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Filamentary Structure in an Objectively-Derived Deep Galaxy Sample?

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Abstract. The deep galaxy sample of MacGillivray & Dodd (1980), obtained from purely objective means, is investigated using the technique of Kuhn & Uson (1982) for the presence of structure of a filamentary nature. A variety of synthetic fields of galaxies (including both 'filament' and 'non-filament' models) generated by means of a computer simulation technique have also been studied for comparison purposes. No strong evidence for filamentary structure in the galaxy distribution is found for this deep sample.

Key words: galaxies, distribution

1. Introduction

Much controversy has surrounded, in recent years, the question of whether galaxies are distributed in space in a filamentary manner. Obviously, the outcome of such lines of enquiry holds important consequences for our understanding of physical processes present in the early Universe, and of the formation of galaxies in particular. It is now generally accepted that large scale agglomerations in the distribution of galaxies do exist (see *e.g.* Oort1984), and that there are large regions of space seemingly devoid of (or at least very deficient in) galaxies (*e.g.* Tarenghi *et al.* 1979; Kirshner *et al.* 1983; Parker *et al.* 1986). However, the picture of galaxies existing mainly in filaments or sheets (Einasto, Jöeveer & Saar 1980; Chincarini, Rood & Thompson 1981; Giovanelli & Haynes1982) is not yet secure Indeed, whilst individual instances of apparent filaments may be found to exist on the sky (Gregory, Thompson & Tifft 198.1; Parker 1986), this does not necessarily indicate that filamentary structure is a general phenomenon, nor that such filaments may not have arisen purely by accident. For example, the results of computer simulations have shown that many chance 'filaments' *do* occur (MacGillivray & Dodd 1982a, b). Clearly, the presence or absence of filamentary structure in the distribution of galaxies must be examined further to see if it *is* indeed a real, non-random phenomenon.

In an attempt to investigate the presence of filamentary structure in 2-D galaxy data, Kuhn & Uson (1982) developed a technique for searching for 'ridges' or filaments. This was applied, with apparent success, to a subset of the Lick galaxy catalogue (Shane &

Wirtanen 1967). Although it is not clear what subjective biases (if any) decided the choice of subset of the data used (which may have artificially enhanced the result), it is perfectly clear that any visual catalogue of galaxies suffers from severe subjective biases and these biases *do* have an effect on the results of statistical analyses (see *e.g.* Geller, de Lapparent & Kurtz 1984; de Lapparent, Kurtz & Geller1986).Ultimately, to avoid criticism due to the presence of subjective biases, analysis must be performed on catalogues obtained by purely objective means.

The COSMOS machine (MacGillivray & Stobie 1984) produces just such objective data. An objective sample of galaxies in a field of 15 square degrees of sky near the South Galactic Pole and containing galaxies done to $B \sim 22$ has already appeared in MacGillivray & Dodd (1980) and has been used for a large number of analyses (*e.g.* Hewett *et al.* 1981; MacGillivray & Dodd 1982a,b, 1984).In particular, the data have been studied by Fesenko (1982, 1984) and Guberman *et al.* (1983)in a search for evidence of filamentary or cellular structure. In the latter searches a negative result was obtained, and this was assumed by Guberman *et al.* (1983) as due to any filamentary structure present being completely swamped out by the sample containing objects over a wide range of distances. However, for consistency the technique of Kuhn & Uson (1982) ought to be carried out on the same data.

In the present paper, we present the results of applying the Kuhn and Uson technique to the MacGillivray & Dodd (1980) galaxy sample. Since the raw galaxy data are at our disposal, it is possible to reanalyse the data with different limiting magnitudes and with different spatial resolutions in order to examine the effects of such on the results. Comparison with synthetic fields of galaxies produced by means of a Monte-Carlo simulation technique will assist the interpretation of the results from the real data and also the assessment of the suitability of the Kuhn-Uson technique for detecting filamentary structure. In Section 2 we present a brief description of the procedural technique, while the results are presented in Section 3 and our conclusions discussed in Section 4.

2. The method

The Kuhn & Uson (1982) technique involves searching for ‘ridges’ or connected high-density points in the projected 2-D galaxy distribution, the latter being in the form of a 2-D array of galaxy density values. Full details of the procedure are given in the above paper, although a brief description is given here in. The technique involves the calculation of the quantity $\bar{\mu}$ which is the mean cosine of the direction between connected high-density array elements. One element in the array is initially chosen at random, and the ‘ridge-finding’ algorithm searches around this point (in the horizontal and vertical directions) until it finds the nearest element of highest density. This is then ‘visited’ next and the cosine of the angle of travel calculated. The procedure is repeated for the next nearest element of highest density and so on, except that elements which have already been visited are not revisited. The algorithm is allowed to continue until a suitable number of elements have been visited (in our case this was set at half the total number of non-zero elements) and the quantity μ calculated. This process is repeated 100 times (always selecting the starting array element at random) and the mean quantity $\langle \bar{\mu} \rangle$ calculated as is the standard error in the mean. In a ‘random’ (*i*.e. non-filament) situation, the expected value for this quantity is ~ 0.39. The presence of any detectable linear features in the galaxy data should be observed as higher values for this quantity. A disadvantage of the method as applied by Kuhn & Uson is that since the ridge-seeking algorithm proceeds in the horizontal and vertical directions in the array, the technique will be more sensitive to filaments which are aligned in these directions. It is conceivable that, given the appropriate spatial resolution, filaments which are not thus aligned will fail to be detected. Application of the technique to include the diagonal directions results in a higher base level for the quantity $\langle \bar{\mu} \rangle$, *e.g.* $\langle \bar{\mu} \rangle \sim 0.59$ for the random situation.

3. Results

The results of applying the technique to the MacGillivray & Dodd galaxy sample are given in Table 1, where we tabulate the quantity $\langle \bar{\mu} \rangle$ and its standard error for a range of limiting magnitudes and 'bin' resolutions. One noticeable observation we can make from Table 1 is that the value $\langle \bar{\mu} \rangle$ systematically increases with decreasing resolution, being larger than 0.40 in 3 out of 4 cases of 10 arc min bins. However, the standard error is also larger, and with these standard errors the results cannot be taken as indicating an effect significantly different from the 'non-filament' situation of $\langle \bar{\mu} \rangle \sim 0.39$.

In Table 2 can be seen the results of applying the technique to various synthetic fields of galaxies. The simulation technique (based on a Monte-Carlo random-number process) for generating these synthetic fields has been described in detail elsewhere (MacGillivray & Dodd 1982a, b). Essentially, galaxies are generated in three dimensional (3-D) space according to a specified clustering description, are projected onto the plane of the sky and subsequently 'detected' by means of a process which attempts to emulate the atmosphere/telescope/photographic-plate/measuring-machine combination. The final data-set for each simulation is a catalogue of simulated galaxies. In the generation of this catalogue, all factors affecting the detection of these simulated galaxies and inclusion in the catalogue are applied in as close a manner as possible to the effects leading to the inclusion of galaxies in the catalogue of real data. Likewise, in the simulations, the angular field dimensions, limiting magnitude and total number of detected galaxies are identical to the observed data in order to make the subsequent analysis of the simulated galaxy data identical to the analysis of the real data. We used herein $H_0 = 75$ km s^{-1} Mpc^{-1}, $q_0 = +1$ and assumed no evolution of the galaxies in terms of luminosity, colour or distribution.

Table 1. The quantity $\langle \bar{\mu} \rangle$ and its standard error for the data of MacGillivray & Dodd (1980) tabulated as a function of limiting magnitude and resolution.

Limiting magnitude B	Resolution (arcmin)		
	5 × 5	$7\frac{1}{2} \times 7\frac{1}{2}$	10 × 10
22	0.387 ± 0.012	0.402 ± 0.016	0.414 ± 0.019
21	0.393 ± 0.012	0.393 ± 0.016	0.390 ± 0.018
20	0.380 ± 0.013	0.392 ± 0.017	0.401 ± 0.024
19.5	0.383 ± 0.015	0.401 ± 0.017	0.407 ± 0.022

Table 2. The quantity $\langle \bar{\mu} \rangle$ and its standard error tabulated as a function of limiting magnitude and resolution.

Limiting magnitude B	Resolution (arcmin) 5 × 5	$7\frac{1}{2} \times 7\frac{1}{2}$	10 × 10
(a) for a synthetic galaxy field consisting of randomly distributed clusters:			
22	0.392 ± 0.012	0.384 ± 0.015	0.408 ± 0.020
21	0.392 ± 0.010	0.381 ± 0.016	0.376 ± 0.027
20	0.389 ± 0.013	0.400 ± 0.018	0.419 ± 0.024
19.5	0.390 ± 0.013	0.381 ± 0.018	0.377 ± 0.024
(b) for a synthetic field consisting of clusters of galaxies clustered into superclusters:			
22	0.374 ± 0.011	0.375 ± 0.018	0.414 ± 0.028
21	0.390 ± 0.012	0.375 ± 0.018	0.385 ± 0.024
20	0.375 ± 0.013	0.365 ± 0.018	0.392 ± 0.023
19.5	0.387 ± 0.015	0.382 ± 0.017	0.404 ± 0.020
(c) for a synthetic field in which galaxies are distributed in long filaments:			
22	0.441 ± 0.018	0.459 ± 0.025	0.444 ± 0.034
21	0.424 ± 0.023	0.478 ± 0.036	0.461 ± 0.033
20	0.418 ± 0.021	0.474 ± 0.032	0.445 ± 0.046
19.5	0.405 ± 0.028	0.476 ± 0.050	0.492 + 0.033

For the purposes of the present paper, three different models were generated:

(a) clusters were generated at random in 3D space;
(b) clusters were themselves clustered into spherical 'superclusters' of size 10 h^{-1} Mpc; and
(c) clusters were generated uniformly within 'filaments' (or prolate spheroids) with major axis of length 15 h^{-1} Mpc and with axial ratio of 20:1. Furthermore, these filaments were allowed to have random orientations in 3D space.

The results of applying the Kuhn–Uson technique to each of the synthetic fields are shown in Table 2 for the above cases (a), (b) and (c). We see from Tables 2(a) and (b) that in both the randomly distributed cluster case and in the supercluster case, the results generally fluctuate about the value of 0.39 which is what we expect. Large values for the quantity $\langle \bar{\mu} \rangle$ are obtained for some situations of 10 arcmin resolution. However, to within their standard errors, the results are not different from the theoretically expected value, and there is no obvious correlation with limiting sample magnitude.

The results from the model involving the presence of filaments (Table 2c) *are,* however, more interesting. There are several points worthy of note in this table. Firstly, high values for the quantity $\langle \bar{\mu} \rangle$ (*i.e.* > 0.4) are consistently obtained for all sample depths (limiting magnitudes) and for all spatial resolutions. In general, the values are higher than the expected value of 0.39 by an amount which is greater than the standard error. It must be pointed out, however, that in these data the standard errors in the statistic $\langle \bar{\mu} \rangle$ are high, and the values in Table 2(c) do not represent a large deviation (in statistical terms) from the random case. We think that this is a problem of small sample size which should be improved in a study of a much larger area of sky. Secondly, the detection of the presence of filamentary structure is stronger for brighter sample limits and for lower spatial resolutions, although nonrandom linear structure is still detected for faint sample limits and high resolution.

We conclude that the Kuhn & Uson technique is capable at least of indicating the presence of linear-type structures in the distribution of galaxies. Table 2(c) represents one particular example of a model involving filamentary structure. In actual fact, several such models were generated (each with a different amplitude for the filamentary structure) and the results studied. Obviously the detectability of filamentary structure depends upon the amplitude of that structure, the depth of the sample and the binning resolution. For example, the presence of features of low amplitude will be very difficult to detect at the best of times, and this task is made more difficult if such weak features are even further diluted by foreground and background contamination over a wide range of redshifts. Nonetheless, our extensive simulations have indicated that if filaments are a major characteristic of the distribution of galaxies (even when of a low-amplitude nature), then the Kuhn-Uson algorithm ought to reveal the presence of such. This is especially true for samples limited at bright magnitudes and with low spatial resolution for binning where, even for such low-amplitude linear features, the results generally reflect the trends shown in Table 2(c).

4. Conclusion

We have applied the technique of Kuhn & Uson (1982) to the galaxy sample of MacGillivray & Dodd (1980). The results indicate that, at least for this galaxy sample, the data do not provide strong confirmation of the presence of filamentary structure. In this respect, the results are in agreement with those of Fesenko (1982, 1984) and Guberman *et al.* (1983). Although large values for the statistic $\langle \bar{\mu} \rangle$ are obtained (especially when the resolution is low), the standard errors are large and the results are not different from the non-filament situation to within these standard errors. The results are not changed when analysis is restricted to the brighter galaxies where we might expect to investigate galaxies in a lower and more localized redshift interval, and hence wherein contamination due to galaxies in a large redshift range is reduced.

The comparison with Monte-Carlo simulations has proved valuable and has enabled an assessment to be made of the usefulness of the Kuhn-Uson technique. As expected, for non-filament models, the results revealed values for $\langle \bar{\mu} \rangle$ which were generally around the value of 0.39. Some higher values for this quantity were obtained but these were all within the associated standard errors. Simulations involving the presence of filamentary structure *do* indeed produce high values for $\langle \bar{\mu} \rangle$ æ, and these values are different from the expected 'random' value by an amount greater than the standard error. The exact values for $\langle \bar{\mu} \rangle$ for such models', and hence the detectability of filamentary structure, depends upon the amplitude of that structure, the depth of the galaxy sample and the resolution of the galaxy counts. However, the presence of even weak structures can still be detected by the technique, especially for samples limited at bright magnitudes.

In the light of the above, it is interesting to note that in the real sample of galaxies (Table 1), there is a slight tendency for high values of $\langle \bar{\mu} \rangle$ at bright magnitudes and low counting resolution. It is tempting to suggest that this is indicative of the presence of very weak linear structure. However, the results are not convincingly different from the non-filament situation, and do not alter our conclusion concerning the lack of strong evidence for filamentary structure in these data.

Although the results herein are not encouraging for the objective verification of the existence of filamentary structure, it must be borne in mind that the sample of galaxies used is restricted to a small angle of sky and we may be looking at a region which (purely by chance) is deficient in filamentary structure. It is now necessary to repeat the analysis on a larger sample of galaxies covering a much larger area of sky, and this we intend to do on the catalogue of galaxies in the southern sky which is being carried out by the COSMOS machine (Collins *et al.* in preparation).

References

Chincarini, G., Rood, H. J., Thompson, L. A. 1981, *Astrophys. J.,* **249,** L47
de Lapparent, V., Kurtz, M. J., Geller, M. J. 1986, *Astrophys. J.,* **304,** 585
Einasto, J., Joeveer, M., Saar,E.1980, *Mon. Not. R. astr. Soc.,* **193,** 353.
Fesenko, B. I. 1982, *Pis'ma Astr. Zh.,* **8**, 458: *Soviet Astr. Lett.,* **8,** 247.
Fesenko, B. I. 1984, *Astrofizika,* **21,** 296: *Astrophys.,* **20,** 495.
Geller, M. J., de Lapparent, V., Kurtz, M. J. 1984, *Astrophys. J.,* **287,** L55.
Giovanelli, R., Haynes, M. P. 1982, *Astr. J.,* **87,** 1355.
Gregory, S. A., Thompson, L. A., Tifft, W. G. 1981, *Astrophys. J.,* **243,** 411.
Guberman, Sh. A., Doroshkevich, A. G., Kotok, E. V., Shandarin, S. F. 1983, *Astrofiz.,* **19,** 97: *Astrophys.,***19,**58.
Hewett, P. C., MacGillivray, H. T., Dodd, R. J. 1981, *Mon. Not. R. astr Soc.,* **195,** 613.
Kirshner, R. P., Oemler, A., Schechter, P. L., Schectman, S. A. 1983, *Astrophys. J.,* **248,** L57.
Kuhn, J. R., Uson, J. M. 1982, *Astrophys. J.,* **263,** L47.
MacGillivray, H. T., Dodd, R. J. 1980, *Mon. Not. R. astr. Soc.,* **193,** 1.
MacGillivray, H. T., Dodd, R. J. 1982a, in *IAU Symp.* 104: *Early Evolution of the Universe and its Present Structure,* Eds G. O. Abell & G. Chincarini, D. Reidel, Dordrecht, p. 401.
MacGillivray, H. T., Dodd, R. J. 1982b, *Astrophys. Space Sci.,* **86,** 437.
MacGillivray, H. T., Dodd, R. J. 1984, *Astrophys. Space Sci.***,** **105,** 331.
MacGillivray, H. T., Stobie, R. S. 1984, *Vistas Astr.,* **27,** 433.
Oort, J. H. 1984, *A. Rev. Astr. Astrophys.,* **21,** 373.
Parker, Q. A. 1986, *PhD Thesis,* Univ. St Andrews.
Parker, Q. A., MacGillivray, H. T., Hill, P. W., Dodd, R. J. 1986, *Mon. Not. R. astr. Soc.,* in press.
Shane, C. D., Wirtanen, C. A. 1967, *Pub. Lick Obs.,* **22,** Part 1.
Tarenghi, M., Tifft, W. G., Chincarini, G., Rood, H. J., Thompson, L. A. 1979, *Astrophys. J.,* **234,** 793.