Inter-cluster Filaments of Galaxies Programme: Abundance and Distribution of Filaments in the 2dFGRS Catalogue

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ABSTRACT
Filaments of galaxies are known to stretch between galaxy clusters at all redshifts in a complex manner. In this Letter, we present an analysis of the frequency and distribution of inter-cluster galaxy filaments selected from the 2dF Galaxy Redshift Survey. Out of 805 cluster-cluster pairs, we find at least 40 per cent have bone-fide filaments. We introduce a filament classification scheme and cast the filaments into several types according to their visual morphology: straight (lying on the cluster-cluster axis; 37 per cent), warped or curved (lying off the cluster-cluster axis; 33 per cent), sheets (planar configurations of galaxies; 3 per cent), uniform (1 per cent) and irregular (26 per cent) We find that straight filaments are more likely to reside between close cluster pairs and they become more curved with increasing cluster separation. This curving is toward a larger mass concentration in general. We also show that the more massive a cluster is, the more likely it is to have a larger number of filaments. Our results are found to be consistent with a Λ cold dark matter cosmology.

Key words: surveys – galaxies: clusters: general – large-scale structure of the Universe – cosmology: observations

1 INTRODUCTION
The filamentary structure of the Universe has long been predicted by structure formation modelling (e.g. Zeldovich, Einasto & Shandarin 1982; Katz et al. 1996; Jenkins et al. 1998). In such N-body simulations, clusters of galaxies reside at the nodes of the network of matter. Filaments of galaxies (FOGs) themselves are observed to stretch between clusters, and indeed superclusters of galaxies, at low redshifts (e.g. Kaldare et al. 2003; Einasto et al. 1997; Kalinkov & Kuneva 1995), forming a characteristic sponge-like structure through the Universe (Erdoğdu et al. 2004; Drinkwater 2000; Bond, Kofman & Pogosyan 1996). Moreover, it is clear from the work of Colberg et al. (1999) that FOGs are very important for the baryonic mass budget of the Universe as they can contain up to 40 per cent of the total cluster mass at clustocentric radii of 4–6.5 h⁻¹ Mpc (we use \( H_0 = 100 \) km s⁻¹ Mpc⁻¹ and \( q_0 = 0.5 \) throughout this work).

Various observational campaigns are underway that are reinforcing this web-like view of the Universe (Colless et al. 2001; York et al. 2000; Einasto et al. 2001). By examining the regions between close cluster pairs, observational evidence for many and varied FOGs is growing (e.g. Pimbblet & Drinkwater 2004; Dietrich et al. 2004; Gal & Lubin 2004; Ebeling, Barrett, & Donovan 2004; Drinkwater et al. 2004, amongst others) and not only at optical wavelengths (e.g. Durret et al. 2003; Bagchi et al. 2002; Tittley & Henriksen 2001; Ensslin et al. 2001; Scharf et al. 2000); although detection of (X-ray emitting gas from) filaments has not been without some failures (Briel & Henry 1995). One is left considering several questions: (i) how common are FOGs? (ii) how surprised should one be to find a filament of a given length or morphology?

In a study designed to address these questions Colberg, Krughoff & Connolly (CKC; 2004) investigate the frequency and distribution of filaments in a Λ cold dark matter (ΛCDM) Universe using simulations from Kauffmann et al. (1999). They show that approximately half of all inter-cluster filaments are warped (lying off the cluster-cluster axis) and are statistically longer than straight filaments. Further, FOGs are more likely to be found between clusters that are spatially close and more massive clusters possess more filaments.

Motivated by CKC, in this Letter, we utilize the 2dF Galaxy Redshift Survey (2dFGRS; e.g. Colless et al. 2001) final data release (FDR) to characterize a spectroscopic sample of inter-cluster filaments and compare this distribution to CKC. The format of this paper is as follows. In Section 2
we define the filament sample from the 2dFGRS FDR. We then visually type our filaments into a new classification scheme that we introduce. In Section 3 we investigate the fractional abundance of different types of filament, the likelihood of finding different types of filament connecting cluster pairs and the average number of filaments per cluster. Our results and caveats are then summarized in Section 4.

2 METHODOLOGY

The observations made by 2dFGRS are summarized by Colless et al. (2001) and here we only recount the pertinent detail. The input catalogue for 2dFGRS is the APM survey of Maddox et al. (1990a,b). Targets are selected to be brighter than an extinction-corrected magnitude limit of $b_J = 19.45$ within three strips of the APM survey (NGP, SGF and random fields) covering an area in excess of 1500 deg$^2$. Subsequently, quality ($quality \geq 3$; see Colless et al. 2001) redshifts for 221414 galaxies have been published as part of the 2dFGRS FDR. The redshift completeness of the 2dFGRS FDR is estimated to be 90 per cent ($b_J < 19.0$) with an rms redshift error of $\Delta z = 85$ km s$^{-1}$ and a median redshift of $<z> = 0.1$ (Colless et al. 2001).

From an earlier sample of 173084 galaxies, De Propris et al. (2002) generate a catalogue of galaxy clusters and cross-correlate them with those of Abell (Abell 1958; Abell, Corwin & Olowin 1989), the Edinburgh-Durham Cluster Catalogue (EDCC; Lumsden et al. 1992) and the APM survey itself (APMCC; Dalton et al. 1997). De Propris et al. (2002) report over 800 individual cluster correlations and calculate new velocity dispersions for them. From their catalogue, we select potential inter-cluster filaments to study by applying the following criteria:

- The clusters must be spatially close, < 10.0 degrees on the sky. At a median redshift of $<z> = 0.1$, this corresponds to a projected length of $\approx 45$ h$^{-1}$ Mpc.
- Their recession velocities must not differ by more than $\Delta v = 1000$ km s$^{-1}$.
- Clusters common to the Abell, EDCC and APMCC catalogues are removed to prevent self-pairing.

Applying these criteria spawns 805 unique potential inter-cluster filaments.

Based upon CKC, we now proceed to classify these potential FOGs into various types. Firstly, we convert all measurements into h$^{-1}$ Mpc. We then draw a vector from one cluster centre to the other and extract all galaxies within 5 h$^{-1}$ Mpc of this axis. These galaxies are then placed onto two orthogonal planes containing the inter-cluster axis and smoothed with a circular top-hat function of radius 1 h$^{-1}$ Mpc. We (KAP & MJD) then visually inspect the two orthogonal projections of the galaxy distribution and classify any filament(s) according to the scheme presented in Table 1. Our scheme attempts to tidy up the definitions used by CKC whilst the number of categories used is determined subjectively by the number of distinct FOG types suggested by the data. After a first pass, we determined that we were missing highly curved filaments (specifically ones that stretch out beyond 5 h$^{-1}$ Mpc from the inter-cluster axis) particularly at large cluster-cluster separations. This prompted us to extend our cut-off width when looking at the orthogonal planes to $\pm 20$ h$^{-1}$ Mpc from the inter-cluster axis (but retaining a depth of $\pm 5$ h$^{-1}$ Mpc: doing so yielded more Types II–V FOGs, especially at larger inter-cluster separations. Typical examples for filaments of Types I through IV–V are displayed in Figure 1. Although we tried to automate the typing process, there are too many (and complex) deviations from the simple configurations described in Table 1 to reliably employ any automated process (c.f. CKC who experience the same problem). Ideally, we would replace our subjectivity with new, objective statistics of FOG structure (Bharadwaj & Pandey 2004), but this is beyond the scope of the present work.

3 RESULTS AND DISCUSSION

The fractions of each type of filament are presented in Table 2. At least > 30 per cent of the cluster pairs in our sample have no filamentary connection between them. This percentage is much smaller than the 81 per cent noted by CKC. This is likely due to: (i) differences in what we classify as a connected cluster pair; (ii) selection effects: CKC only use Abell richness class $R = 0$ clusters (Abell 1958) in their analysis whereas our 2dFGRS sample contains much richer clusters and may therefore be more likely to display filamentary connections; (iii) they intentionally avoid clusters pairs that have tertiary clusters near the cluster axis. (iv) we probe a larger width from the inter-cluster axis (see Section 2).

To compare our fractions with CKC, we firstly note that their classifications do not quite have a one-to-one correspondence with ours. CKC type filaments as: straight, off-centre, warped/irregular and other. Whilst their definition of a straight filament is identical to our Type 1, we have rearranged their ‘off-centre’ and ‘warped/irregular’ into Types II and V. Their ‘other’ configurations, however, include definitions of our Types III and IV, so a direct comparison (albeit as a fraction of the whole sample) is possible. In Table 3, we compare the overall fractions of our sample (Table 2) to the CKC fractions. There is an excellent similarity between the percentages for all filament types. We note that accounting for probing a larger width from the inter-cluster axis than CKC does not significantly change the relative overall fractions in Table 2. We conclude that the distribution of filament morphology is the same as found by CKC. This suggests that the cluster richness differences in our two samples are not driving the form of the filamentary connections: Type III and IV filaments are equally rare between all richness classes.

3.1 Filament length

For Type I and II filaments, we are able to measure their length ($\approx$ inter-cluster separation) and calculate their fractional abundance in the whole sample as a function of cluster separation. Figure 2 displays the result of this abundance analysis.

Very close cluster pairs, within 5 h$^{-1}$ Mpc of each other, will always possess a filament. Such a filament will nearly always be a Type I (if it is discernable from a Type 0). This is
Table 1. The classification scheme used in this work.

| Type | Filament Description |
|------|----------------------|
| 0    | Near-coincident clusters. The cluster pair overlaps to such a degree that any filament present cannot be isolated. |
| I    | Straight. The filament of galaxies runs along the axis from one cluster centre to the other. At small separations, the infall regions of the clusters likely overlap. |
| II   | Warped (Curved). The galaxies lie off the axis and continuously curve (in a ‘C’ or ‘S’-shape for example) from one cluster centre to the other. |
| III  | Sheet (Planar; Wall). The filament appears as Type I or II viewed from one direction but are the galaxies are approximately evenly spread out in the orthogonal view. |
| IV   | Uniform. Galaxies fill the space between the clusters in an approximately uniform manner viewed from any direction. |
| V    | Irregular (Complex). There are one or more connections between both cluster centres, but the connections are irregular in shape and often have large density fluctuations. |

Figure 1. Orthogonal pairs of projected galaxy density for selected examples of Type I with overlapping cluster infall zones (top left), Type II (top right), Type III (bottom left) and Type IV–V (bottom right) FOGs. The outermost contour denotes 1 galaxy per $h^{-1}$ Mpc and each contour inward is an increase of 2 galaxies per $h^{-1}$ Mpc to a maximum of 19 galaxies per $h^{-1}$ Mpc. The vertical solid line running up the centre of these plots is the inter-cluster axis. The intersection of the horizontal solid lines and the inter-cluster axis denote the (sometimes ill-defined) locations of the cluster centres. All units are in $h^{-1}$ Mpc and the depth of each plane is 10 $h^{-1}$ Mpc.

of little surprise given that such close cluster pairs will typically possess overlapping infall regions (CKC; Rines et al. 2003; Diaferio & Geller 1997). With increasing separation, the likelihood of being connected by a Type I or II filament drops \(\sim\) linearly. However, straight filaments of Type I are much more likely to be extant in close cluster pairs than Type II (Figure 2). As with CKC, our visual inspections of the longer Type II filaments indicate that they are often tidally arched toward secondary masses.

We note that there are differences in comparison to CKC. At just over 40 $h^{-1}$ Mpc inter-cluster separation, we have a Type II fraction of \(\approx 0.23\) (Figure 2) compared to
Table 2. Filament percentages for different samples. The column headed ‘nil’ indicates that no filament is detected. Where present, the number in brackets is the percentage of uncertain classifications within each type. The ‘Connected’ sample removes the ‘nil’ detections from the whole sample. Similarly; ‘Filaments’ removes Type 0 from the ‘Connected’ sample and ‘Certain Filaments’ removes all the uncertain classifications from the ‘Filaments’ sample.

| Sample     | Percentage by Type |
|------------|--------------------|
|            | 0   | I   | II  | III | IV  | V   | nil |
| Whole Sample | 6.2 (0) | 20.8 (16.5) | 22.0 (32.7) | 3.9 (56.0) | 1.9 (75.0) | 14.7 (22.7) | 30.2 (0) |
| Connected   | 8.9 (0) | 28.4 (16.5) | 32.1 (32.7) | 5.8 (56.0) | 2.7 (75.0) | 21.5 (22.7) | n/a |
| Filaments   | n/a | 31.3 (16.5) | 35.2 (32.7) | 6.3 (56.0) | 2.9 (75.0) | 23.7 (22.7) | n/a |
| Certain Filaments | n/a | 30.9 | 33.5 | 3.6 | 0.8 | 25.9 | n/a |

Table 3. Comparison of our filament fractions (rounded) to CKC. Quoted errors are simple Poissonian ones. The percentages are relative to the ‘certain filaments’ or ‘whole sample’ (Table 2) as quoted by CKC.

| Type     | Sample | CKC (%) | This work (%) |
|----------|--------|---------|---------------|
| I        | certain | 38±4   | 37±3          |
| II+V     |        | 62±5   | 63±3          |
| III      | whole  | 2±1    | 3±1           |
| IV       |        | 3±1    | 2±1           |

≈ 0.09 by CKC. Since we have a larger search radius from the inter-cluster axis than CKC, we find more Type II filaments at these radii (see Section 2) than CKC. Restricting ourselves to smaller radii from the inter-cluster axis reduces the number of long Type II filaments and we are able to recover (within error) the distribution presented by CKC.

3.2 Cluster connections

How inter-connected are the clusters and how many filaments can we expect a given cluster to have? We can address this question by computing the average number of filaments per cluster as a function of cluster velocity dispersion. However, due to the geometry of 2dFGRS, clusters located at the edges of the observed strips may have a smaller number of filaments than those in the centre of the strips. To attempt to alleviate this, we only consider those clusters inside a 10 h⁻¹ Mpc buffer from the observational edges of 2dFGRS. Further, we cull from the sample high redshift clusters (cz > 45000 km s⁻¹) as the cluster sample is more likely to be incomplete at such redshifts. Finally, if a given cluster is connected to two or more clusters by the same filament, we only count that filament once.

The result of this analysis is shown in Figure 3. There is a clear trend for clusters with larger velocity dispersions to possess more filaments. Since the virial mass of a cluster, \( M_{\text{virial}} \propto (\text{velocity dispersion})^2 \) (e.g. Binney & Tremaine 1987), we can inductively state that more massive clusters are more likely to have more filaments. This is consistent with ΛCDM cosmology as more massive objects are more clustered than lower mass objects (c.f. CKC who obtain a similar result).

Figure 2. Abundance of filaments as a function of cluster separation (solid line). The dotted and dashed lines show show the individual contributions of Types I and II (respectively) to the abundance whilst the dot-dash line is the combined abundance of Types I plus II. Poissonian errorbars are given for Types I and II.

Figure 3. Histogram of the average number of filaments per cluster as a function of cluster velocity dispersion with 1σ error bars. There is a trend for the number of filaments to increase with velocity dispersion.

4 CAVEATS AND SUMMARY

Clearly, our classifications of the filaments are subjective. For example, in ~ 15 per cent of cases we are confident that a filament conjoins the cluster pair, but are unable to agree upon (or discern) a definite typing according to Table 1. Further, the inter-cluster filament can be a small segment or chord of a much larger FOG that connects more than two galaxy clusters. As such, it is possible that the inter-cluster FOG may locally be straight (Type I), but on larger
The result of this is to increase the number of uncertain classifications and the number of ‘nil’ entries by $\sim$ few per cent compared to the values presented in Table 2. The relative fractions of ‘certain filaments’ (Table 2), remain statistically the same, however. We therefore do not view that this assumption has a great effect on the results presented here.

In our selection criteria, we extract cluster pairs with $\Delta cz < 1000 \text{ kms}^{-1}$. In doing so, we may have eliminated some pairings (i.e. potential filaments within a small solid angle along the line of sight) and effects caused by ‘finger-of-god’ elongations in redshift space (see Hawkins et al. 2003 and references therein). An examination of the distribution of angles to the line of sight, however, shows no evidence that we have have misclassified ‘fingers-of-god’ as FOGs.

Our results enforce the view that cluster of galaxies are not simple, isolated objects but nodes along a filament of galaxies that can be made up of many sub-entities (e.g. other clusters). Our main results are:

- We introduce a new classification scheme for FOGs that stretch between galaxy clusters. This scheme is based upon the different types of filament observed in 2dFGRS and we emphasize that it is a purely visual classification scheme.

- Filamentary connections between galaxy clusters are common at the median 2dFGRS redshift of $<cz> = 0.1$. In close cluster pairs, there is almost always a Type I filament (Straight) connecting them. At larger cluster separations (> 5 h$^{-1}$ Mpc), Type II filaments (Curved) become more common. Type II filaments are often seen to bend toward other mass concentrations nearby.

- Whilst Type I, II and V (Irregular/Complex) filaments are very common, Types III (Sheets) and IV (Uniform) are very rare, comprising no more than 4 per cent of the total filament population.

- The vast majority of all clusters have a filamentary connection with their (close) neighbours. The number of filaments per cluster scales with the velocity dispersion, and hence mass, of a given cluster.

All of these results are consistent with a ΛCDM cosmology (CKC). In the future, it will be interesting to compare these results to the Sloan Digital Sky Survey (e.g. York et al. 2000) and on-going higher redshift surveys such as the Luminous Red Galaxy Survey (e.g. Padmanabhan et al. 2004; Cannon et al. 2003). We can then address the interesting question of if FOGs have evolved significantly over a large cosmologically significant timescale (e.g. are Type II filaments more abundant at lower redshifts?). We also plan to investigate alternative statistical techniques that may provide more objective, quantitative measurements of filamentary structure in datasets such as this.

This work follows Pimbblet & Drinkwater (2004) and is the second publication in a series on inter-cluster filaments of galaxies.

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