Evidence for galaxies being pre-processed before accreted into clusters

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ABSTRACT

I use the spectroscopic data for galaxies in and around 28 nearby (0.02 ≤ z ≤ 0.06) X-ray bright galaxy clusters, to show that the incidence of k+A (or post-starburst) galaxies (EW(Hβ)< 2 Å in emission and EW(Hα)> 3 Å in absorption) may be correlated with the accretion of small galaxy groups in clusters. At r < 2r200, the k+A galaxies are found in regions of higher galaxy density relative to other cluster galaxies. The k+A galaxies have a positively skewed distribution of absolute velocity, |vlos|/σv, where vlos is the difference between the line-of-sight velocity of the galaxy and the cluster's mean, and σv is the cluster's velocity dispersion. This distribution is statistically different from that of other cluster galaxies within 2r200, and in the same absolute velocity range. Moreover, 87% of clusters in the sample studied here show statistically significant substructure in their velocity distribution, and 91.4% of all k+A galaxies are found to be a part of one of these substructures with 4-10 members. These results suggest that star formation in these k+A galaxies is likely to have been quenched due to "pre-processing" in a poor group-like environment before they are accreted into clusters. I also find a mild, but statistically significant trend in the fraction of k+A galaxies increasing with the temperature of the X-ray emitting gas in clusters.

Key words: galaxies: clusters: general; galaxies: evolution; galaxies: groups: general; X-rays: general

1 INTRODUCTION

Environment of galaxies play a key role in their evolution at all epochs. Recent work utilising data from the wide-field surveys such as the Sloan Digital Sky Survey (SDSS), have evidently shown that the galaxy number density and velocity fields play equally important roles in defining the immediate and the global environment of a galaxy (e.g. Baloer et al. 2004; Mahajan, Haines, & Raychaudhury 2011; Mahajan, Mamon, & Raychaudhury 2011). Several authors have also speculated the role played by the large-scale supercluster environment in modulating galaxy properties, thereby extending the impact of environment to lower density regions such as galaxy groups (Rasmussen et al. 2012), outskirts of clusters (Haines et al. 2011; Mahajan, Raychaudhury & Pimbblet 2012), and even the inter-cluster filaments feeding them (e.g. Fadda, Biviano & Darrel 2008; Porter et al. 2008; Pereira et al. 2010; Haines et al. 2011). Since galaxies span a continuous range in all observables such as broadband colours and star formation rate (SFR), most of these studies suggest that galaxies are likely being "pre-processed" before they are accreted into clusters.

Galaxies presently transiting from an active, star-forming phase to passive evolution are called post-starburst (or post-starburst) galaxies (Dressler & Gunn 1983). Spectra of such post-starburst galaxies are often characterised by negligible emission, but strong absorption in Balmer lines such as Hα and Hβ. While the former indicates absence of ongoing star formation, the latter feature is an indicator of the presence of late A and early B-type stars, implying that star formation in the galaxy was quenched 500–700 Myr ago. Although post-starburst galaxies are found at all redshifts and in all environments, their frequency varies with environment, galaxy mass and redshift (Poggianti et al. 2003; Peng et al. 2010).

If star formation in a galaxy is quenched because of mechanisms related to the intra-cluster medium (ICM), the incidence of post-starburst galaxies should correlate with the properties of the ICM. The fraction of post-starburst galaxies has been reported to be as high as a quarter of the total population of cluster galaxies (Dressler & Gunn 1983; Dressler et al. 1999; Tran et al. 2004) at intermediate redshifts (0.3 < z < 0.6). The trend continues to z ~ 0, in the sense that in the nearby Universe most of the stars are

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3 Although the terms k+A, E+A and post-starburst correspond to different spectral features depending upon the time since the last major starburst in a galaxy, they have been used interchangeably in the literature. In the context of this letter, a post-starburst galaxy as defined in 3 is called a k+A galaxy unless stated otherwise.
forming in dwarf galaxies, and, star formation in a large fraction of such cluster dwarfs is found to be quenched in dense environments (Mahajan, Haines, & Ravindra)(2010). However, it is noteworthy that not only are different studies of post-starburst galaxies limited by different data attributes, but also employ different selection criteria for selecting post-starburst galaxies. Hence, a comparison of relative fraction of post-starburst galaxies amongst different environments in the same study is more insightful than a comparison between absolute fractions.

At $z \sim 0$, post-starburst galaxies seem to prefer less-dense environments, similar to blue star-forming galaxies (Balogh et al. 2005; Hogg et al. 2006; Yan et al. 2009), suggesting that environmental mechanisms related to dense clusters are not the only phenomena responsible for quenching star formation in galaxies. Some post-starburst galaxies, however, may be a result of pre-processing of galaxies before they are accreted into clusters (Hogg et al. 2006; Yan et al. 2009), suggesting that environments in the cluster core (Mahajan, Haines, & Ravindra)(2010). As I will show below, while the immediate neighbourhood has an immediate impact on the properties of galaxies, the global environment can play an indirect role in the incidence of k+A galaxies.

In the next section I describe the datasets used in this work, followed by the analysis and results in $\S 3$ and $\S 4$ respectively. The major findings are summarised in $\S 5$. This analysis makes use of a $\Lambda$CDM concordance cosmological model with $H_0 = 70\, \text{km s}^{-1}\, \text{Mpc}^{-1}$, $\Omega = 0.7$ and $\Omega_M = 0.3$ for calculating distances and magnitudes.

## 2 DATA

### 2.1 Cluster parameters

I selected Abell clusters (Abell et al. 1989) at $0.02 < z < 0.06$ having X-ray temperature measurement from BAX (http://bax.ast.obs-mip.fr). The spectroscopic data, complete to the SDSS spectroscopic galaxy catalogue. These data were used to evaluate the k+A galaxies using galaxies (Blanton et al. 2001) using the SDSS (DR7) spectroscopic galaxy catalogue. These data were used to evaluate the fraction of k+A galaxies using galaxies ($M_* < -19.35$) within $2r_{200}$ and $|v_{200}/\sigma_v| \lesssim 5$. The magnitude limit is chosen so as to evaluate the k+A fraction with the same lower luminosity bound for clusters at all redshifts. Figure 2 shows the fraction of k+A galaxies as a function of the X-ray temperature of the ICM.

In this letter a galaxy is defined as post-starburst (or k+A), if its equivalent width (EW) in H$\alpha < 2\, \text{Å} in emission, and EW(H$\delta$) $> 3\, \text{Å}$ in absorption (e.g. Poggianti et al. 2003). This gives a total of 165 k+A galaxies within $2r_{200}$ and $|v_{200}/\sigma_v| \lesssim 5$ in 28 X-ray bright clusters ($0.02 < z < 0.06$). Distribution of these galaxies in some typical clusters from the sample studied here are shown in Figure 1.

### 2.2 Cluster galaxies

In order to estimate the cluster parameters mentioned above, I started with all galaxies within $\pm 3,000\, \text{km s}^{-1}$ of the cluster’s mean line-of-sight (l.o.s.) velocity, and within two degree radius. The final dataset comprises 5,735 galaxies within $2r_{200}$ of the cluster centre, and having l.o.s. velocity such that the absolute velocity, $|v_{200}| < 3\sigma_v$, where $v_{200}$ is the difference between the l.o.s. velocity of the galaxy, and the cluster’s mean l.o.s. velocity. The factor of five is chosen to include all cluster galaxies, as well as those falling into clusters. The position, $\sigma_v$ and Tx for all clusters are listed in Table 1.

| Cluster | RA (J2000) | Dec (J2000) | $z$ | $\sigma_v$ (km s$^{-1}$) | Tx (keV) |
|---------|------------|------------|-----|--------------------------|----------|
| Abell 85 | 10.4613 | -9.3067 | 0.056 | 710.40 | 6.45 |
| Abell 119 | 14.0500 | -1.2575 | 0.044 | 744.19 | 5.62 |
| Abell 160 | 18.2117 | 15.1016 | 0.041 | 800.99 | 1.68 |
| Abell 168 | 18.7479 | 0.3664 | 0.045 | 501.82 | 2.56 |
| Abell 671 | 127.1292 | 30.4072 | 0.050 | 835.43 | 4.20 |
| Abell 779 | 139.9713 | 33.7639 | 0.024 | 559.22 | 2.97 |
| Abell 957 | 153.4913 | -0.9175 | 0.046 | 760.08 | 2.75 |
| Abell 1142 | 165.2333 | 10.5439 | 0.036 | 865.57 | 3.96 |
| Abell 1185 | 167.7075 | 28.6753 | 0.031 | 542.75 | 3.90 |
| Abell 1291 | 173.0392 | 56.0386 | 0.021 | 735.74 | 3.55 |
| Abell 1656 | 194.9583 | 27.9825 | 0.023 | 860.91 | 8.25 |
| Abell 1890 | 214.3925 | 8.1908 | 0.057 | 505.68 | 5.77 |
| Abell 1913 | 216.7167 | 16.6808 | 0.053 | 527.82 | 2.78 |
| Abell 1983 | 223.1842 | 16.7528 | 0.045 | 516.82 | 2.18 |
| Abell 1991 | 223.6267 | 16.6333 | 0.059 | 492.23 | 5.40 |
| Abell 2040 | 228.1879 | 7.4367 | 0.045 | 822.15 | 2.4 |
| Abell 2052 | 229.1892 | 7.0236 | 0.035 | 617.87 | 3.12 |
| Abell 2063 | 230.7571 | 8.6461 | 0.035 | 666.17 | 3.57 |
| Abell 2107 | 234.9504 | 21.7792 | 0.041 | 582.52 | 4.00 |
| Abell 2147 | 240.5708 | 15.9197 | 0.035 | 694.16 | 4.34 |
| Abell 2151 | 241.3133 | 17.7553 | 0.037 | 752.15 | 2.58 |
| Abell 2152 | 241.3429 | 16.4564 | 0.037 | 1986.56 | 2.41 |
| Abell 2197 | 247.0429 | 40.9131 | 0.030 | 677.81 | 2.21 |
| Abell 2199 | 247.1533 | 39.5300 | 0.030 | 726.92 | 3.99 |
| Abell 2399 | 329.3896 | -7.7886 | 0.058 | 320.62 | 2.46 |
| Abell 2593 | 351.1288 | 14.6417 | 0.041 | 651.04 | 3.10 |

## 3 k+A GALAXY FRACTION AND ICM TEMPERATURE

Nearby clusters offer a unique opportunity to study galaxies in a ‘continuous’ range of environments. Hence, whether galaxies are being transformed due to the environmental effects of the ICM, or prior to encountering it, they can be caught in the act. In order to test the hypothesis that the incidence of k+A galaxies is related to the cluster environment, I chose the most extreme environments in the nearby Universe by using the temperature of the X-ray emitting gas in the cluster as a proxy. This allowed me to sample cluster galaxies down to at least $M_* + 1.48$ (Blanton et al. 2001) using the SDSS (DR7) spectroscopic galaxy catalogue. These data were used to evaluate the fraction of k+A galaxies using galaxies ($M_* < -19.35$) within $2r_{200}$ and $|v_{200}/\sigma_v| \lesssim 5$. The magnitude limit is chosen so as to evaluate the k+A fraction with the same lower luminosity bound for clusters at all redshifts. Figure 2 shows the fraction of k+A galaxies as a function of the X-ray temperature of the ICM.

Figure 2 shows a mild trend for an increase in the k+A fraction with Tx, with product moment correlation coefficient, $r = 0.481$ ($P = 0.023$). The two hottest systems in the sample (Abell 85 and Coma), are also known to have substantial substructure in galaxy distribution (Porter & Ravindra)(2005; Mahajan, Haines, & Ravindra)(2010, 2011), and, X-ray data (Neumann et al. 2003; Bravo-Alfaro et al. 2009). Simulations...
Evidence for galaxies being pre-processed before accreted into clusters

Figure 1. Some typical clusters in my sample showing the position of all (grey) and $k$+(red stars) galaxies within $2r_{200}$ of the cluster centre (green star).

Figure 2. The fraction of $k$+A galaxies as a function of the temperature of the X-ray emitting gas in cluster. Clusters are colour-coded by redshift, in increasing order black, blue, pink and red, for $0.02 \leq z \leq 0.6$ at an interval of 0.01 respectively. The solid black line shows the mean absolute deviation (MAD) relation for all clusters, with ±1σ deviation in the fit shown by the black dashed line. The fraction is calculated for galaxies brighter than $M_r < -19.35$, which is the magnitude limit for the SDSS spectroscopic catalogue at $z = 0.06$.

by Bekki, Owers, & Couch (2010) showed that the post-starburst galaxies may be related to the presence of substructure in galaxy clusters. But with only a couple of data points at $T_x > 6$ keV, no substantial conclusions can be drawn to defend (or reject) any correlation between the fraction of $k$+A galaxies and $T_x$.

4 LOCAL ENVIRONMENT OF $k$+A GALAXIES

Figure 3 shows the distribution of the mean distance to the three closest neighbours of a galaxy ($D_3$; chosen to be within a redshift slice, $\Delta z = \pm 2.000 \text{ km s}^{-1}$ around the galaxy), for the samples mentioned above. The Kolmogorov-Smirnov (KS) test in favour of the hypothesis that both samples are drawn from the same parent population yields a probability of 0.0190 with median $D_3 = 248.9$ and 199.5 kpc, and maxima for the distributions being 118.1 and 63.6 kpc, for all and $k$+A cluster galaxies, respectively. In order to test if the discrepancy in the relative local densities of the two galaxy samples is dependent on $\Delta z$ chosen for evaluating $D_3$, I re-calculated median $D_3$ including neighbours only within $\Delta v = \pm 1.000 \text{ km s}^{-1}$ to be 294.4 and 257.3 kpc for all and $k$+A galaxies respectively. This suggests that the $k$+A galax-

Figure 3. The distribution of the mean distance to the three closest neighbours (within $\pm 2.000 \text{ km s}^{-1}$) for all (grey hatched) and $k$+A (solid black) cluster galaxies are statistically different. Together with the results from Figure 4, this show that most of the $k$+A galaxies near rich clusters are being pre-processed in poor group environments before they mingle with the cluster population.

Figure 4. The distribution of absolute l.o.s. velocity for all (solid black) and $k$+A (red dashed) galaxies within $2r_{200}$ of the cluster centre and $1 \leq |v_{\text{los}}|/\sigma_v \leq 3$. These distributions are statistically different (see text), confirming that most $k$+A galaxies are likely to be falling into clusters.
ies are found in locally over-dense regions within clusters. Ideally, such an analysis should be performed in small radial bins in order to disentangle the impact of local over-density from that of the large-scale environment on \(k + A\) galaxies, but the rarity of \(k + A\) galaxies in low-redshift clusters only permits a stacked analysis.

Figure 5 shows the distribution of absolute velocity of all cluster galaxies within \(2r_{200}\) and \(1 \leq |v_{los}|/\sigma_{c} \leq 3\), along with the \(k + A\) galaxies in the same radial and absolute velocity range. The exclusion of galaxies with \(|v_{los}|/\sigma_{c} < 1\) allows me to focus on the population of mostly non-virialized galaxies. The KS statistic probability in favour of the hypothesis that these two distributions are drawn from the same parent population is 0.0098, suggesting that a non-negligible fraction of \(k + A\) galaxies may have accreted into the clusters recently.

Poggianti et al. (2009) found \(k + A\) galaxies to be more frequent in low velocity dispersion galaxy groups (200–400 km s\(^{-1}\)) and massive clusters (0.4 < \(z\) < 0.8; also see Vergani et al. 2010), relative to the field and rich groups. In the Coma supercluster \((z = 0.03)\), Mahajan, Haines, & Ravchaudhury (2011) found that \(k + A\) galaxies mainly occurred on cluster outskirts and galaxy groups. I applied the “\(k\)-test” devised by Colless & Dunn (1996) to test for localized variations in the velocity distribution of galaxies in each cluster. This test compares the velocity distribution of a group of \(N\) nearest neighbours of each galaxy to the cluster’s mean. The significance of \(\kappa_N\) is estimated by Monte Carlo simulations in which velocities of cluster galaxies are shuffled randomly. The test shows that 24/28 clusters in this sample are at least 95% likely to have substructures with 4-10 member galaxies. Furthermore, 91.4% of all \(k + A\) galaxies are found to be a part of one of these substructures \((P(\kappa_N > \kappa_{obs})=0.03\%)\). Together, these results suggest that the \(k + A\) galaxies locally reside in marginally denser environment such as poor galaxy groups, and their presence may be correlated with accretion of such groups into clusters.

Quenching of star formation in \(k + A\) galaxies may be a result of the “pre-processing” happening in these small groups assembling into larger clusters. Struck (2006) suggested that for a poor group falling into a rich cluster with comparable halo core density, the galaxy density for group galaxies can increase by an order of magnitude and their collision rate by a factor of about 100 (density squared), thereby increasing the probability of a burst of star formation in the process. Such bursting galaxies will eventually be observed as the post-starburst population such as that studied here.

Simulation of a galaxy group merging with a cluster four times more massive than itself, shows that starburst can be triggered in gas-rich galaxies due to the external pressure of the ICM (Bekki, Owers, & Couch 2010). These starburst galaxies will eventually be transformed into a population of post-starburst galaxies. Bekki et al. argued that after the structure has finally relaxed (~ 5 Gyr), such galaxies will not show any preferred spatial distribution. For the sample studied here, I find that although the absolute velocity distribution of the \(k + A\) galaxies is statistically different from other cluster galaxies in the same absolute velocity regime, they do not show any preferred spatial distribution relative to the cluster centre (the KS test probability in favour of the hypothesis is 0.0927 for galaxies within \(2r_{200}\)). If we assume several small groups merging into present day galaxy clusters, such a random distribution of group galaxies being pre-processed is expected.

However, several authors (Hogg et al. 2006, De Lucia et al. 2009, Yan et al. 2009) have argued against any correlation between the incidence of post-starburst galaxies and their global environment, suggesting that the post-starburst phase is not a dominant channel for converting the blue, star-forming galaxies to passively evolving red cluster galaxies. This letter presents a new angle to this dichotomy, by evidently showing that the incidence of \(k + A\) galaxies in nearby rich clusters is correlated with locally over-dense regions within clusters. Since most of the \(k + A\) galaxies in these clusters belong to group scale substructures, it is likely that the \(k + A\) galaxies are being pre-processed in such galaxy groups during their accretion into the cluster. Evidence for such pre-processing has also been reported by Jaffe et al. (2012) in galaxy groups falling into a cluster at \(z \sim 0.2\). Using optical and ultraviolet data for galaxies in optically-selected groups (\(z \sim 0.06\)), Rasmussen et al. (2012) showed that not only SFR, but also SFR/\(M^*\) is quenched in group galaxies. Moreover, these authors found the effect to be strongest for low-mass \(10^9 - 10^7 M_\odot\) galaxies.

Figure 5 shows the distribution of all cluster galaxies, and \(k + A\) galaxies in the \((g - r) - M^*\) space. The stellar masses are estimated using the relation given by Bell et al. (2003). This figure shows that \(k + A\) galaxies around clusters are mostly less than \(10^{10} M_\odot\) in stellar mass, but span almost the entire colour range populated by all cluster galaxies taken together. This result is in agreement with previous studies which showed that at \(z \sim 0\) post-starburst \(k + A\) galaxies are more frequent among low-mass galaxies (e.g. Mahajan, Haines, & Ravchaudhury 2010, 2013, Geha et al. 2012, also see Rasmussen et al. 2012). This may happen because (i) most of the star formation at the present epoch is happening in low-mass galaxies, which are quenched during accretion into clusters, or, (ii) only low-mass galaxies go through a post-starburst phase when quenched. Advanced simulations including better semi-analytic models of galaxy formation, environmental processes and feedback recipes are required to throw more light on this subject. Incidentally, some work has already begun in this direction (e.g. De Lucia et al. 2012).

\(^2\) Different authors have used different combinations of spectroscopic indices such as the EW of balmer lines and the 4000Å break, to classify post-starburst galaxies.
5 SUMMARY

I have used the X-ray and optical spectroscopic data for nearby (0.02 \( \leq z \leq 0.06 \)) galaxy clusters to show a mild trend of an increase in the incidence of k+A galaxies with Tx. However, a cluster sample uniformly spanning the whole range in Tx is required to confirm this. Such a correlation, if found, will confirm that the ICM plays a critical role in quenching star formation in infalling galaxies.

For the X-ray bright clusters studied here, although k+A galaxies show only a marginal (statistically insignificant) preference for higher clustercentric distances, their absolute velocity distribution is different from other cluster galaxies \( ( < 2r_{200}, \ 1 \leq |v_{disp}|/\sigma_{v} \leq 3 ) \). These k+A galaxies are also found in locally overdense regions relative to other cluster galaxies. 86% of clusters in this sample show statistically significant substructure on group scales in velocity distribution, with 91.4% of all k+A galaxies belonging to one of these groups with 4-10 members. Together, these results suggest that k+A galaxies are likely to be members of poor galaxy groups, whose star formation may have been quenched as a result of pre-processing during accretion into clusters.

These results favour the argument that the SFR in galaxies falling into clusters may be enhanced on the cluster outskirts by a burst of star formation triggered due to galaxy-galaxy interactions (e.g. Fadda, Biviano & Durret 2008; Porter et al. 2008; Mahajan, Raychaudhury & Pimbblet 2012, and references therein). However, it remains debatable whether the global environment plays any significant role in accelerating these interactions when the group encounters the cluster potential (Struck 2006; Bekki, Owens, & Couch 2010; Jaffé et al. 2012), or, the group environment self-sufficiently aids the evolution of galaxies (Pereira et al. 2010; Rasmussen et al. 2012), irrespective of the large-scale environment.

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