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THE EVOLUTION OF GALAXIES IN CLUSTERS

E. Ellingson
Center for Astrophysics and Space Astronomy,
UCB 389, University of Colorado, Boulder, CO 80309

The dramatic differences between present-epoch cluster and field galaxy populations indicate that environment plays a strong role in galaxy evolution. Here we present a brief overview of some of the recent observations of moderate to high redshift clusters. A consistent picture of galaxy evolution in clusters appears to be emerging, which includes a population of galaxies which formed early in the cluster history, as well field galaxies which have had their star formation truncated upon falling into the cluster potential. Galaxy interactions probably play an important role in exhausting star formation in some of these galaxies. However, there is significant variation in the populations of different cluster samples, with substantial evidence that some galaxies have their star formation terminated more gradually. This suggests that different mechanisms may dominate, perhaps because of differences in the recent merging history of the clusters. We also present a recent analysis of population gradients in clusters which suggests that the observed evolution in cluster populations is consistent with a scenario where changing infall rates drive the fraction of star forming galaxies in clusters, rather than a changing physical mechanism within the cluster. Thus, galaxy populations may provide a fundamental measure of the growth of large scale structure.

1 Introduction

The evolving populations in galaxy clusters offer a unique opportunity to directly observe evolution on scales ranging from individual galaxies to large scale structure. Present-day rich clusters have strikingly different populations from galaxies in poorer environments, suggesting that some mechanism is at work on the cluster population which is related to the dense cluster environment. This connection between galaxies and their large scale surroundings allows us to use the observed populations in galaxy clusters to investigate both galaxy evolution and the changing conditions within the clusters themselves.

The primary goals of investigations of cluster galaxy populations can be summarized by our efforts to explain two major observational results. The first is the morphology-density relationship seen at low redshifts.[17,48,21] The large fraction of elliptical and S0 galaxies in low redshift clusters stands in dramatic contrast to the field population. In addition, cluster ellipticals tend to inhabit the dense center cores of rich clusters, with later-type galaxies found more prevalently in the less-dense outer regions. Morphologies of galaxies in cluster substructures suggest that this is fundamentally a density relation, rather than a radius relation (see, however, Whitmore et al.[48]). Physical mechanisms which may be responsible for the lower fraction of star-forming galaxies in dense environments include galaxy-galaxy mergers or "harassment", ram-pressure stripping of gas from infalling galaxies, or tidal disruption from the cluster potential. [34,19,37,25] Each of these mechanisms may play a role, depending on the details of the cluster environment.

The second challenge is explaining the Butcher-Oemler effect: higher redshift clusters have a larger fraction of blue, star forming galaxies than those at the present epoch [11,12,39,21,5,7] Even if a mechanism is identified which can suppress star formation in clusters, this observed evolution in galaxy populations requires an explanation of why star formation is more common at higher redshift. Thus, cluster galaxy populations are linked not only with evolutionary processes within galaxies, but also with cosmic evolution on much larger scales.

In this paper, we briefly summarize recent observations of galaxies in intermediate redshift ($z < 1$) clusters, in the context of understanding the morphology-density relationship and the Butcher-Oemler effect. We then present an analysis of populations gradients within clusters which further explores the relationship between galaxy evolution and cluster evolution.

2 Galaxy Populations in Clusters

Rich clusters of galaxies universally appear to contain a population of red galaxies whose properties are consistent with a passively evolving population. While the fraction of galaxies with these properties can vary widely from cluster to cluster, and appears to be a function of the cluster richness, redshift and possibly its recent merging history, the properties of these galaxies themselves are quite homogeneous. Galaxy colors, specifically the color, slope and scatter of the "red sequence" on the color-magnitude diagram, can be used to constrain the star formation history of these galaxies.[9,33,26,8,45] The galaxies appear to consistent with early formation ($z_f > 2$) and a remarkably small range of formation times within a given cluster.

Galaxy clusters also provide a convenient set of elliptical galaxies at a common redshift that can be used to constrain the details of galaxy evolution. Fundamental plane measurements have been made in several high redshift clusters, yielding estimates of the evolution of the galaxy M/L ratio as a function of redshift. [46,47,32] Galaxies from the cluster red sequence, again, appear to be consistent with an early formation epoch, and passive evolution thereafter. The implications of these results are that a significant population of cluster galaxies were formed very early in the cluster's history and have evolved only passively since then.

In contrast, the star forming galaxies in clusters appear to have undergone significant evolution in the last several billion years. The initial photometric Butcher-Oemler effect was confirmed spectroscopically[18,19,34,24] (Figure 1) and populations of both star forming and recently post-star formation galaxies in moderate redshift clusters have been identified (i.e., the Balmer-strong H-δ or K+A galaxies.) [18,19,39,14,7] Many subsequent investigations have focused on the details of how these galaxies are transformed into the population seen in clusters today The emerging picture is that after the first episode of galaxy formation in the cluster environs, subsequent generations of field galaxies have fallen into the cluster. These infalling field galaxies have had their star formation disrupted, possibly with an associated starburst. As this transformation progresses, these galaxies might be identified with normal-looking spirals, then galaxies with strong Balmer absorption spectra, and finally S0 galaxies which have retained some of their disk structure but have ceased active star formation[21] (see however Andreon[2]; Postman[40]).

While there is much evidence for this basic evolutionary sequence, the mechanism responsible for the truncation of star formation is still unknown. One important clue would be whether galaxies undergo a strong starburst before ceasing to form stars altogether. The "E+A" or "k+A" galaxies which appear common in some galaxy clusters at $z \sim 0.3$ are candidates for post-starbursts, as their strong Balmer absorption appears to require a significant stellar population

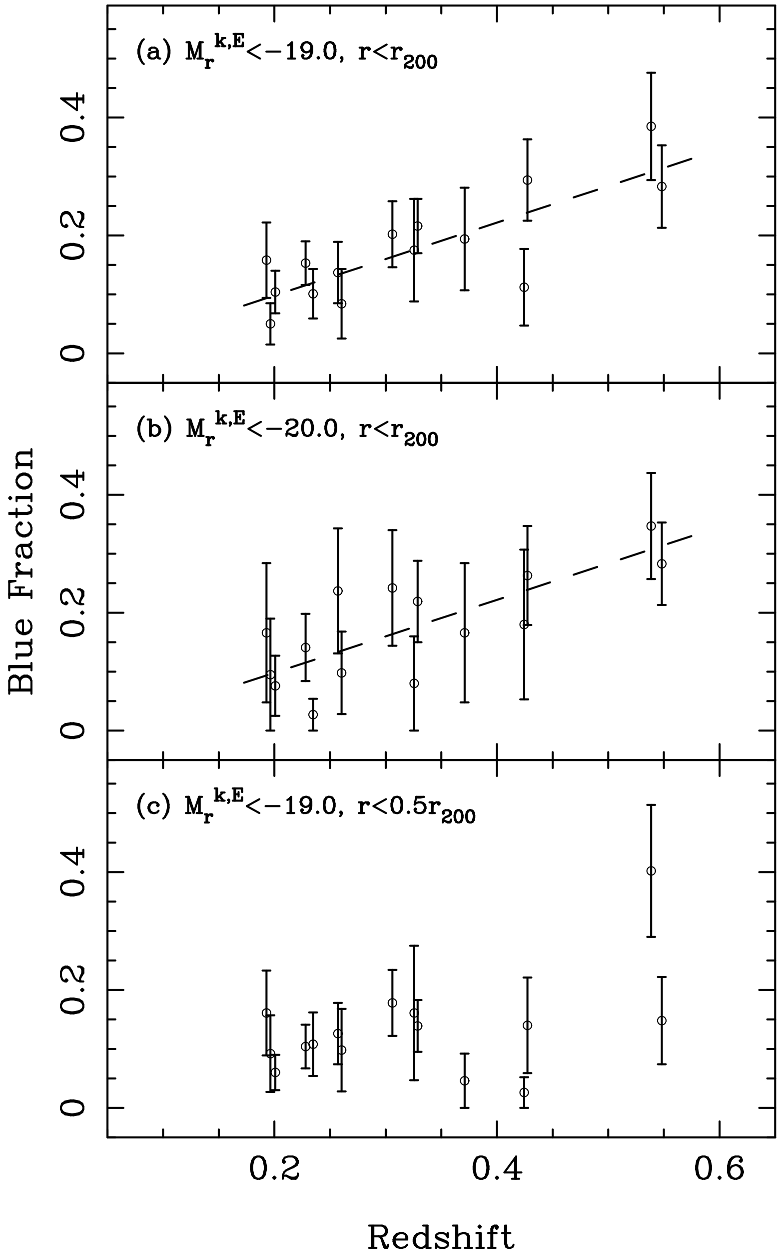

Figure 1: The Butcher-Oemler effect for the CNOC1 x-ray selected cluster sample. The blue fraction for spectroscopically confirmed cluster galaxies is plotted versus redshift. The data shown in panel a) uses a counting radius of r_{200} and a k+e corrected absolute magnitude limit of $M_r^{k,E} = -19.0$. Values for f_b in panel b) are based on a magnitude limit of −20.0, and in c), a radius of $0.5r_{200}$ and a magnitude limit of −19 were used. The dashed line in panel a) is the best fit to the data. The same line is plotted in panel b) to illustrate that a sample with a brighter limiting magnitude also shows the Butcher-Oemler effect, but with a larger scatter.

on the order of $\sim$ 1 Gyr old.[14,7,39,5] A complementary population of galaxies with moderate emission line signatures, strong Balmer absorption and substantial radio luminosities appears consistent with the dusty starbursts which might be the progenitors of these galaxies.[39,44] Such systems are probably associated with a strong merger, which argues that galaxy interactions play an important role in the evolution of cluster galaxies. However, while morphologies of post-starburst galaxies do show some evidence for recent merging activity, many are also seen to have relatively undisturbed disks, which argues for a different mechanism which quenches their star formation [15,22].

The need for at least two mechanisms may be highlighted when comparing results from different cluster samples at intermediate redshifts. Balogh et al.[5] found that the X-ray selected CNOC1 cluster sample[49] contained a very small fraction of galaxies with the strong Balmer lines that indicated a recent massive starburst. In comparison with the coeval field, they found no significant excess of such galaxies. A similar lack of evidence for massive starbursts was found in studies of S0 galaxies.[29] These result lies in stark contrast with the results from the optically-delected MORPHS cluster sample [21,39] where upwards of 20% of the galaxy population is in the post-starburst phase.

A possible reason for this discrepancy may lie in the cluster sample selection. The CNOC1 sample is X-ray selected and contains primarily massive, relaxed systems which are remarkably homogeneous in their overall dynamics and X-ray properties.[13,36] A large fraction of these clusters show cooling flows in their X-ray profiles, which may imply that they have not undergone a merging event recently. If galaxy interactions occur primarily in low-velocity dispersion substructure rather than in the virialized high velocity cluster potential,[35] these clusters may indeed lack numerous examples of recent galaxy merging. For these clusters, the decrease in star formation in the individual cluster galaxies may be caused by ram-pressure stripping by the well-developed intra-cluster medium or by tidal effects. The MORPHs sample, by contrast, is much more heterogeneous in nature and contains both relaxed and subclustered systems. The larger fraction of post-starburst galaxies may thus be a reflection of the higher rate of larger scale merging in this sample.

3 Population Gradients in Clusters

While studies of the properties of individual galaxies may illuminate the mechanism which is responsible for stopping star formation in cluster galaxies and hence explain the morphology-density relation, they do not necessarily explain the Butcher-Oemler effect. In the hierarchical scenario of cluster formation, the observed galaxy populations are a balance between the infall of new field galaxies into the cluster potential and the rate at which their stellar content is transformed into the passively evolving cluster population. Thus, cluster populations are probes of evolution on both the galaxy and the galaxy cluster scale. For clusters which are not currently undergoing a strong subcluster merger, the balance between infalling and evolved populations will be a strong function of cluster-centric radius, with the cluster population eventually becoming indistinguishable from the field galaxy population at large radii. There is much evidence for these population gradients in clusters. The density-morphology, inasmuch as density and radius are degenerate, is one example. At higher redshifts, a number of clusters show gradients in galaxy colors, spectral types or morphologies. [1,21,46,38,4] The evolution of these gradients with redshift reflects the relative evolutionary time scales of galaxies and large scale structure.

Here we present galaxy population gradients for 15 rich clusters at $0.18 < z < 0.55$ from the CNOC1 sample. Galaxy spectra were deconstructed into components representing distinct stellar populations via principal component analysis.[23] Three components are defined. The "Old Population" component is designed to match empirically the reddest galaxies observed in the clusters, and are representative of stellar populations which are more than 3 Gyr old. The

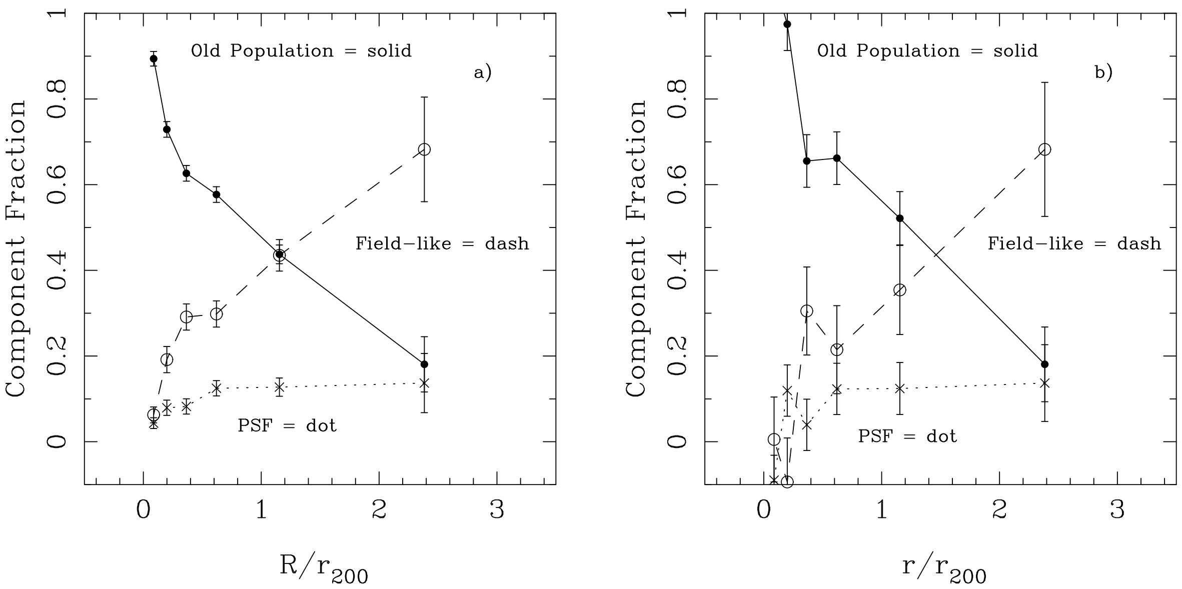

Figure 2: Composite radial gradients from 913 galaxies in 15 clusters based on the principal component analysis from Ellingson et al. (2001). The "Old Population" fraction is denoted by closed circles and a solid line, the "Field-like" component by open circles and a dashed line, and the "PSF" component by crosses and a dotted line. Panel a) is plotted in projected radial coordinates, and panel b) in deprojected radial coordinates (see text).

"Field-like" component is defined as a function of redshift by the properties of field galaxies at the cluster redshift, based on spectra of field galaxies from the CNOC2 survey.[50] Finally, the "Post-Star Formation (PSF)" component is defined by the "k+A" galaxies in the clusters. Each of $\sim$ 900 spectra is described by the sum of these three components.

Figure 2 shows composite population gradients for 15 clusters, as a function of cluster-centric redshift. A k+e limiting magnitude of $M_r = -19$ mag was used, and each galaxy was weighted as a function of its apparent magnitude, color and position according to the spectroscopic completeness of the sample (see Ellingson et al.[23] for details). Scaling the radii by r_{200} allows us to combine clusters with different masses and also places each galaxy in the same dynamical context with respect to cluster infall. For these clusters, t,he average value of r_{200} is about 1 h^{-1} Mpc. The virial radius is about $1.8r_{200}$. The expected gradients are clearly seen, with old populations dominating the cluster core, and the field-like component dominating at large radii. The "PSF" fraction is small for these clusters, remaining just a few percent of the population. Figure 2b shows the same distribution, but with a self-consistent correction for projection effects, assuming a spherical distribution on average. The gradients are qualitatively the same, with the "Old Population" fraction now at 100% in the cluster core, and possibly a small "PSF" component at 0.5–2 r_{200}.

The evolution of these gradients is illustrated in Figure 3. Here only the unprojected "Old Population" is shown, plotted for subsamples at $0.3 < z < 0.55$ and $0.18 < z < 0.3$. The evolutionary trend is clear, with the gradients becoming steeper at higher redshift. This is entirely consistent with the Butcher-Oemler effect in these clusters (Figure 1a); at a fixed aperture relative to r_{200}, the fraction of blue galaxies will be larger for higher redshift clusters. Also plotted are the population gradients inferred from the morphological gradients seen in intermediate [21] and low redshift [48] clusters. Here, the elliptical + S0 fraction is equated to the "Old Population" component, and $r_{200} = 1$ h^{-1} Mpc is assumed. Note that the high fraction of evolved galaxies in the cluster core remains fairly constant with epoch. This is also seen in the independent blue fraction measure in Figure 1c: the Butcher-Oemler effect is much diminished if only the cluster cores are observed. This effect has also been noted in other investigations of rich X-ray

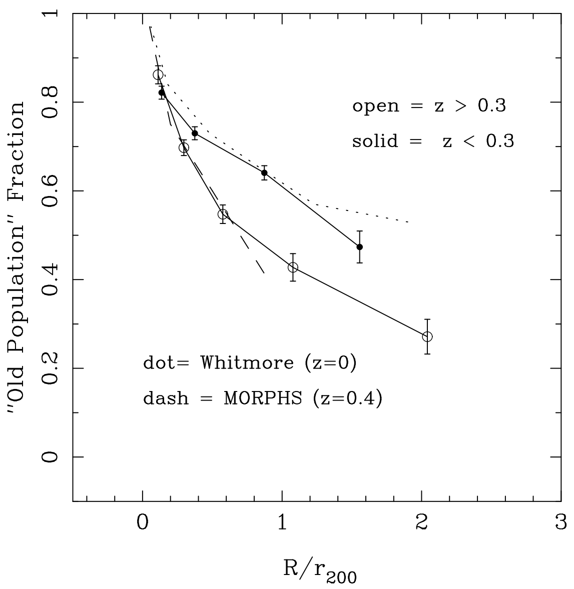

Figure 3: Composite radial gradients in the "Old Population" component for two redshift bins. Open and closed circles are for CNOC1 cluster galaxies at $z > 0.3$, and $z < 0.3$, respectively. The dashed line represents the morphological gradients from Dressler et al. for the $z \sim 0.4$ MORPHS sample, and the dotted line is from gradients adapted from Whitmore et al. at $z \sim 0$.

clusters.[43] This result suggests that the observed evolution in the cluster populations is linked to changing populations at large radii– most likely the infalling galaxies– rather than changes in the evolutionary mechanisms operating in the core.

Converting the gradients to luminosity surface densities for the different components shows the evolution of the spatial distributions of the different populations. Figure 4a illustrates that the spatial distribution of the old population appears to be quite constant in shape relative to r_{200}, indicating a stable dynamical state. Figure 4b shows the evolution of the infalling population, represented by the sum of the "PSF" and "Field-like" components. Here the fairly constant distribution shape (outside of the cluster core) appears to be decreasing in amplitude over time. If this component is interpreted as infalling galaxies, this result implies a factor of ~ 3 decrease in galaxy infall rates over the observed epoch $z \sim 0.45$ to $z \sim 0.2$.

Within this simple infall scenario, population gradients can thus place constraints on the growth of galaxy clusters and other large scale structure. However, the relatively steep drop in infall that is seen here is qualitatively inconsistent with low-density cosmological models, which predict relatively little evolution at intermediate redshifts. In general, the Butcher-Oemler effect does appear to contradict the otherwise slow rate of evolution of the cluster population as a whole at $z < 1$.[30,28,41] A possible solution is if galaxies are allowed to remain in the cluster potential for some length of time before undergoing their spectral transformation to the "Old Population," the actual time of infall for these galaxies identified here as infalling might actually be several billion years prior to the observed epoch. This delay in the transformation of the field population to cluster populations must be on the order of several billions of years. Even if star formation is abruptly terminated upon a galaxy's first entry to the cluster, the population evolution itself takes several billion years to complete. Interactions with the cluster potential or intra-cluster medium may in addition require several crossing times to completely snuff out star formation in a typical field galaxy.[16,6] Thus, the blue galaxies seen at these intermediate redshifts may be the last remnant of infall that happened at $z \sim 0.7$ or higher.

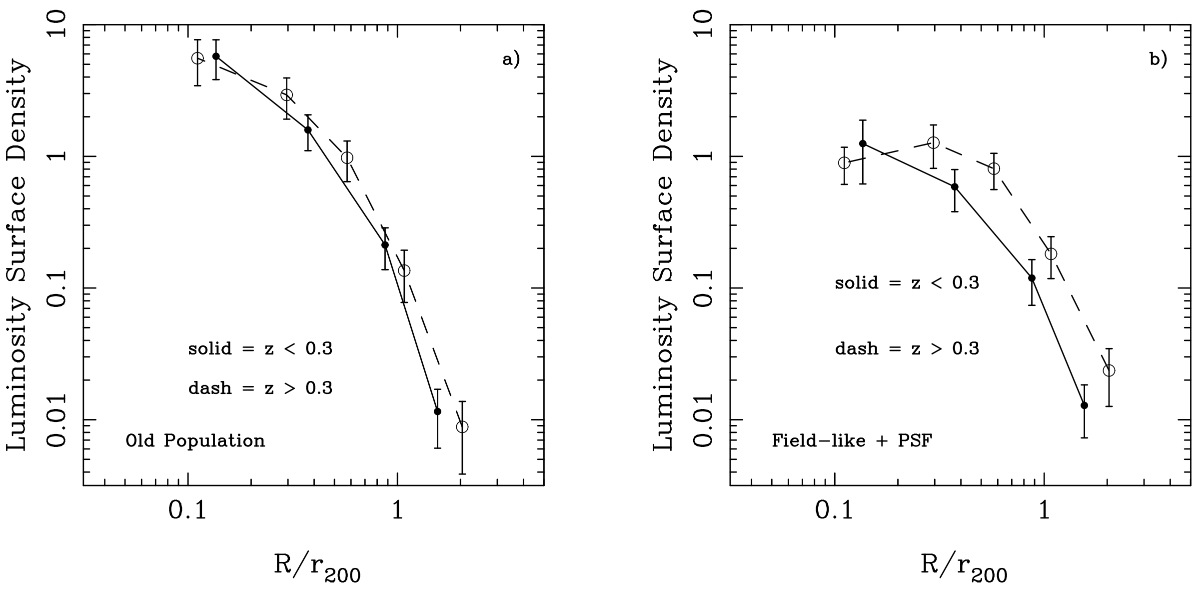

Figure 4: Composite luminosity density profiles in the "Old Population" component, in relative units, for two subsamples at different redshifts. Panel a) shows profiles for the "Old Population" component for clusters with $0.18 < z < 0.30$ (solid circles and line) and $0.30 < z < 0.55$ (open circles and dashed line). Panel b) shows the profiles for the sum of the "Field-like" and "PSF" components and the same redshift bins. The profiles are normalized by the richnesses of the clusters observed in each subsample so that the profiles are not affected changing average cluster richnesses with redshift.

4 Conclusions

The observed evolution of cluster galaxy populations allows a unique probe of the relationship between galaxies and structure on larger scales. Understanding the evolutionary sequence of individual galaxies changing from the field to the cluster population can place constraints on the effects of environment on galaxies. Complementarily, observing the overall evolution of the cluster populations as a function of redshift can allow us to trace the cosmological growth of clusters. While recent work has provided much progress towards a consistent scenario on both scales, a number of questions remain. A single mechanism for explaining the origin of the cluster population remains elusive, and it may be that different mechanisms dominate, depending on the recent merging history of the cluster. New samples of high redshift rich clusters [27,51,42] will provide a wider range of cluster types in order to explore the dependence of population on cluster morphology and perhaps provide a more representative cluster sample than has been available. Wide-field imaging and spectroscopic surveys, perhaps coupled with photometric redshift techniques [10,3] will allow population studies of even larger samples of both cluster and field galaxies. This new generation of observational data will allow us to map the evolution of galaxies in a wide range of environments, and place galaxy evolution in clusters more precisely in the overall cosmological context.

Acknowledgments

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Figure 5:

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