Star formation in galaxies along the Pisces-Cetus Supercluster filaments

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ABSTRACT
We investigate the variation of current star formation in galaxies as a function of distance along three supercluster filaments, each joining pairs of rich clusters, in the Pisces-Cetus supercluster, which is part of the two-degree Field Galaxy Redshift Survey (2dFGRS). We find that even though there is a steady decline in the rate of star formation, as well as in the fraction of star forming galaxies, as one approaches the core of a cluster at an extremity of such a filament, there is an increased activity of star formation in a narrow distance range between $3-4h^{-1}_{70}$ Mpc, which is 1.5–2 times the virial radius of the clusters involved. This peak in star formation is seen to be entirely due to the dwarf galaxies ($-20 < M_B < -17.5$). The position of the peak does not seem to depend on the velocity dispersion of the nearest cluster, undermining the importance of the gravitational effect of the clusters involved. We find that this enhancement in star formation occurs at the same place for galaxies which belong to groups within these filaments, while group members elsewhere in the 2dFGRS do not show this effect. We conclude that the most likely mechanism for this enhanced star formation is galaxy-galaxy harassment, in the crowded infall region of rich clusters at the extremities of filaments, which induces a burst of star formation in galaxies, before they have been stripped of their gas in the denser cores of clusters. The effects of strangulation in the cores of clusters, as well as excess star formation in the infall regions along the filaments, are more pronounced in dwarfs since they are more vulnerable to the effects of strangulation and harassment than giant galaxies.

Key words: Galaxies: clusters: general; Galaxies: evolution; Galaxies: starburst; Cosmology: observations.

1 INTRODUCTION
Star formation within individual galaxies is triggered by gravitational instabilities, induced by pressure variations due to density waves or shear forces, random cloud collisions or shocks due to stellar winds and supernova explosions (e.g. Kennicutt [1998]). It is becoming increasingly clear that, in addition to these, the influence of external effects, related to the immediate environment of the galaxy, are equally important in inducing star formation. Among the latter are the effects of merger and collision, stripping, accretion and harassment, which are responsible for both the triggering of star formation and quenching the process as the galaxy loses its gas content.

It has been shown that the average rate of star formation in galaxies varies widely with redshift (e.g. Madau, Pozzetti, & Dickinson 1998; Poggianti et al. 2006), and so does the relative morphological fraction of galaxies (e.g. Abraham et al. 1996; Goto et al. 2003), providing direct evidence of the chemical evolution of galaxies with time. At any given redshift, however, the rate of star formation in a galaxy, and the morphological content of the galaxy population, change with the local environment. Early studies showed that the relative morphological content of galaxies in a given volume of space depends on the local projected galaxy density (e.g. Dressler 1980). Even though there is a clear link between the average star formation rate (SFR) of a galaxy and its morphology (e.g. Menanteau et al. 2006), detailed photometric and spectroscopic studies covering a large range of redshift (e.g. Ravindranath et al. 2006; Yuan et al. 2007) show that they cannot be used as proxies of one another.

Effects of this nature have been extensively studied in galaxy clusters, where there is clear evidence of a systematic variation of properties like morphology, shape and SFR with distance from the centre of the cluster (e.g. Melnick & Sargent 1977; Whitmore, Gilmore, & Jones 1993; De Propris et al. 2003), even at higher redshifts (e.g. [2006]).
It is therefore interesting to investigate further into the nature of the evolution of galaxies, and which aspects of their physics respond to the local environment of the galaxy, and in what way. In the cores of rich clusters, for instance, it has been long known that the star formation rate in galaxies is highly suppressed \citep{Dressler1980, Whitmore1983}, and the current rate of star formation progressively decreases as the environment becomes denser \citep[e.g.][]{Balogh1998, Lewis2002, Gomez2003}. This effect seems to be more pronounced among giant galaxies ($M_R < 20$), whereas dwarfs are found to be passive only within the virial radius of the cluster, outside which almost all dwarfs are found to be star-forming \citep{Haines2006a}.

Given that only a minority of galaxies lie in clusters, is this a representative picture of galaxy evolution? The projected local density of galaxies seems to be a naive representation of the environment of the galaxy, given the complex histories of galaxies. Observations and simulations of the large-scale structure of the Universe have also shown galaxies to be arranged in a network of filaments and voids \citep{Einasto1994, Jenkins2003}. In simulations, galaxies seem to form in groups on this filamentary network, and with time the groups merge with others as they fall into rich clusters which lie at the intersections of these filaments. Indeed, observational evidence of such infall of groups, preferentially from the directions to neighbouring rich clusters, have been found in nearby systems \citep[e.g. the Coma cluster\!][]{Adami2003}. Much of the evolution of the galaxies thus happens in the group environment, but the potential effect of the larger-scale environment is undeniable, given that it would fundamentally affect the history and dynamics of the parent group of the galaxy.

In this paper we investigate the nature of star formation in galaxies along supercluster filaments, paying attention to the whether the galaxy is a dwarf or a giant, and the whether the galaxy is a dwarf or a giant, and the presence of position along a filament is expected to provide insights into the processes involved in galactic evolution and cluster formation. Here we have chosen an ensemble of filaments, lying within the volume of the Pisces-Cetus supercluster, covered by the two-degree Field Galaxy Redshift Survey \citep{Colless2003} (2dFGRS).

The clusters comprising the Pisces-Cetus supercluster within the 2dFGRS region, taken from the minimal spanning tree (MST) analysis of Bhavsar & Raychaudhury \citeyear{Bhavsar2000}, form the core of our sample. A complete list of positions and redshifts of the entire Pisces-Cetus supercluster, which extends some 15 degrees to the north of the 2dFGRS region, can be found in \cite{Porter2005}. The filamentary nature of the 2dFGRS region can clearly be seen in the distribution of galaxies in the groups in Fig. 1, where the 2dFGRS galaxies within 1840 km s$^{-1}$ (three times the velocity dispersion of the clusters belonging to the supercluster), are plotted. The 2PIGG groups found within the same velocity bounds \citep{Eke2004} also show the same large-scale structure. The rich clusters, plotted as large circles on the same plot, can be seen to be mostly along these filaments forming the supercluster structure.

### 2.1 Filament membership

The 2dFGRS Percolation-Inferred Galaxy Group (2PIGG) catalogue \citep{Eke2004} is a list of galaxy groups and their members, based on the North and South strips of the 2dFGRS redshift catalogue. It consists of approximately 190,000 galaxies, about 55% of which are members of the \~29,000 galaxy groups and clusters found using a friend-of-friends algorithm. This work leaves out about 20\% of 2dFGRS galaxies in under-sampled regions. In this paper, we use this subset of 2dFGRS galaxies, and hereafter, 2dFGRS refers to this subsample. Due to the varying survey limit, the absolute magnitude limit of the 2dFGRS at the mean redshift of the Pisces-Cetus supercluster varies across the supercluster region between $B_J = 17.2$ to $17.9$.

From this sample, galaxies which belong to the three most prominent filaments longer than 20 $h^{-1}_{70}$ Mpc, seen in Fig. 1, namely those joining Abell 2800–Abell 2734, Abell 2734–EDCC 0365 and EDCC 0365–Abell 2716 \cite[clusters from][]{Abell1989, Lumsden1993}, were extracted (hereafter we refer to the clusters only with the ‘A’ and ‘E’ prefixes). The filamentary structure of the supercluster is further discussed in \cite{Porter2005}.

We define the extent of each filament as a prolate spheroid, with the centres of the two clusters involved being at each end, the distance between them being the major axis of the spheroid, and $6 h_{70}^{-1}$ Mpc being the semi-minor
axis. All galaxies falling inside this spheroid were taken to be members of the filament. So as to not omit cluster galaxies at each end of the filament, we added the galaxies found from a percolation analysis to belong to the corresponding 2PIGG “group” in Eke et al. (2004). The resulting 965 filament members can be seen in Fig. 2 highlighted as crosses in the general field of all 2dFGRS galaxies in this part of the sky.

The distance between two clusters, and between a galaxy and a cluster, was calculated as the comoving proper distance between them (see Hogan 1999). We used the measured redshift of each galaxy as a measure of its distance from us, except if it is a member of a rich cluster, where the mean redshift of the cluster was used.

Figure 1. (a, Left) All 2dFGRS Galaxies within 1840 km s$^{-1}$ (3$\sigma$) of the mean recessional velocity of the Pisces-Cetus supercluster. The filamentary structure is clearly visible. (b, Right) Clusters of galaxies belonging to Pisces-Cetus supercluster filaments within the 2dFGRS region and within 1840 km s$^{-1}$ (3$\sigma$) of the mean supercluster velocity. The largest circles represent Abell clusters, and the medium-sized ones are supplementary Abell and Edinburgh-Durham clusters within the same redshift range. The groups of galaxies (Eke et al. 2004, 2PIGG) within the same velocity bounds, identified from a friends-of-friends analysis of the 2dFGRS are shown as the smallest circles.

Figure 2. The galaxies that are members of the three filaments of the Pisces-Cetus supercluster, as defined in the text (2.1), are shown as crosses. All galaxies within the 2dFGRS in the region are shown as dots.

Figure 3. A histogram of the $\eta$ parameter for all 2dFGRS galaxies within $z < 0.1$ is shown as the dashed line. Of these, the solid histogram shows galaxies within the bounds of the Pisces-Cetus supercluster and 1840 km s$^{-1}$ (3$\sigma$) of the mean recessional velocity of the supercluster.

3 STAR FORMATION PROPERTIES OF GALAXIES ALONG SUPERCLUSTER FILAMENTS

Having identified the major filaments in the Pisces-Cetus supercluster, and the galaxies, groups and clusters that lie on them, in this section we look at their rate of star formation (represented by the $\eta$ parameter) as a function of distance along the filaments.

3.1 The $\eta$ Parameter

Since our filaments are in the region covered by the 2dFGRS, we opt to use a simple parameter, related to the star formation rate, that has been derived for most 2dFGRS galaxies. Madgwick et al. (2002) used Principal Component Analysis of de-redshifted 2dF galaxy spectra to define a parameter $\eta$, a linear combination of the first two principal components, which correlates well with the equivalent width of the H$\alpha$ emission line, which in turn is a measure of SFR (e.g., Kennicutt 1983; Gallagher, Hunter, & Tutukov 1984).
With some scatter, $\eta \approx -2.0$ correspond to no H$\alpha$ emission at all, increasing to $\eta \approx 7$ for EW(H$\alpha$) = 50Å (Madgwick et al. 2003).

A histogram of the $\eta$ parameter for all 2dFGRS galaxies (Fig. 2 dashed line) shows two distinct peaks in the distribution, at $\eta \sim -2.5$ and at $\eta \sim 0.05$. This reflects the well-known bimodality of the local galaxy population, of red, passive, galaxies, and bluer, star forming galaxies (e.g. Kauffmann et al. 2004; Balogh et al. 2004). The dip or divide between the two peaks is at $\eta \sim -1.4$. The first peak only contains $\sim 30\%$ of the galaxies with $z < 0.1$. Madgwick et al. (2003) show that the first narrow peak corresponds to E/S0 galaxies while the second broader peak represents later-type galaxies. Indeed, they also find a tight correlation between $\eta$ and the birth rate parameter $b$, which is the ratio of current to past-averaged SFR. The dividing line between the two peaks at $\eta \sim -1.4$ corresponds to $b \sim 0.1$, the value where the current SFR is only a tenth of that in the past. The $\mu_\eta$ parameter of Lewis et al. (2002), which is the SFR normalised to the characteristic Schechter luminosity $L_\ast$, is shown to be $\mu_\eta = 0.087$ EW(H$\alpha$). Therefore, $\eta \sim -1.4$ would correspond to $\mu_\eta \sim 0.4$.

Also shown in Fig. 3 is the corresponding histogram (solid line) for the galaxies within the supercluster region as defined in 2. The supercluster histogram has a higher peak corresponding to passive galaxies. This would be consistent with a higher proportion of early type galaxies in the supercluster filaments, according to the morphology-density relation, in accord with the SDSS-derived results of Tanaka et al. (2004).

In this study of the star formation properties of galaxies, we look at the variation of two quantities as a function of position along the filaments and distance away from the nearest cluster:

(i) the value of the $\eta$ parameter, which correlates with the current SFR of the galaxy, and
(ii) the fraction of galaxies with $\eta < -1.4$, which represents the fraction of non-star-forming (passive) galaxies in a subsample.

### 3.2 Star formation along the A2734-A2800 filament

We begin by looking in detail at the most prominent filament in the Pisces-Cetus supercluster, that linking A2734 and A2800, which is about $32\ h^{-1}_70\ Mpc$ long. The comoving distance of each of the filament galaxies from one end (A2734) was calculated as described above. Members of A2800 were assigned a distance equal to the separation of the two clusters minus their projected distance from the centre of A2800.

Along the filament, we chose bins of varying size according to the numbers of galaxies available. Closer to the two clusters, we chose smaller bins of 0.3–0.6 $h^{-1}_70\ Mpc$ to sample the rapid variation of SFR within the virial radius of the cluster. For each bin, the mean distance of all member galaxies, and the mean $\eta$, were calculated.

Fig. 4 shows the resulting plot of mean $\eta$ as a function of distance from the centre of A2734. We also plot, in the bottom panel, the fraction of passive ($\eta < -1.4$) galaxies in each bin. It can be seen, as expected, that the SFR is minimum at the cores of the two rich clusters, where the number of passive galaxies is the highest. The mean value of the $\eta$ parameter increases with distance to approximately the field value, since the mean $\eta$ for all galaxies of the 2dFGRS is around zero.

However, it can also be seen that between 3–4 $h^{-1}_70\ Mpc$ from the centre of A2734, there is a peak in the value of mean $\eta$. Correspondingly, there appears to be another peak at the other end of the plot, at a slightly closer distance from the centre of A2800, although, within errors, it does not rise above the field. To investigate the reality of the signal, we will now stack all three filaments in our sample, and fold Fig. 4 such that we consider distances along the filament from the nearest cluster.

Fig. 5 shows the distribution of the passive and star forming galaxies, in the immediate vicinity of the clusters A2800 and A2734 respectively. The concentric circles are at 1 $h^{-1}_70\ Mpc$ intervals. It can be seen that in the 3–4 $h^{-1}_70\ Mpc$ annulus there are more star forming than passive galaxies for both clusters.

### 3.3 Star formation properties of galaxies in all three filaments combined

Here we combine the three filaments longer than 20 $h^{-1}_70\ Mpc$, namely those joining A2800–A2734, A2734–E0365 and E0365–A2716, as seen in Fig. 2. All galaxies belonging to the three filaments were grouped in bins of varying size according to their distance from the nearest cluster (representing the extremities of the filaments). As above, we plot
Figure 5. The distribution of passive ($\eta < -1.4$) galaxies shown as filled circles and star forming ($\eta > -1.4$) galaxies shown as crosses in the region surrounding (left) A2800 and (right) A2734. Only galaxies belonging to the A2734–A2800 filament are shown. The concentric circles represent 1 $h_{70}^{-1}$ Mpc intervals.

Table 1. Virial radii for Pisces-Cetus clusters involved in this analysis

| Cluster | $\sigma_v$ (km s$^{-1}$) | $N_{\text{gal}}$ | Virial radius ($h_{70}^{-1}$ Mpc) |
|---------|-------------------------|-----------------|-------------------------------|
| A2734   | 848                     | 141             | 2.5                           |
| A2716   | 812                     | 77              | 2.4                           |
| A2800   | 567                     | 79              | 1.7                           |
| E0365   | 442                     | 78              | 1.3                           |

The virial radius of a cluster can be approximately derived from its radial velocity dispersion as $R_{\text{vir}} \sim 0.002 \sigma_v h_{70}^{-1}$ Mpc (Girardi et al. 1998), where $\sigma_v$ is given in km s$^{-1}$. For the four clusters that lie at the intersection of the three filaments involved in this study, we computed the virial radii from this relation, which are given in Table 1. The radial velocity dispersions were calculated using the algorithm of Danese, de Zotti, & di Tullio (1980), from 2dFGRS redshifts. The mean virial radius for these clusters is about 2 $h_{70}^{-1}$ Mpc, which means that the abrupt peak of enhanced star formation appears at about 1.5–2 virial radii from the centres of the clusters concerned.

A corresponding dip in the fraction of passive galaxies is also seen at this distance. Of course, star formation is suppressed as the galaxy approaches the core of the cluster, leading to a low mean $\eta$ and a higher fraction of passive galaxies interior to this distance. The implications of these trends are discussed in §4.

Figure 6. (a, Top) For the three filaments combined, the mean $\eta$ as function of distance from the nearest cluster is shown. The dashed line shows the mean $\eta$ as function of distance from the nearest 2PIGG group with $\geq 30$ members for all 2dFGRS galaxies. (b, Bottom) For the same galaxies as above, the fraction of these galaxies with an $\eta < -1.4$ is shown as a function of distance from the nearest cluster. The dashed line showing the same fraction as a function of distance from the nearest 2PIGG group with $\geq 30$ members for the whole 2dFGRS.
3.4 Star formation in giant and dwarf galaxies

As samples of galaxies with estimated star formation properties grow larger, it would become easier to study the relation between star formation in a galaxy and various properties of its environment, and those of the galaxies themselves. From SDSS-DR4, for example, Haines et al. (e.g. 2006a) find that among giant \((M_B < -20)\) galaxies, the fraction of passive galaxies \((H_a \text{ EW}<44\alpha)\) declines steadily out to \(3\)--\(4\) times the virial radius \(R_V\), whereas the fainter dwarfs are passive only within \(R_V\), outside of which they are overwhelmingly star-forming. The fact that passive dwarf galaxies are rare even in the infall regions of rich clusters (where low velocities would make mergers more probable) would imply either, that star formation in dwarfs is not easily quenched by mergers, or more plausibly, that the mergers between dwarfs are not very common. Instead, dwarfs seem to be more vulnerable, in the more crowded regions, of the stripping away of the outlying diffuse gas, which is the potential fuel for star formation, by the more massive haloes of the giants they become gravitationally bound to (e.g., Larson, Tinsley, & Caldwell 1980, also known as strangulation).

Here, we ask whether this trend in the SFR of galaxies along the filament depends on whether the galaxy in question is a giant or a dwarf. We divide the galaxies plotted above in Fig. 6 into two subsamples: giant galaxies \((M_B \leq -20)\) and dwarf galaxies \((-20 < M_B \leq -17.5)\). As a result, there are 119 giants and 846 dwarfs in the three filaments used above. We plot the mean value of \(\eta\) as a measure of star formation, and the fraction of passive galaxies, as a function of their distance from the nearest cluster, in Fig. 7 with dwarfs plotted as open triangles and giants as filled circles.

It seems that the peak in mean \(\eta\) seen in Fig. 6 between \(3\)--\(4\) \(h_7^{-1}\) Mpc, is almost entirely due to enhanced star formation in dwarfs indeed there are no passive dwarf galaxies in the bin containing the peak in mean \(\eta\) (see bottom panel of Fig. 7).

The more luminous galaxies \((M_B \leq -20)\) seem to have the same deficiency in star formation at the very cores of clusters, and have an overall lower rate of star formation than the dwarf galaxies, thus not contributing much to the trend of \(\eta\) with distance. Although, the mean \(\eta\) with distance from the centre of the nearest cluster of just these giant galaxies, seems to show a peak in activity in the range \(1.5\)–\(2\) \(h_7^{-1}\) Mpc, the small number of galaxies in that bin \((N = 13)\) put a large element of doubt on its validity. These results are discussed in more detail in 4.

Figure 7. Star formation in giant galaxies \((M_B \leq -20)\), compared to that in dwarfs \((-20 < M_B \leq -17.5)\), in the sample used in Fig. 6 (a, Top) The mean star formation rate parameter \(\eta\) is shown as function of distance from the nearest cluster, for dwarfs (open triangles) and giants (filled circles). It appears that the enhanced star formation at \(\sim 3\) Mpc appears only in the dwarfs. (b, Bottom) The fraction of the galaxies with \(\eta < -1.4\) (passive galaxies) is shown as a function of distance from the nearest cluster. There are no passive dwarf galaxies in the bin containing the peak in mean \(\eta\).

3.5 Enhanced star formation as a function of cluster richness

If the tidal influence of the galaxy cluster at the end of the filament were responsible for the enhanced star formation seen above, then we would expect to see a correlation of the position of the peak SFR with the richness of the cluster. One would indeed expect galaxies falling into clusters of larger velocity dispersion to encounter tidal forces at larger distances.

We therefore split the four clusters that form the extremities of our filaments into those with high velocity dispersions \((A2716: 812 \text{ km s}^{-1}, \ A2734: 848 \text{ km s}^{-1})\) and those with low velocity dispersions \((A2800: 567 \text{ km s}^{-1}, \ E0365: 426 \text{ km s}^{-1})\). Fig. 8 shows the resulting values for mean \(\eta\) as a function of distance for the high and low velocity dispersion cluster samples. It can be seen that there is no significant difference in the position of the low velocity dispersion cluster peak in mean \(\eta\) (filled circles) and the peak in the high velocity dispersion cluster peak (open circles).

3.6 Star formation in groups on inter-cluster filaments

The suppression of star formation with increasing local density of galaxies has been observed to occur in giant galaxies at very low values \((\sim 1\ \text{Mpc}^{-2})\) of the local projected density (e.g. Lewis et al. 2002, Gómez et al. 2003), which are typical of densities well outside the virialised regions in clusters, indicating that the cause does not lie entirely in the influence of the cluster environment. One suggestion is that much of the evolution of galaxies occurs in groups during their life on the filaments, before the groups are assimilated in clusters. Evidence supporting this is found in the existence of galaxies with hot X-ray emitting haloes in groups (O’Sullivan, Forbes, & Ponman 2001). If so, the trend seen in the previous section would be different for filament galaxies that belong to groups and those that are relatively isolated.

We could have looked for differences in star-forming properties between galaxies belonging to groups and those not in groups on these filaments, but the test proved inconclusive due to small numbers, since only 8% of galaxies in our sample do not belong to any 2PIGG group of 4 or more members.
Figure 8. The dependence of the mean star formation rate of galaxies, on the richness of clusters closest to them, is shown here, for the sample of three filaments used in Fig. 6 (a, Top) Mean $\eta$ as a function of distance from the nearest cluster is shown, where galaxies closest to the low velocity dispersion clusters (A2800 and E0365) are shown as filled circles, while galaxies closest to the high velocity dispersion clusters (A2734 and A2716) are shown as open circles. (b, Bottom) For the same galaxies as above, the fraction of the galaxies with $\eta < -1.4$ (passive galaxies) is shown as a function of distance from the nearest cluster. The dashed line in both cases shows the corresponding parameter for all galaxies in the 2dFGRS, where the nearest “cluster” is defined as the nearest 2PIGG group with $\geq$ 30 members.

Instead, Fig. 9 compares the same quantities considered above, for galaxies that belong to groups in these three filaments, to those for similar group galaxies elsewhere in the 2dFGRS. The dashed line represents the variation of mean $\eta$ and passive galaxy fraction as a function of distance from the nearest cluster for all galaxies that belong to a 2PIGG group of four or more members (a cluster being defined as a 2PIGG group of 30 or more members). The crosses represent the galaxies belonging to our sample of three Pisces-Cetus filaments.

The plots suggest that the star formation rate is more or less uniform in galaxies which are members of groups in the entire 2dFGRS catalogue, though at a slightly lower mean level than found in the field (shown as the dashed line in Fig. 6) irrespective of their distance from the nearest cluster, except for those group galaxies within $\sim 3 \times 10^{-1}$ Mpc of the centres of rich clusters. In sharp contrast, the trend we find of a peak in SFR between $3 - 4 \times 10^{-1}$ Mpc is seen in the group galaxies which belong to filaments, indicating that the presence of the filaments markedly influences star formation properties in galaxies that belong to groups. The variation is even more highlighted in the bottom panel, showing the fraction of passive galaxies in each bin. The physical processes that govern the excess of star formation in these galaxies clearly are more related to the supercluster environment than the group environment.

Figure 9. Star formation in galaxies in 2PIGG groups: those in the Pisces-Cetus filaments compared to those in the whole of the 2dFGRS. (a, Top) The mean value of $\eta$ as a function of distance from the nearest cluster. Filament galaxies which are members of groups (2PIGG groups, $N \geq 4$) are shown as crosses, while all galaxies in the 2dFGRS which are members of similar 2PIGG groups are represented by the dashed line. The peak in $\eta$ is not seen in the latter category. (b, Bottom) The fraction of passive filament galaxies ($\eta < -1.4$) as a function of distance from nearest cluster for the same samples.

4 DISCUSSION

The most striking of our results are those seen in Fig. 6 where we look at galaxies which are members of filaments connecting pairs of rich clusters of galaxies. Firstly, we see, as expected, the decline in SFR in these galaxies, from those in the filament environment on the periphery of a cluster, to the galaxies in the cluster core. This indicates that a physical mechanism is at work that quenches star formation progressively as a galaxy approaches the core of the cluster potential well. This trend is consistent with that seen in other environmental studies, both in the dependence of current star formation rate (e.g., Balogh et al. 1998, Kauffmann et al. 2004), and the variation in the incidence of recent star formation (Nolan, Raychaudhury, & Kabani 2006), on local galaxy density. However, the unusual feature, in the case of galaxies belonging to inter-cluster filaments, is that on top of this decline, there seems to be evidence for a sharp burst of star formation at $\sim 3 \times 10^{-1}$ Mpc (1.5-2 times the virial radius) from the centre of the nearest rich cluster.

It has been shown that galaxies can be surrounded by haloes of hot X-ray emitting gas (e.g., Pedersen et al. 2004). However, it is likely that many more galaxies have a warm halo of gas with temperatures of $10^5 - 10^6$ K, which is too cool to be detected in X-ray observations. This reservoir of warm gas would be expected to provide for continued star formation in the galaxy, and its loss would amount to the strangulation of star formation.

As a galaxy approaches the gravitational potential well of the rich cluster at the extremity of a filaments, it would begin to encounter the hot/warm intra-cluster Medium
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(IMC), possibly at a distance of the order of the virial radius from its centre. As the gaseous halo of the galaxy interacts with the hot ICM, the galaxy would lose their warm gas haloes through evaporation and possibly ram pressure stripping. This will lead to a steep decline in the SFR of galaxies within \(1.5-2h_{70}^{-1}\) Mpc of the centre of the cluster. This is seen in Fig. 5. In this region, galaxy-galaxy harassment (Moore et al. 1999) will also be an important effect. However, with most of the thermal reservoir of gas already having been removed by this stage, star formation will not be induced by the harassment, and the remaining gas of the galaxy will continue to be stripped, leading to the observed steep dip in SFR in the first two bins in Fig. 4 from the centre of the cluster.

Even before this effect of the hot ICM begins to manifest itself on the SFR of infalling galaxies, the density of galaxies will already have begun to increase rapidly, which could be appreciable at distances as large as twice the virial radius. Approaching the outer regions of the cluster along a filament, galaxies would experience close interactions even before they experience any significant influence of the cluster gravity and ICM. Thus, the most likely cause for this observed sudden burst in SFR at \(\sim 3h_{70}^{-1}\) Mpc from the centre of the cluster, would be galaxy-galaxy harassment, which is a rapidly acting process which works efficiently in crowded environments. This effect would be superposed on the general trend of decrease in SFR towards the core of the cluster, as found in galaxies elsewhere. These galaxies are yet to encounter the hot and dense ICM of the cluster, and thus would have not had their gas stripped or evaporated, but the close interaction with other galaxies would lead to density fluctuations in the gas, resulting in bursts of star formation. Moore et al. (1999) show that harassment is a rapid effect, which would account for the sharpness of the peak in the SFR in this region. The range of distance over which this peak is seen is a narrow one, also because its existence depends on both the existence of substantial fuel for star formation, as well as sufficient external influence which would act as trigger, and this occurs over a limited range between the sparser expanse of the filament and the dense ICM of the core of the cluster.

A photometric study (Haines et al. 2006b) of the nearby Shapley supercluster (Raychaudhury 1989) reveals an excess of faint \((M_{R} > -18)\), bluer star-forming galaxies at \(\sim 1.5h_{70}^{-1}\) Mpc from the centres of the rich clusters in the core of the supercluster. At higher redshift, Moran et al. (2003) observe a similar sharp peak in SFR (evident from redshifted [OII] emission) in the outskirts of the rich cluster CL0024 at \(z = 0.4\), at \(1.8h_{70}^{-1}\) Mpc from the cluster centre, where galaxy harassment is cited as a possible cause. While it is encouraging to observe similar effects in other studies using different observables, the SFR peak found in the case of the Shapley supercluster or CL0024 is a factor of 1.5-2 closer to the cluster core than the distance at which the SFR peak is found in our study. It is possible that the galaxies in the Pisces-Cetus filaments experience the effect of galaxy-galaxy harassment at a larger distance from the cluster centre, since the accretion of galaxies in this case occurs along relatively narrow filaments, resulting in similar galaxy densities further out than would be seen in the case of clusters where galaxies are being accreted from all directions.

Fig. 8 reveals no discernible dependence of the position of the peak in SFR on the velocity dispersion of the cluster involved, which would have been expected if the SFR trigger had been dominated by the gravitational effect of the cluster. Even if the tidal effects of the cluster potential contributes to the enhanced SFR, it is evidently dominated by local effects as described above.

The effect of “backsplash” (Gill, Knebe, & Gibson 2005), which results from a galaxy on an oscillating orbit at the bottom of the potential well at the core of a cluster, is expected to be strongest at about \(\sim 1\) Mpc from the centres of clusters, and is thus not likely to have a strong effect on the peak in SFR seen in our filament galaxies, which occurs further out in distance. However, it may mean that the increase in SFR in some galaxies in the sharp peak may be even stronger than our mean suggests.

The observed peak in SFR may even contribute to our steep gradient within \(3h_{70}^{-1}\) Mpc, making it steeper. The galaxies that are star forming will have had their gas temperature raised and thus when they encounter the ICM they will be more prone to evaporation and stripping and hence have a rapidly decreasing SFR (for a similar effect seen in starburst galaxies in a poor group, see Rasmussen, Ponman, & Mulchaey 2006).

The caveat in the use of the \(\eta\) parameter as a proxy for current SFR might be that the principal component analysis used in obtaining the \(\eta\) parameter might not have removed contributions from active galactic nuclei (AGN). It therefore remains a possibility that part of enhancement in mean \(\eta\) is due to AGN activity rather than conventional star formation, consistent with the results of Ruderman & Ebeling (2003) who find a prominent spike in the number of X-ray AGN in clusters at \(\sim 2.5h_{70}^{-1}\) Mpc. However, not all X-ray detected AGN have the usual emission lines in their optical spectra (Shen et al. 2007).

Fig. 7 shows that the enhanced SFR is almost exclusively seen in galaxies of lower luminosity (dwarfs) than in the giant galaxies, as is indeed also seen in the study of CL0024 galaxies (Moran et al. 2005). Other studies of low-redshift galaxies (e.g. Haines et al. 2006b) have also revealed differences between the SFR properties of giant and dwarf galaxies. This supports our favoured scenario, since dwarf galaxies are expected to be more vulnerable to galaxy harassment than giants. Moran et al. (2003) shows this, where almost all the galaxies in their peak in the [OII] equivalent width are dwarfs (also see Sato & Martin (2006)). It also shows that the merging of galaxies is unlikely to be a major contributor, in which case the SFR would have been more enhanced in giants, which have a higher cross-section for mergers.

5 CONCLUSIONS

We have explored the environmental dependence of star formation in galaxies, belonging to supercluster filaments connecting rich clusters of galaxies, in the Pisces-Cetus supercluster, which lies within the 2dF galaxy redshift survey. We have used the \(\eta\) parameter, a quantity derived from a principal component analysis (Madgwick et al. 2002) of the 2dFGRS galaxy spectra, which is known to correlate well
with the equivalent width of the Hα emission line, as an index of current star formation rate within a galaxy.

For galaxies belonging to three Pisces-Cetus filaments (each over $20 h^{-1}_{70}$ Mpc long), connecting three pairs of rich clusters, we have studied the variation of the mean $\eta$ parameter with distance along the filaments, from the cores of the rich clusters out to the sparser reaches of the filament. We have also investigated the variation of the fraction of passive galaxies with distance from the cluster cores.

It is well known that the star formation rate in galaxies is the lowest in the cores of rich clusters, and we confirm this by showing that the value of mean $\eta$ falls to its lowest value, corresponding to a maximum in the fraction of passive galaxies, for both giant and dwarf galaxies in the cores of clusters, both in the supercluster filaments, as well as elsewhere in the 2dFGRS. Away from the cores of clusters, while the SFR increases steadily as the local galaxy density drops, everywhere in the 2dFGRS, there is an increased activity of star formation, in a short distance interval between $3-4 h^{-1}_{70}$ Mpc from the centre of the clusters, for the galaxies belonging to the three Pisces-Cetus inter-cluster filaments studied here. This peak in star formation in filament galaxies is seen to be almost entirely due to dwarf galaxies ($-20 < M_B < -17.5$). The position of the peak does not depend on the richness of the cluster.

We conclude that the most likely cause for this sharp enhancement in SFR in the outskirts of the clusters is galaxy-galaxy harassment. This occurs when galaxies falling into the cluster along narrow filaments reach a certain density where close interactions between galaxies become important. For this to be effective, this has to occur before the galaxy loses most of its gas to stripping and evaporation due to the dense of ICM of the rich cluster. The predominance of SFR in dwarfs indicates that galaxy merging is not an important factor.

Encouraged by the evidence of enhanced galaxy interaction found in the luminosity function of groups [Miles et al. 2004 (2006)], we have examined the influence of the group environment on the variation of SFR in our sample of galaxies. However, we find that while the group members show the same general trend of gradually declining star formation in denser environments, as seen in all galaxies in the 2dFGRS, the sharp enhancement in SFR in the outskirts of clusters, as seen in this work, occurs at the same position for group members as for non-group members on the Pisces-Cetus filaments, and is not seen elsewhere. This suggests that the enhancement in SFR is mostly related to properties of the filament environment than the group environment for the galaxies concerned.

Finally, although the results in this work are indicative of interesting environmental effects on star formation in galaxies, where the environment is characterised by parameters beyond the usual projected local densities that are commonly found in the literature, they come from a small sample of about a thousand galaxies in three filaments in a single supercluster. Moreover, we have used an indirect measure of star formation (the $\eta$ parameter) derived from the optical spectra of galaxies, and no allowance has been made for the possible contribution of AGN to the spectral parameters. We look forward to exploring these effects in a larger ensemble of filaments from both the 2dFGRS and SDSS surveys, not only using various measures of star formation, but also scrutinising the effects of a wider range of environmental parameters that large samples would be able to afford.

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