated random variables have, in principle, no upper limit to their possible values. On the other hand, the distribution of \( \hat{m}_{31} \) is Binomial since that variable cannot exceed \( \hat{m}_4 \) (there cannot be more discordant quartets than there are quartets).

We wish to find the probability of observing \( \hat{m}_{31} \) or more 3+1 quartets given the other known quantities, under the hypothesis of chance projection. This is given by
\[ P = \sum_{x=\hat{n}_3} P(x \mid q, \hat{m}_4) \] (4)

\[ x \equiv q \hat{m}_4. \] Unfortunately, \( q \) is not known, as one does not know the precise ratio \( s = \hat{n}_3/n_3 \) of triplets to quartets. Therefore this uncertainty must be folded in the determination of \( P \), giving:

\[ P = \sum_{x=\hat{n}_3} P(x|\hat{n}_3, \hat{m}_4, \hat{m}_4, p). \] (5)

An examination of the dependencies in Eq. (3) shows that the probability on the RHS of Eq. (3) can be factored:

\[ P(x|\hat{n}_3, \hat{m}_4, \hat{m}_4, p) = \int P(x|q, \hat{m}_4, q)P(q|\hat{n}_3, \hat{m}_4, p) dq \]
\[ = \int \int P(x|q, \hat{m}_4, q)P(q|\hat{n}_3, n_4, p)P(n_4|\hat{n}_4) dq dn_4 \] (6)

where the integration is performed over the ranges of \( q \) and \( n_4 \). Now for given \( n_4 \) and \( p, q \) is a function of \( n_3 \) by virtue of Eq. (3). Thus,

\[ P(q|\hat{n}_3, n_4, p) = P(n_3|\hat{n}_3 \frac{dn_3}{dq}) = P(n_3|\hat{n}_3 \frac{n_4}{p}). \] (7)

This probability can, in turn, be transformed using Bayes’ theorem:

\[ P(n_3|\hat{n}_3) = P(\hat{n}_3|n_3)P(n_3)/P(\hat{n}_3). \] (8)

where \( P(n_3) \) is the prior probability of \( n_3 \), which is unity because there is no prior information about this quantity, and

\[ P(\hat{n}_3) = \int P(\hat{n}_3|n_3) dn_3 = 1, \] (9)

which follows from Eq. (3). Thus we have

\[ P(n_3|\hat{n}_3) = P(\hat{n}_3|n_3), \] (10)

and similarly,

\[ P(n_4|\hat{n}_4) = P(\hat{n}_4|n_4). \] (11)

Substituting Eqs. (3), (9) and (10) into Eq. (3) and then inserting the explicit probability distributions from Eq. (3), we obtain

\[ P(x|\hat{n}_3, \hat{m}_4, \hat{m}_4, p) = \left( \frac{\hat{m}_4}{x} \right)^{\frac{1}{n_3|\hat{n}_3|\hat{m}_4}} \int_0^1 \int_0^{\infty} q^{\hat{n}_3 - x} (1 - q)^{\hat{n}_4 - x} \left( \frac{n_4 q}{p} \right)^{\hat{n}_3} \cdot \exp(-n_4 q/p) \frac{dn_4}{dn_4} \exp(-n_4) dn_4 dq \]
\[ = \left( \frac{\hat{m}_4}{x!} \frac{p^{-\hat{n}_3 - 1}}{\hat{m}_4|n_3|\hat{m}_4} \int_0^1 q^{\hat{n}_3 + x} (1 - q)^{\hat{n}_4 - x} dq \right) \int_0^\infty dn_4 \frac{dn_4}{dn_4} \frac{\hat{n}_4 + \hat{n}_3 + 1}{\hat{n}_4 + \hat{n}_3 + 1} \exp(-n_4 (1 + q/p)). \] (12)

The \( n_4 \) integral is easily evaluated using the result

\[ \int_0^\infty z^n \exp(-az)dz = \frac{n!}{a^{n+1}}, \] (13)

which leaves,

\[ P(x|\hat{n}_3, \hat{m}_4, \hat{m}_4, p) = \frac{\hat{m}_4 (\hat{m}_4 + \hat{n}_4 + 1) p^{-\hat{n}_3 - 1}}{x! (\hat{m}_4 - x)! \hat{m}_4 |\hat{m}_4|} \int_0^1 q^{\hat{n}_3 + x} (1 - q)^{\hat{n}_4 - x} \cdot (1 + q/p)^{-\hat{n}_4 - \hat{n}_3 - 2} dq. \] (14)

### Table 2: Probabilities of Discordant Redshifts

| \( \mu \) | \( \hat{n}_3 \) | \( \hat{n}_4 \) | \( \hat{m}_4 \) | \( \hat{m}_31 \) | \( p \) | \( \hat{p} \) | \( \hat{p} \) |
|---|---|---|---|---|---|---|---|
| 20.2 | 0 | 0 | 1 | 0 | 0.000 | 0.000 | 1.000 |
| 21.2 | 1 | 0 | 1 | 0 | 0.015 | 0.000 | 1.000 |
| 22.2 | 4 | 2 | 3 | 1 | 0.014 | 0.096 | 0.907 |
| 23.2 | 28 | 5 | 12 | 5 | 0.019 | 0.042 | 0.023 |
| 24.2 | 42 | 6 | 19 | 1 | 0.073 | 0.212 | 0.999 |
| 25.2 | 105 | 16 | 15 | 8 | 0.119 | 0.197 | 0.895 |
| 26.2 | 173 | 47 | 2 | 2 | 0.187 | 0.229 | 0.491 |

### 3+2 Quintets with \( m < 15.5 \)

| \( \mu \) | \( \hat{n}_3 \) | \( \hat{n}_4 \) | \( \hat{m}_4 \) | \( \hat{m}_31 \) | \( p \) | \( \hat{p} \) | \( \hat{p} \) |
|---|---|---|---|---|---|---|---|
| 21.2 | 1 | 0 | 1 | 0 | 0.000 | 0.000 | 1.000 |
| 22.2 | 2 | 0 | 2 | 1 | 0.003 | 0.050 | 0.972 |
| 23.2 | 4 | 1 | 7 | 3 | 0.010 | 0.057 | 0.020 |
| 24.2 | 5 | 1 | 3 | 1 | 0.062 | 0.175 | 0.879 |
| 25.2 | 14 | 4 | 11 | 4 | 0.100 | 0.262 | 0.508 |
| 26.2 | 45 | 12 | 1 | 0 | 0.124 | 0.160 | 1.000 |

### 4+1 Quintets with \( m < 15.5 \)

| \( \mu \) | \( \hat{n}_4 \) | \( \hat{n}_5 \) | \( \hat{m}_5 \) | \( \hat{m}_41 \) | \( p \) | \( \hat{p} \) | \( \hat{p} \) |
|---|---|---|---|---|---|---|---|
| 22.2 | 2 | 3 | 4 | 2 | 0.008 | 0.034 | 0.001 |
| 23.2 | 5 | 1 | 4 | 1 | 0.029 | 0.065 | 0.404 |
| 24.2 | 6 | 0 | 6 | 0 | 0.117 | 0.217 | 1.000 |
| 25.2 | 16 | 11 | 8 | 3 | 0.121 | 0.234 | 0.193 |
| 26.2 | 47 | 13 | 2 | 1 | 0.128 | 0.104 | 0.699 |

\( a: \) Seyfert’s Sextet (\( \mu = 21.52 \)) is included here

The remaining integral can be computed numerically, to give the desired probability. We find, as expected that

\[ \sum_{x=0}^{\hat{n}_4} P(x|\hat{n}_3, \hat{m}_4, \hat{m}_4, p) = 1. \] (15)

Probabilities for other cases (such as making 3+2 quintets by projection of two field galaxies on a quintet) are determined in a similar manner.

The results are given in Table 2, in which the values of the relevant observables are listed along with the probability \( P \) that the observed number of discordant systems, or more, would be found due to chance alignments with unrelated field galaxies.

### 5 DISCUSSION

From the tables it is clear that the numbers of discordant redshifts found in the HCG catalogue are in accord with the projection hypothesis in almost all cases. The exception is the highest surface brightness 4+1 quintet. Seyfert’s sextet (HCG 79) has a surface brightness of 21.52 mag arcsec\(^{-2}\), which would place it in the \( \mu = 21.2 \) interval. However,
there are no SCG quartets or quintets with surface brightness in this range, probably due to the smaller area of the sky explored, so no statement can be made about probability for this interval (formally, the probability evaluates to 1.000). We have therefore conservatively included Seyfert’s sextet in the 22.2 mag arcsec$^{-2}$ interval. The other group in this interval is Stephan’s Quintet (HCG 92). With these two together, the probability of these objects being due to uniform random projection is very small. If clustering is taken into account, the probability increases to 1.7%. If Seyfert’s Sextet is not included in the $\mu = 22.2$ interval, the probabilities $P$ and $\tilde{P}$ become 0.024 and 0.119 respectively. Another well-known discordant group, VV 172 (HCG 55) falls in the $\mu = 23.2$ interval. However, according to our analysis, the chance probability of finding a discordant group in this interval is high.

We conclude that practically all discordant redshifts in the HCG catalogue can be explained by chance. On the other hand, it would seem that Seyfert’s Sextet, and to a lesser degree Stephan’s Quintet are unique objects, and that a resolution of their nature must rest upon direct observations rather than statistical arguments. Independent distance estimates, from the Tully-Fisher and $D_n - \sigma$ relations, have been obtained for galaxies in Stephan’s Quintet (Kent 1981) and HCG 61 (Mendes de Oliveira 1995). In all cases the distances were found to be consistent with a cosmological interpretation of the redshifts. The higher redshifts of galaxies in Seyfert’s Sextet make direct distance determinations difficult (unless of course they are all much closer than their redshifts suggest). It has been suggested (Hammer & Nottale 1986, Mendes de Oliveira 1995) that some of these groups may be cases of gravitational lensing, but as we have seen above, there is no statistical evidence for this. Detailed observations of Seyfert’s Sextet in particular might indicate whether or not lensing plays a role in this group. We note for this group that the discordant galaxy is located close to the geometric center of the group, and is the smallest and faintest member.

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APPENDIX A: PROBABILITY OF A GALAXY BEING INTERNAL

In this appendix we derive the probability $P_n$ that any galaxy in a group of $n$ galaxies will be internal, under the assumption that the galaxies are (uniformly) randomly distributed. Each galaxy is represented by a point on a plane, corresponding to the location of the galaxy’s geometric centre.

Define the boundary of a set of $n$ points to be the smallest circle that contains all points. An internal point is a point which lies inside the boundary of the set formed by the other points. An external point is a point that is not internal.

It is easy to see that all points inside the boundary of a set are internal and all internal points lie inside the boundary: If a point is inside the boundary it can be removed without changing the boundary, so it is internal. If a point is internal it is inside the boundary of the remaining points, and so is inside the boundary of the full set.

It is evident that set (of 2 or more points) has either 2 or 3 external points. Two points suffice to define a circle by specifying a diameter. Three points are sufficient in general. Since a circle has zero width the probability of a 4th point falling on it is zero.

The probability of there being 2 external points in a set of $n$ points is

$$P = \frac{n - 2}{n}$$

(Mamon, private communication) which can be deduced from Eqns 3, 4 and 5 of Walke & Mamon (1989).

We can now obtain the probability of a point being internal in a set of $n \geq 3$ points. If the set contains 2 external points, the probability that a given point will be internal is $(n - 2)/n$. If the set contains 3 external points the probability is $(n - 3)/n$. Weighting these two probabilities by the relative frequencies of 2 or 3 external points (from Eq. 11) gives

$$P_n = \frac{n - 2}{n} P + \frac{n - 3}{n} (1 - P)$$

$$= \frac{(n - 1)(n - 2)}{n^2}.$$  

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