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Inclination-Dependent Extinction Effects in Disk Galaxies in the Sloan Digital Sky Survey

A Senior Honors Thesis

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ABSTRACT

Using the Sloan Digital Sky Survey (SDSS) Data Release 6 (DR6), I study the effects of inclination on the observed color and luminosity of disk galaxies. As disk inclination increases, the galaxy’s light must pass through more dust, which tends to scatter blue light, more so than red. Hence, dust present within galaxies can redden the observed color and cause an overall decrease in the galaxy’s observed luminosity. Assuming the observed disk galaxies are circular, as the galaxy’s inclination increases, their observed shape becomes more eccentric. Hence, I am able to use the ratio of the galaxy’s observed axes (q) as a substitute for inclination. I therefore segregate the spiral galaxies into edge on ($q \approx 0$) and face on ($q \approx 1$) groups. Because the light coming from an edge-on disk galaxy passes through more dust, these galaxies tend to be much redder and dimmer on average when compared to the face-on sample. Edge-on disk galaxies also tend to have a much broader spread in their overall color distribution, due to differing types and amount of dust present in each galaxy. These two observations can be corrected by utilizing the face-on sample. In the face-on disks sample, the light from each galaxy passes through a minimum amount of dust, and the effects of luminosity and color extinction are also minimized. Thus, face-on galaxies act as a standard for deriving corrections in color and luminosity for galaxies with higher inclinations. Effectively, the goal is to turn an edge-on galaxy into a face-on galaxy, thus minimizing the effects of inclination dependent extinction on the entire sample of galaxies. By utilizing simple statistical tests, I find that the shifts in luminosity tend to correlate $\propto (1 - q)^4$, instead of the long thought correlation $\propto \log(q)$. Utilizing these results will allow for more robust inclination independent samples for investigations using SDSS.

Subject headings: galaxies: spiral, cD — galaxies: fundamental parameters — galaxies: photometry — galaxies: statistics

1. INTRODUCTION

Galaxies are massive, gravitationally bound collections of stars, dust, and dark matter. There are two general types of bright galaxies in our universe: disklike spiral galaxies and more ellipsoidal elliptical galaxies. The stellar populations inside of spiral galaxies tend to be younger, and hence bluer, on average when compared to their elliptical counterparts (Holmberg 1958, Strateva et al. 2001). This younger stellar population has yet to expel, via stellar winds, the remnants of dust present after their birth. Thus, bright spiral galaxies can be seen with vast dust lanes present within their disk. Elliptical galaxies, on the other hand, contain very little dust. This is due to the fact that elliptical galaxies tend to be much older than the spiral galaxies, and have had time to expel the leftover dust.

The Sloan Digital Sky Survey (SDSS) is a multi-institutional, systematic survey of the night

sky. As a survey tool, SDSS makes easily available to astronomers vast amounts of observational data on galaxies. Observationally, the SDSS parameter `fracDev` can help to differentiate between disklike and elliptical galaxies. `FracDev` is a fractional parameter that measures the amount of flux contributed by fitting a galaxy image to a de Vaucouleurs surface brightness profile (de Vaucouleurs 1948). A de Vaucouleurs profile follows the relation:

$$I(R) = I_e \exp\left(-7.67[(R/R_e)^{1/4} - 1]\right) . \quad (1)$$

SDSS also fits each galaxy image to an exponential surface brightness profile, with the relation:

$$I(R) = I_e \exp(-1.68[R/R_e - 1]) . \quad (2)$$

SDSS finds the best fit linear combination for each galaxy image, and the fraction that is best fit by a de Vaucouleurs profile determines the parameter `fracDev`. `FracDev` varies from 0 for a pure exponential profile, to 1 for a pure de Vaucouleurs profile. `FracDev` is an important tool because it is found that bright elliptical galaxies tend to display de Vaucouleurs profiles, while disk galaxies follow an exponential surface brightness profile. Figures 1-5 show the color-magnitude relations for the entire sample, as well as various `fracDev` cuts adopted by Vincent & Ryden (2005), using my data set. Figure 1 shows that the galaxies tend to fall into two groups, a “blue cloud” and a characteristically brighter “red ridge.” Figures 2-5 show that as `fracDev` is increased, galaxies tend to fall closer to the “red ridge.” Thus, this “red ridge” is mostly populated by elliptical galaxies with de Vaucouleurs ($fracDev \approx 1$) brightness profiles, while the “blue cloud” is mostly dominated by disklike spiral galaxies with exponential profiles ($fracDev \approx 0$). However, the blue distribution is more extended in color than the “red ridge.” This is most likely due to varying dust effects inside of each type of exponential galaxy. This dust tends to scatter blue light within the galaxy, hence reddening the galaxy while decreasing its overall brightness. In order to study galaxies accurately, the reddening effects of dust must be taken into account. One extinction effect that must be accounted for when studying galaxies is extinction due to observed inclination angle. Observing a spiral galaxy at higher inclination angles will cause the galaxy’s light to pass through more dust, increasing the extinction effects and causing systematic biases in one’s galaxy sample if not corrected. Understanding the errors associated with dust effects has broad implications. For example, the Tully-Fisher relation (Tully & Fisher 1977) is a redshift-independent measure of distance to a galaxy; however, it is strongly dependent on accurate luminosity measurements. Giovanelli et al. (1995) found that if extinction effects due to inclination are not taken into account the Tully-Fisher relation becomes non-linear, creating a luminosity and inclination bias, thus weakening the predictive power of the Tully-Fisher relation.

Assuming the observed spirals are circular, as the galaxy’s inclination increases, their observed shape becomes more eccentric. Hence, the ratio of the galaxy’s apparent short to long axes (q) can be used as a substitute for inclination. Early studies of dust attenuation in spiral galaxies adopted a logarithmic relation between apparent axis ratio and extinction (de Vaucouleurs et al. (1991) and references therein). However, recent studies have examined this relation over a broad range of photometric bands, and are finding deviations from this simple logarithmic scaling. Shao et al. (2007)

examines dust extinction effects in the SDSS *ugriz* bands, while Masters et al. (2003) and Tully et al. (1998) explore the IJK near infrared bands. Each finds that a simple logarithmic scale does not hold for all observed axis ratios. Furthermore, recent numerical simulations (Rocha et al. 2007), find similar deviations when looking at models with realistic dust properties. This paper seeks to further the understanding of these inclination based effects for a “pure” spiral galaxy sample taken from the SDSS DR6, and to examine the overall effect of inclination on the color-magnitude relation among “blue-cloud” galaxies.

2. DATA

The Sloan Digital Sky Survey (York et al. 2000, Stoughton et al. 2002) is a survey to observe nearly 25% of the celestial sphere. SDSS images the sky in five photometric bands (*ugriz*; Fukugita, Shimasaku, & Ichikawa 1995, Smith et al. 2002). SDSS DR6 images the sky over 9500 square degrees with 7425 square degrees of spectroscopic coverage (J. Adelman-McCarthy et al. 2007). Because SDSS is a flux limited survey, I utilize a volume limited sample out to redshift $z = .06$. A volume limited survey will include only galaxies bright enough to be seen by the SDSS telescope, if they were placed at a certain redshift. Hence, a volume limited survey allows me to create a sample with no bias towards dim galaxies. Absolute magnitudes were calculated using the equation:

$$M_r = 43.17 - 5\log(z) - 1.683z. \quad (3)$$

The SDSS spectroscopic sample has a limiting apparent magnitude of 17.77 in the *r* band; thus, in order to be a part of the volume limited survey, a galaxy’s absolute magnitude must be $M_r \leq -19.4$. The SDSS DR6 pipeline separates observed objects into extended objects (galaxies) and point sources (stars). Data were selected to be those marked as galaxies within the spectroscopic survey between redshifts $.004 < z < .06$, with at least 35% confidence in redshift measurements (*zconf*). I also required $\tau > 6.25\tau_{psf}$, where τ is effecti in order to confirm that only well resolved galaxies were a part of the sample, where τ represents the observed size of the galaxy and τ_{psf} the size of the object’s corresponding point spread function. Strateva et al. (2001) determined that $u - r$ is the best color to resolve the bimodality of galaxy populations; therefore I adopt it as my measure for galaxy color. I use the “Model mag” colors for both *u* and *r* to measure color; “Model mag” is the apparent magnitude of the best fitting surface brightness model. For my galaxy sample this magnitude is very near the Petrosian magnitude in each band. Absolute magnitudes for each galaxy were calculated using the Model mag *r* band magnitude and the spectroscopic redshift using a Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and assuming a flat universe with $\Omega_{m,0} = 0.3$ and $\Omega_{\Lambda,0} = 0.7$. No K-corrections were applied to the data, because the amount of correction necessary for a galaxy with small redshifts or with bluer colors is very small (Fukugita, Shimasaku, & Ichikawa 1995). My main, volume limited, galaxy sample contains 44,229 galaxies. In order to designate a “pure” spiral galaxy, I adopt the classification of Vincent & Ryden (2005). They find that galaxies with the parameter $\text{fracDev} \leq 0.1$ on average have a flatter disklike shape corresponding to a spiral galaxy. My final “pure” spiral galaxy count, after the cut in fracDev , is 16,363. For apparent axis

ratio values, I use the ratio of the 25 mag arcsec⁻² isophotes. SDSS finds the best fit ellipse using these isophotes, and calculates the semi-major (A_{25}) and semi-minor (B_{25}) axes. Assuming that each spiral galaxy is roughly circular when viewed face-on, one can use the ratio of these axes as a measure of inclination. Therefore, I define this ratio as $q = \frac{B_{25}}{A_{25}}$, with $q \approx 0$ corresponding to an edge-on galaxy, and $q = 1$ as a face-on galaxy.

3. Analysis

Figure 6 shows the uncorrected color-magnitude relation for different cuts in apparent axis ratio in my flux limited sample. For $M_r \leq -18$, the mean $u - r$ color is clearly correlated with q ; apparently flatter galaxies are redder, on average. For fainter galaxies with $M_r \geq -18$ no such correlation is seen. Dwarf spheroidals most likely dominate at $M_r \geq -18$; therefore for all subsequent analysis I only use the galaxies with $M_r \leq -18$.

Inclination based dust effects are clearly visible in comparing figures 7 and 9. At higher deduced inclination, dust effects broaden the galaxy distribution in color space with a redder mean color, while dimming the distribution in magnitude space. The magnitude distribution of galaxies (figure 9) demonstrates this dimming more directly. The luminosity function for the low q distribution (solid pink line) is noticeably shifted to dimmer values of M_r when compared to the face on distribution (purple line). In order to correct for dust effects, I utilize two statistical tests, a χ^2 and Kolmogorov-Smirnov (KS). These tests provide a tool to determine whether two one dimensional distributions vary, in this case the magnitude distributions of face-on versus edge-on galaxies. Effectively by shifting the lower q distribution’s luminosity function and comparing this to the face-on distribution via these tests, I found the optimum shift necessary to correct for dust attenuation. Both tests yielded similar results. Figure 10 plots the best corrections from the KS test, and the best fitting equations. It is apparent from this figure that the logarithmic relation between magnitude corrections and q found in de Vaucouleurs et al. (1991) is not accurate. However, the best fit equation found for my data set is:

$$\Delta M = -1.51(1 - q)^4. \tag{4}$$

These points are also well fit by the equation

$$\Delta M = -0.70(1 - q^2)^6. \tag{5}$$

It should be noted from figure 10 that, in general, the best shift in M_r is actually no shift for galaxies with $q \geq 0.5$. Using the $\Delta M = -1.51(1 - q)^4$ equation to apply corrections to M_r corrections into account, figure 11 shows a fairly linear relationship between color and corrected magnitude. The slopes and intercepts for the linear fits are shown in Table 1. In order to correct for $u - r$ color, I use the distance between these best fit lines, at a respective q value, as the optimum correction to color. Figure 12 shows the fully corrected color magnitude diagram for the highest inclination galaxies in my sample. After correcting for absolute magnitude and color extinctions, the overall

distribution is shifted to brighter values, and the overall spread in color is greatly diminished for galaxies above $M_r < -19.4$. However, as figure 13 shows, lower values of q generally correspond to a higher standard deviation at most corrected absolute magnitudes. With higher standard deviations, my first order corrections to color are not especially accurate for every galaxy at a given q . When compared to the face on galaxy color-magnitude distribution, the color corrections are actually quite good, overall.

4. Conclusion

As shown in figure 10, corrections to absolute magnitude do not follow a logarithmic relation (de Vaucouleurs et al. 1991) with q . Other studies (Masters et al. (2003) and Tully et al. (1998)) as well as numerical simulations (Rocha et al. 2007), provide evidence to support this. Zhengyi Shao et al. (2006) found corrections to inclination based dust extinction using SDSS pass bands, however this data included galaxies up to $FracDev \leq 0.5$. According to Vincent & Ryden (2005), a data set containing galaxies above $FracDev = 0.1$ can be polluted by elliptical galaxies. My sample contains only $FracDev \leq 0.1$, and is still statistically robust ($N \sim 16,000$).

Using this data and applying χ^2 and Kolmogorov-Smirnov tests, I determined the best absolute magnitude shift in the SDSS r band necessary to correct for dust extinction resulting from observed inclination. After correcting for absolute magnitude effects, I determined the best correction to $u-r$ color. However, because the standard deviation in the color distribution is larger for low values of q , the corrections for these galaxies contain more error on average.

These corrections can be applied to a multitude of astronomical problems using SDSS. By having first order corrections to absolute magnitude and color, large statistical undertakings using SDSS data are not limited to using merely face-on galaxies. By applying these corrections, data sets can increase, and error bars shrink.

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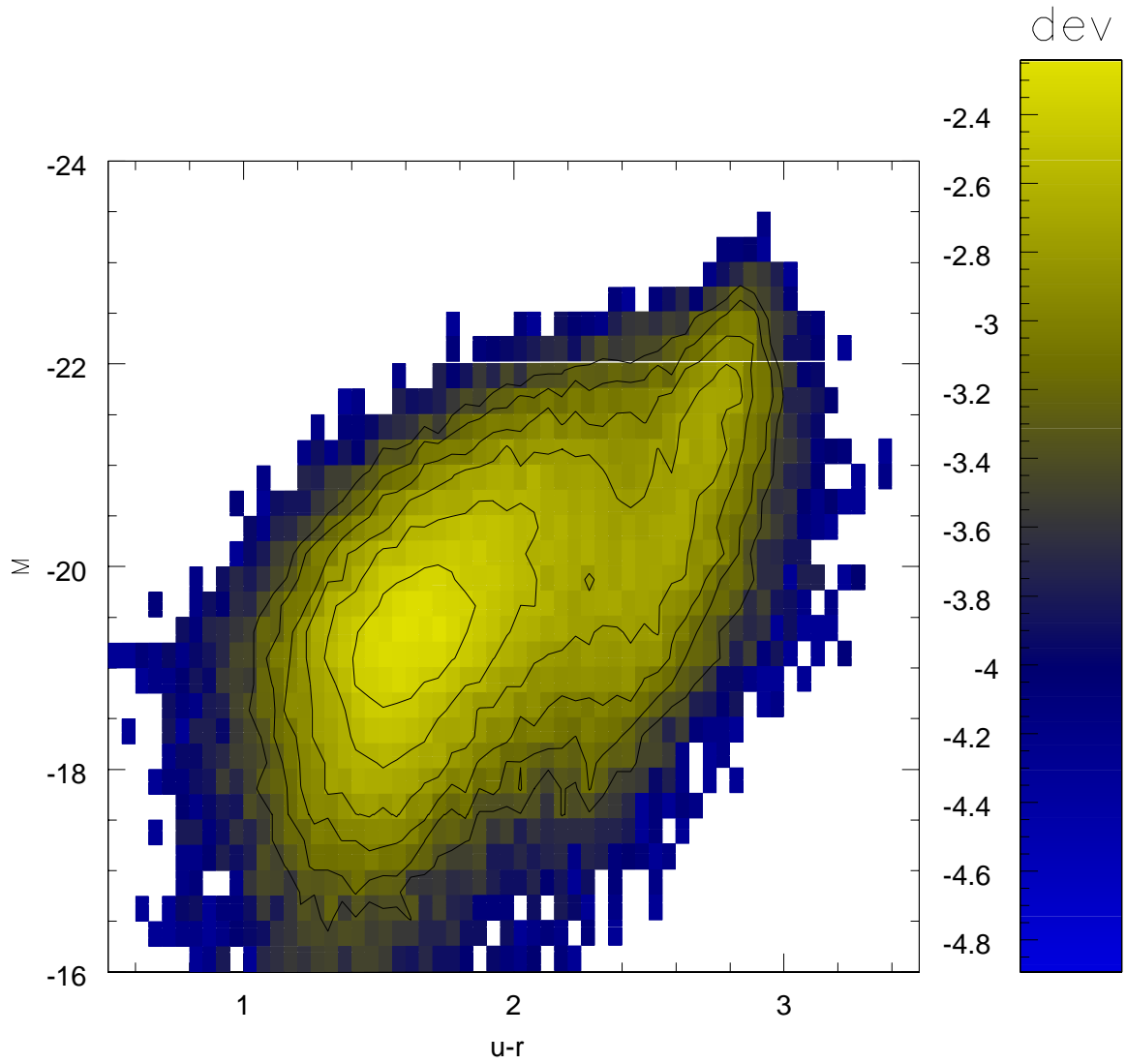


Fig. 1.— Normalized distribution of all galaxies within volume limited sample. Color represents $\text{Log}(N)$, with yellow values corresponding to greater number of galaxies in each bin. Bin sizes are .25 for M_r and .05 for $u - r$.

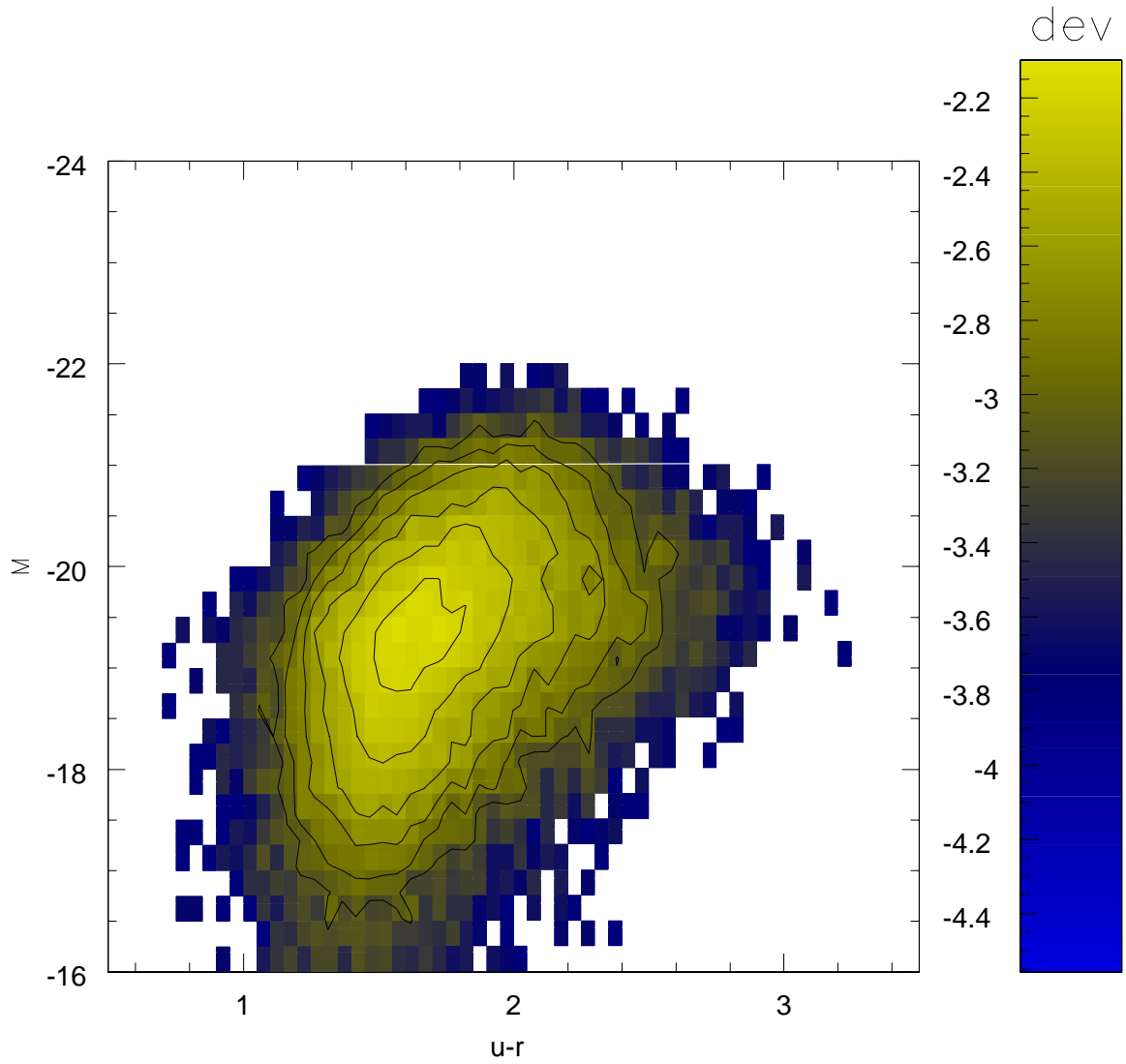


Fig. 2.— Normalized distribution of all galaxies within volume limited sample and $fracDev \leq 0.1$. Color represents $Log(N)$, with yellow values corresponding to greater number of galaxies in each bin. Bin sizes are .25 for M_r and .05 for $u - r$.

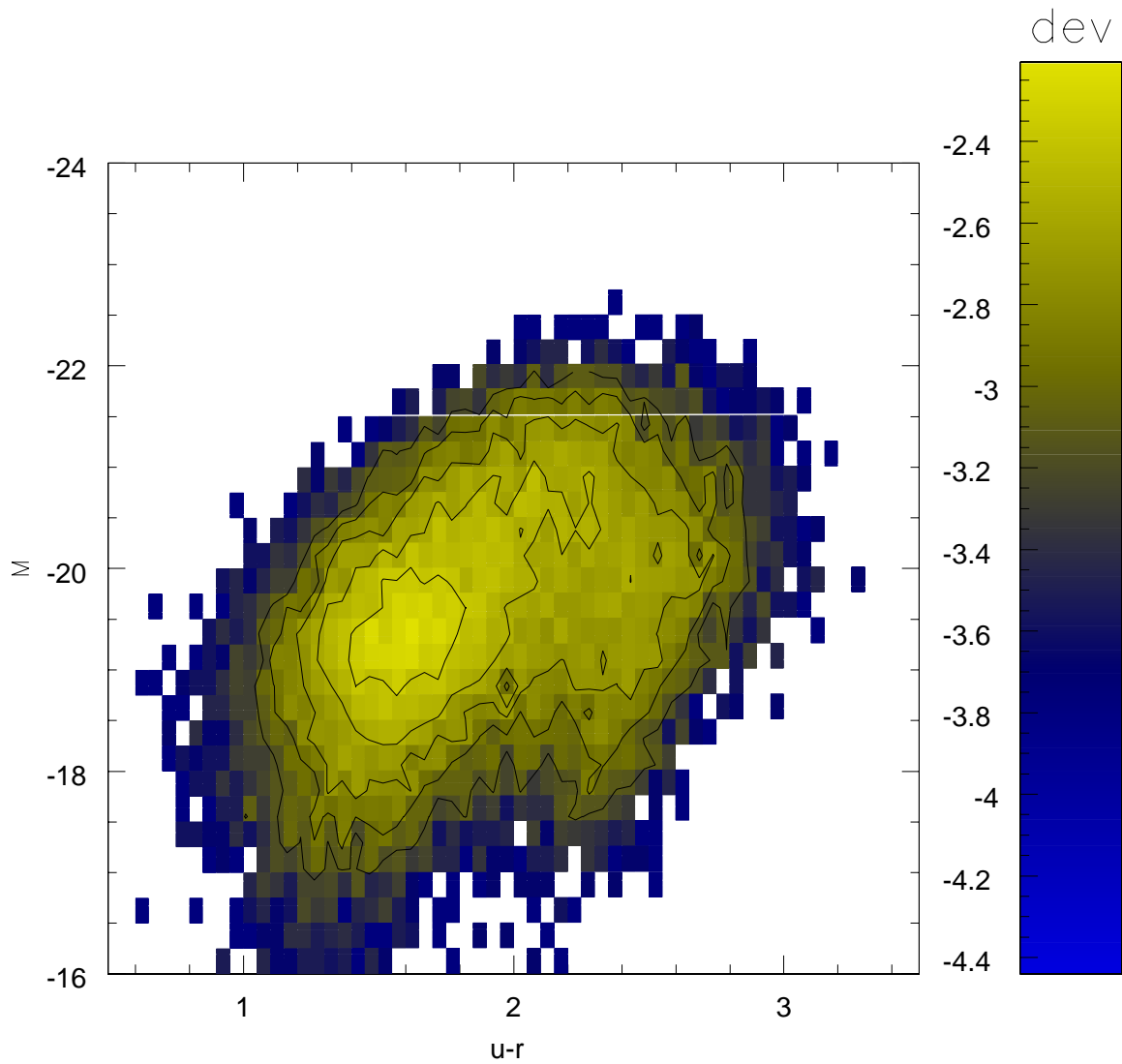


Fig. 3.— Normalized distribution within volume limited sample and $0.1 < fracDev \leq 0.5$. Color represents $Log(N)$, with yellow values corresponding to greater number of galaxies in each bin. Bin sizes are .25 for M_r and .05 for $u - r$.

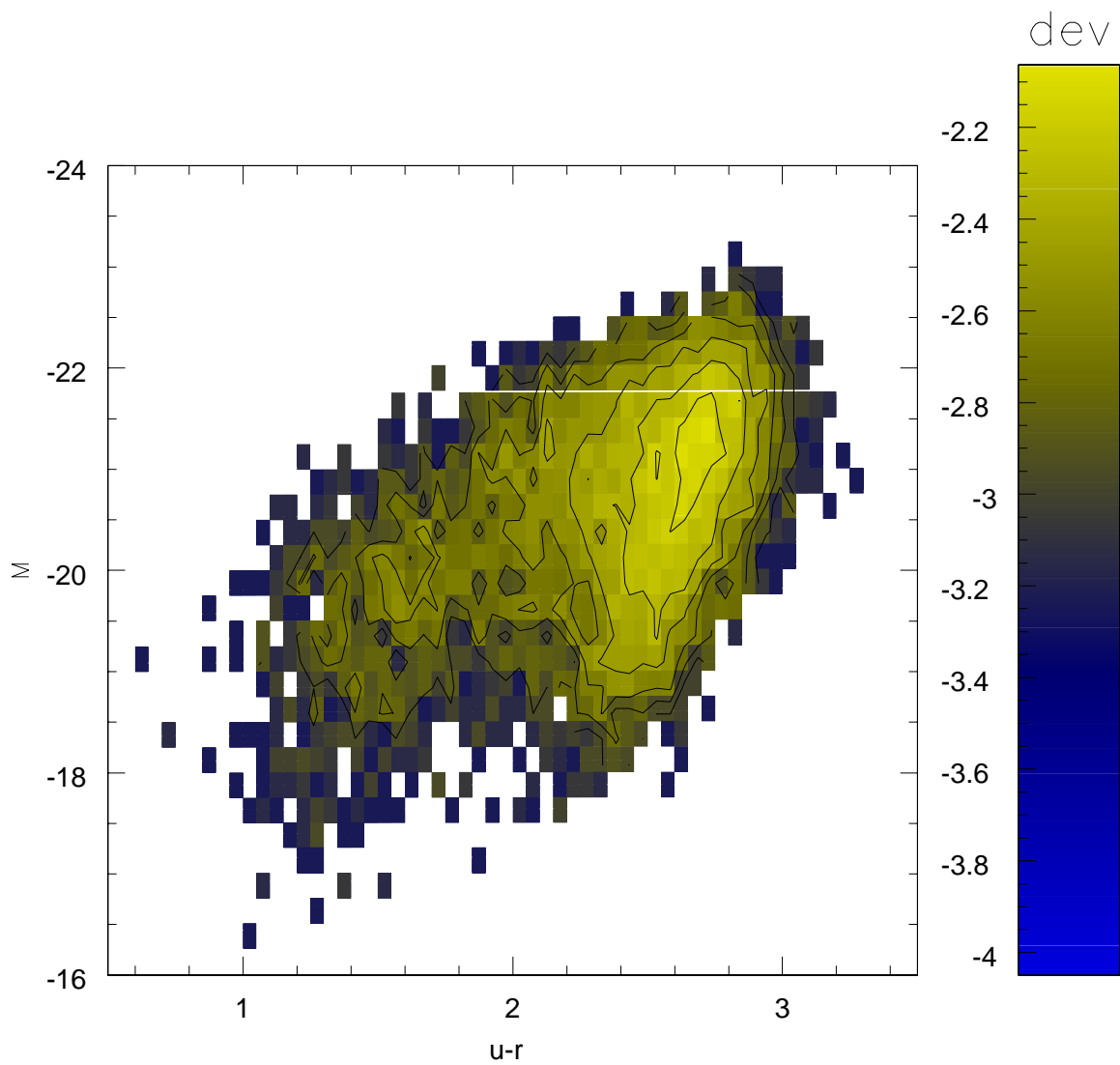


Fig. 4.— Normalized distribution within volume limited sample and $0.5 < fracDev \leq 0.9$. Color represents $Log(N)$, with yellow values corresponding to greater number of galaxies in each bin. Bin sizes are .25 for M_r and .05 for $u - r$.

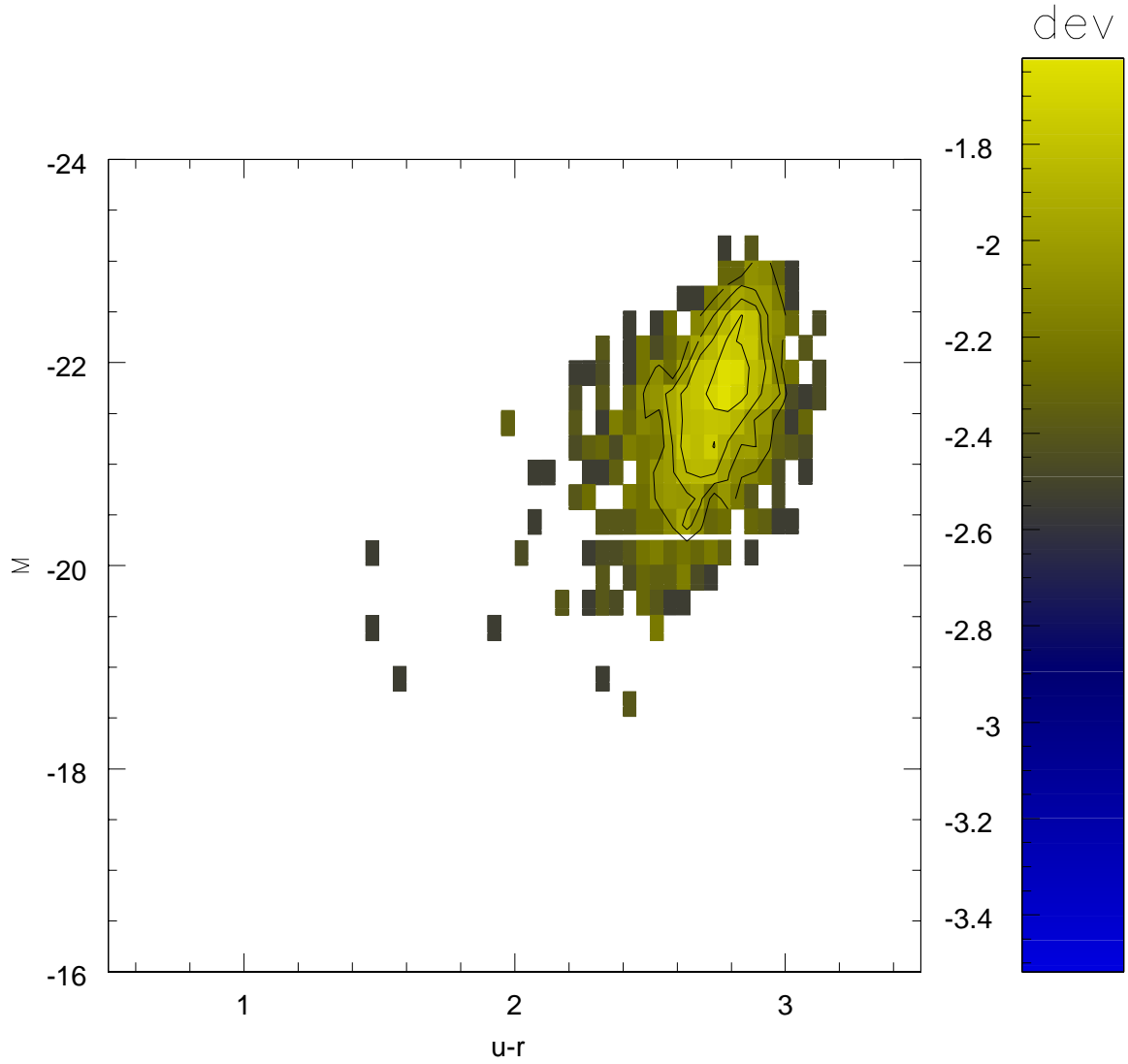


Fig. 5.— Normalized distribution within volume limited sample and $fracDev \geq 0.9$. Color represents $Log(N)$, with yellow values corresponding to greater number of galaxies in each bin. Bin sizes are .25 for M_r and .05 for $u - r$.

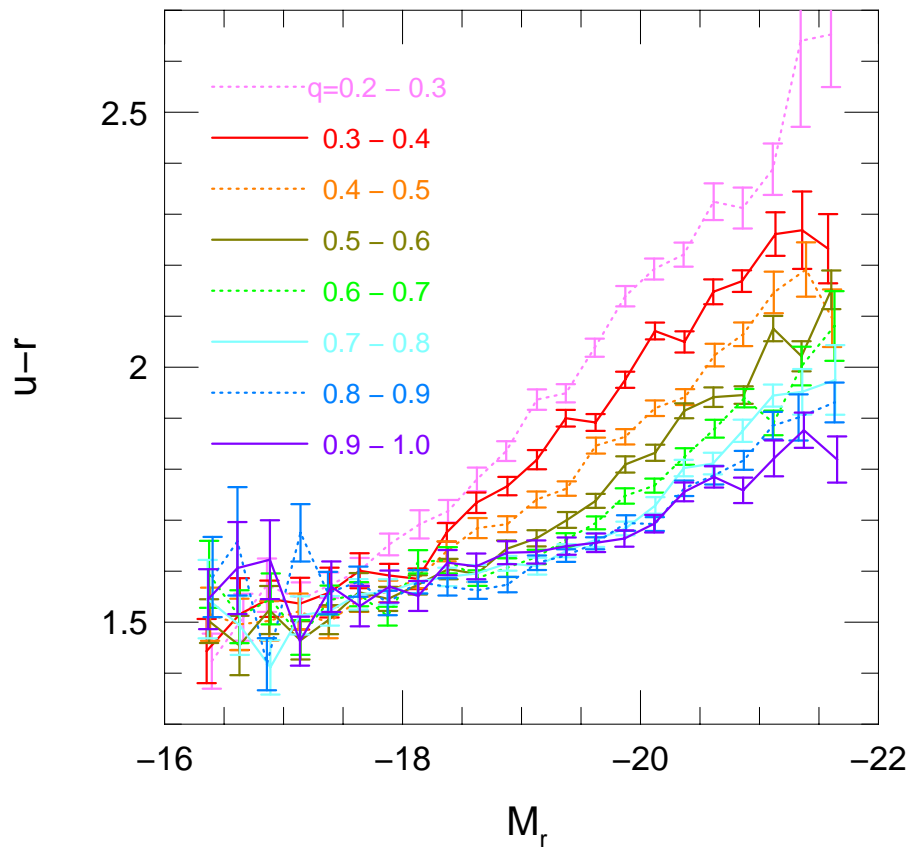


Fig. 6.— Average color versus M_r for my flux limited sample of galaxies. At $M_r \geq -18$, I believe dwarf spheroidals begin to pollute the sample. Error bars represent the estimated error in the mean

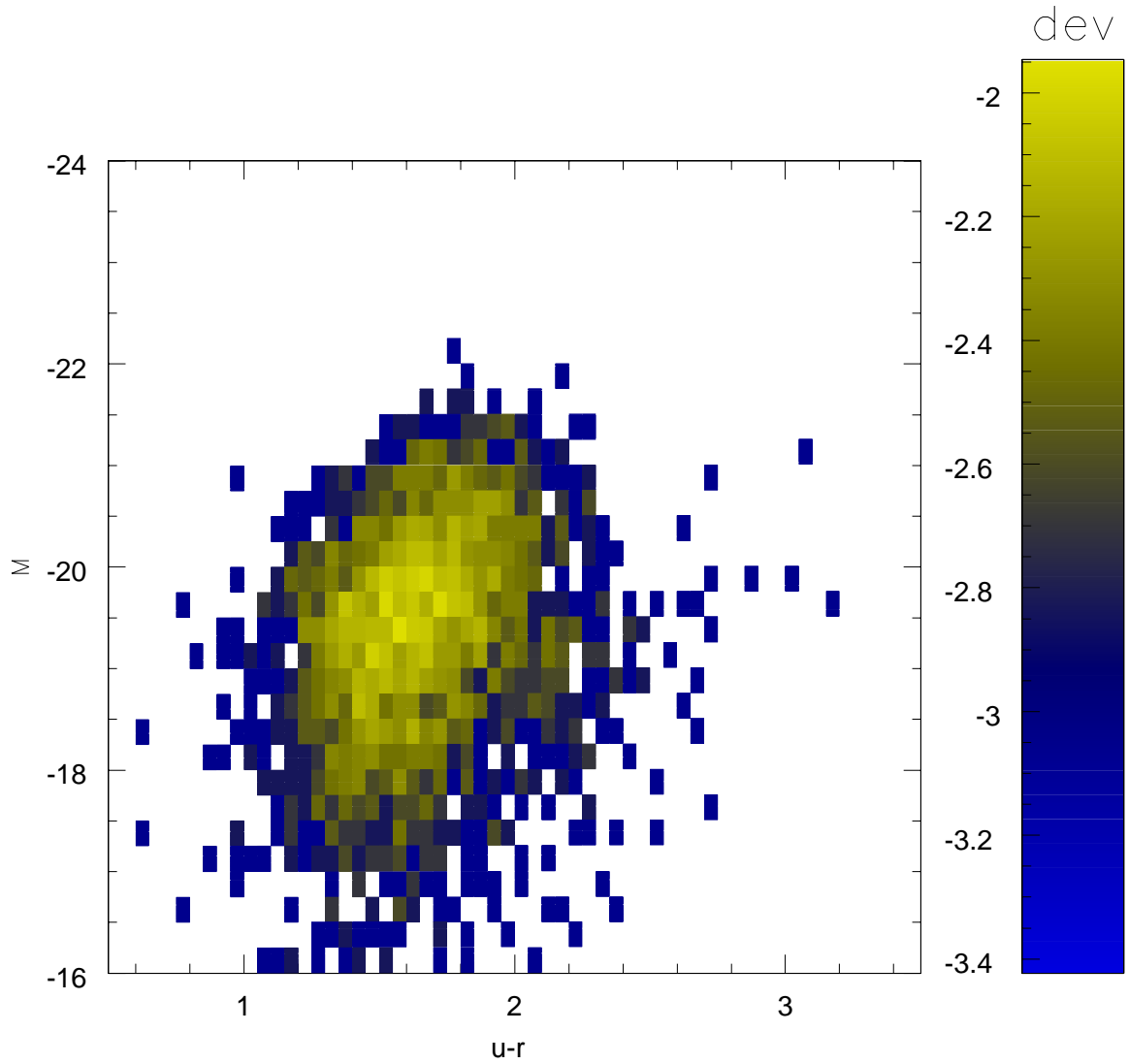


Fig. 7.— Normalized distribution of all “face-on” galaxies within volume limited sample and $fracDev \leq 0.1$. Color represents $Log(N)$, with yellow values corresponding to greater number of galaxies in each bin. Bin sizes are .25 for M_r and .05 for $u - r$.

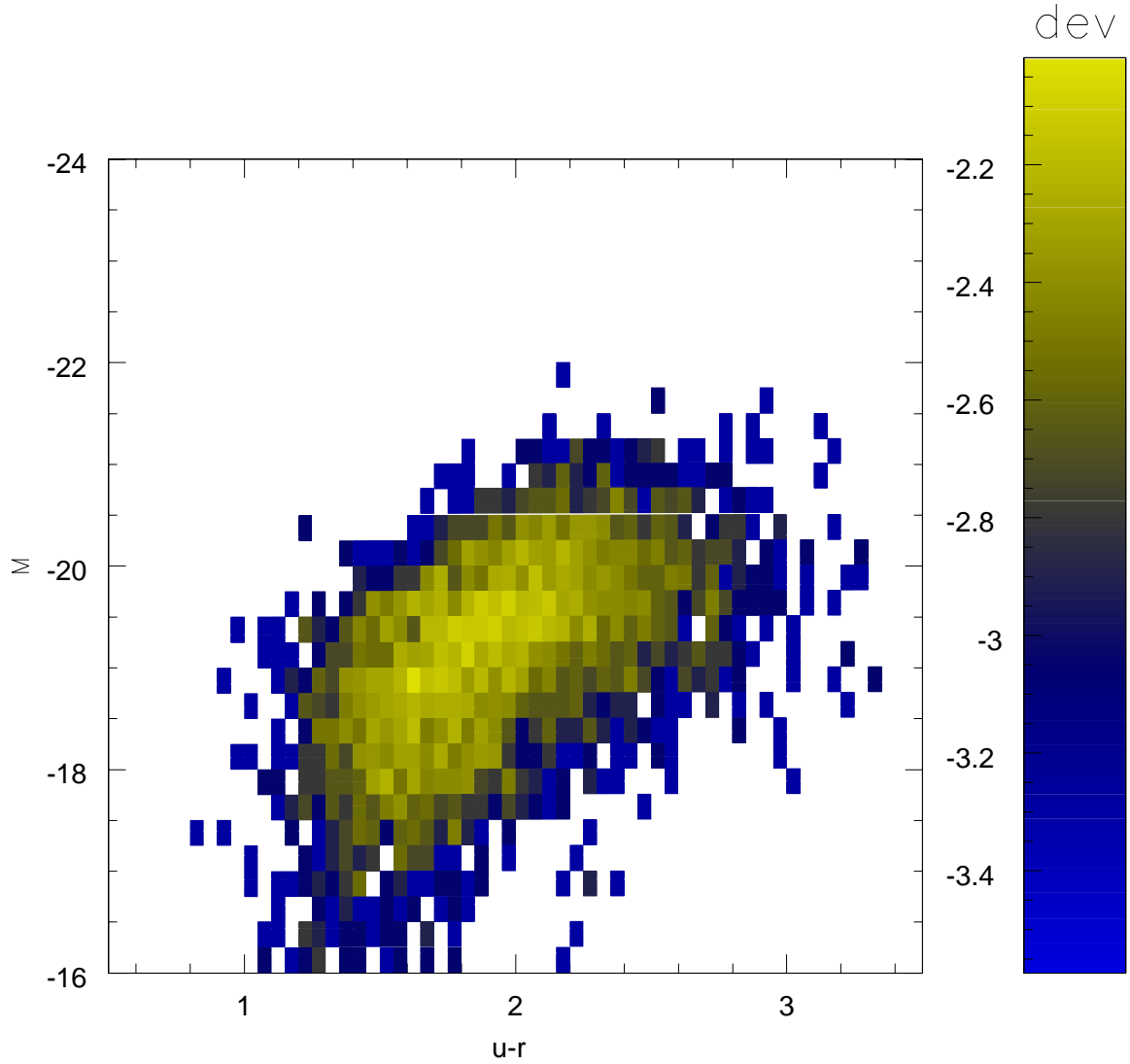


Fig. 8.— Normalized distribution of all “edge-on” galaxies within volume limited sample and $fracDev \leq 0.1$. Color represents $Log(N)$, with yellow values corresponding to greater number of galaxies in each bin. Bin sizes are .25 for M_r and .05 for $u - r$.

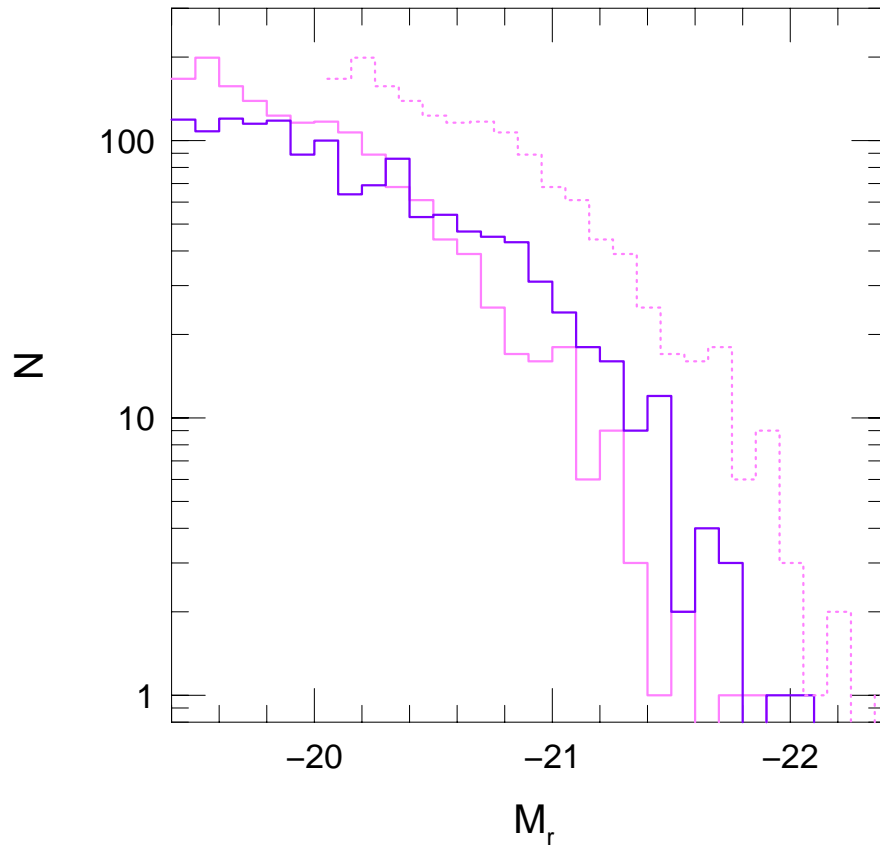


Fig. 9.— Luminosity functions for both face-on, $q \geq 0.9$ (purple curve) and edge-on, $0.2 < q \leq 0.3$ (solid pink curve). The dotted pink curve, represents the edge-on distribution when the best M_r shift is applied. Note that there is no up or down shift of any kind.

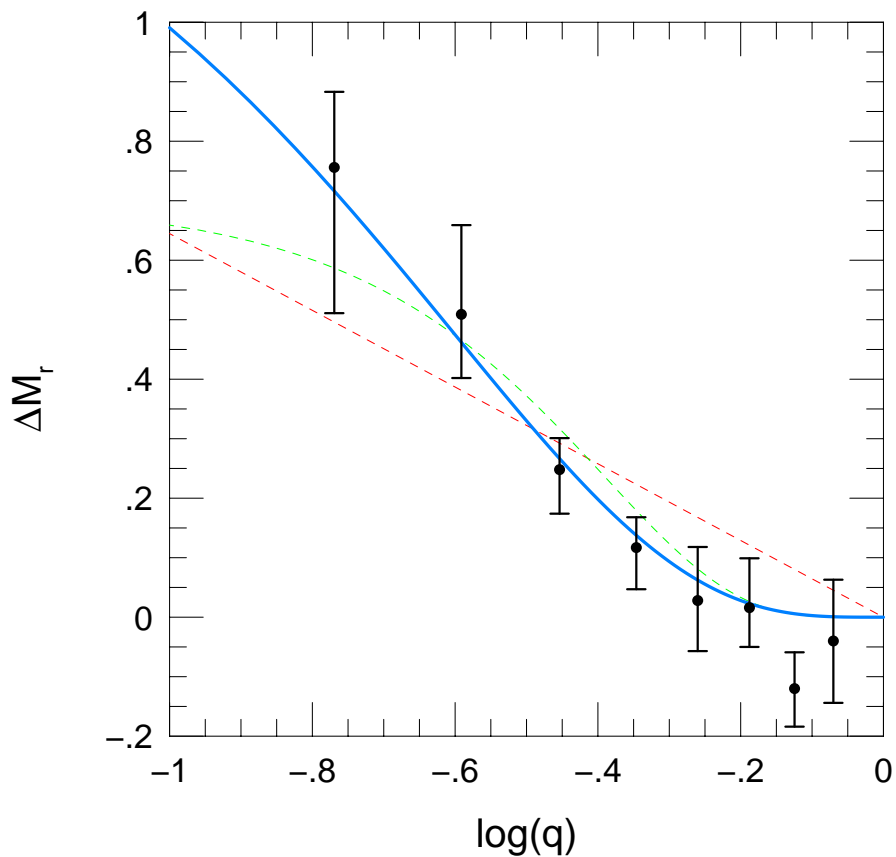


Fig. 10.— Shift in M_r as a function of apparent axis ratio (q). The red curve represent the standard $\log(q)$ correction from de Vaucouleurs et al. (1991). The blue curve corresponds to $\Delta M = -1.51(1-q)^4$, and green to $\Delta M = -0.70(1-q^2)^6$. Error bars represent when the probability from the KS test $P_{ks} > 0.1$

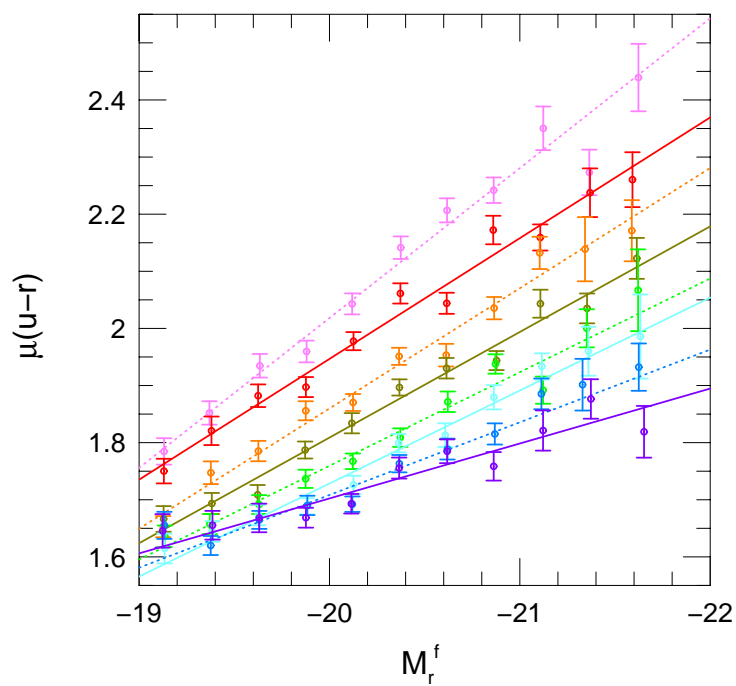


Fig. 11.— Average color vs. corrected M_r for flux limited sample. Error bars represent estimated error in the mean.

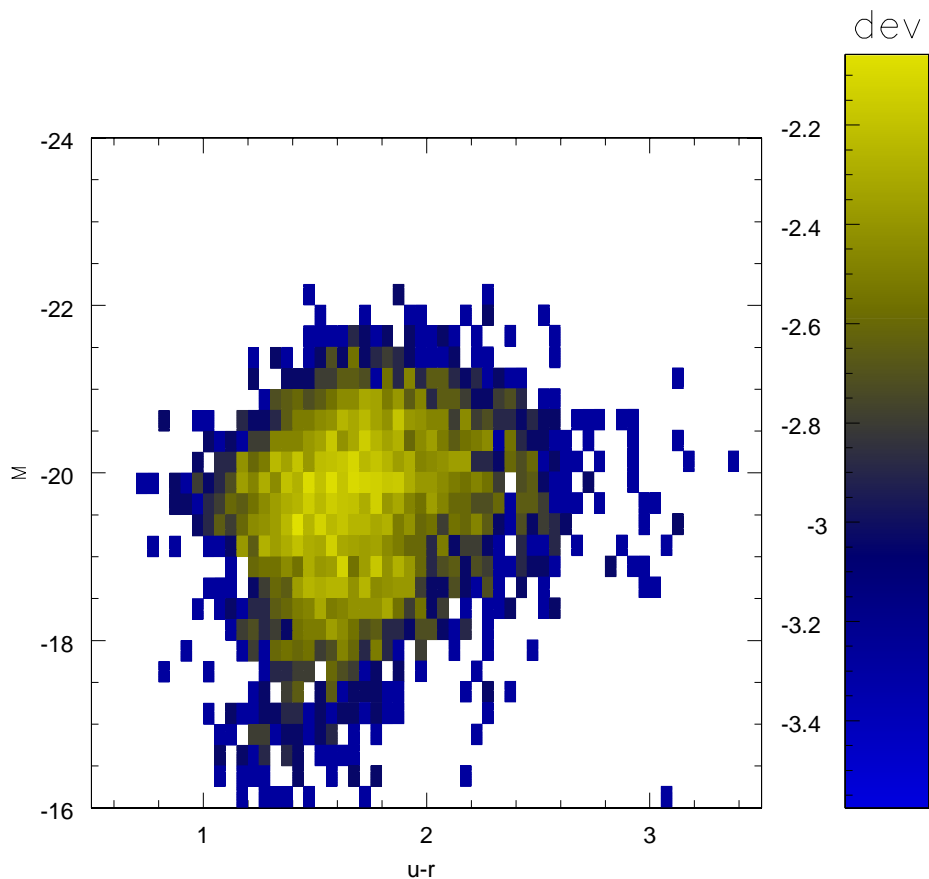


Fig. 12.— Normalized distribution of all edge-on ($0.2 < q \leq 0.3$) galaxies within flux limited sample and $fracDev \leq 0.1$, however both color and M_r corrections are taken into account. Color represents $Log(N)$, with yellow values corresponding to greater number of galaxies in each bin. Bin sizes are .25 for M_r and .05 for $u - r$.

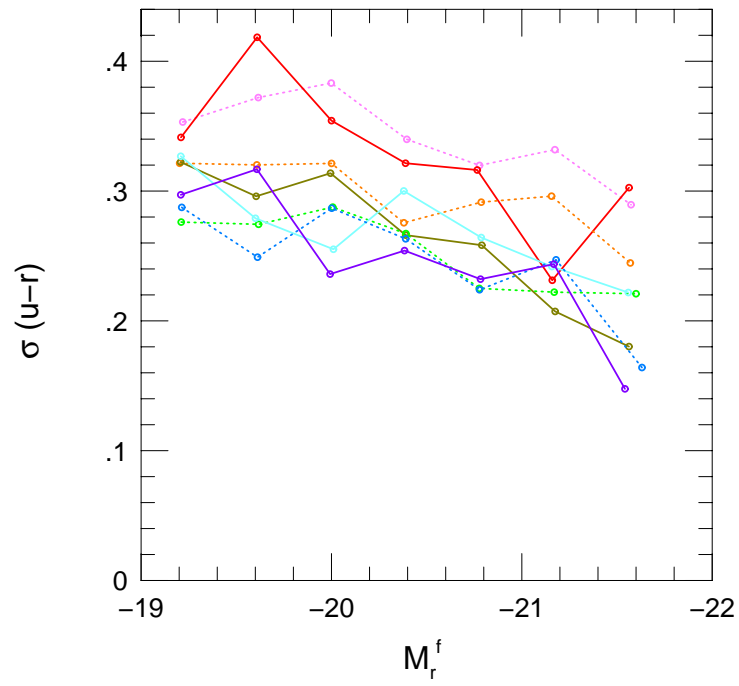


Fig. 13.— Standard deviation in color vs. corrected M_r . Color scheme is same as figure 6.

Table 1. Linear color fit parameters with form: $\langle u - r \rangle = a + b(M_r + 20.5)$

q	a	b
0.2 – 0.3	2.149	-0.262
0.3 – 0.4	2.052	-0.211
0.4 – 0.5	1.965	-0.210
0.5 – 0.6	1.901	-0.184
0.6 – 0.7	1.841	-0.164
0.7 – 0.8	1.809	-0.162
0.8 – 0.9	1.772	-0.127
0.9 – 1.0	1.750	-0.096