DRAFT — The environments of post-starburst galaxies — DRAFT

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ABSTRACT

Star-formation history is strongly related to environment; the most massive and least star-forming galaxies reside in the highest density environments. There are now good observational reasons to believe that the progenitors of these massive, old galaxies undergo starbursts, followed by a post-starburst phase. Post-starburst ("K+A" or "E+A") galaxies appear in the SDSS visible spectroscopic data by showing an excess of A star light (relative to K giant light) but deficient $\mathrm{H}\alpha$ line emission. Comparison star-forming populations can be identified by A-star excess or $\mathrm{H}\alpha$ emission. We investigate the environments of these galaxies by measuring *(1)* number densities in $8\,h^{-1}$ Mpc radius comoving spheres, *(2)* transverse distances to nearest Virgo-like galaxy clusters, and *(3)* transverse distances to nearest luminous-galaxy neighbors. We find not only that post-starburst galaxies are in the same kinds of environments as star-forming galaxies; we find that at each value of the A-star excess, the star-forming and post-starburst galaxies lie in very similar distributions of environment. We conclude that the relationship between star-formation rate and environment is primarily governed by processes that occur over long (> 1 Gyr) timescales. The only deviations from this "null hypothesis" are barely significant: a slight deficit of post-starburst galaxies (relative to the star-forming population) in very low-density regions, a slight excesses inside clusters, and a slight excess with nearby neighbors. None of these effects is strong enough to make the post-starburst galaxies a high-density phenomenon, or to argue that the starburst events are primarily triggered by tidal (as opposed to either purely internal or major-merger) events. We also see no excess post-starburst abundance in or near the infall regions of clusters, implying that any quenching of star-formation activity during infall into dense environments must occur over long (> 1 Gyr) timescales.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: statistics — galaxies: stellar content — stars: formation

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1. Introduction

[Co-authors: the introduction is totally scrod; I can't figure out how to organize it. Please keep those cards and letters rolling in. Hogg]

How do old, dead, early-type galaxies form? There are two strong arguments that bulge-dominated galaxies (*e.g.*, ellipticals, lenticulars, and very early-type spirals) have progenitors that went through a starburst phase. The first is that bulge-dominated galaxies show enhancements in α-type elements over the Solar chemical abundance mix (*e.g.*, Worthey 1998; Eisenstein et al. 2003). These abundance patterns are naturally produced when star formation—or the last phase of star formation—has occured in a burst too rapid to allow recycling of the elements ejected by Type 1a supernovae. The second argument is that the post-starburst galaxies identified spectrally in large surveys of the Local Universe have the colors, surface brightnesses, and radial profiles that would be expected if they are to evolve passively into new bulge-dominated galaxies; they cannot evolve passively into disk-dominated or other late types. Starburst origin is also supported indirectly by the uniformity seen in early-type galaxies' stellar populations (*e.g.*, Eisenstein et al. 2003) and their lack of large resevoirs of cold gas and dust.

Post-starburst galaxies are identified spectroscopically by having a large contribution to their spectral energy distribution from A stars—*i.e.*, new stars must have formed within the last ~ 1 Gyr—but no, or very little, contribution from O and B stars—*i.e.*, no new stars have formed within the last ~ 0.01 Gyr. In practice, these "K+A" or "E+A" galaxies[3] are identified by having strong Balmer absorption or blue continua (A-star indicators) but no Hαor [O II] emission lines (O and B-star indicators).

What is not known is what precedes or triggers the truncation of star-formation; is it a violent event, such as a tidal interaction or major merger, or is it a purely internal event, such as an AGN flare or the abrupt exhaustion of star-formation fuel? Either way, since disk-dominated galaxies are the galaxies that contain young stars and the cold-gas fuel to make more, post-starburst galaxies must lie on some kind of evolutionary pathway between the disk-dominated and bulge-dominated populations.

A stars have known lifetimes, so the evolution of the population can be "timed" and rates computed; we find that of order 1 percent of the galaxy population is going through this phase each Gyr at $z \sim 0.1$ (Quintero et al. 2004) and this rate appears to be much higher at earlier epochs [DWH:citations].

The distribution of galaxy star-formation rates is a strong function of environment, with much lower star-formation rates in higher density regions (*e.g.*, Kennicutt 1983; Balogh et al. 2001; Martínez et al. 2002; Lewis et al. 2002; Gomez et al. 2003; Blanton et al. 2003b; Hogg et al. 2003,

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[3] The terminology "K+A" is to be preferred to "E+A" because the identification is spectral, not morphological, and "K" and "A" name spectral types. "E" names a morphological type.

2004; Kauffmann et al. 2004; Blanton et al. 2005). Although it is customary to think of this as being a consequence of the morphology–density relation (Dressler 1980; Postman & Geller 1984), in fact recent studies with large samples have shown that in fact the star-formation–environment relation has more explanatory or informative power than the morphology–density relation, at least with the morphological proxies currently available for large samples (Kauffmann et al. 2004; Blanton et al. 2005). How is the information about environment transmitted to galaxy star-formation activity? Are there violent events when galaxies fall into high density regions? Or do the galaxies reduce their star-formation rates gradually as they find themselves in denser and denser environments?

[DWH: B-O effect, infall regions, supply of blue galaxies changed to red (Poggianti et al. 1999; Balogh et al. 2000; Kodama & Bower 2001).]

The distribution of galaxy star-formation rates is also evolving very rapidly with redshift in the field (*e.g.*, Lilly et al. 1996; Hammer et al. 1997; Rowan-Robinson et al. 1997; Hogg et al. 1998; Cowie et al. 1999; Flores et al. 1999; Mobasher et al. 1999; Haarsma et al. 2000; Jones & Bland-Hawthorn 2001) [DWH: not complete list??]. This is usually imagined as being related not to infall into dense regions but rather to the supply of cold gas. On the other hand, since gravitational clustering brings galaxies into more and more dense environments with cosmic time, this might not be unrelated to the star-formation–environment relation and the Butcher–Oemler effect.

As transition objects between the star-forming, disk-dominated and dead, bulge-dominated populations, the post-starburst galaxies could in principle have the environmental characteristics of either. Originally, K+A galaxies were found in high-density regions (Dressler & Gunn 1983; Couch & Sharples 1987), and thought to be a "cluster" population. Of course the early searches for such galaxies were made in cluster fields. Once systematic searches for K+A galaxies were made in large redshift surveys, it was found that they are not particularly concentrated in clusters or high density regions, but rather live in a wide range of environments (Zabludoff et al. 1996; Quintero et al. 2004; Blake et al. 2004). In the large SDSS and 2dFGRS samples, it can be shown that the mean environment (Quintero et al. 2004) and distribution of environments (Blake et al. 2004) are both similar to those of spiral or disk-dominated galaxies.

The environments of disk-dominated galaxies (isolation and small groups) are the best environments in the Local Universe for galaxy–galaxy mergers, which are the top candidates for triggers for the post-starburst galaxies. After all, the major mergers observed in the Local Universe are all associated with very high star-formation rates, and major mergers are expected to disrupt disks and leave behind the dynamically hot stellar orbits characteristic of the bulge-dominated population.

With a sample of more than 10^3 K+A galaxies (Quintero et al. 2004), we are in a position to ask much more detailed questions about the range of environments in which they lie, and the relationships between environmental and star-formation properties. That is the purpose of this *Article*, with the goal of constraining the possible triggering mechanisms for this very important galaxy population.

In what follows, a cosmological world model with $(\Omega_\mathrm{M}, \Omega_\Lambda) = (0.3, 0.7)$ is adopted, and the

Hubble constant is parameterized $H_0 = 100\,h\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, for the purposes of calculating distances(*e.g.*,Hogg 1999).

2. Data

The SDSS is taking *ugriz* CCD imaging of 10^4 deg^2 of the Northern Galactic sky, and, from that imaging, selecting 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; Abazajian et al. 2004).

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), spectroscopic target selection (Eisenstein et al. 2001; Strauss et al. 2002; Richards et al. 2002), spectroscopic fiber placement (Blanton et al. 2003a), spectral data reduction and analysis (Schlegel & Burles, in preparation, Schlegel in preparation) are performed with automated SDSS software.

Galaxy absolute magnitudes and colors are computed in fixed bandpasses, using Galactic extinction corrections (Schlegel et al. 1998) and K corrections (computed with `kcorrect v1_11`; Blanton et al. 2003). They are K corrected not to the redshift $z = 0$ observed bandpasses but to bluer bandpasses ${}^{0.1}g$, ${}^{0.1}r$ and ${}^{0.1}i$ "made" by shifting the SDSS g, r, and i bandpasses to shorter wavelengths by a factor of 1.1 (*cf.*,Blanton et al. 2003; Blanton et al. 2003b). This means that galaxies at redshift $z = 0.1$ (typical of the sample used here) have trivial (but non-zero!) K corrections.

We capitalize on the extremely good spectrophotometric calibration of the SDSS data and measure, for each galaxy, the excess light in each fiber spectrum in the wavelength range $3800 < \lambda < 5400$ Å coming from A-type stars relative to K-type stars, normalized to the mean spectrum of an old galaxy in the SDSS. This measurement is described elsewhere (Quintero et al. 2004); briefly, we perform a linear fit of the spectral section to a linear combination of the mean SDSS old galaxy spectrum (the "K" spectrum) and the mean SDSS A-star spectrum (the "A" spectrum) with the locations of possible emission lines masked out. The A-star excess is then the ratio A/K of the amplitudes of the two spectral components from the fit. We also measure the line flux and equivalent width (EW) of the Hα line using the "K+A" fit as a continuum model (which effectively removes the absorption contribution to the flux at Hα). These measurements are performed exactly as described by us previously (Quintero et al. 2004).

The "units" in which the A-star excess is measured are arbitrary, but used here (where the units correspond to a luminosity ratio in the abovementioned wavelength band) they can be calibrated by their relationship to Hα EW; typically

$$\frac{A}{K} \sim \frac{\mathrm{H}\alpha\ \mathrm{EW}}{40\ \text{Å}} \tag{1}$$

(Quintero et al. 2004). For the purposes of what follows, we define "low Hα" galaxies to be those with Hα EW less than 1/8 the value implied by equation (1). We define star-forming "Hαexcess" galaxies to be those with Hα EW > 5.0 Å and star-forming "A-star excess" galaxies to be those with $(A/K) > 0.2$ in our arbitrary units. K+A galaxies, the subject of this study, are those that are "low Hα" but "A-star excess"; *i.e.*, they are star-forming according to the A-star excess, but not according to the Hα emission.

Around every galaxy a density ρ_8 is measured as described elsewhere (Blanton et al. 2003b; Hogg et al. 2003); briefly, it is a count of the number of neighbors in the SDSS spectroscopic sample inside a $8\,h^{-1}$ Mpc radius comoving sphere in comoving distance space (with no correction for redshift distortions), divided by the uniform-density predicted number, made from the galaxy luminosity function (Blanton et al. 2003c) and the SDSS window function, to make a dimensionless density. The sample used to infer ρ_8 is flux-limited and not volume-limited, but the resulting overdensity estimates have been shown to be redshift-independent in the median (Blanton et al. 2003b). The relatively large radius of $8\,h^{-1}$ Mpc is chosen to provide good signal-to-noise per object, although we have shown that there is in fact more information on smaller scales (Blanton et al. 2004).

For each galaxy we estimate a second environment measure by finding the transverse distance $D_{\rm cl}$ to the nearest Virgo-like (or greater) galaxy cluster that is within $1000\ {\rm km\,s^{-1}}$ in radial distance, divided by the virial radius $R_{\rm vir}$ of the cluster. The galaxy clusters are ≥ 10-member clusters taken from a friends-of-friends cluster catalog constructed from SDSS Main Sample galaxies with [DWH: mag limits??] (Berlind et al. 2008). Cluster abundance as a function of multiplicity is used to convert multiplicity to mass and the mass is used to compute a virial radius $R_{\rm vir}$ at which the cluster represents an overdensity of 200.

On the smallest scales, we measure galaxy environment in a third way by the transverse nearest-neighbor distance $r_{\rm p,min}$. This is defined here to be the transverse proper distance $r_{\rm p}$ to the closest neighbor galaxy in the SDSS spectroscopic sample with ${}^{0.1}i$-band absolute magnitude $M_{^{0.1}i}$ brighter than -20.0 mag and within $200\ {\rm km\,s^{-1}}$ in line-of-sight velocity.

As in previous work (Quintero et al. 2004), we limit targets to redshifts $z > 0.05$ to mitigate the issues of interpreting spectra taken through a small (3 arcsec diameter) aperture on low-redshift (and thus large in angle) galaxies. In addition, when using the clustocentric distance $D_{\rm cl}$, targets are limited to the redshifts $z < 0.10$ because the cluster catalog is limited at redshift $z = 0.10$. When using the nearest-neighbor distance $r_{\rm p,min}$, targets are limited to redshifts $z < 0.10$ because redshift $z = 0.1$ is the redshift at which a galaxy with absolute magnitude $M_{^{0.1}i} = -20.0$ mag approaches the flux limit of the SDSS Main Sample.

3. Results

Figure 1 shows the conditional distribution of environmental density ρ_8 as a function of A-star excess $\log_{10}(A/K)$, in detail, at each A-star excess, it shows the 5th, 25th, 50th, 75th, and 95th percentile in ρ_8. The top panel is for all galaxies with A-star excesses, and the bottom is for those characterized as low in Hα, as described above. The result is not just that the median environment is similar for K+A and star-forming galaxies; the result is that at every value of A/K for which we have reasonable signal-to-noise, the full distribution of ρ_8 is indistinguishable between the two populations. This shows that between Hα and A/K, it is A/K that best predicts the large-scale environment in which the galaxy lies.

We have made the equivalents of Figure 1 for the other environment indicators, *i.e.*, transverse clustocentric distance $\log_{10}(D_{\rm cl}/R_{\rm vir})$ and transverse nearest-neighbor distance $\log_{10}(r_{\rm p,min})$. In both cases, the result is the same as in Figure 1: The environment distribution is the same for star-forming and post-starburst galaxies, to within the precision of the experiment, at each value of the A-star excess.

The top panel of Figure 2 shows the fraction of galaxies classified as star-forming by the criteria described above, in the SDSS spectroscopic sample in the redshift range $0.05 < z < 0.20$, as a function of environmental density ρ_8. The absolute fraction is not an interesting number, because it depends on the luminosity and redshift ranges in the sample, and on the severity of the star-formation-rate cut (indeed, the fractions show that the A-star excess cut is more severe). The bottom panel shows the fraction of galaxies classified as K+A, with scaled versions of the curves from the top panel plotted in grey. It is remarkable how well the three curves match one another. The only exception is at very low densities (recall that the mean density is well above unity because galaxies are clustered), where there is a slight underdensity of K+A galaxies relative to star-forming galaxies.

Figure 3 is similar to Figure 2 but with transverse clustocentric distance $\log_{10}(D_{\rm cl}/R_{\rm vir})$ acting as the environment indicator. Again it is remarkable how similar are the three curves. The only exception is a slight excess in the fraction of K+A galaxies relative to star-forming galaxies. Another way to express the discrepancy is that the K+A fraction is a weaker function of environment than the star-forming fraction.

Figure 4 is similar to Figure 2 but with transverse nearest-neighbor distance $r_{\rm p,min}$ acting as the environment indicator. Even on these very small scales, the three curves are very similar. Again the exception is that there is a very slight excess of K+As relative to star-formers with nearby neighbors, or, the K+A fraction is a weaker function of small-scale environment than the star-forming fraction.

4. Discussion

As we have discussed elsewhere (Quintero et al. 2004), post-starburst galaxies plausibly lie on an evolutionary sequence between disk-dominated galaxies, which are forming stars and contain the neutral gas fuel for further star formation, and bulge-dominated galaxies, which have no star-formation fuel and show chemical signatures of past star-formation bursts. Post-starburst galaxies might even be the remnants of major mergers. A priori, the environments of these galaxies could be either like those of disk-dominated galaxies or those of bulge-dominated galaxies, or somewhere in-between. Of course, prior to this study, it was already known that the mean environments of post-starburst galaxies are more similar to those of disk-dominated galaxies than those of bulge-dominated galaxies (Zabludoff et al. 1996; Quintero et al. 2004; Blake et al. 2004). Here we have not only confirmed this result, we have shown that for each value of the A-star excess, the post-starburst galaxies with that A-star excess find themselves in similar environments to star-forming galaxies with that same A-star excess. In other words, A-star excess is a better environment predictor than Hα EW, since the post-starburst galaxies have Hα EWs like bulge-dominated galaxies.

This result confirms our "null hypothesis" that the processes that connect a galaxy's star-formation history to its environment act on long timescales, longer than A-star lifetimes ($\sim$ 1 Gyr). This is not surprising, since at typical cosmological velocities ($\sim$ 100 $\mathrm{km\,s^{-1}}$), a galaxy can only travel $\sim$ 1 Mpc in a Gyr, and there is now pretty good empirical evidence that everything important about galaxy environments happens on the $\sim$ 1 Mpc scale (Blanton et al. 2004).

We showed that the fraction of the whole SDSS galaxy sample classified as "K+A" (post-starburst) is a function of environment, and that its dependence on environment is very similar to that of the fraction of the sample classified as star-forming. This is also consistent with our null hypothesis. The only deviations all have the sense that the K+A fraction is a slightly weaker function of environment than the star-forming fraction; we find slightly fewer K+As in extremely low density environments, and slightly more close to the centers of massive clusters and close to luminous neighbors than we would expect by naive scaling of the star-forming fraction. None of these deviations from the predictions of the null hypothesis are large, but they may point to triggering mechanisms for the starburst and post-starburst phases; perhaps close neighbors play a role.

We can rule out two hypotheses for the triggering of starbursts, both plausible at the outset: Post-starburst galaxies are not, primarily, the remnants of tidal interactions caused by close passages by massive galaxies, and post-starburst galaxies are not over-represented in the infall regions of massive clusters. This latter result is important. The galaxy populations inside clusters are very different in morphological and star-formation-history mix than galaxy populations in groups, in isolation, and in voids. What physical process are involved in enforcing these differences? Many have hypothesized that radical transformations happen on infall (Poggianti et al. 1999; Balogh et al. 2000; Kodama & Bower 2001); indeed some galaxies have been "caught in the act" of a radical transformation (*e.g.*, Vogt et al. 2004). The results presented here suggest that any transformations must—in the main—be gradual rather than abrupt. This is consistent with prior work in this area (Poggianti et al. 1999; Balogh et al. 2000; Kodama & Bower 2001). Either the infall process is "gentle" or else the galaxies in clusters somehow "knew in advance" (from their pre-infall group or filament environment) that they were destined to end up in a cluster.

[DWH: expand on the above a bit, making the point that everyone assumes that the txmn must be occuring at infall and not before.]

The remaining hypotheses for the triggering of the starburst (or, more properly, star-formation truncation) events that preceeds the post-starburst phases of these galaxies are: some kinds of random internal catastrophes or some kinds of galaxy–galaxy mergers. This latter hypothesis is exciting, because merging is one of the fundamental processes of cosmogony, and holds great promise for providing precise connections between cosmological obeservations and theory at small scales.

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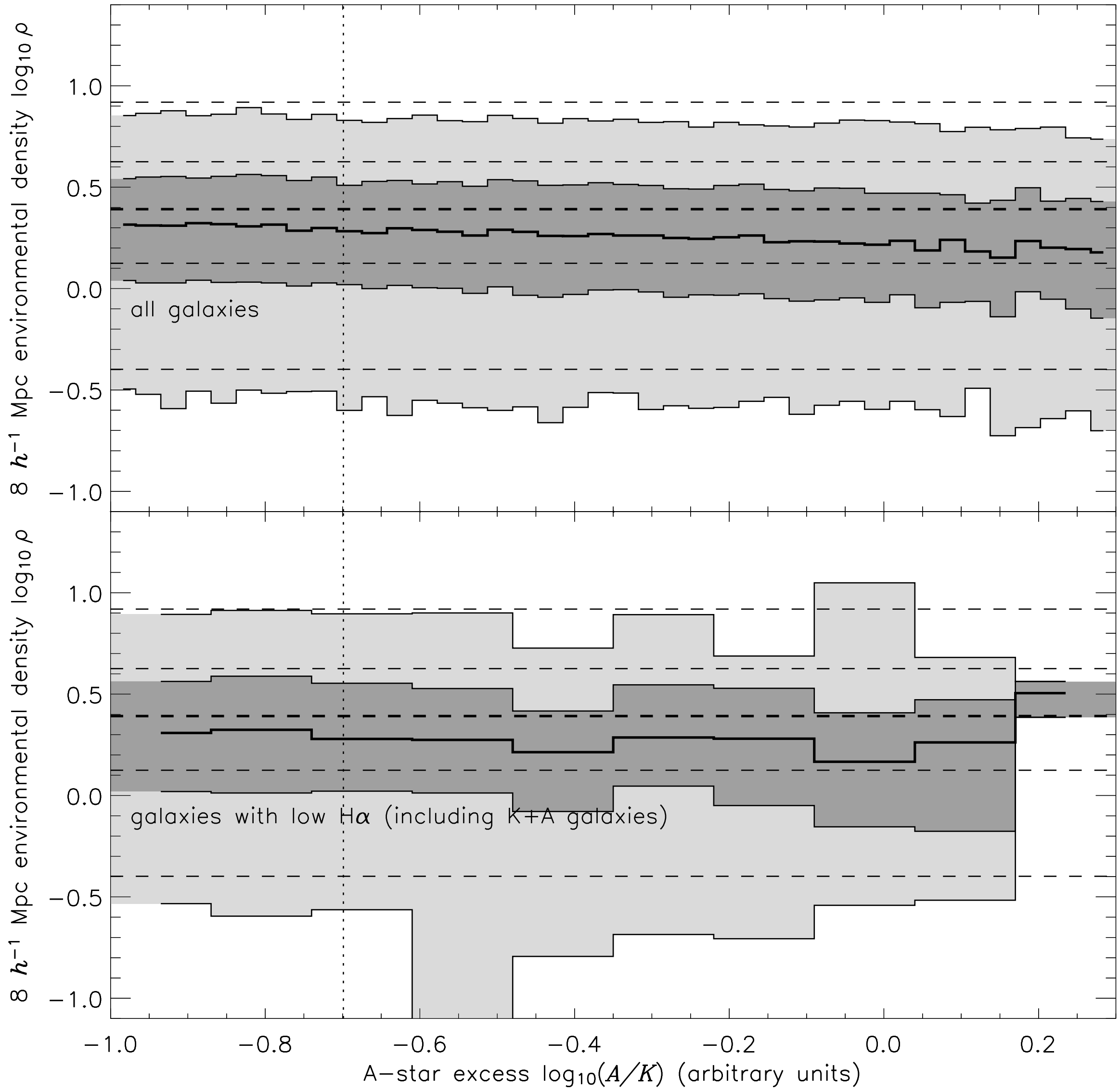

Fig. 1.— The density distribution conditioned on A-star excess. The five lines show the 5, 25, 50, 75, and 95 percentiles in density ρ_8 (normalized to cosmic mean density) of galaxies in $8\,h^{-1}$ Mpc radius spheres in comoving redshift space [DWH: check??] around target galaxies as a function of the A-star excess $[A/K]$ in the target galaxies. See text for details of the density and A-star excess measurements. The top panel is for all galaxies in the sample, and the bottom is for those deficient in Hα relative to the A-star excess (see text for details); the post-starburst or K+A galaxies are in this lower panel. The horizontal dashed lines show the same percentiles but for galaxies with no A-star excess, and the vertical dotted line is the minimum A-star excess required for a galaxy to be classified as star-forming (top panel) or K+A (bottom panel) in this work. Note that both populations have very similar dependences of environmental quantiles on A-star excess.

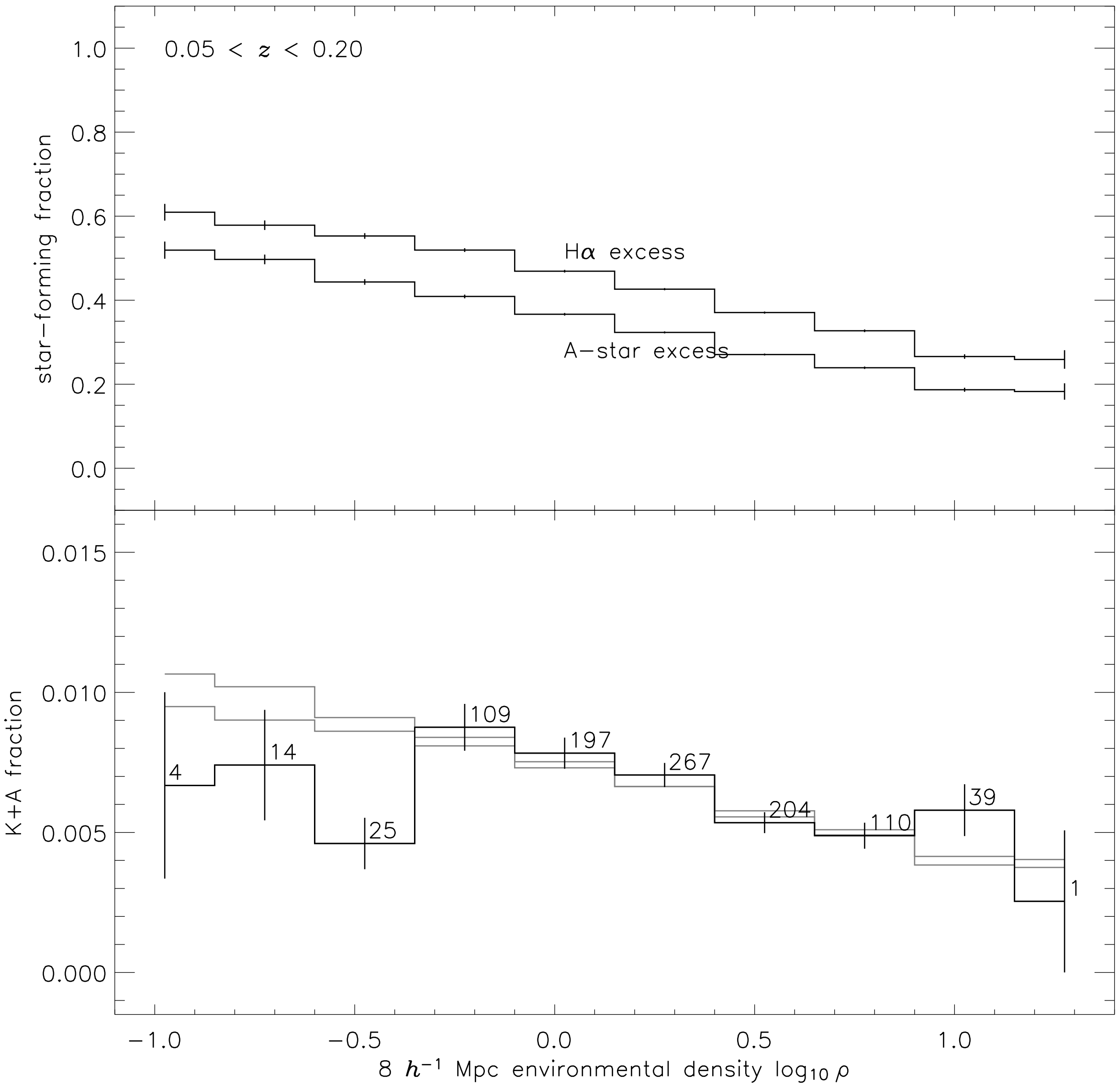

Fig. 2.— The fractional abundance of galaxy populations as a function of environmental density. The top panel shows the fraction of galaxies deemed "star forming" by Hα EW (top curve) and by A-star excess $[A/K]$ (bottom curve). The vertical offset of the curves comes from the fact that the A-star excess cut is more severe than the Hα EW cut (see text for details). The bottom panel shows the same but for the galaxies deemed K+A (see text for definition). Also shown in the bottom panel are scaled versions of the curves from the top panel, scaled by the mean abundance ratio.

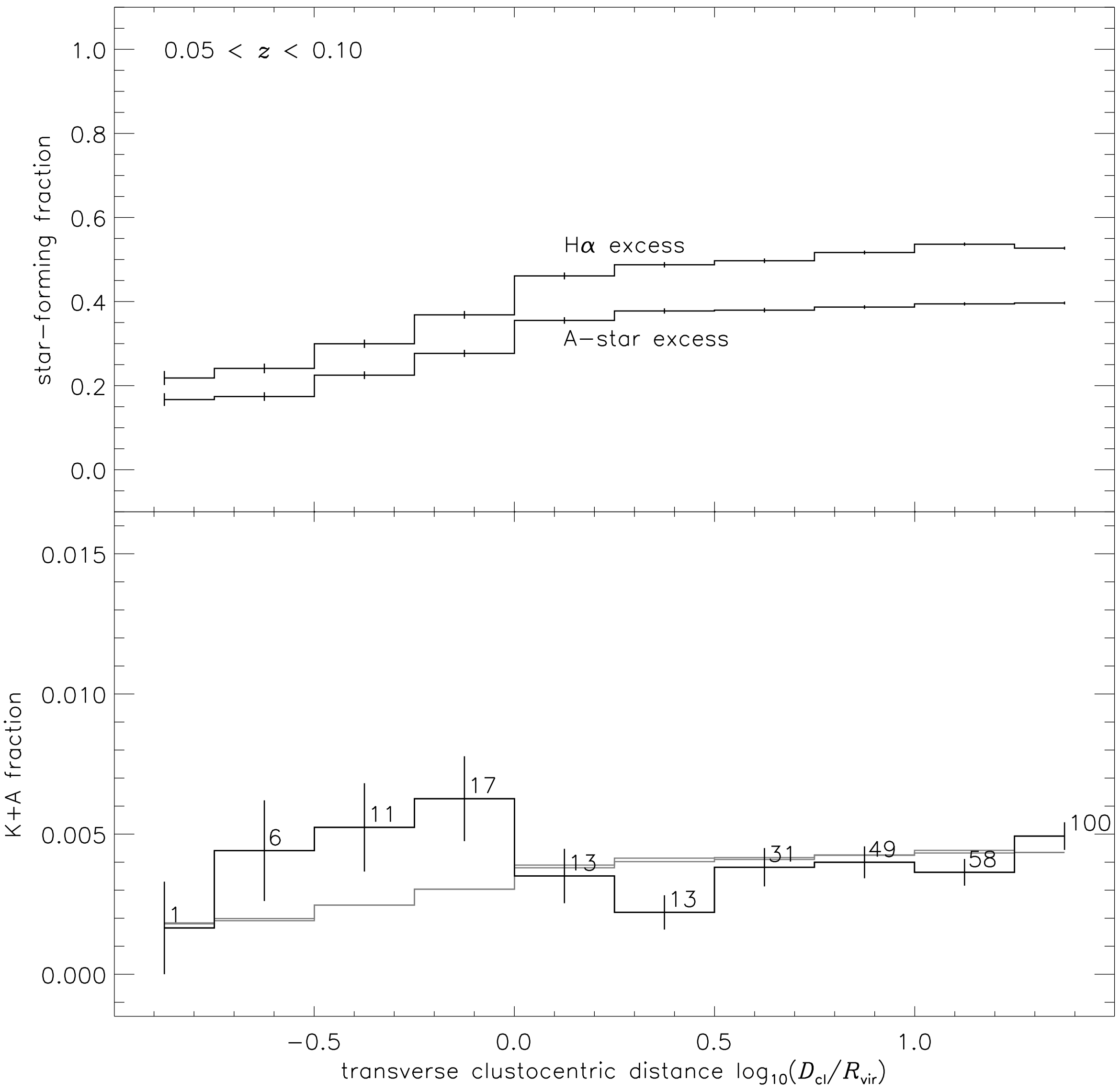

Fig. 3.— Same as Figure 2, except using the transverse, virial-scaled clustocentric distance $D_{\rm cl}/R_{\rm vir}$ (see text) as the environment indicator.

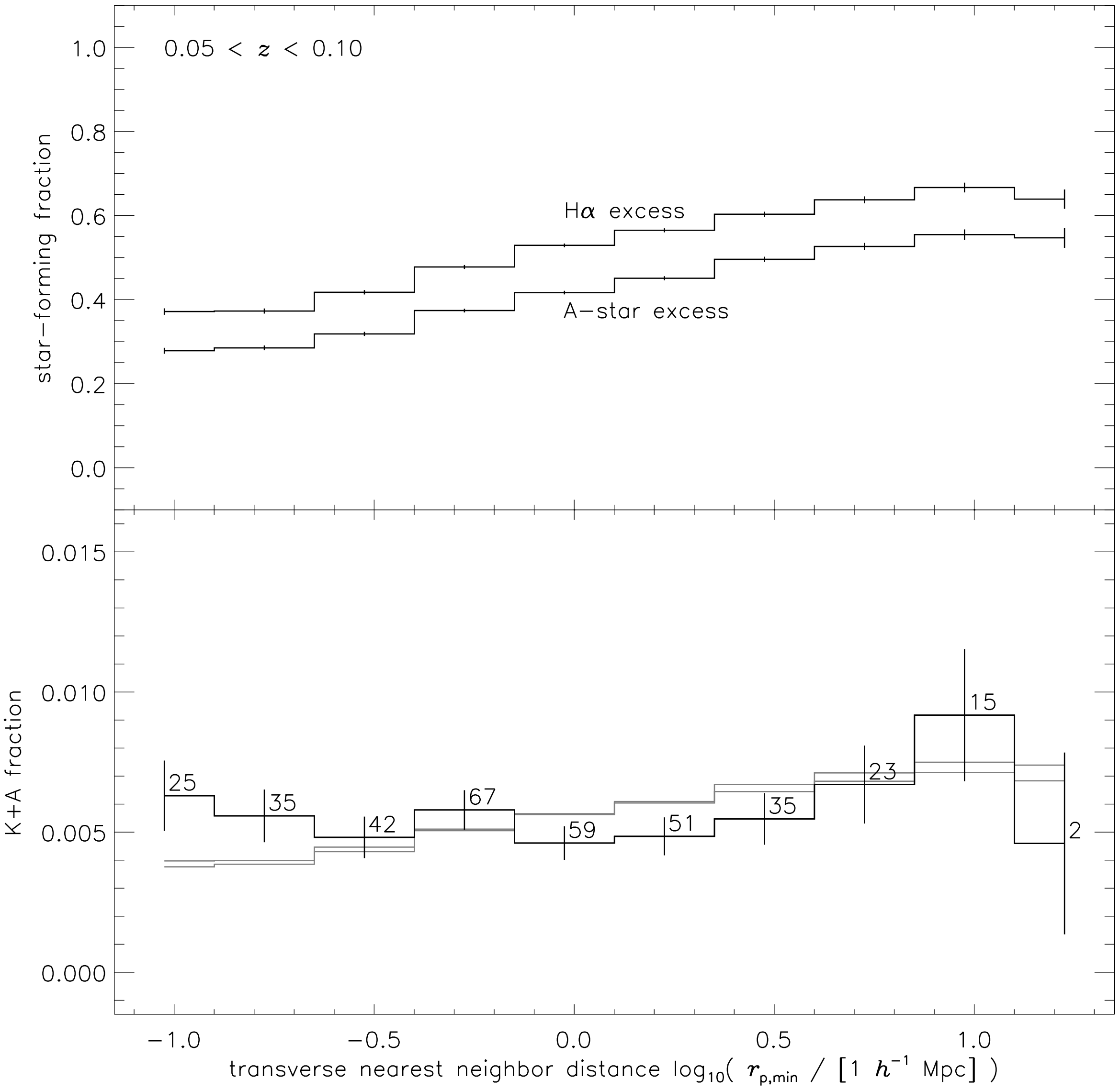

Fig. 4.— Same as Figure 2, except using the transverse, proper, nearest-neighbor distance $r_{\rm p,min}$ (see text) as the environment indicator.