The Absence of Passively Evolving Ellipticals in Deep Optical and Near-Infrared Surveys

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The traditional view of elliptical galaxies has been that they formed in a single, rapid burst of star formation at high redshift, and have evolved quiescently since that time. In opposition to this traditional view is evidence that at least some elliptical galaxies have formed from the merger of two disk galaxies. What has not been clear is which process is the dominant formation mechanism for the large majority of elliptical galaxies. This question has significant implications for cosmological models, as different models make different predictions for the formation mechanism and epoch of elliptical galaxies\textsuperscript{1}. Here I use deep optical\textsuperscript{2} and near-infrared\textsuperscript{3-6} images to show that there are fewer galaxies with very red optical and near-infrared colors than predicted by models in which typical elliptical galaxies have completed their star formation by \( z > 5 \). These observations require that elliptical galaxies have significant star formation at \( z < 5 \). This requirement, combined with constraints on lower redshift starbursts from the modest ultraviolet luminosities of galaxies in the Hubble Deep Field\textsuperscript{7,8} and the properties of galaxies from \( 0 < z < 1 \) (refs 9-13), suggests that elliptical galaxies form at moderate redshift in dusty starbursts and/or through the hierarchical merging of smaller objects.

Very deep images at optical and near-infrared wavelengths provide a sensitive test of models of elliptical galaxy evolution. Passive models in which ellipticals form in a single, rapid burst at high redshift predict the existence of a population of high redshift galaxies with extremely red colors. In particular, galaxies that have formed the bulk of their stars at high redshifts will have extremely red optical and near-infrared colors when observed at \( 1 \lesssim z < z_f \), where \( z_f \) is the formation redshift. The red colors are the result of the absence of hot, young massive stars combined with the effect of redshift which causes the observed near-infrared and optical colors to become redder as they probe farther into the restframe blue and ultraviolet. This trend towards redder colors at higher redshifts only changes as the redshift of formation is approached, when the hot and blue massive stars have not yet died out.

The predictions of these models are shown in Figure 1, which traces the colors of galaxies formed in bursts of star formation at various redshifts for representative cosmologies. This diagram demonstrates that galaxies which have completed a large majority of their star formation by \( z \simeq 5 \) reach extremely red colors of \( V_{606} - K > 7 \). Galaxies with significant star formation at
lower redshifts do not have these colors, unless reddened greatly by dust. Therefore, the number of objects with $V_{606} - K > 7$ gives an upper limit to the comoving number density of passively evolving elliptical galaxies with $z_f \gtrsim 5$.

Only recently have surveys become deep enough in both the optical and near-infrared bands to test for the presence of these extremely red galaxies at $z > 1$. This advance is due in large part to the optical images of the Hubble Deep Field (HDF) that allow detections or useful upper limits on objects with the very faint $V$ magnitudes expected of red objects at these redshifts. These optical images have been followed up by several near-infrared surveys that can be used to determine the number of galaxies in the HDF with very red $V_{606} - K$ colors. One of these surveys provides K magnitudes to very faint limits for about 20% of the HDF. Near-infrared images of the entire HDF to a somewhat brighter limit have also been obtained and made publically available, and these have been analyzed as part of this work. Two ground-based surveys in different fields provide additional constraints on the number of extremely red galaxies. Although these ground-based surveys are not as deep, as the HDF surveys, particularly at optical wavelengths, they are valuable because they are in completely independent fields, widely separated on the sky.

The results of these surveys are compared to the predictions of passively evolving models in Figure 2. The surface density of extremely red galaxies objects is far below the expectations of a model in which all early-type galaxies form in bursts at high redshift. The predictions for the surface density of extremely red galaxies are calculated using a constant comoving number density of early-type galaxies set by studies of the K-band luminosity function at low redshift, the stellar populations models discussed earlier, and the appropriate cosmology for each plot. This calculation may underestimate the number density of extremely red galaxies expected in passively evolving models because the adopted local luminosity function has a density normalization which is about a factor of two lower than more global measures at modest redshifts. Alternatively, the calculation may be an overestimate in that the luminosity function used includes both ellipticals and S0s, whereas passive models could be said to only apply to ellipticals, which are about 50% of the total.

The strong deficit of galaxies with extremely red colors, seen in widely separated fields and at different flux limits, rules out models in which typical elliptical galaxies are fully assembled and have formed all of their stars at $z \gtrsim 5$. This constraint cannot be escaped simply by breaking ellipticals into many pieces which formed their stars at high redshift. Near-infrared surveys are now deep enough to detect the individual pieces, and thus such models dramatically overproduce red galaxies within the observed range of K magnitudes. An illustrative example with $z_f = 5$, a constant total stellar mass in the early-type population, and a comoving number density of this population that increases as $(1 + z)^3$, is plotted in Figure 2. Models with more modest density evolution follow curves between this model and the $z_f = 5$ passive model with constant number density. Therefore, typical elliptical galaxies must have had significant star formation at $z < 5$.

Single-burst models at lower redshifts are strongly constrained by other observations. In
particular, the modest ultraviolet luminosities observed for galaxies in the HDF\textsuperscript{7,8}, as well as the failure of searches for strong emission-line objects\textsuperscript{16} rule out these models, unless the objects are obscured greatly by dust\textsuperscript{17,18}. Dusty models produce high luminosities in the far-infrared and sub-mm, and are close to current observational limits at these wavelengths\textsuperscript{7}.

Alternatively, the simple passive model at high redshift can be altered to incorporate a much longer starburst duration that extends to lower redshift. In order to make the colors sufficiently blue, this component must form about five percent or more of the stellar mass of ellipticals from $z_f$ through $z = 1$. For example, if 5\% of the stellar mass forms in an additional star formation component that is constant from $z_f$ to $z = 1$ and then shuts off, the resulting $V_{606} - K$ color is slightly redder than 5 over most of this redshift range. If the mass in the extended component is only a few percent, then the $V_{606} - K$ color is greater than 6, and far more red galaxies are expected than observed. Thus, the extended star formation must represent at least 5\% of the stellar mass to accommodate the absence of very red galaxies. This modification of the passive model runs into several problems with other observational constraints. Firstly, it increases the evolution to brighter luminosities at higher redshifts expected in passive models, contrary to the results of deep, red-selected galaxy redshift surveys which find little or no luminosity evolution\textsuperscript{9–11}. Moreover, an extended star formation history is unable to account for the elemental abundance ratios in ellipticals\textsuperscript{12}.

A more natural answer is that most elliptical galaxies form at $z < 5$ through merging and associated starbursts, which are likely to be at least moderately dusty. This result is consistent with a large body of other evidence which indicates that merging plays a major role in the formation of ellipticals, ranging from detailed studies of nearby galaxy mergers to the discovery of bimodality in the globular cluster systems of elliptical galaxies\textsuperscript{13}. The formation of elliptical galaxies in this way is consistent with the predictions of hierarchical clustering models of galaxy formation \textsuperscript{19–21}.

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Figure Captions

Figure 1. A plot of the observed $V_{606} - K$ color as a function of redshift for a stellar population formed in a single short burst ($\tau = 0.01$ Gyr). Galaxies with higher formation redshifts ($z_f > 5$) have extremely red colors that are not reached by galaxies with lower formation redshifts ($z_f \lesssim 3$). The arrow marks the color cut used in Figure 2. Both the closed model plotted in the top panel and the open model in the bottom panel exhibit the same effect. An approximate translation from the HST $V_{606}$ bandpass to the standard $V$ bandpass is given on the right side of the plots. These figures are based on the Bruzual & Charlot models (manuscript in preparation) with solar metallicity and a Miller-Scalo stellar initial mass function (IMF). The results are not sensitive to the IMF within the usual range of parameters (e.g. Salpeter vs. Miller-Scalo), and a short burst duration is used only to isolate the effect of the formation redshift. For simplicity, absorption by intervening HI has not been accounted for\textsuperscript{22}, which will only make the colors redder at $z > 3$.

Figure 2. The surface density of extremely red galaxies ($V_{606} - K > 7$) at different limiting K magnitudes compared to the predictions of passive models of elliptical galaxy formation. The data points are inconsistent with $z_f > 5$ models, including the light dotted line representing a pure density evolution model with $z_f = 5$. The two circles represent surveys in HDF. The deeper of these is the Hogg et al. survey with the Keck telescope of roughly one arcmin\textsuperscript{2} to a 50\% completeness limit of $K \approx 23.5$, in which no objects with colors red as $V_{606} - K > 7.0$ are found, and only one is even within one magnitude of this color\textsuperscript{3}. The second HDF data point is based on the publically available Kitt Peak imaging survey\textsuperscript{4} that covers the full five arcmin\textsuperscript{2} of the HDF, to a 50\% completeness limit of $K \approx 22.25$. Using an updated version of the SExtractor image analysis program\textsuperscript{23}, we find that all sources with $K < 22$ are detected in the HDF optical images and have significantly bluer colors than the passive model predictions. At the fainter limit of $K < 22.5$, there is one good candidate and two marginal candidates for objects with $V_{606} - K > 7.0$. The point plotted accounts for all three of these candidates, and is therefore shown as an upper limit. The square and triangle are from ground-based surveys in other fields by Moustakas et al.\textsuperscript{5}, and Cowie et al.\textsuperscript{6} respectively. The former covers approximately two arcmin\textsuperscript{2} to a 50\% completeness limit of $K \approx 22.5$. Within these limits, there are three galaxies that are undetected in $V$, with approximate lower limits to their $(V-K)$ color of 7.5, 6.1, and 5.3 (ref. 5). These three represent an upper limit to the number of extremely red objects in this field. The latter survey covers about six arcmin\textsuperscript{2} to a limiting $K$ magnitude of 20.9. Because the bluer bandpass is not very deep in these data, I adopt $(I-K) > 4.5$ as the best estimate of the equivalent $V_{606} - K > 7$ cut used above. There are approximately nine galaxies with colors this red. This number is more properly considered an upper limit, as there are several objects with red $(I-K)$ but blue optical colors\textsuperscript{5,6}.
