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REVEALING VELOCITY DISPERSION AS THE BEST INDICATOR OF A GALAXY's COLOR, COMPARED TO STELLAR MASS, SURFACE MASS DENSITY, OR MORPHOLOGY

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ABSTRACT

Using data of nearby galaxies from the Sloan Digital Sky Survey we investigate whether stellar mass ($M_{\rm star}$), central velocity dispersion (σ), surface mass density (Σ), or the Sérsic n parameter is best correlated with a galaxy's rest-frame color. Specifically, we determine how the mean color of galaxies varies with one parameter when another is fixed. When $M_{\rm star}$ is fixed we see that strong trends remain with all other parameters, whereas residual trends are weaker when Σ, n, or σ is fixed. Overall σ is the best indicator of a galaxy's typical color, showing the largest residual color dependence when any of the other three parameters are fixed, and $M_{\rm star}$ is the poorest. Other studies have indicated that both the central black hole mass and possibly host dark matter halo properties (mass or concentration) are also better correlated with σ than with $M_{\rm star}$, Σ, or n. Therefore, it could be the case that the strong correlation between color and σ reflects an underlying relationship between a galaxy's star formation history and/or present star formation rate and the properties of its dark matter halo and/or the feedback from its central supermassive black hole.

Key words: galaxies: formation – galaxies: fundamental parameters – galaxies: kinematics and dynamics – galaxies: statistics

1. INTRODUCTION

It is well established that the stellar populations of galaxies in the nearby universe correlate with their luminosities and masses, such that the stars in more massive galaxies are on average older and more metal-rich (e.g., Bower et al. 1992; Blanton et al. 2003a; Kauffmann et al. 2003). The old ages of the most luminous galaxies are somewhat puzzling, as it implies that there must be some mechanism responsible for shutting off their star formation (e.g., Kauffmann & Haehnelt 2000; Croton et al. 2006; Naab et al. 2007; Kereš et al. 2005). Another puzzle is that the correlation between star formation history and mass is complex: low-mass galaxies are typically younger and high-mass galaxies are typically older, with a bimodal transition region at $\sim 3 \times 10^{10}\,M_{\odot}$ (Kauffmann et al. 2003). This bimodality and the associated transition mass scale have been the subject of intense debate in the past years (e.g., Bundy et al. 2006; Peng et al. 2010; Brammer et al. 2011).

An intriguing possibility is that luminosity and mass are not the "right" parameters for interpreting galaxy evolution, and that other parameters exist that show more straightforward correlations with stellar population parameters. As demonstrated by Kauffmann et al. (2003, 2006), the star formation histories of galaxies show less scatter when the structure of galaxies is taken into account. In particular, the ages and star formation rates of galaxies are better correlated with their surface densities Σ (which is proportional to M_*/r_e^2 where r_e is the size of the galaxy) than with mass alone. Franx et al. (2008) find that the strong correlation between color and M_*/r_e^2 (and M_*/r_e) persists all the way to $z \sim 2$. Similar trends have been found for velocity dispersion (σ) and for the Sérsic (1968) index n (e.g., Blanton et al. 2003b; Bell 2008; Wuyts et al. 2011; van Dokkum et al. 2011; Bell et al. 2012). When considering just early-type galaxies, such trends become even more apparent, with σ proving the dominant parameter in determining a galaxy's stellar population (e.g., Trager et al. 2000; Bernardi et al. 2005; Graves et al. 2009; Smith et al. 2009).

Although it seems clear that the correlation between color and mass is weaker than the correlations between color and Σ, σ, or n, it is not clear which of these parameters is the best predictor of a galaxy's color. This is important to establish as it provides information on the physical processes that govern galaxy evolution. As an example, if n best correlates with color (as suggested by Bell et al. 2012) it may imply that the merger history determines the star formation history, whereas if σ is the key parameter, it could suggest that the star formation history is influenced by a galaxy's host dark matter halo or central supermassive black hole, since the properties of both appear to be most strongly correlated with σ rather than $M_{\rm star}$, Σ, or n (Wake et al. 2012; Beifiori et al. 2012).

In this Letter we investigate which of the four parameters—$M_{\rm star}$, Σ, σ, or n—is most closely correlated with the star formation history, as parameterized by the color. We determine this by fixing each parameter in turn and measuring to what extent the color depends on the other three parameters. The homogeneous, large data sets required for this study are now available from the seventh data release of the Sloan Digital Sky Survey (SDSS DR7; Abazajian et al. 2009).

2. DATA

The galaxy data used in this analysis are gathered from the seventh data release of the SDSS (Abazajian et al. 2009). We begin with the Large Scale Structure samples of the DR7 NYU Value Added Galaxy catalog (VAGC; Blanton et al. 2005). The sample we use has an r-band magnitude range of $14.5 < r < 17.6$. In addition, the NYU VAGC gives k-corrected (to $z = 0.1$) absolute magnitudes (Blanton et al. 2003a), velocity dispersion measurements from the Princeton Spectroscopic pipeline, and circularized Sérsic fits for each galaxy all of which we make use of in this analysis.

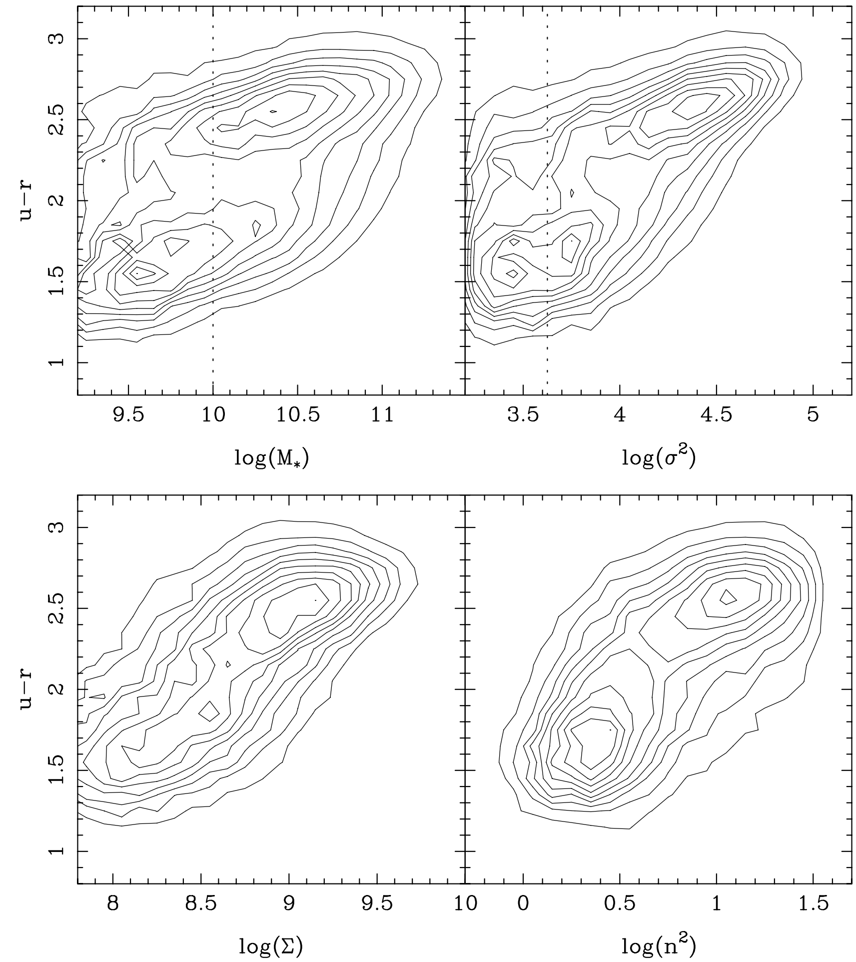

Figure 1. $u-r$ color distribution as a function of $M_{\rm star}$, σ^2, Σ, and n^2. The $u-r$ color is positively correlated with all four parameters. The correlation with $M_{\rm star}$ has large scatter, particularly near $M_{\rm star} \sim 3 \times 10^{10}\, M_\odot$. The dotted lines show the cuts we apply in $M_{\rm star}$ and σ to define our primary sample.

For estimates of the stellar mass we make use of the MPA/JHU DR7 value added catalog which provides stellar mass estimates based on stellar population fits to the SDSS photometry (Kauffmann et al. 2003; Salim et al. 2007). After making some minor quality cuts this leaves a total sample of 521,313 galaxies over 7640 deg^2.

The SDSS velocity dispersions are measured within the 3″ diameter SDSS fiber. We correct to a common aperture of one-eighth of an effective radius (r_e), the central velocity dispersion, using the relation $\sigma_0 = \sigma_{\rm ap}(8r_{\rm ap}/r_e)^{0.066}$ where $r_{\rm ap} = 1\farcs5$ (Cappellari et al. 2006). r_e is taken from the best-fitting circularized Sérsic profile fit.

Throughout we use $u-r$ color from the k-corrected NYU VAGC absolute magnitudes (Blanton et al. 2003a; Blanton & Roweis 2007). As already stated these are corrected to $z = 0.1$; although they are not quite $u-r$ at rest we will refer to them as $u-r$ colors. We also make use of the morphological classifications from Galaxy Zoo (Lintott et al. 2011) utilizing the probability that a galaxy is an edge-on disk ($P_{\rm edge}$) (see Lintott et al. 2011 for details).

3. DEPENDENCE OF COLOR ON $M_{\rm star}$, σ, Σ, AND N

We wish to understand how the typical color of a galaxy depends on its stellar mass, central velocity dispersion, surface mass density, and Sérsic profile. We begin in Figure 1 where we show the $u-r$ color distribution for all SDSS galaxies with $0.02 < z < 0.11$ as a function of each parameter. We have applied to this figure (and all subsequent figures) a V/Vmax weight for each galaxy to correct for the varying stellar mass completeness limit with redshift. We plot the color distributions as a function of log($M_{\rm star}$), log(Σ), log(σ^2), and log(n^2).

We have chosen these units as they are all approximately linearly proportional to one and other. This is illustrated in Figure 2 where we show the relationships between these four parameters. The contours show the full distributions and the points show the mean of y in bins of x (black) and x in bins of y (red). While we may expect Σ and σ^2 to be approximately linearly proportional to $M_{\rm star}$ and each other, we find that n^2 shows the same trends over a broad range in those parameters. Therefore, we can meaningfully compare the predictive power of n^2 to that of the other three parameters.

Figure 1 shows that there is a clear color dependence on each parameter but with significant scatter. It also illustrates, as has been previously found (e.g., Kauffmann et al. 2003), that $M_{\rm star}$ is a relatively poor discriminator of a galaxy's color, particularly around the "transition mass" of $\sim 3 \times 10^{10}\, M_\odot$. It is important to note that distributions become noisy at both low $M_{\rm star}$ and low σ. The number of galaxies becomes increasing small at low masses, due to the apparent magnitude limit of the SDSS, which also strongly affects the sample at low σ due to the tight correlation between the two parameters. σ measurements also become more uncertain below 65 km s^{-1} due to the resolution

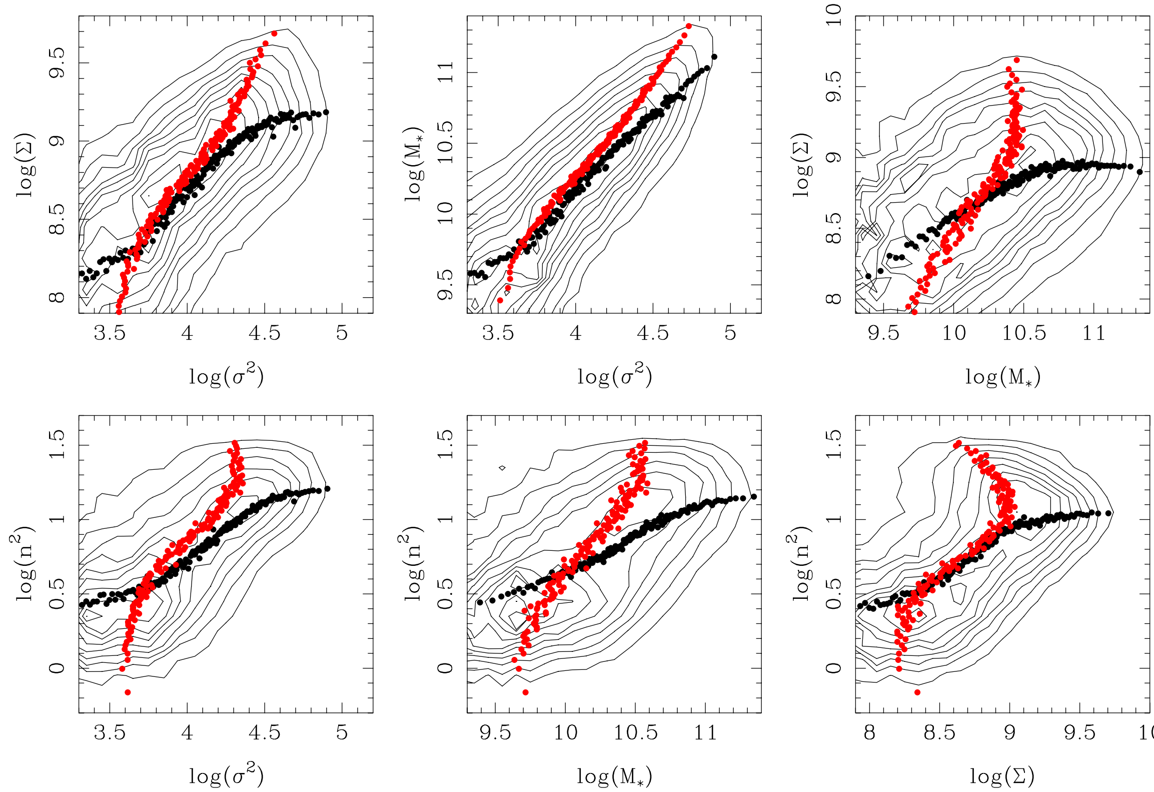

Figure 2. Relationships between $M_{\rm star}$, Σ, σ^2, and n^2. Galaxies are V/Vmax weighted to correct for the redshift-dependent stellar mass completeness limit. The black points show the mean of y in bins of x containing 500 galaxies, whereas the red points show the mean of x in bins of y. We can see that over a significant range of each parameter they are all approximately linearly proportional to one another.

of the SDSS spectra. For these reasons we limit the remainder of the analysis to galaxies with $M_{\rm star} > 10^{10} M_\odot$ and $\sigma > 65$ km s^{-1}.

We also remove edge-on disk galaxies from our sample to minimize the influence of dust on our measurements (e.g., Patel et al. 2011), although we expect the dust contribution to be low in the local universe. We make a cut using the Galaxy Zoo $P_{\rm edge}$ parameter, limiting it to be <0.3. We note that this cut changes our results very little and has no effect on any of our conclusions.

4. WHICH PARAMETER CORRELATES BEST WITH COLOR?

In order to determine which parameter shows the strongest correlation with color we determine whether any color dependence remains on $M_{\rm star}$, Σ, σ, and n when each of these parameters is held fixed. We divide our parent sample ($0.02 < z < 0.11$, $M_{\rm star} > 10^{10} M_\odot$, $\sigma > 65$ km s^{-1}, and $P_{\rm edge} < 0.3$) into a series of samples selected to have narrow ranges in each parameter. We select bins of 0.05 in log($M_{\rm star}$) and log(Σ), 0.025 in log(σ) and 0.2 in n. We then calculate the mean $u - r$ color of galaxies in each of these narrow binned samples as a function of the other three parameters, where the mean is calculated in bins of 300 galaxies.

4.1. Residual Correlations

We show the resulting relationships between mean color and $M_{\rm star}$, Σ, n, and σ in Figures 3 and 4. Each row shows a pair of parameters with the binning and abscissa parameter switched. That is, in each row the left panel shows the effect of varying parameter 1 at fixed parameter 2, and the right panel shows the effect of varying parameter 2 at fixed parameter 1. The left and right panels therefore essentially show the same information, but highlight the trends in a complimentary way. If the trends of all of the binned samples lie on top of each other in any of the plots it would mean that the color would be independent of the parameter used for the binning. Similarly, if the abscissa parameter is unimportant, each of the individual binned trends will be flat.

Turning to the first pair of parameters at the top of Figure 3, Σ and $M_{\rm star}$, we can see something close to this extreme situation. When $M_{\rm star}$ is held fixed (left panel) a clear trend remains with Σ, such that higher Σ galaxies are redder. The trend is particularly strong at low $M_{\rm star}$ and gradually decreases at the highest masses, resulting in some spread but a generally low dispersion between the $M_{\rm star}$ bins. The same trend is visible when Σ is held fixed; there is only a very weak dependence of mean $u - r$ color on $M_{\rm star}$ with more massive galaxies being redder. The individual Σ bins are well separated, showing the strong color dependence on Σ, and are generally parallel. It appears that Σ gives a better indication of a galaxy's color than stellar mass does.

We next consider $M_{\rm star}$ and n, shown in the middle panel of Figure 3. For low n (< 2.5) there is a strong dependence of the color on n at fixed $M_{\rm star}$, but for higher n the trends with $M_{\rm star}$ are all the same with no n dependence. At all n there is a trend for more massive galaxies to be redder on average, although this is very weak for galaxies with log($M_{\rm star}$) < 11. Again $M_{\rm star}$ appears a poorer indicator of a galaxy's color than n, although this is less true at high n or high $M_{\rm star}$.

The bottom panels of Figure 3 concern Σ and n. At low n there is a strong relationship between color and Σ with higher Σ galaxies being redder. While this trend remains for all

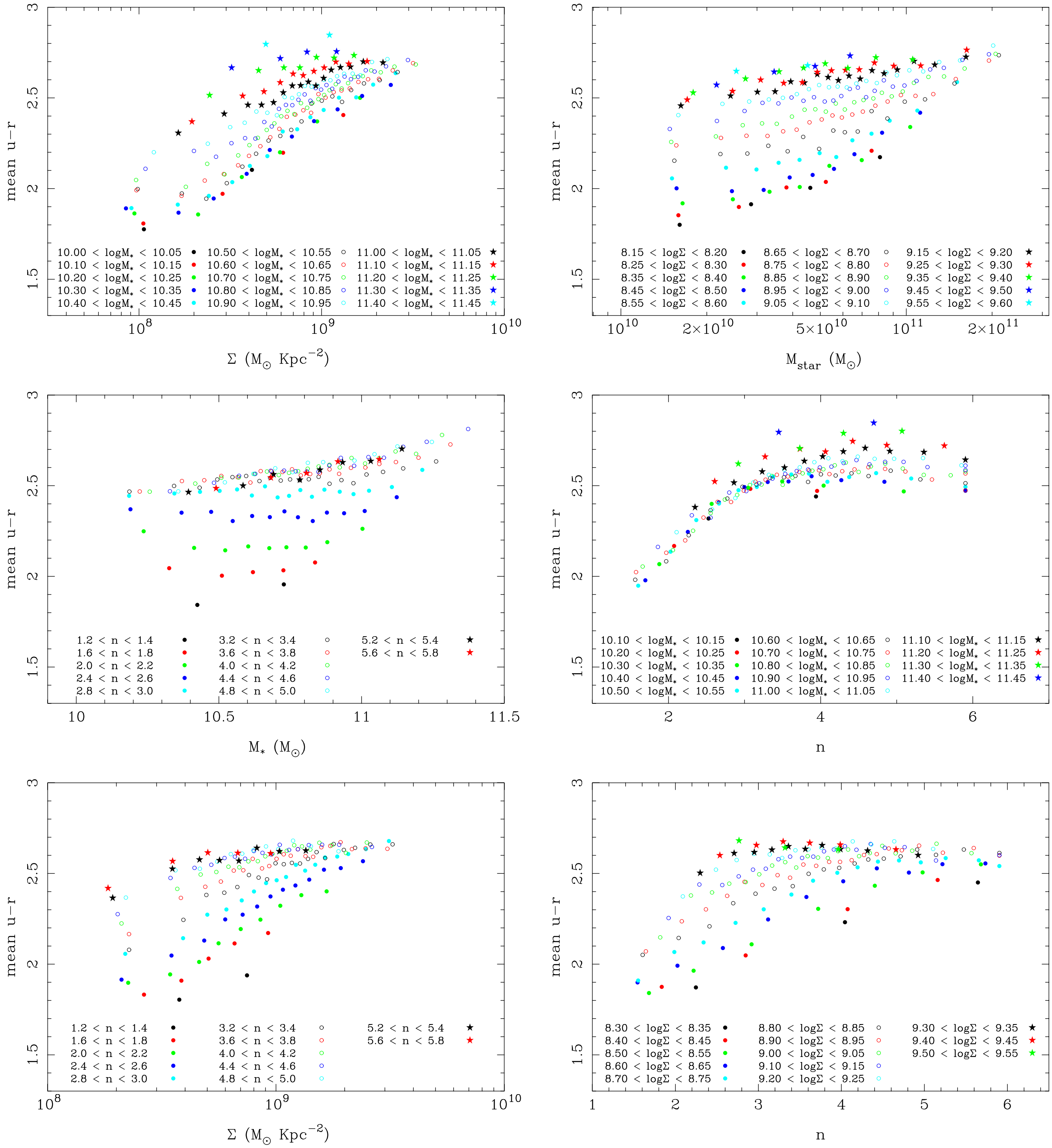

Figure 3. Relationship between mean $u-r$ color and mass surface density at fixed stellar mass (top left), stellar mass at fixed mass surface density (top right), stellar mass at fixed Sérsic n (middle left), Sérsic n at fixed stellar mass (middle right), mass surface density at fixed Sérsic n (bottom left), and Sérsic n at fixed mass surface density (bottom right).

n the slope of this correlation reduces as n increases. There is a similar dependence of color on n at fixed Σ, although the relation becomes very weak at the highest Σ.

In Figure 4 we show how the color depends on σ at fixed $M_{\rm star}$, Σ, and n on the left and how color depends on $M_{\rm star}$, Σ, and n at fixed σ on the right. It is striking how tight all of the trends are in the left panels and how separated they are in the right panels. This indicates that the mean galaxy color is more strongly dependent on σ than $M_{\rm star}$, Σ, or n. This is particularly true at σ (> 200 km s^{-1}) where all the trends lie almost completely on top of each other on the left and are very close to flat on the right. At lower σ interesting trends emerge; perhaps surprisingly, the mean color becomes bluer as $M_{\rm star}$ increases, with this trend increasing as σ decreases. This probably reflects an increasing disk component in more massive galaxies at fixed σ. At low σ (<175 km s^{-1}) a trend emerges

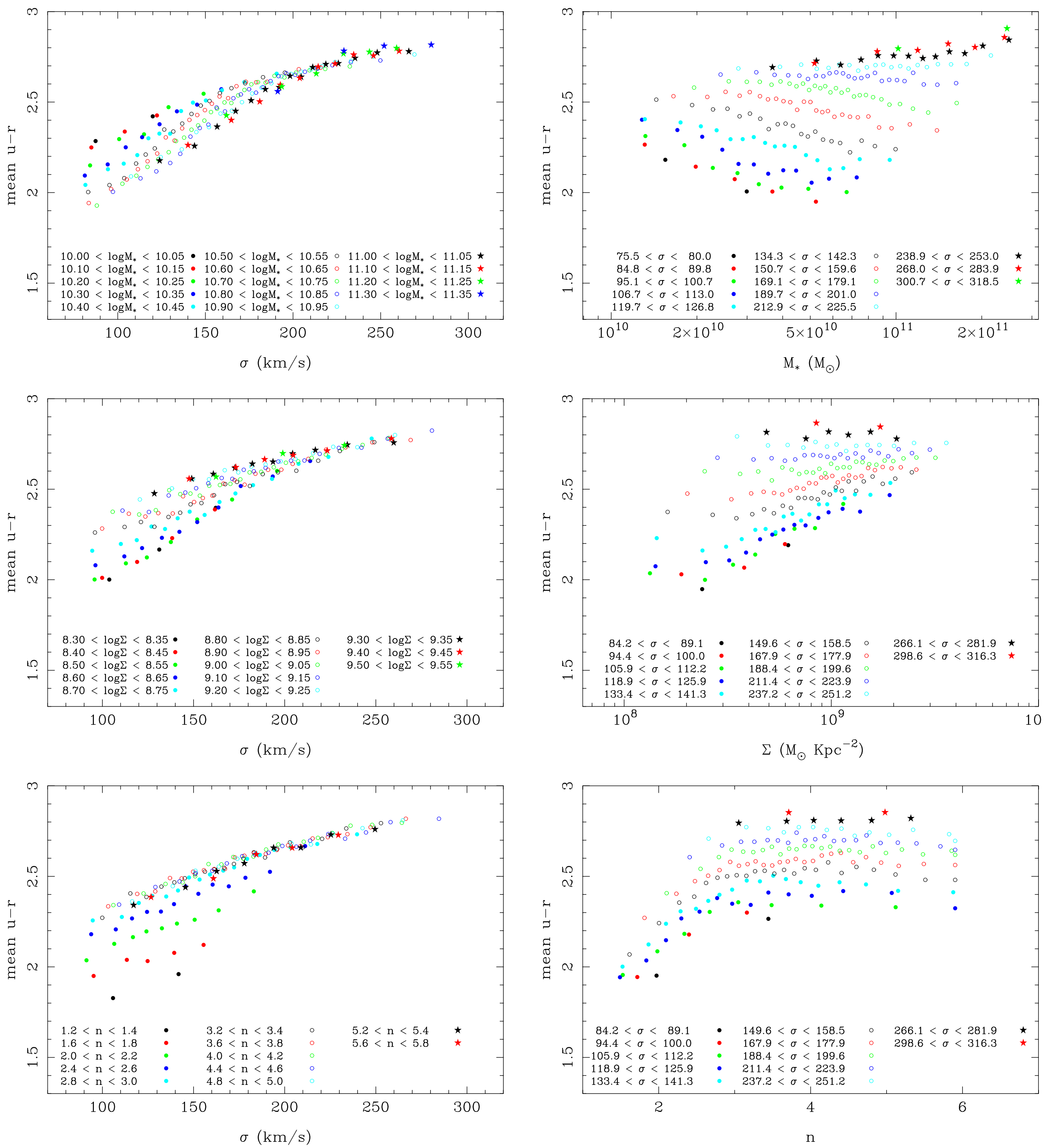

Figure 4. Relationship between mean $u - r$ color and velocity dispersion at fixed stellar mass (top left), stellar mass at fixed velocity dispersion (top right), velocity dispersion at fixed mass surface density (middle left), mass surface density at fixed velocity dispersion (middle right), velocity dispersion at fixed Sérsic n (bottom left), and Sérsic at fixed velocity dispersion (bottom right).

with Σ such that galaxies with higher Σ at fixed σ have redder colors, with the trend becoming more significant as σ decreases. There is also a trend with n when $n < 2.5$ such that galaxies with higher n are redder. There is no color dependence on n at fixed σ for higher n galaxies. While some trends with M_{star}, Σ, and n emerge in some regions of the parameter space, there is always a strong dependence of the mean color on σ over the full range of the other parameters.

4.2. *Quantifying the Residual Correlations*

We show in Figure 5 an attempt to both simplify and quantify the trends that are displayed in Figures 3 and 4. In narrow bins of one parameter we calculate the difference in the mean $u - r$ color of the galaxies lying in the lowest and highest 10 percentiles of the other three parameters. Since the size of the range of the second parameter may vary with the first and between the

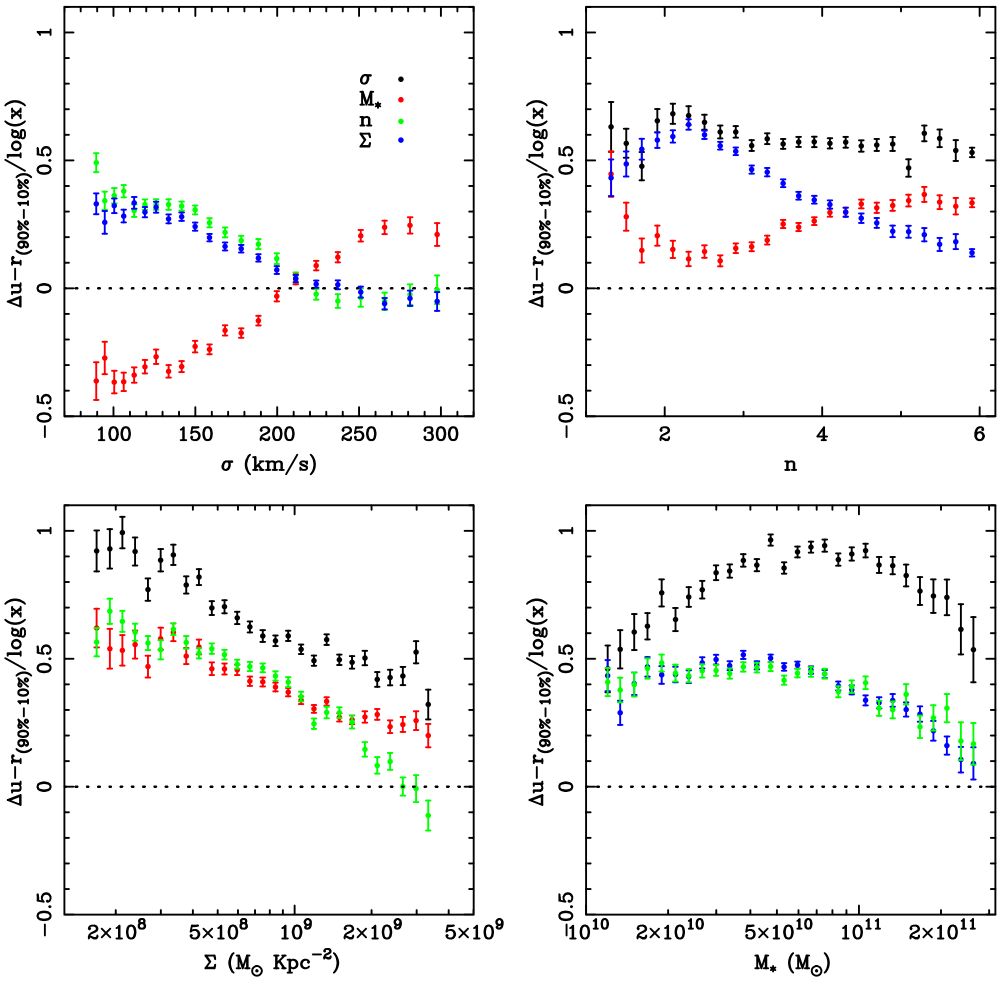

Figure 5. Gradient in the dependence of the mean u–r color on each parameter ($M_{\rm star}$, Σ, σ, and n) when each is fixed in turn. This is calculated as the difference in u–r color between the 90th and 10th percentile of parameter x per unit parameter x when a second parameter is fixed. The units of parameter x are $\log(M_{\rm star})$, $\log(\sigma^2)$, $\log(\Sigma)$, and $\log(n^2)$ which are all roughly equivalent. A color difference of zero means that there is no change in the color as parameter x is varied when the second parameter is fixed, as is the case for n and Σ when σ is fixed at values >220 km s^{-1} (top left). Positive values indicate that galaxies become redder as parameter x is increased. When σ is fixed (top left) the absolute color variation over the other parameters is always less than 0.5. When the other parameters are fixed the magnitude of the color variation with σ is always largest and is almost always larger than 0.5. The implication is that color depends more strongly on σ than on any other parameter.

different parameters we calculate this color difference per unit $\log(M_{\rm star})$, $\log(\Sigma)$, $\log(\sigma^2)$, and $\log(n^2)$. For example, the blue points in the top left panel of Figure 5 show the difference between the mean $u-r$ color of galaxies with the 10% highest Σ and 10% lowest Σ per unit $\log(\Sigma)$ in narrow bins of σ. This is essentially the vertical scatter in the center left panel of Figure 4 or the gradient of the individual trends in the center right panel.

The color gradients shown in Figure 5 reinforce the conclusions we have already drawn. When σ is fixed (top left panel) the magnitude of the color gradient is always less than 0.5, showing that there is only a weak dependence of color on $M_{\rm star}$, Σ, or n at constant σ. This is particularly true at high σ (> 200 km s^{-1}) where the gradient is essentially zero for both Σ and n. When the other three parameters are held fixed, the color gradient with σ is always the largest and is greater than 0.5 regardless of the values of the other parameters. Clearly, there is a significantly larger dependence of the color of galaxies on σ than on $M_{\rm star}$, Σ, or n.

Figure 5 again confirms the negative color gradients with $M_{\rm star}$ at low σ (red points, top left panel), such that more massive galaxies are bluer when σ is fixed. We also see negative color gradients with n for the highest Σ galaxies. Otherwise, it is always the case that galaxies with higher $M_{\rm star}$ or n are redder, and always the case that galaxies with higher σ or Σ are redder when the other parameters are fixed.

5. DISCUSSION

The central result of this Letter is that the colors of galaxies depend more strongly on σ than on $M_{\rm star}$, Σ, or n. We have demonstrated this by examining, for each of these parameters, how strong the residual correlations with the other three parameters are when the parameter under consideration is held fixed. At fixed σ residual trends with other parameters are weak, and when any of the other parameters are fixed there are strong residual trends with σ.

Recently Bell et al. (2012) studied how the fraction of passive (i.e., not star-forming) galaxies depends on a similar set of parameters and reached the conclusion that n was the best indicator of the passive fraction. This seems to be at odds with our findings where σ shows the strongest color trends. The difference may stem from the fact that Bell et al. (2012) use $M_{\rm star}/R_e$ to approximate velocity dispersion. While there is a correlation between σ and $M_{\rm star}/R_e$, which is improved if corrections based on n are applied (Taylor et al. 2010), there is significant scatter (∼0.1 dex). This may be the cause of our differing conclusions and illustrate the importance of directly measured dynamical properties.

Our results, and those of others (e.g., Kauffmann et al. 2003; Franx et al. 2008; van Dokkum et al. 2011; Bell et al. 2012), call into question whether "mass quenching" (e.g., Peng et al. 2010) and other mass-driven effects are actually manifestations of underlying trends with velocity dispersion. The velocity dispersion may in turn reflect a yet more fundamental parameter. It is known to correlate well with central black hole mass (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000; Beifiori et al. 2012) and also with the properties of dark matter halos (Wake et al. 2012), both of which are likely to play an important role in shaping a galaxy's star formation history (e.g., van de Voort et al. 2011; Booth & Schaye 2011).

This study can be extended and improved in many ways. The dispersions are currently corrected to a common aperture with reasonable assumptions, but it would be very useful to measure radial trends in dispersion in a systematic way. This is particularly relevant for low-mass galaxies and star-forming galaxies, as they have significant disks which presumably dominate at large radii. Blue disks may well be the cause of the peculiar fact that, at low σ, more massive galaxies are *bluer* at fixed dispersion (see Figure 4). Modeling of the effects of various physical processes (such as merging) on the velocity dispersion may help us understand *why* velocity dispersion is so well correlated with many aspects of galaxies. One possibility is that σ may well be indicating both the halo mass (or other halo properties such as concentration or age), in a similar or more precise manner than $M_{\rm star}$ (Wake et al. 2012), and at the same time be an indicator of the relative bulge to disk components. So at fixed $M_{\rm star}$ a higher σ galaxy has a larger bulge to disk ratio and so is redder, whereas at fixed n a higher σ galaxy typically occupies a more massive (or more concentrated) dark matter halo and so is also redder. σ is then the best of the four parameters at encapsulating both color dependencies (halo properties and bulge to disk ratio) as illustrated by the tightness of the $\sigma - M_{\rm star}$ and $\sigma - n$ relations shown in Figure 2.

Finally, it would be interesting to do similar systematic studies at earlier cosmic epochs, extending those pioneered by Franx et al. (2008) and Bezanson et al. (2011), which will give further insight into the physical parameters that drive galaxy formation and evolution.

REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Blanton, M. R., Brinkmann, J., Csabai, I., et al. 2003a, AJ, 125, 2348
Blanton, M. R., Hogg, D. W., Bahcall, N. A., et al. 2003b, ApJ, 594, 186
Blanton, M. R., & Roweis, S. 2007, AJ, 133, 734
Blanton, M. R., Schlegel, D. J., Strauss, M. A., et al. 2005, AJ, 129, 2562
Beifiori, A., Courteau, S., Corsini, E. M., & Zhu, Y. 2012, MNRAS, 419, 2497
Bell, E. F. 2008, ApJ, 682, 355
Bell, E. F., van der Wel, A., Papovich, C., et al. 2012, ApJ, in press (arXiv:1110.3786)
Bernardi, M., Sheth, R. K., Nichol, R. C., Schneider, D. P., & Brinkmann, J. 2005, AJ, 129, 61
Bezanson, R., van Dokkum, P. G., Franx, M., et al. 2011, ApJ, 737, L31
Booth, C. M., & Schaye, J. 2011, MNRAS, 413, 1158
Bower, R. G., Lucey, J. R., & Ellis, R. S. 1992, MNRAS, 254, 601
Brammer, G. B., Whitaker, K. E., van Dokkum, P. G., et al. 2011, ApJ, 739, 24
Bundy, K., Ellis, R. S., Conselice, C. J., et al. 2006, ApJ, 651, 120
Cappellari, M., Bacon, R., Bureau, M., et al. 2006, MNRAS, 366, 1126
Croton, D. J., Springel, V., White, S. D. M., et al. 2006, MNRAS, 365, 11
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Franx, M., van Dokkum, P. G., Schreiber, N. M. F., et al. 2008, ApJ, 688, 770
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJ, 539, L13
Graves, G. J., Faber, S. M., & Schiavon, R. P. 2009, ApJ, 698, 1590
Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576
Kauffmann, G., Heckman, T. M., De Lucia, G., et al. 2006, MNRAS, 367, 1394
Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003, MNRAS, 341, 33
Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, MNRAS, 363, 2
Lintott, C., Schawinski, K., Bamford, S., et al. 2011, MNRAS, 410, 166
Naab, T., Johansson, P. H., Ostriker, J. P., & Efstathiou, G. 2007, ApJ, 658, 710
Patel, S. G., Holden, B. P., Kelson, D. D., et al. 2011, ApJ, 748, L27
Peng, Y.-j., Lilly, S. J., Kovač, K., et al. 2010, ApJ, 721, 193
Salim, S., Rich, R. M., Charlot, S., et al. 2007, ApJS, 173, 267
Sérsic, J. L. 1968, Atlas de Galaxias Australes (Cordoba: Observatorio Astronomico)
Smith, R. J., Lucey, J. R., & Hudson, M. J. 2009, MNRAS, 400, 1690
Taylor, E. N., Franx, M., Brinchmann, J., van der Wel, A., & van Dokkum, P. G. 2010, ApJ, 722, 1
Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 120, 165
van de Voort, F., Schaye, J., Booth, C. M., Haas, M. R., & Dalla Vecchia, C. 2011, MNRAS, 414, 2458
van Dokkum, P. G., Brammer, G., Fumagalli, M., et al. 2011, ApJ, 743, L15
Wake, D. A., Franx, M., & van Dokkum, P. G. 2012, ApJ, submitted (arXiv:1201.1913)
Wuyts, S., Förster Schreiber, N. M., van der Wel, A., et al. 2011, ApJ, 742, 96