Einstein CLUSTER ALIGNMENTS REVISITED
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ABSTRACT

We examine whether the major axes of rich galaxy clusters tend to point toward their nearest neighboring cluster. We have used the data of Ulmer, McMillan, and Kowalski, who used position angles based on X-ray morphology. We also study a subset of this sample with updated positions and distances from the MX Northern Abell Cluster Survey [for rich clusters (R > 1) with well-known redshifts]. A Kolmogorov-Smirnov (K-S) test shows no significant signal for nonrandom angles on any scale ≤100 h⁻¹ Mpc. However, refining the null hypothesis with the Wilcoxon rank-sum test, we found a high confidence signal for alignment. Confidence levels increase to a high of 99.997%, since only near neighbors that are very close are considered. We conclude that there is a strong alignment signal in the data, consistent with gravitational instability acting on Gaussian perturbations.

Subject headings: galaxies: clusters: general — large-scale structure of universe

1. INTRODUCTION

It is well documented that clusters of galaxies tend to be elongated, elliptical systems (e.g., Carter & Metcalfe 1980), giving them major axes and "position angles" in the sky. Bingelli (1982) found that the major axes of rich galaxy clusters have the tendency (in projection) to point toward their nearest neighbor cluster, whose distance, dₚ, was closer than ~30 h⁻¹ Mpc. Since then, there have been multiple studies of whether this "Bingelli effect" actually exists. Much of this literature supports the reality of the effect. Flin (1987) and Rhee & Katgert (1987) both found significant alignments for dₚ less than ~30 h⁻¹ Mpc. West (1989) and Rhee, van Haarlen, & Katgert (1992) have also detected a signal for alignment. Plionis (1994) found weak alignment signals up to dₚ ~ 60 h⁻¹ Mpc, with more significant cluster alignments on smaller scales (10–30 h⁻¹ Mpc). Moreover, West, Jones, & Forman (1995) found evidence that galaxy cluster substructure tends to be aligned with its host cluster and surrounding environment out to ~10 h⁻¹ Mpc, which might help explain these alignments.

Not all authors favor an alignment effect, however. Both Struble & Peebles (1985) and Ulmer, McMillan, & Kowalski (1989; hereafter UMK) found no significant evidence that clusters point toward their nearest neighbor (see, however, Argyles et al. 1986).

Galactic positions may not be good tracers of the shape of a cluster, since galaxies contribute discreteness noise. Most clusters contain much more mass in hot, X-ray-emitting gas than in the galaxies themselves. Dark matter contributes more mass to the system than gas and galaxies combined. Thus, the shape of the actual cluster mass cannot be directly seen. However, it is believed that the X-ray-emitting gas within a cluster traces its gravitational potential (Sarazin 1986). X-ray morphology is then probably the best observable for determining galaxy cluster shape and orientation.

Cluster alignments are not crucial in distinguishing cosmological models, but they provide additional evidence in support of the gravitational instability hypothesis ofstructure formation (Shandarin & Klypin 1984; Splinter et al. 1997; Onuora & Thomas 2000).

For these reasons, the negative results of UMK are interesting. Whereas most authors used galaxies to define ellipticity and spatial orientation, both UMK and West et al. (1995) chose to use X-ray morphology. UMK did not find a statistical alignment for any nearest neighbor distance scale. There are many more papers (including West et al. 1995) that found an alignment effect than did not. Since UMK used the shape of the X-ray gas in their search for alignment, their negative results are even more important. Most analyses of numerical simulations of structure formation by gravitational instability from Gaussian initial perturbations predict alignments on some scale, which provides some physical motivation for detecting the alignments searched for by UMK.

Both Onuora & Thomas (2000) and Splinter et al. (1997), for example, predicted alignments for dₚ of at least 15 h⁻¹ Mpc for standard CDM models. Onuora & Thomas extended this distance to 30 h⁻¹ Mpc for ΛCDM models. Both of these studies showed that the predicted alignment differences for individual cosmological background models are not practical means for determining cosmological parameters, such as Ω. However, Splinter et al. presented evidence that cluster ellipticity and the scale dependence of cluster alignments probe the primordial power spectrum independently of the parameters of the background cosmology. The alignments in these simulations fit a general picture of cluster formation by hierarchical clustering in which material falls into the cluster along the large-scale filamentary structure, as interpreted by Shandarin & Klypin (1984). This picture has been supported by dynamical evidence of drainage along such filaments (Novikov et al. 1999).

2. DATA AND ANALYSIS

2.1. Subject Clusters and Position Angles

UMK determined the major-axis and position angles of 46 X-ray clusters observed by Einstein (UMK Table 1). The major axis served to define a position angle on the celestial sphere (measured counterclockwise from north). UMK used both R = 0 and R ≥ 1 Abell clusters in their original analysis. However, R = 0 clusters were never part of Abell's (1958) statistical sample and should not be used in nearest-
neighbor analyses (since one needs to be sure of the existence of both the source cluster and its nearest neighbor). UMK also created smaller subsets of clusters (out of their original 46) for analysis. We will re-examine only the largest (46 cluster) subset from UMK, since this was the only one that was large enough to use after we eliminated clusters for which we did not have good redshift information. We analyzed the data in UMK Table 1 as given, again with updated redshifts (results we show here), and then reanalyzed a subset of it that met our stringent selection criteria, as described below.

2.2. Potential Neighbor Sample

We start out with the 46 clusters from UMK Table 1 (see also Fig. 1). However, over the past 10 yr many clusters have new or revised redshifts, so we also searched an updated Abell cluster redshift survey to revise any of the nearest neighbors in UMK and also to apply constraints that will limit any selection effects and biases in our data. Our angles are measured counterclockwise from north, as in UMK. Our distances are measured for a Friedmann universe with $q_0 = 0$ and $H_0 = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

The recent success of galaxy cluster surveys (Miller et al. 1999, 2000, and references therein) gives us a large and uniform sample compared to previous efforts. The cluster redshifts and coordinates we have used are mainly from the MX Northern Abell Cluster Survey (MX; Slinglend et al. 1998; Miller et al. 2000). There are 256 Abell $R \geq 1$ clusters (i.e., decl. $\geq -27^\circ$) having measured redshifts and lying within $0.012 \leq z \leq 0.10$ and $|b| \geq 30^\circ$. These clusters have an average of 25 measured galaxies each, and 90% have more than one measured redshift. Having multiple redshifts per cluster is quite important, since the elongation in redshift space due to internal velocity dispersion in the cluster is easily comparable to typical nearest neighbor distances. Miller et al. (1999) found that cluster redshifts based on only one galaxy redshift are erroneous by $\pm 500 \text{ km s}^{-1}$ 41% of the time. While this error may seem small ($\sim 5 \text{ h}^{-1} \text{ Mpc}$), such an error can easily throw off the determination of the nearest neighbor in dense environments. This northern hemisphere sample is nearly complete to $z = 0.10$ (e.g., Miller & Batuski 2000). To define potential nearest neighbors, we searched through these 256 clusters, noting the distance and direction to the nearest neighbor and the distance to the nearest edge of the survey. We then made a potentially important cut: if the boundary of the survey region was closer than the nearest neighbor, the pair would not be used for our alignment statistics. This is because there is a potential nearer neighbor hidden outside the boundary.

After we applied the above constraints to the original UMK data, we were left with 25 clusters out of their original 46 (see Fig. 2). We call this our statistical sample, and we present our data in Table 1. We also found that 10 of these 25 clusters now have different nearest neighbors from those found by UMK. In four of these 10 cases, UMK used an $R = 0$ cluster as their nearest neighbor. In other words, the original UMK data set remains relatively unchanged, with 40/46 clusters having the same nearest neighbor in our new analysis. It is worth noting that the constraints that we apply to the original UMK data prevent a large number of biases from entering the analysis. For example, by using only $R \geq 1$ clusters, we are ensuring that our base cluster subset is a statistically complete sample. We also use clusters with multiple-galaxy–determined redshifts, so that we can be sure of their location. Finally, perhaps our most important improvement over the UMK data is that we exclude clusters for which the edge of the survey is closer than the nearest neighbor.

2.3. Analysis

We first analyze the UMK data as given (in their Table 1), with revised nearest neighbors for six clusters. Our purpose in reanalyzing the original UMK data is to deter-
mine whether their statistical analyses were sensitive enough to actually detect a cluster alignment. We note that the UMK data set contains \( R = 0 \) clusters and does not exclude clusters that have a survey edge that is closer than the nearest neighbor. We then analyze our subset of 25 clusters that meet our stringent selection criteria designed to produce a uniform well-controlled sample.

UMK have provided a position angle for the major axis of the cluster as measured via the X-ray emission. Since this is an orientation, not a direction, the angle between it and the projected direction to the nearest neighbor, the pointing angle \( \phi_p \), can only have a range of \(-90 \leq \phi_p \leq 90\). We also assumed that the sign is not significant, so we examine \( |\phi_p| \leq 90\). This coincides with the UMK procedure.

We therefore define alignment as a tendency for the angles \(|\phi_p|\) to be smaller than they would be if distributed isotropically, that is, uniformly over this interval. Most previous work has not really tested for alignment; rather, it has tested for any kind of anisotropy.

### 2.3.1. Reanalysis of UMK Data

We repeated the Kolmogorov-Smirnov (K-S) test as used by UMK to test against a distribution sampled from a population uniformly distributed over this interval, as \( \phi_p \) would be if there were no correlations. The K-S test (Lehman 1975) is used to test against the null hypothesis that the sample (our angles \( \phi_p \)) could be drawn from a parent population of \( \phi_p \). We have no a priori reason to believe that the parent distribution of \( \phi_p \) should be anything other than random. In other words, the null hypothesis is that the angles \( \phi_p \) are uniformly distributed with a uniform distribution of \( \phi_p \). The K-S test uses the maximum value of the difference between cumulative distribution functions as its diagnostic.

The K-S test assumes that the parent distribution is the same as our hypothetical parent distribution. The K-S test measures the significance of the null hypothesis being false. Although widely used in the "cluster alignment" literature, in fact it is more powerful at detecting a more specific signal (in our case, the signal of alignment) than some other tests. Using the K-S test, we conclude that the null hypothesis can be discounted with only 73% confidence. This is too small a confidence level to rule out the null hypothesis. We have also looked only at those clusters with \( d_p \) below some critical value, \( d_p \). For \( d_p \) down to 10 \( h^{-1} \) Mpc, the confidence for ruling out the null hypothesis is still too small.

Refinement of the null hypothesis makes an enormous difference. We are not looking for just any difference; we are looking for alignments, which means that the angles \( \phi_p \) are systematically lower than they would be if drawn from a uniform parent population of \( \phi_p \). The Wilcoxon rank-

### Table 1

| Abell No. (1) | R.A. (hr) (2) | Decl. (deg) (3) | Distance \( h^{-1} \) Mpc (4) | \( \phi \) (5) | Abell No. (6) |
|---------------|--------------|----------------|----------------|----------|--------------|
| 85 ........... | 0.652        | -9.617         | 162 166 87      |
| 119 ........... | 0.897        | -1.533         | 130 168 164     |
| 154 ........... | 1.138        | 17.400         | 185 150         |
| 168 ........... | 1.210        | -0.017         | 132 156 119     |
| 399 ........... | 2.920        | 12.817         | 210 31 401      |
| 401 ........... | 2.937        | 13.383         | 214 38 399      |
| 1367 ........... | 11.698       | 20.117         | 65 137 1656     |
| 1656 ........... | 12.957       | 28.250         | 69 49 1367      |
| 1767 ........... | 13.570       | 59.467         | 204 145 1904    |
| 1775 ........... | 13.660       | 26.617         | 208 117 1795    |
| 1795 ........... | 13.778       | 26.833         | 184 21 1831     |
| 1809 ........... | 13.847       | 5.400          | 228 1 1780      |
| 1904 ........... | 14.338       | 48.783         | 205 84 1767     |
| 1991 ........... | 14.870       | 18.833         | 171 56 1913     |
| 2029 ........... | 15.142       | 9.590          | 224 131 2028    |
| 2063 ........... | 15.343       | 8.817          | 104 5.9 2147    |
| 2065 ........... | 15.343       | 27.900         | 210 151 2056    |
| 2079 ........... | 15.433       | 29.050         | 192 41 2092     |
| 2107 ........... | 15.627       | 21.933         | 121 167 2152    |
| 2124 ........... | 15.718       | 36.217         | 192 135 2122    |
| 2147 ........... | 16.000       | 16.583         | 103 159 2151    |
| 2151 ........... | 16.050       | 17.883         | 116 2147        |
| 2152 ........... | 16.052       | 16.583         | 121 113 2151    |
| 2199 ........... | 16.448       | 39.633         | 88 43 2197      |
| 2670 ........... | 23.860       | -10.683        | 221 104 2659    |

### Table 1: Data Summary for Statistical Sample

| Clusters | Nearest Neighbor |
|----------|-----------------|
| R.A. (hr) (7) | Decl. (deg) (8) | Distance \( h^{-1} \) Mpc (9) | \( d_p \) (deg) (10) |
| 0.675 | -10.067 | 161 2.1 23.6 |
| 1.210 | -0.017 | 132 11.5 54.1 |
| 1.110 | 12.900 | 172 19.6 51.7 |
| 0.897 | -1.533 | 130 11.5 83.9 |
| 2.937 | 13.383 | 214 4.3 7.8 |
| 2.920 | 12.817 | 210 4.3 7.8 |
| 12.957 | 28.250 | 69 22.3 70.3 |
| 22.330 | 11.698 | 65 22.3 77.7 |
| 14.338 | 48.783 | 205 44.9 12.2 |
| 13.778 | 26.833 | 184 24.8 34.0 |
| 13.948 | 28.233 | 179 9.7 40.2 |
| 13.702 | 3.133 | 227 12.4 42.8 |
| 13.570 | 49.467 | 204 44.9 48.8 |
| 14.408 | 16.900 | 154 25.7 18.4 |
| 15.118 | 7.717 | 225 7.1 37.5 |
| 16.000 | 16.033 | 103 21.7 1.2 |
| 15.285 | 28.450 | 216 7.0 28.7 |
| 15.522 | 31.317 | 194 8.9 10.5 |
| 16.052 | 16.583 | 121 17.0 37.0 |
| 15.710 | 36.283 | 192 2.7 16.2 |
| 16.050 | 17.883 | 108 5.9 43.1 |
| 16.000 | 16.033 | 103 5.9 86.1 |
| 16.050 | 17.883 | 108 13.0 65.7 |
| 16.442 | 41.017 | 91 3.4 46.7 |
| 23.708 | -15.750 | 226 22.0 79.8 |

Note: Col. (1): Abell cluster number. Cols. (2)–(3): Right ascension and declination of the cluster (1950 epoch). Col. (4): Distance to the cluster. Col. (5): Position angle of the cluster. Cols. (6)–(10): For the nearest neighbor cluster. Col. (6): Number of the Abell cluster. Cols. (7)–(8): Right ascension and declination of the cluster (1950 epoch). Col. (9): Distance to the cluster. Col. (10): Distance between the cluster (1) and its nearest neighbor (given in col. [6]). Col. (11): "pointing" angle; see text for definition.

* Different nearest neighbor from that found by UMK.

** Different nearest neighbor from that found by UMK. However, UMK used an R = 0 cluster.
sumtest (WRS; Lehmann 1975) tests for this. The null hypothesis of WRS is that the sample is not systematically smaller or larger than the parent population. Thus, while WRS is more sensitive to alignment (small angles), it would not (for example) be sensitive to a tendency for the pointing angles to clump around 45°. The WRS ranks the populations and is thus sensitive to alignment differences between the real and assumed parent population. The WRS returns a signed result, indicating that our sample has systematically higher or lower \( \phi_p \)’s. By defining more precisely what is tested, a great increase in statistical power can be achieved.

Using WRS on the updated UMK data, we found no significant effect. However, if we use it only on the UMK clusters with \( d_s \leq 30 \, h^{-1} \) Mpc, we find (for the 38 UMK clusters that meet this criterion) 99.8% confidence in alignment. Restriction to smaller distances produces alignments with much higher confidence, as seen in Table 2. Refinement of the null hypothesis combined with restrictions to nearer neighbors produces a strong signal. We also note that the original UMK data (i.e., with six erroneous nearest neighbors) also shows a similarly strong significance (99.6%) for alignment. In other words, had UMK used a more targeted statistical tool (such as the WRS), they too would have certainly noted this alignment effect.

2.3.2. Analysis of Revised UMK Data

We next examined the set of our 25 clusters with corrected distances in our statistical sample. We observe that this set has fractionally fewer nearest neighbors at large distances than in UMK’s Table 1, suggesting corrections of misidentification of near neighbors in that sample. However, we still found no significant signal with the K-S test. Applying WRS to our entire controlled sample of 25 clusters produced, as it did with the entire UMK sample, no substantial confidence in alignment. Restricting the study to the clusters with \( d_s \leq 20 \, h^{-1} \) Mpc leaves 17 clusters, with a confidence level of 98.4%. More restrictive limits on distance produce increased confidence, up to very high levels, as with the UMK data.

Table 2 shows the results of the WRS test applied to both the original UMK data (with six revised cluster neighbors) and to the 25 clusters with corrected distances and stringent constraints to account for any biasing or selection effects. Table 2 shows the strength of the alignment effect as we vary the restrictions on how near the neighbors must be in order to be considered.

There are suggestive trends in the data. Although the UMK data contain nearly twice as many clusters, as more restrictive distance cuts are applied, the number of surviving clusters converge until both sets are nearly the same size for \( d_s \leq 10 \, h^{-1} \) Mpc. Because clusters have correlated spatial positions, a random error in cluster position measurement is much more likely to move a cluster away from a near neighbor than to create a spurious one. Our more well-controlled sample has a smaller mean nearest neighbor distance.

The UMK result, in this case, nevertheless shows a strong signal when even moderately restrictive cuts are made. By making these cuts we are most likely removing erroneous near-neighbor identifications. The surviving close near neighbors in UMK may well be correct, in spite of being at low Galactic latitude (where obscuration is a problem), being in poorly sampled regions, or being too close to a survey boundary.

3. CONCLUSIONS AND DISCUSSION

Re-examining the UMK Einstein cluster data, we find that testing for alignment (with WRS) rather than for any departure from uniformity of angles (as with K-S) allows us to find a significant signal for alignment in this data for clusters with nearest neighbors at distances \( d_s \leq 30 \, h^{-1} \) Mpc. When we use a more stringently defined sample, we still find a strong signal for alignment, reaching 3.34 \( \sigma \) when we restrict \( d_s \leq 10 \, h^{-1} \) Mpc. Thus, refinement of the null hypothesis has proven crucial in finding the alignment signal. Use of the well-controlled sample was in this case not necessary to find a signal, but it confirms (with a lower confidence due to a smaller sample size) that the X-ray emission from galaxy clusters does tend to point to the nearest cluster neighbor.

A potential weakness in most alignment studies is the search for nearest neighbor alignment rather than super-cluster axis alignment. In future, we plan to examine a larger sample using the supercluster axis finding procedure defined in Novikov et al. (1999). The work we present here serves to remove an inconsistency from the data analysis and help clarify some issues of statistical methodology.

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