THE TRANSPARENCY OF GALAXY CLUSTERS

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ABSTRACT

If galaxy clusters contain intracluster dust, the spectra of galaxies lying behind clusters should show attenuation by dust absorption. We compare the optical (3500–7200 Å) spectra of 60,267 luminous, early-type galaxies selected from the Sloan Digital Sky Survey to search for the signatures of intracluster dust in z ~ 0.05 clusters. We select massive, quiescent (i.e., non-star-forming) galaxies using an EW(\text{H}α) ≤ 2 Å cut and consider galaxies in three bins of velocity dispersion ranging from 150 to 300 km s⁻¹. The uniformity of early-type galaxy spectra in the optical allows us to construct inverse-variance-weighted composite spectra with high signal-to-noise ratios (ranging from 10^3 to 10^4). We compare the composite spectra of galaxies that lie behind and adjacent to galaxy clusters and find no convincing evidence of dust attenuation on scales of ~0.15–2 Mpc; we derive a generic limit of E(B − V) < 3 × 10⁻³ mag on scales of ~1–2 Mpc at the 99% confidence level, using conservative jackknife error bars, corresponding to a dust mass ≤10^8 M⊙. On scales smaller than 1 Mpc, this limit is slightly weaker, E(B − V) < 8 × 10⁻³ mag.

Subject headings: dust, extinction — galaxies: clusters: general — intergalactic medium — methods: statistical

Online material: color figures

1. INTRODUCTION

Galaxy clusters are known to contain galaxies and hot gas, and they may contain extragalactic but intracluster dust or be accreting intergalactic dust from their neighborhoods. Indeed, there must be some intracluster dust created by winds from the intracluster stars, which make up a significant fraction of the total stellar mass in the cluster (Ferguson et al. 1998). Alternatively, dust could be introduced into the intracluster medium (ICM) through such processes as cooling flows (Fabian et al. 1994), galaxy or cluster mergers and collisions (Popescu et al. 2000), supernova-driven galactic winds (Okazaki et al. 1993), ram pressure stripping of galaxies as they travel through the ICM (Gunn & Gott 1972), and accretion of primordial dust (Popescu et al. 2000). Many of these processes have associated timescales of order 10^5–10^6 yr. A crucial question is then whether the dust thus injected into the ICM can survive thermal sputtering in the hot gas. Typical dust-grain sputtering timescales are τ_{\text{sput}} \sim 10^6–10^8 yr (Draine & Salpeter 1979), similar to the timescales of the dust-producing processes. These timescales imply that only the most recently injected dust is still surviving at any given moment in time, from which we conclude that the amount of dust in the ICM should be small and nonuniformly distributed.

Measurements of intracluster dust have a long and rich history. The presence of dust was first hypothesized to explain the discrepancy between counts of galaxies located behind and adjacent to the Coma Cluster (Zwicky 1957). A first estimate of 0.4 mag for the magnitude of the B-band extinction was suggested (Zwicky 1961, 1962), although infrared emission of dust in the Coma Cluster was not detected (Dwek et al. 1990). Zwicky’s method was improved over the years as catalogues of galaxy clusters became available and B-band extinctions of order 0.2 mag were reported based on various procedures, including using essentially the same approach as Zwicky, but using a larger sample of 15 galaxy clusters (Karachentsev & Lipovetskii 1969); considering color residuals to arrive at the amount of absorption within the Local Supercluster (de Vaucouleurs et al. 1972); looking at angular correlations among clusters and quasars, leading to an extinction of about 0.12 mag over radii of several Mpc (Bogart & Wagoner 1973); and considering correlations of high-redshift quasars with low-redshift galaxies, which gave evidence for dust in clusters at redshift z ~ 0.15 at a characteristic linear radius of 500 h⁻¹ kpc, corresponding to a dust sphere of mass 10^{10} M⊙ (Boyle et al. 1988). However, galaxy number counts are subject to a variety of biases, and the dearth of galaxies behind clusters could have causes other than dust (Nolleneberg et al. 2003).

Correlations of quasars with nearby clusters were reconsidered, and a B-band extinction of 0.15 mag was found (Romani & Maoz 1992). A similar result was found to explain an excess of redshifted infrared dust in nearby small galaxy groups (Girardi et al. 1992). However, comparing the color distribution of quasars behind a cluster with those in the vicinity of the cluster limited the relative reddening of the two samples to E(B − V) ≤ 0.05 mag (Maoz 1995). Similar limits were obtained by comparing color distributions of galaxies behind and removed from APM clusters (Nolleneberg et al. 2003) on 1.3 Mpc scales and using large, elliptical galaxies (Ferguson 1993).

There have been some contradictory reports on dust in the central regions of clusters. A study of IRAS images of 56 clusters found two clusters with far-infrared color excesses that could be due to 10^8 M⊙ of dust (Wise et al. 1993). An average excess reddening of 10 cool-flow galaxy clusters of E(B − V) ~ 0.19 mag was reported for lines of sight to the center of these clusters (Hu 1992). However, a later report found no convincing evidence of submillimeter dust emission in 11 cool-flow clusters and set an upper limit of 10^8 M⊙ on the total mass of the dust (Annis & Jewitt 1993).

More recently, observations of six Abell clusters found a rough dust-mass estimate of 10^7 M⊙ in the Coma Cluster but no evidence of dust in the other five observed clusters (Stickel et al. 2002), and no significant amount of infrared emission from intracluster dust in Abell 2029 was found (Bai et al. 2007). Chelouche et al. (2007) reported reddening in a 0.1 < z < 0.3 sample of ~10^4 galaxy clusters by correlating the Sloan Digital
Sky Survey (SDSS) cluster and quasar catalog and comparing photometric and spectroscopic properties of quasars behind the clusters to those in the field. They found mean \( E(B-V) \) values of a few \( 10^{-3} \) mag for sight lines passing \( \sim 1 \) Mpc from the clusters’ centers. However, a recent study found no evidence of dust in 0.2 \( < z < 0.5 \) clusters from a photometric study of color excesses in several bands and, assuming a Galactic extinction law, derived an average visual extinction of \( \langle A_V \rangle = 0.004 \pm 0.010 \) mag (Muller et al. 2008).

In this paper we study the dust content of galaxy clusters by comparing the spectra of galaxies behind clusters of galaxies with those of galaxies not behind clusters. More specifically, we use the optical (3500–7200 Á) spectra of luminous, early-type galaxies because they are known to dominate the stellar mass density of the universe (Fukugita et al. 1998; Hogg et al. 2002) and show great regularities in their properties (e.g., Oke & Sandage 1968; Faber 1973; Visvanathan & Sandage 1977; Djorgovski & Davis 1987; Dressler et al. 1987; Kormendy & Djorgovski 1989; Bower et al. 1992; Roberts & Haynes 1994; Bernardi et al. 2003a, 2003b, 2003c, 2003d). Their spectra show a remarkable similarity, with any variation that does exist explained by the environment and luminosity (Eisenstein et al. 2003). Any dust-attenuation-like difference that can be found between the composite spectra of galaxies behind galaxy clusters and galaxies in the field can be reliably attributed to interactions of the galaxies’ light with the ICM.

The differences between our study and the other precise studies cited above are that (1) we have more control over our galaxy population, (2) we are selecting based on properties that only weakly involve color and are therefore less likely to be biased, and (3) we have well-calibrated spectrophotometry of all the objects. On the other hand, these considerations limit the size of our sample, so what we gain in per-object precision, we lose in number of objects, in some sense. Despite our relatively small sample, we obtain some of the most stringent upper limits ever.

In what follows, AB magnitudes are used throughout, a cosmological world model with \( (\Omega_m, \Omega_{\Lambda}) = (0.3, 0.7) \) is adopted, and the Hubble constant is \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\) (Komatsu et al. 2008) for the purposes of calculating distances (e.g., Hogg 1999).

2. DATA

The SDSS obtains \( u, g, r, i, \) and \( z \) CCD imaging of \( 10^4 \) deg\(^2\) of the northern Galactic sky, and from that imaging it selects roughly \( 10^6 \) targets for spectroscopy, most of them galaxies with \( r < 17.77 \) mag (Gunn et al. 1998; York et al. 2000; Stoughton et al. 2002; Abazajian et al. 2003, 2004, 2005). All the data processing, including astrometry (Pier et al. 2003), source identification, deblending and photometry (Lupton et al. 2001), calibration (Fukugita et al. 1996; Smith et al. 2002; Ivezic et al. 2004), spectroscopic target selection (Eisenstein et al. 2001; Strauss et al. 2002; Richards et al. 2002), spectroscopic fiber placement (Blanton et al. 2003), and spectral data reduction and analysis (D. J. Schlegel & S. Burles, in preparation; D. J. Schlegel, in preparation) are performed with automated SDSS software. We use the spectroscopic and photometric data from the NYU Value Added Galaxy Catalog (NYU-VAGC; Blanton et al. 2005) compiled from the SDSS Data Release Four (DR4; Adelman-McCarthy et al. 2006).

As we are averaging the spectra of galaxies coming from different spectral “plates,” we depend on the calibration of these fluxes. The calibration procedure is as follows (D. J. Schlegel, in preparation; Stoughton et al. 2002): Every spectral “plate” of fiber positions includes several faint (15.5–18.5 mag) F8 sub-dwarf stars. The spectrum of each standard star is spectrally typed by comparing it with a grid of theoretical spectra generated from Kurucz model atmospheres (Kurucz 1992) using the spectral synthesis code SPECTRUM (Gray & Corbally 1994; Gray et al. 2001). The spectra are calibrated with these F-star spectra; i.e., they are multiplied by the function of wavelength that makes the F-star spectra match the F-star spectrophotometry (after correcting for Galactic reddening). This calibration procedure produces consistent calibration at the 5% level.

In addition to this, the SDSS does not use an atmospheric refraction corrector, so the effective fiber position on the sky shifts slightly as a function of wavelength. In the presence of brightness gradients, this creates a fluxing error.

Redshifts are measured on the reduced spectra by an automated system, which models each galaxy spectrum as a linear combination of stellar eigenspectra (D. J. Schlegel, in preparation). The central velocity dispersion \( \sigma_e \) is determined by fitting the detailed spectral shape as a velocity-smoothed sum of stellar spectra (D. J. Schlegel & D. P. Finkbeiner, in preparation).

The equivalent width (EW) of the H\( \alpha \) line is measured exactly as described in Quintero et al. (2004). Briefly, a linear fit of the spectral section to a linear combination of the mean SDSS old galaxy spectrum and the mean SDSS A-star spectrum with the locations of possible emission lines marked out is performed. This best-fit model is then scaled down to have the same flux continuum as the data in the vicinity of the H\( \alpha \) emission line and subtracted to leave a continuum-subtracted line spectrum. The H\( \alpha \) line flux is then measured in a 20 Á width interval centered on the line and converted to a rest-frame EW with a continuum found by taking the inverse-variance-weighted average of two sections of the spectrum about 150 Á in size and on either side of the emission line. This method fairly accurately models the absorption trough in the continuum, although in detail it leaves small negative residuals.

The galaxy clusters used here are \( 0.015 < z < 0.067 \) member clusters taken from a friends-of-friends cluster catalog constructed from the SDSS DR3 main sample galaxies with absolute magnitudes \( M_{\text{bol}} < -19.9 \) mag (Berlind et al. 2006). We first consider a \( N_{\text{gal}}^{\text{min}} = 10 \) member minimum, corresponding to a total absolute \( r \)-band magnitude \( M_r \leq -21.9 \); for reference, the Virgo Cluster contains 13 galaxies brighter than this limit (Trentham & Hodgkin 2002). However, we also vary the minimum number of galaxies in the cluster between \( N_{\text{gal}}^{\text{min}} = 5 \) \( (M_r \leq -20.8 \) mag) and \( N_{\text{gal}}^{\text{min}} = 20 \) \( (M_r \leq -23.1 \) mag).

3. ANALYSIS

3.1. Sample Construction

Our technique is analogous to the classic “foreground screen” test of using stars to measure the Galactic extinction curve (e.g., Calzetti 2001 and references therein). Here, we compare the spectra of galaxies that lie behind a cluster of galaxies, i.e., galaxies whose light has had to traverse a galaxy cluster on its way to observational astronomers, against the spectra of galaxies that do not lie behind a cluster. Galaxies that lie behind a galaxy cluster will constitute the target galaxies, and galaxies that are not behind a cluster will form the control sample. The optical spectra of these objects must be intrinsically similar so that we can ascribe any measured differences to dust attenuation as it passes through a cluster of galaxies; massive, early-type galaxies are known to have exactly this property (Eisenstein et al. 2003).

\footnote{For galaxies, \( \sim 4.4\% \) in \( g - r \) and \( \sim 2.8\% \) in \( r - i \); see http://www.sdss.org/dr4/products/spectra/spectrophotometry.html.}
Luminous, early-type galaxies are part of the red sequence of galaxies and can be identified in many different ways. Here, we select galaxies from the SDSS sample based on two properties derived from their optical spectra: the EW of the H\(_\alpha\) emission line, EW(H\(_\alpha\)), and the stellar velocity dispersion, \(\sigma_v\). We select quiescent (i.e., non-star-forming) galaxies using EW(H\(_\alpha\)) < 2 Å. In addition, we restrict the sample to the redshift range 0.1 ≤ \(z\) ≤ 0.2. Figure 1 shows plots of EW(H\(_\alpha\)), \(\sigma_v\), color, and absolute magnitude of relevant galaxies in the SDSS sample.

The galaxy clusters used to define our target and control subsamples were taken from a friends-of-friends cluster catalog (Berlind et al. 2006). We emphasize that this catalog is not complete and that we only use part of it to select our target and control galaxies. In addition to this, our galaxy spectra come from SDSS DR4, which has a larger coverage than SDSS DR3, out of which the cluster catalog was constructed. We expect the number of “false negatives,” i.e., galaxies that might be cataloged as control galaxies that are actually behind a cluster, to be small. In addition, because of the large number of galaxies in the control sample, the effect of any contaminating or misclassified galaxies is diluted in the stacking procedure. Finally, we see that the principal source of error is due to the target galaxies, for which this effect is not important.

We can now specify when a galaxy is part of the target subsample of galaxies and when it belongs to the control subsample. For each galaxy cluster, every galaxy at a redshift exceeding that of the cluster that is found to be within 0.5 Mpc transverse distance of it is considered to be behind the cluster. We define \(R_{\text{target}} = 0.5\) Mpc, which we vary to investigate the radial dependence of any measured effect. Galaxies that are more than
\( R_{\text{control}} = 2 \text{ Mpc} \) removed from every galaxy cluster are classified as control galaxies. Any galaxy between these bounds is excluded from the analysis.

Based on these criteria, a primary sample with target and control subsamples was constructed as follows: Galaxies with \( \text{EW}(\text{H} \alpha) \leq 2 \text{ Å}, 200 \text{ km s}^{-1} \leq \sigma_v \leq 250 \text{ km s}^{-1}, \) and \( 0.1 \leq z \leq 0.2 \) were classified as target or control based on the values \( R_{\text{target}} = 0.5 \text{ Mpc} \) and \( R_{\text{control}} = 2 \text{ Mpc} \), using groups from the cluster catalog with a minimum of 10 members. Figure 2 shows plots of several of these properties for the primary sample, as well as their distribution on the celestial sphere. This figure illustrates that the distribution of target and control galaxies is approximately uniform in these properties. Several secondary samples were also considered based on variations of some of these properties, i.e., \( \sigma_v, N_{\text{gal}}^{\text{min}}, \) and \( R_{\text{target}} \) (see Table 1 for an overview of the properties of the various samples used).

Added together, the total number of galaxy spectra that we consider in this paper is 60,267. This number includes the number of galaxies in the primary and secondary samples, broken down in Table 2 by subsample (note, however, that there is a significant overlap of used spectra between certain samples), as well as the sizes of the target subsamples used in the determination of the radial dependency of dust attenuation (see below).

3.2. Stacking Procedure and Comparison

Since we are creating composite spectra from individual spectra that are intrinsically very similar, we weight the pixels of each spectrum with their inverse variance, as this gives us the highest

\[ \text{Fig. 2.} \text{- Galaxy properties for the primary sample. Shown are plots of the quantities relevant for the sample selection for the primary sample (see Table 1 for the definition of the primary sample). The target subsample is represented by diamonds, and the control subsample is represented by dots. Left to right, top to bottom: Velocity dispersion vs. \text{EW}(\text{H} \alpha), \text{redshift vs. EW}(\text{H} \alpha), \text{velocity dispersion vs. redshift, and angular distribution of the target and control subsamples (right ascension vs. sin[declination]). [See the electronic edition of the Journal for a color version of this figure.]} \]
Results of the comparison of the average of the target galaxies and the average of the control galaxies for the primary and secondary samples. \(N_{\text{target}}\) gives the number of galaxies in the target subsample, \(N_{\text{control}}\) gives the number of galaxies in the control subsample, and \(\tau_V\) is the best-fit parameter to the dust law (eq. [1]); 1 \(\sigma\) errors on \(\tau_V\) are given in the \(\sigma_{\tau_V}\) column.

TABLE 1

| Sample\(^a\) | EW (H\(_\alpha\)) (\(\AA\)) | \(\sigma_V\) \((\text{km s}^{-1})\) | \(N_{\text{min}}^\text{target}\) | \(R_{\text{target}}\) \((\text{Mpc})\) | \(R_{\text{control}}\) \((\text{Mpc})\) |
|----------------|----------------------|-----------------|----------------|------------------|------------------|
| Primary .......... | \(\leq 2\) | \(200 \leq \sigma_V \leq 250\) | 10 | 0.50 | 2 |
| \(150 \leq \sigma_V \leq 200\) ...... | \(\leq 2\) | \(150 \leq \sigma_V \leq 200\) | 10 | 0.50 | 2 |
| \(250 \leq \sigma_V \leq 300\) ...... | \(\leq 2\) | \(250 \leq \sigma_V \leq 300\) | 10 | 0.50 | 2 |
| \(N_{\text{min}}^\text{control} = 5\) .......... | \(\leq 2\) | \(200 \leq \sigma_V \leq 250\) | 5 | 0.50 | 2 |
| \(N_{\text{min}}^\text{control} = 20\) .......... | \(\leq 2\) | \(200 \leq \sigma_V \leq 250\) | 20 | 0.50 | 2 |
| \(R_{\text{control}} = 0.25\) Mpc .. | \(\leq 2\) | \(200 \leq \sigma_V \leq 250\) | 10 | 0.25 | 2 |
| \(R_{\text{target}} = 1\) Mpc .......... | \(\leq 2\) | \(200 \leq \sigma_V \leq 250\) | 10 | 1.00 | 2 |

\(\text{Notes.—}\)

\(\text{a}\) The redshift range for all these samples is 0.1 \(\leq z \leq 0.2\).

\(\text{b}\) Minimum number of members to define a galaxy cluster.

\(\text{c}\) Galaxies within a transverse distance \(R\) of a cluster (and at a larger redshift) are considered behind that cluster and make up the target subsample.

\(\text{d}\) Galaxies more than \(R\) control from every cluster make up the control subsample.

\section{3.3. Error Estimation}

The error on the individual pixels of the average spectra follows immediately from the stacking procedure. The inverse variance of an inverse-variance-weighted average is given by the sum of the individual weights. The composite target spectra obtained have a median signal-to-noise ratio of \(\sim 200\), while the larger control subsamples lead to composite spectra with a median signal-to-noise ratio of \(\sim 2500\). Therefore, it is clear that the main source of error is due to the composite target spectrum.

The error \(\sigma_{\tau_V}\) on the value of \(\tau_V\) is obtained by a jackknife procedure. In general, a jackknife estimate of the variance of a statistic is obtained by dividing the sample into a number of subsamples and obtaining the relevant statistic for each of these subsamples. The estimate of the variance of the statistic is then approximately equal to the variance of the values obtained for the subsamples (with a proportionality constant that depends on the number of subsamples, which rapidly converges to unity as the number of subsamples increases; Efron & Tibshirani 1993). Theoretically, this estimate is obtained from subsamples created by leaving out one of the “data points” (in our case, a “data point” is the spectrum of a galaxy, consisting of many individual points); however, due to computational constraints, this calculation is not always feasible. A possible way of dealing with this limitation is by dividing the sample into a number of subsets, based on a property that is unrelated to the relevant statistic, and creating jackknife subsamples as unions of all but one of these subsets (Shao & Tu 1995).

Whenever a full-fledged jackknife estimate was deemed too computationally intensive, an equal number of quantiles in declination were chosen to subdivide the sample, and a minimum of 200 jackknife subsamples were used to calculate errors in all

\begin{equation}
\tau(\lambda) = \tau_V \left(\frac{\lambda}{5500 \text{ Å}}\right)^{-\alpha},
\end{equation}

where \(\tau_V\) is the \(V\)-band optical depth. As in Charlot & Fall (2000), we adopt \(\alpha = 0.7\), which is a reasonable approximation to the shape of the Milky Way optical extinction curve. Note that our parameterization ignores the possibility that the emission of the cluster itself is influencing our results; however, since we expect the cluster light to be similar to the light of early-type galaxies, this should not bias our conclusions.

\section{Results of the Comparison of the Average of the Target Galaxies and the Average of the Control Galaxies for the Primary and Secondary Samples}

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these cases. Since the error is mostly due to inaccuracies in the composite target spectrum, jackknife subsamples were only created using the target subsample; i.e., for the purpose of the jackknife procedure, the composite control spectrum was supposed to be known exactly.

As a check on the validity of our error estimates, we performed a careful examination of the error estimates for the primary sample. Jackknife error estimates were obtained using different numbers of subsamples, ranging from 10 to the maximum of 110, the number of galaxies in the primary target subsample; see below. In addition, we implemented a bootstrap procedure, which works in much the same way as the jackknife procedure but creates bootstrap samples by randomly picking data points with replacements from the set of, in this case, target spectra. Values up to 300 for the number of bootstrap samples were used. All jackknife and bootstrap estimates agreed on the first two significant figures of the error.

3.4. Algorithm Tests

In order to examine the consistency of the stacking procedure and the estimation of the error on $\tau V$, we have designed two algorithm tests, which also tell us about the precision with which we can perform our measurement. First, we tested the accuracy and precision with which our stacking algorithm could recover a known value of the reddening, $\tau V$. We selected a random subset of 200 objects from the control subsample of the primary sample and reddened them with a value of $\tau V = 0.025$ with Gaussian noise of standard deviation 0.027 (i.e., mimicking the result for the primary sample; see below). We found that our stacking algorithm retrieved a value of $\tau V = 0.024$, with a $1\sigma$ error of 0.038. Similar results were found for different input-reddening values; however, the errors computed using the jackknife procedure were consistently larger but of the same magnitude as the variation that went in.

To better simulate the actual parameter estimation for the primary sample, a larger random sample of 8000 spectra from the control subsample was chosen to be a mock control subsample, and a randomly chosen subsample of this of 100 spectra was artificially reddened to provide the mock target subsample. Several orders of magnitude of reddening were tried, and we found that for values of $\tau V$ of $\sim10^{-3}$ and Gaussian noise of the same magnitude, our algorithm returns the exact amount of reddening and error, which means that our algorithm should be able to detect reddening of this magnitude in the real samples. Values of $\tau V$ of order $10^{-2}$ were recovered by our algorithm as well; however, the jackknife estimate of the error is consistently larger than the variation that was put in. We were unable to recover values of $\tau V$ of order $10^{-3}$ and noise of the same magnitude. The computed error in this case is still of order $10^{-2}$, which indicates that this is a lower bound set by measurement errors. Any errors obtained that are larger than this are likely due to an intrinsic variation in dust absorption among clusters, while errors of this size and smaller are consistent with being true measurement errors.

4. RESULTS

Figure 4 shows the result of averaging the spectra in the control subsample (top panel) and those in the target subsample (middle panel) for the primary sample. The bottom panel shows

Fig. 3.—Convergence of the average of the control spectra for the different velocity dispersion bins. Left to right: $200 \leq \sigma_v \leq 250$, $150 \leq \sigma_v \leq 200$, and $250 \leq \sigma_v \leq 300$.

Fig. 4.—Result for the primary sample; average and comparison for the subsamples of the primary sample. Top: Inverse-variance-weighted average spectrum of the galaxies in the control subsample, multiplied by the wavelength. Middle: Same, but for the galaxies in the target subsample. Bottom: Comparison of these two composite spectra (which should be exactly equal to zero if there is no dust absorption in galaxy clusters and the averaged spectra are exact) and a fit to a standard dust law (see the text for more details on this procedure). The bottom panel shows error bars (the top curve is an upper bound and the bottom curve a lower bound). Errors on the composite spectra in both the top and middle panel are of the order of the line thickness. [See the electronic edition of the Journal for a color version of this figure.]
a difference plot of these two quantities, with the fractional difference defined as

$$\frac{f_{\text{target}} - Q_{\text{control}}}{Q_{\text{control}}}$$

which for the dust attenuation in equation (1) equals $e^{-\tau_f} - 1$. A fit to equation (1) gives the value of $\tau_f$, which together with the sizes of the samples is given in Table 2. Only the calculated error on the difference in the bottom panel is shown here. This error is substantial, and the error in $\tau_f$ is, likewise, not negligible (see Table 2 for the error on $\tau_f$).
Figure 5 gives the same analysis as Figure 4 for the secondary samples (see also Table 2). Inspection of this figure and the results in the table show that, for smaller target subsamples, the errors are significantly larger.

We computed the radial dependence of $\tau_V$ for the various velocity dispersion bins by varying the value of $R_{\text{target}}$ for these samples, while keeping the value of $R_{\text{control}}$ and other parameters fixed. The result is shown in Figure 6. The plots shown are cumulative in the sense that each value of $R_{\text{target}}$ gives dust attenuation for dust within a volume of radius $R_{\text{target}}$. The range between 0.15 and 1 Mpc was examined more carefully by increasing $R_{\text{target}}$ in steps of 0.05 Mpc, whereas between 1 and 2 Mpc, steps of 0.1 Mpc were used. For smaller values of $R_{\text{target}}$, the target sub-sample consists of only a few galaxies, for which the composite spectrum cannot be reliably obtained.

5. DISCUSSION

Figure 4 (bottom) shows a value of the difference that is nearly flat over the whole wavelength range, and the 1 $\sigma$ error estimate on the value of $\tau_V$ in Table 2 confirms that a null value is within the uncertainties. The other samples confirm this result; most of them give results that are well within 1 $\sigma$ of the null hypothesis, with a few of them giving a formally negative value for $\tau_V$, i.e., a negative absorption. None of the values of $\tau_V$ are statistically significant indicators of positive or negative absorption. Regarding the negative absorption, it must be noted that the two most negative
values are obtained from relatively small target subsample sizes, about 30 spectra in the target subsample (they both have the largest error values as well), which could account for an estimate that is significantly off. The other negative value is essentially zero and occurs for the $R_{\text{target}} \sim 1$ Mpc sample, which could simply indicate that, generically, at this radial distance there is no dust in galaxy clusters (see below for a discussion of the radial dependence).

The dust law used in equation (1) is related to the extinction by

$$A(\lambda) = 2.5 \ln \left( \frac{\lambda}{5500 \text{ Å}} \right)^{-0.7} \mu \text{mag}, \quad (4)$$

which gives values of $E(B-V)$ for the $\tau_B$ values obtained of the order of $10^{-3}$ mag. Our estimate of the typical error on $\tau_B$ is 0.03, sets an upper bound on $E(B-V)$ of $\sim 5 \times 10^{-3}$ mag for values of $R_{\text{target}} = 0.5$ Mpc. Comparing these errors to what we found for our mock samples in § 3.4, we see that the obtained errors are consistent with being true measurement errors. The most positive value of $\tau_B$ is found for the 150 $\leq \sigma_e \leq 200$ sample, which gives a reddening of $E(B-V) = (8 \pm 5) \times 10^{-3}$ mag. The most statistically significant value of $\tau_B$ is found for the $N_{\text{gal}} = 5$ sample, with a value of $\tau_B$ that is 2 $\sigma$ from the null result, corresponding to $E(B-V) = (5.0 \pm 2.5) \times 10^{-3}$ mag. These are still not very significant, but they are remarkable in that they are obtained for samples that have both a large target and a large control subsample.

The radial-dependence plots are the most instructive of the resulting plots, as they might reveal the radial location of the dust content of galaxy clusters. If there were dust in a certain radial distance range, we would expect the $\tau_B$ versus $R_{\text{target}}$ plot to be essentially zero up to the dust range, after which a sharp increase would occur over the range in which the dust occurs, followed by a gradual decline for larger values of $R_{\text{target}}$ as more and more unattenuated spectra were added to the target subsample. For example, to confirm the results of Chelouche et al. (2007), who found evidence of dust around 1 Mpc with no dust at smaller radii, we would expect to see a peak around 1 Mpc.

In the range $< 1$ Mpc we do not find a consistent result in the three velocity dispersion bins we consider. The errors in this range are large because of the small number of galaxies in the target subsamples of these bins ($\sim 100$ for $R_{\text{target}} \sim 0.5$ Mpc). The value of $\tau_B$ in the range $150 \leq \sigma_e \leq 250$ is positive; however, $\tau_B$ is in the negative range in the 250 $\leq \sigma_e \leq 300$ bin. The amount of absorption rises in the interval between $R_{\text{target}} = 0.3$ and 0.7 Mpc for the 150 $\leq \sigma_e \leq 200$ bin, but the opposite happens for the 200 $\leq \sigma_e \leq 250$ bin. In Figure 6 (bottom right), we see that the combined result of the three bins is essentially flat within the error range.

The results are more consistent in the range between 1 and 2 Mpc. All of the bins show a small amount of dust absorption, but all the values contain the null value in their error range. The overall significance of the result is only slightly smaller than the significance of an individual point because of strong correlations between different $R_{\text{target}}$ values (since this is a cumulative plot, the overlap between the different samples is significant). Combining the results in the 1–2 Mpc range, we find an average extinction of $E(B-V) = 0.002$ mag with a significance of 1.5 $\sigma$. At the 99% confidence level, we conclude that $E(B-V) < 3 \times 10^{-3}$ mag.

A similar analysis for $R_{\text{target}} \sim 0.5$ Mpc gives an average extinction of $E(B-V) = 0.004$ mag, with a significance of 1.2 $\sigma$. Therefore, in this range we can derive a limit of $E(B-V) < 8 \times 10^{-3}$ mag. Both of these upper bounds are more stringent than the ones previously found.

We can translate an upper bound on the extinction into an upper bound on the dust mass using (Krügel 2003)

$$M_{\text{dust}} = 1.5 \times 10^8 \frac{E(B-V)}{3 \times 10^{-3}} \text{mag} \left( \frac{R}{1 \text{ Mpc}} \right)^2 M_{\odot}, \quad (5)$$

which gives an upper bound $M_{\text{dust}} \leq 10^8 M_{\odot}$ for approximately Mpc scales.

Figure 6 (bottom right) summarizes our results; over the whole range we considered, $R_{\text{target}} \sim 0.15–2$ Mpc, we find a signal that is essentially flat and consistent with zero. Our upper limit on $E(B-V)$ for distances between 1 and 2 Mpc from the center of a cluster is a few $\times 10^{-3}$ mag, which is consistent with the amount of dust extinction observed in 0.1 < z < 0.3 clusters in Chelouche et al. (2007). Future work that could significantly increase the size of the target subsample could lower the upper bound found here or confirm the existence of dust on the outskirts of galaxy clusters.

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