Following the crumbs: Statistical effects of Ram Pressure in Galaxies

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ABSTRACT

We analyse the presence of dust around galaxy group members through the reddening of background quasars. By taking into account quasar colour and their dependence on redshift and angular position, we derive mean quasar colours excess in projected regions around member galaxies and infer the associated dust mass. For disc-like galaxies perpendicular to the plane of the sky, and at group-centric distances of the order of the virial radius, thus likely to reside in the infall regions of groups, we find systematic colour excess values $c \sim 0.009 \pm 0.004$ for $g - r$ colour. Under the hypothesis of Milky Way dust properties we derive dust masses of $5.8 \pm 2.5 \times 10^8 M_\odot/h$, implying that a large fraction of dust is being stripped from galaxies in their path to groups.

We also studied the photometry of member galaxies to derive a colour asymmetry relative to the group centre direction from a given galaxy. We conclude that the regions of galaxies facing the centre are bluer, consistent with the effects of gas compression and star-formation.

We also combine these two procedures finding that galaxies with a small colour asymmetry show the largest amounts of dust towards the external regions compared to a control sample. We conclude that dust removal is very efficient in galaxies on infall. The fact that galaxies redder towards groups centres are associated to the strongest reddening of background quasars suggest that gas removal induced by ram pressure stripping plays a key role in galaxy evolution and dust content.

Key words: galaxies: fundamental parameters - intergalactic medium - galaxies: groups: general – galaxies: star formation – quasars: general – surveys

1 INTRODUCTION

Galaxies have evolved simultaneously with their environment and at the present-day they have formed groups and clusters via their infall onto denser regions. This fact is key to explain galaxy properties in systems though the action of mergers (Barnes & Hernquist 1996), ram pressure (Gunn & Gott 1972) and harassment (Moore et al. 1996) that shape and affect galaxies as they fall onto a group or cluster (for a review see Boselli & Gavazzi 2006). In particular, ram pressure stripping from the intra-cluster medium can play a key role in removing gas from galaxies, thus affecting future star-formation once the galaxies have entered in these systems.

Besides the fact that properties of galaxies in clusters differ from those elsewhere, there is also mounting observational evidence of stripped material from galaxies in groups and clusters (Poggianti et al. 2016; Jaffé et al. 2018).

Numerical simulations also provide useful information on the transformation process of galaxies. For instance, hydrodynamical simulations show how efficiently ram pressure quenches star-formation during infall (see for instance Steinhauser et al. 2016). Also, semi-analytical models need to model the effect of ram pressure to reproduce some observed galaxy properties (De Lucia et al. 2004; Tecce et al. 2010; Guo et al. 2011). Ram pressure stripping is an effective mechanism by which a galaxy can lose a significant amount of gas and dust and so, galaxies in their first infall onto a group/cluster can suffer a strong change leaving a sub-
2 METHODS

In order to assess the presence of dust associated to member galaxies, we characterise background quasars excess colours in zones near to these galaxies. For this aim, we select group member galaxies (with low semi-major/semi-minor axis ratio, \(b/a < 0.5\)), located in projection at least at 0.5 halo radius from the centre of their corresponding group. By doing so, we maximise the number of galaxies in the infall region (see Fig. 6 in Jaffé et al. 2018). We consider a circle of 600 kpc/\(h\) projected radius around each galaxy and select background quasars within these circles. We notice that a given quasar can be associated to more than one galaxy, in this case the quasar information is used more than once. For each quasar, we calculate the angle between the vector of the corresponding galaxy to the centre and the vector between the member galaxy and the quasar. Fig. 1 schematises the position of the member galaxy, the group centre and the background quasar, and the angle \(\theta_i\), which ranges between \(-180^\circ\) and \(180^\circ\). With this setup we stack galaxies scaling to the angular size corresponding to 600 kpc/\(h\) in projection and use \(\theta_i\) as the angular position for each of the background galaxies, oriented with respect to the direction of the centre of each group.

Since it could be possible that the dependence of colour excess on \(\theta_i\) is not due to the presence of galaxies but rather intrinsic to groups, we create control samples of positions within groups. To construct these samples we take the position and the angular size of the projected 600 kpc/\(h\) radius of each of the member galaxies and replace it by a random position at the same distance to the centre of the group with no other galaxy within 300 kpc/\(h\) of projected separation. We obtain a sample of background quasars for these control zones. The difference of quasar colour excess between galaxy and control zones as a function of \(\theta_i\) can then be considered as caused by the presence of debris associated to the member galaxies.

2.1 Difference between halves.

Additionally, we provide an analysis of the impact of ram pressure by looking at colour asymmetries of galaxies taken from the same sample of member galaxies studied in the previous case including those members at less than 0.5 halo radius from the centre. For each of these galaxies we use the images in the \(r\) and \(b\) bands, and we obtain photometry corresponding to an ellipse with semi-major axis \(\sqrt{a/b} r_{90}\) and semi-minor axis \(\sqrt{b/a} r_{90}\) that contain 90 percent of the galaxy total flux in each band. The ellipses are then separated in two halves by a line perpendicular to the vector to the centre of the group. We remark the fact that we cannot use the velocity vector as in T16 given the lack of kinematic information. In Fig. 1 this line appears as a dashed line in the member galaxy. Following T16, we call the half ellipse closer to the centre as the leading-half, and the other one as the trailing-half. Then, we use the two bands to calcu-
Table 1. The median values of magnitudes and colours.

|               | Median         |
|---------------|---------------|
| $M_r - 5 \log(h)$ | $-19.658 \pm 0.013$ |
| $m_r$         | $16.782 \pm 0.009$ |
| $m_g$         | $17.596 \pm 0.009$ |
| $g - r$       | $0.87 \pm 0.002$  |

late the $g - r$ colour for each half and calculate the relative colour difference between the two halves. T16 and T19 define trailing/leading half the sides separated according to the three-dimensional velocity vector, while here we use the projected direction to the group centre.

The calculation of the relative difference of colour is done as follows: For each half we calculate the colour ($C_l$ for the leading, $C_t$ for trailing), then the difference $\Delta C = C_l - C_t$.

This allows a study of a possible relation between the values of $\Delta C$ and the angle between the semi-major axis and the vector to the centre (In Fig. 1 labelled as $\phi_\lambda$). Any correlation between the internal asymmetries and the intra-group dust mass content would be mostly interesting for the interpretation of the results.

3 GROUP, GALAXY AND QUASAR SAMPLES

We use the group catalogue from Yang et al. (2012). This catalogue has been produced using DSS-DRT (Abazajian et al. 2009). Since the Yang et al. (2012) groups are identified assuming an overdensity of 180 we use $r_{180}$ as halo radius, computed using equation 5 in Yang et al. (2007). From the total group sample we consider only those with at least 4 member galaxies with a halo mass larger than $10^{12.5} M_\odot / h$.

Additionally, we select galaxies brighter than -15 absolute magnitude in the $r$ band and with $r_{50}$ values, measured in the $r$-band, of at least 5 arcsec, and $b/a < 0.5$. This last restriction is applied in order to restrict our sample to galaxies nearly edge-on so that if at infall onto the groups in the plane of the sky, their projected area of debris is larger than the area of face-on galaxies, since those galaxies would have their motion perpendicular to the disc planes.

We expect to find the most significant effects in late-type galaxies due to their higher amount of dust and cold gas with respect to early-type ones. In order to measure $\Delta C$ values for individual galaxies, we take galaxy images in the $g$ and $r$ bands reprocessed in SDSS-DR8 (Aihara et al. 2011). The number of selected galaxies for this analysis is 12440, which reside in 5323 groups. Table 1 shows the median values of magnitudes and colours for this galaxy sample.

The adopted sample of quasars to derive reddening in regions around group galaxies was taken from the BOSS quasar sample (Páris et al. 2017). These background quasars are further restricted to the redshift range $2 < z < 3.5$ since the maximum of the quasar distribution is in this region, and we aim to avoid possible incompleteness issues. The total number of quasars within the area covered by groups is 139294.

It is necessary to take into account several effects on the observed quasar colour besides the reddening from dust associated to local structures. The K-correction (Oke & Sandage 1968) is strongly redshift dependent and so as a first step we consider the relation between the median observed quasar colour and redshift (left panel of Fig. 2). With this information we compute the mean excess colours of individual quasars taking into account the expected colour as a function of quasar redshift. This correction allows to decrease the colour dispersion by 20%, which in turn improves our measurement uncertainties by 30%. The other relevant effect is due to the extinction and reddening from the interstellar (see for instance Schlegel et al. 1998) and zodiacal dust (May 2007). To tackle this issue, we measure the median of quasar excess colours (previously redshift corrected) according to their position in the sky. Then we apply a 2 degrees low pass filter to construct maps which are only affected by reddening at scales larger than 2 degrees (middle and right panels in Fig. 2) since 2 degrees is larger than the largest 600 kpc area around galaxies in our sample. Thus, the total correction applied to quasar colours are the sum of the previously described redshift corrections plus the angular correction from the interstellar medium.

In order to minimise the effects of the presence of strong absorption regions close to the galactic plane we restrict our samples of galaxies and quasars to galactic latitude $\lambda > 40^\circ$.

4 RESULTS

4.1 Observational effects of the debris

Fig. 3 shows the angular distribution of the $g - r$ colour excess of background quasars associated to galaxies in groups. The group centre direction is to the right along the positive $x$ axis. We can see a positive colour excess of background quasars as we move away from the group centre. However, a similar excess can be observed in the direction to the centre of the group, an effect that could be owed to the group medium and is not necessarily related to the presence of a galaxy. To explore this issue into more detail, we compare these results with those derived from the control sample where a similar colour excess is seen in the direction to the group centre, while in the positive radial direction, colours of background quasars tend to be bluer.

A total of 10399 quasars were used for our analysis, and on average, 7 quasar sightlines crossed each galaxy. We find that approximately 26% of quasars passed through more than one target galaxy.

We interpret these results as a consequence of a global reddening of background quasars by the intra-group medium plus an important contribution of material removed by infalling galaxies. This hypothesis is reinforced by inspection to Fig. 4 that shows the relation of the relative colour excess as a function of $\theta_i (g - r$ in the left panel and $g - i$ in the right panel) subtracted to the colour excess of quasars associated to the control zones. It can be seen that both the $g - r$ and $g - i$ colour excess relative to the control sample increase towards the external radial direction ($\theta_i \sim 180^\circ$), as well as a marginal reddening towards the centre ($\theta_i \sim 0^\circ$). Thus, this analysis suggests that there is a contribution of ram pressure stripped dust in the infall region around groups.

Following, Equation 5 in McGee & Balogh (2010), we can estimate a dust mass density related to the colour excess measurements. Using the observed $g - r$ reddening of
quasars at $\sim 180^\circ$ and assuming Milky Way dust physical properties as in (McGee & Balogh 2010), we calculate a dust column density of $2034 \pm 877 M_\odot/ kpc^2 h$. Taking into account the corresponding area under consideration (the area of the last bin), we obtain a dust mass of $5.8 \pm 2.5 \cdot 10^8 M_\odot/h$ (the median stellar mass of the sample is $10^{10.15} M_\odot$). We acknowledge that the estimated removed dust mass is quite high compared to the median galaxy stellar mass content by a factor of 2 or more (Calura et al. 2017; Dale et al. 2017). However, we notice that a significant fraction of the stripped material can be associated to the extended gas reservoirs of galaxies, as well as to other galaxies in the same substructure.

4.2 Dependence on group and galaxy parameters

We have also explored the dependence of the observed trends of quasar colour excess and $\theta_i$ on different characteristics of group and member galaxies. For this aim, we have considered different sub-samples selected according to different properties of galaxies and groups. These sub-samples take into account i) the angle between the vector to the centre of the group and the semi-major axis with $\phi_s < 45$, ii) luminosity cuts $M_r - 5 \log h < -19.5$ and $M_r - 5 \log h > -19.5$, iii) concentration cuts ($r_{90}/r_{50} < 2.5$ and $r_{90}/r_{50} > 2.5$), iv) the effects of the group halo mass by considering a threshold in $M_{\text{halo}} < 10^{13.9} M_\odot/h$ and $M_{\text{halo}} > 10^{13.9} M_\odot/h$, and v) galaxy colour. Given the relation between galaxy colour and luminosity we have not applied a single threshold colour cut, but use the median $g - r$ value as a function of absolute magnitude to separate the sample into red and blue galaxy sub-samples.

All the sub-samples show the trend where background quasars with high $\theta_i$ tend to be redder in the presence of a galaxy. However, there is a strong variation with the sub-sample luminosity, colour and group mass. In the case of concentration and $\phi_s$ all the samples show a similar behaviour than the total sample, within uncertainties (determined via bootstrap). Fig. 5 shows the results for the sub-samples divided by absolute magnitude of the galaxy, galaxy colour and group halo mass. As can be seen, the largest colour excess is associated to red, bright galaxies, and higher group mass, indicating larger amounts of removed dust.

These results are reasonable since bright galaxies have larger gas masses than the faint ones, and therefore more dust is likely to be stripped along their orbits in the groups.
Observable effects of ram pressure

Figure 4. Difference between the average colour excess of background quasar as a function of the angle defined by the background galaxy, the galaxy in the group and the group centre, and the average colours of background galaxies in the control zones. LEFT: Average values for $g - r$ colour. RIGHT: Average values for $g - i$ colour.

We also expect that galaxies suffering a stronger ram-pressure tend to loose higher amounts of material, in particular cold gas. Therefore star-formation should decrease and therefore redden their colours. These effects can be seen in the middle panel of Fig. 5. We also observe that galaxies orbiting massive groups are likely to experience more stripping than galaxies in less massive groups with more tenous intragroup medium, as seen in the right panel of Fig. 5. We have tested the effects of the uncertainty of group centre positions due to different number of members, which could affect more strongly low mass groups. We find that using the same number of galaxies (n=4) to determine group centres for all group masses, the results remain unchanged.

4.3 Internal effects on member galaxies

Following T16, we have computed the mean colour difference between the leading and trailing galaxy halves $\Delta C$. Fig. 6 shows the behaviour of $\Delta C$ as a function of $\phi_s$ for subsamples selected according to the projected distance to the centre of the groups in units of $r_{180}$. It is important to stress the fact that these results can only be compared with caution since the results in T16 are based on 3-D measure-
ments, and consider the efficiency of star-formation of the
gas particles instead of colour.

As can be seen, there are noticeable systematic differ-
ences between the mean colours of the leading and trailing
halves for sub-samples of galaxies located beyond 0.75 \( r_{180} \)
with high \( \phi_s \), i.e. galaxies whose disk tend to be perpendicu-
lar to the vector towards the group centre. Given their large
group centric distance, it can be argued that the vector to
the centre is a suitable proxy for the galaxy infall velocity
vector. This is supported by the analysis of Jaffé et al. (2018)
who find that galaxies in infall are preferentially located be-
Yond 0.5 the group virial radius.

This result gives support to the idea that, under an
appropriate setting, the leading half of galaxies residing in
groups is bluer than the trailing half. This is in good agree-
ment with the results of T16 and T19, where the leading
half of galaxies in the simulation presents a higher SFR due
to the compression of the gas as the galaxy moves in the
intracluster medium. This gas compression causes an increase
of pressure and density. This result is of small amplitude
and no combination of other photometric colour bands (\( u, g, r \)
and \( i \)) provide larger differences than those observed in
\( g - r \). We notice that a stronger effect is expected in the
\( u - r \) colour index since it comprises the 4000 Å break, often
used as a proxy for star-formation activity (e.g. Kauffmann
et al. 2003). Yet, photometric errors and low statistics, i.e.
small extension of the galaxies make it not useful for this
particular dataset.

4.4 Exploring the relation between the effect on
galaxies and removed debris

In this subsection we explore possible relations between the
results obtained in the two previous sub sections (§4.1 and
§4.3). To this aim, we select galaxies with \( r/r_{180} > 0.5 \)
and separate this sample between those galaxies with \( \Delta C \)
larger than the mean (the leading half is bluer) and those with
lower \( \Delta C \) values (the trailing half is bluer). Fig. 7 shows
the behaviour of the colour excess of the background quasars for
these samples and the corresponding control zones.

It can be appreciated that there is a statistically sig-
nificant difference between these two. Relative colour ex-
cess of quasars around galaxies with large \( \Delta C \) values (i.e.
galaxies whose leading halves are redder than their cor-
responding trailing halves) have a much stronger signal
compared to the low \( \Delta C \) sub-sample. This signal is even
stronger for galaxies with high \( \Delta C \) located in massive halos
(\( M_{\text{halo}} > 10^{13.9} M_\odot/h \), green dots).

It can be argued that galaxies which have experienced
strong stripping due to ram pressure are those associated to
the strongest removal of dust. These more efficiently stripped
galaxies have a weaker gravitational potential and their
leading regions should experience gas stripping rather than
gas compression. Another explanation is that most massive
halos are more efficient stripping the gas as it is observed in
Fig. 7 (green dots). This scenario could explain why galax-
ies with a leading half with a lower star-formation exhibit
signs of removed gas as measured by the background quasar
colour excess. Therefore, we interpret the previous result as
a further evidence that the same astrophysical processes,
ram-pressure, acting on galaxies making them asymmetric,
also generates the quasar reddening which we associate to
dust removed from their interstellar medium.

5 DISCUSSION AND CONCLUSIONS

In this paper we have studied the presence of dust around
galaxies in groups in the local universe. The procedures were
based on the systematic reddening of background quasars in
regions neighbours of groups. We carefully take into account
the redshift and angular position dependence of the observed
mean quasar colours, which allow us to derive more precise
mean colour excesses around group galaxies. We have fo-
cused on disc galaxies observed perpendicular to the plane
of the sky, and at distances to group centers consistent with
the infall regions of groups. Assuming dust proper-
ties consistent with those of the Milky Way, dust masses of
5.8 \pm 2.5 \cdot 10^8 M_\odot/h per galaxy are inferred, implying large
fraction of dust stripped from galaxies orbiting groups.

We stress the fact that significant reddening of back-
ground quasars are derived for the subsample of the most
massive groups, \( M_{\text{halo}} > 10^{13.9} M_\odot/h \), as expected under
the assumption of ram pressure stripping by the intragroup
medium as the cause for the stripped dust.

A photometric study of the galaxies is performed to de-
rive a colour asymmetry parameter relative to the group cen-
tre direction from the galaxy position. This analysis shows
that regions of galaxies facing the centre are bluer than their
opposite counterparts, a fact that we interpret in terms of
the effects of gas compression and star-formation along the
galaxy motion towards the group centre.

Consistently, galaxies with the smallest colour asym-
bmetries show the largest amounts of dust radially outwards
compared to a control sample with no galaxy at the same
group-centric distance. In control regions, it is certainly pos-
sible that the colour excess measurements come from a cor-
related filament environment hosting infalling galaxies. This
issue will be studied in more detail in a forthcoming paper.

We conclude that dust removal is very efficient in galax-
ies infalling onto groups, particularly onto the most massive
ones. The fact that galaxies with the smallest group-centric
colour asymmetries are associated to the strongest reddening

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure7}
\caption{\textit{g – r} colour excess of background quasars relative to
the control sample according to the difference of colour between
the leading and trailing halves of the member galaxy.}
\end{figure}
of background quasars suggests that gas dynamics and removal induced by ram pressure from the intragroup medium are suitable mechanisms acting on the leading and trailing regions of galaxies.

We notice that other mechanisms aside from ram pressure may be present in infalling galaxies. For instance, gas expelled by supernovae winds isotropically from galaxies likely to be destroyed by the radiation from the hot ICM towards groups centres, creating the observed reddening trends. However, the internal radial colour asymmetry and its correlation to the background quasar colour excess around galaxies with redder leading halves provides a hint that ram pressure may be the most appropriate mechanism to explain the observations.

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