Structural Characteristics of Faint Galaxies Serendipitously Discovered with the HST WFPC2

Karen O'Neil[1]

Arecibo Observatory, HC03 Box53995, Arecibo, PR 00612

email:koneil@naic.edu

G.D. Bothun

Dept. of Physics, University of Oregon, Eugene OR, 97403

email:nuts@bigmoo.uoregon.edu

and

C. D. Impey

Steward Observatory, University of Arizona, Tucson AZ, 85721

email:impey@as.arizona.edu

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[1]work done while at the University of Oregon

ABSTRACT

Utilizing the F814W and F300W filters, Hubble Space Telescope Wide Field Planetary Camera-2 (WFPC2) images were taken of four low surface brightness galaxies in the direction of the Virgo cluster – V7L3, V2L8, V1L4, and Malin 1. The high resolution of the WFPC2 combined with the extremely diffuse nature of the four galaxies makes them essentially transparent, allowing for the serendipitous discovery of 139 background galaxies visible through both the disks and nuclei of the foreground galaxies. Surface photometry was done on the newly discovered galaxies through the F814W (I-band) filter. The detected galaxies have both $r^{1/4}$ and exponential type profiles with radii (to the μ_{F814W} = 25.0 mag arcsec^{-2} limit) less than 5.0". Their total magnitudes range from 18.9 through the survey cut-off at 25.0 in the F814W filter. The median central surface brightness of those galaxies with exponential profiles is approximately one magnitude brighter than the background F814W "sky". Thus, with this dataset we recover Freeman's law and hence know that we do not have a representative sample of distant galaxies (and neither does anyone else). When possible, the B, V, and I colors of these galaxies were determined using ground-based images, which show the galaxies to be fairly red. Coupled with their small angular size, we estimate the redshifts to be $0.5 \leq z \leq 1.5$.

Classification of the galaxies was done strictly in structural terms, based only on the form of the derived luminosity profile. No morphological considerations were made during the classification process. 23% of the galaxies we detected have the $r^{1/4}$ profile typical of early type galaxies, matching most previous studies of both the Hubble Deep Field and the Medium Deep Survey which typically find 15% − 40% E/S0 galaxies. In addition, we have attempted to perform bulge/disk deconvolutions. While we find that most of the sample cannot be easily deconvolved into a classic bulge+disk, 7 objects could be fit in this way. For these 7 objects we find a) a large range in bulge-to-total luminosity and b) some disks which have a large bulge-to-disk ratio. We also present one object, 283-10, which is an excellent example of the structural ambiguity that exists in the luminosity profiles of distant galaxies.

In agreement with other studies we also found a significant percentage of galaxies which have disturbed luminosity profiles indicative of probable galaxy-galaxy interactions or mergers. Indirect indicators suggest that the volume over which $r^{1/4}$ objects are selected is significantly larger than the volume over which disk galaxies are selected. This implies a relatively low space density of $r^{1/4}$ at all redshifts out to $z \sim 2.5$ and is consistent with the general idea that $r^{1/4}$ galaxies are largely confined to galaxy clusters.

Subject headings: galaxies: elliptical and lenticular,cD — galaxies: evolution — galaxies: irregular — galaxies: photometry — galaxies: spiral — galaxies: surveys

1. Introduction

With the advent of deep ground based imaging, significant datasets are being compiled that can address the issue of galaxy evolution. While a representative sample of galaxies at any redshift has not yet been obtained, there are by now several hundred galaxies with redshifts available in distant galaxy surveys (e.g. Ellis *et.al.* 1996; Lilly *et.al.* 1995; Cowie *et.al.* 1996; Steidel *et.al.* 1996; Cohen *et.al.* 1996; Morris *et.al.* 1998). These datasets include both galaxies in clusters as well as the general "field". Individual investigations of these data sets are centered around three primary themes: 1) studying the morphological mix of galaxies (e.g. ellipticals versus spirals) as a function of redshift (see Marleau & Simard 1998; Abraham *et.al.* 1996); 2) studying the luminosity function of "blue" vs "red" galaxies over various redshift ranges (e.g. Lilly *et.al.* 1995; Hammer *et.al.* 1997); 3) studying the evolution in the star formation rate as a function of redshift (e.g. Madau *et.al.* 1997; Meurer *et.al.* 1997; Steidel *et.al.* 1999).

In general, there is a fairly wide range of opinion on these matters which reflects various levels of bias and incompleteness in the available spectroscopic and photometric samples. This is to be expected as we are now just in the beginning phases of data acquisition for distant galaxies and, after all, it took at least 50 years to recognize that our surveys of nearby galaxies are strongly biased towards selecting mostly high surface brightness objects (see Impey & Bothun 1997 and references therein). The level of surface brightness and spectroscopic bias in the selection of distant galaxies is likely to be very complex and difficult to sort out (see Hogg *et.al.* 1999). This, coupled with the difficulty of morphological classification of objects only 1-2 arcseconds in diameter may be responsible for the current divergence of opinion on the evolutionary rate of early type galaxies and their possible dependence on environment. (see for instance, Barger *et.al.* 1998; Balogh *et.al.* 1999, von Dokkum *et.al.* 1998; Silva & Bothun 1998; Schade *et.al.* 1999). As pointed out succinctly by Andreon (1998), much of this disagreement may simply be a reflection of morphological classification errors that cause confusion or ambiguity in the E/SO classification. Such confusion can easily arise as the disk component of an SO galaxy is of lower surface brightness and may be difficult to visually detect at small angular diameters. At the very least, it seems that the current results obtained by different investigators are highly sample dependent and hence may not have general applicability to galaxy evolution.

In this paper we try a different approach in characterizing the properties of small, faint galaxies that are seen in the background of deep WFPC2 images obtained with HST. Our approach, while considerably more time consuming, relies entirely on the surface profiles of identified galaxies for classification. Unlike other investigations, which rely in some measure on eyeball morphology (i.e. Driver, *et.al.* 1995a, 1995b; Abraham, *et.al.* 1996) no morphological considerations, based on visual image inspection, are ever made during the *classification process*. Instead, once we decide an object has a high probability of being a distant galaxy we categorize it strictly on a structural basis depending on the form of its luminosity profile. In this way, a fairly explicit distinction can be made between early type ($r^{1/4}$ profiles) and late type ($e^{-r/\alpha}$) galaxies in a way that is largely independent of angular size (the galaxy just needs to be resolved by HST) and surface brightness. Indeed this approach, in principle, does allow for the detection of galaxies with large bulge-to-disk (B/D) ratios which could, visually, be classified as pure ellipticals. Examples of such objects are found in this study. Overall, our approach is complementary to that of Simard *et.al.* (1999) who study, to some extent, the evolution in the bulge-to-total luminosity ratio. Previous groups (e.g. Marleau & Simard 1988, Ratnatunga *et.al.* 1999) have also used a similar model fitting approach. In our treatment here, however, we rely *only* on the surface brightness decomposition for galaxy classification.

Our sample of background galaxies is a result of an interesting consequence associated with observing foreground low surface brightness (LSB) galaxies located in the Virgo cluster with the high angular resolution of the HST WFPC2. Basically, at 0.1 arcsecs per pixel, the HST WFPC2 doesn't really detect a LSB galaxy but rather only records an elevated pattern of noise (see O'Neil *et.al.* 1999 for the explicit demonstration of this). As a result, the LSB is quite transparent (O'Neil *et.al.* 1998) and background galaxies are readily detected, even when the LSB takes up much of the WFPC2 frame. Although our sample is small, consisting of 139 identified galaxies in the fields of 4 deep WFPC2 images, we are able to extract a variety of useful structural information. Our fields are shown in Figure 1 where it should be immediately obvious that its difficult to discern the foreground LSB object, which in this case is typically an arcminute in diameter. These WFPC2 fields have been previously imaged using the Las Campanas 2.5m Dupont telescope (Impey, Bothun, & Malin 1988; IBM hereafter) so when identified on the WFPC2 images, we have some color information for a subset of the galaxies.

In this paper we outline and apply our structural classification scheme for analyzing distant galaxies. Section 2 of this paper describes the basic procedure of data reduction and identification of galaxies in the WFPC2 data. Section 3 presents the data and section 4 discusses the properties of the galaxies we can infer. Section 5 contains a brief comparison of our results to other analysis of similar kinds of data. In an appendix we discuss the peculiarities that are associated with some of the more unusual individual galaxies we have detected.

2. Data Reduction

2.1. Observations and Instrumentation

All the data for this survey was taken using the HST WFPC2 on 1 May 1996, 3 August 1996, and 3 October 1996. Each field was centered around a known LSB galaxy in the direction of the Virgo cluster and imaged through both the F814W (814) and the F300W (300) filters. The center of each LSB galaxy is located in the WF3 field. Figure 1 shows the full (mosaicked) images through the 814 filter, while the fields imaged are listed in Table 1 – the foreground galaxy name is given in column 1 while the coordinates of the center of the field are given in column 2 and the observing dates are in column 3. Each galaxy was imaged for a total of 2200 seconds (two 600s and two 500s images) through each filter.

The WFPC2 consists of three Wide Field cameras and one Planetary camera. The Wide Field cameras have a focal ratio of f/12.9 and a field of view of 80" x 80" with each pixel sub-tending 0.0996 arcsec^2. The three cameras form an L-shape, with the Planetary camera completing the square. The Planetary camera has a focal ratio of f/28.3, 0.0455 arcsec^2/pixel, and an overall field of view of 36 arcsec^2. All four cameras have an 800 x 800 pixel silicon CCD with a thermo-electric cooler to suppress dark current. The WFPC2 has two readouts formats – single pixel resolution (FULL mode) and 2x2 pixel binning (AREA mode).

Images were taken of each field through both the 814 and the 300 filter. The 814 filter is a broadband filter with $\lambda_0 = 7924$ Å and $\Delta\lambda_{1/2} = 1497$ Å. It is designed to be similar to the Cousins I-band filter. The 300 filter has $\lambda_0 = 2941$ Å and $\Delta\lambda_{1/2} = 757$ Å, and is designed to be similar to the Johnson U-band filter. Images were for either 500s or 600s. The 814 images were all taken in FULL mode, while the 300 images were all taken in AREA mode. As the noise level through the 814 images was considerably lower then through the 300 images, and most galaxies tended to be much brighter through the 814, all galaxy identification was done with the 814 images. If a galaxy region could then be identified in the 300 image it was analyzed in both colors. Otherwise all information on the galaxy is from the 814 image.

The data reduction process, and calibration was performed at STScI using the standard WFPC2-specific calibration algorithms (the pipeline). See the HST/WFPC2 Instrument Handbook for more information about the calibration fields and procedures.

Four images were taken of each field, through each filter. After the images were reduced, they were inspected for obvious flaws such as filter ghosts or reflections. If any flaws existed in the frame an alternate frame was used and the offending frame was tossed. Each frame was then shifted, registered and combined, using the STSDAS CRREJ ($\sigma = 10$, 8, & 6) procedure to eliminate cosmic rays and other small scale flaws. The resultant images were then checked by eye to insure any registration errors were under 0.5 pixel.

As few stars existed in the images, a stellar point spread function (PSF) was determined for each image using the Tiny Tim software (Krist 1996; Remy, *et.al.* 1997) with multiple wavelengths (based on a F-type main sequence star), a base PSF of 3.0" (1.5" for the PC images), no sub-sampling, and no jitter correction. The IRAF MEM routine was then used to deconvolve the stellar PSF from the images, running it separately on each image and each chip. As the PSF appeared to primarily affect only the inner 0.20" of each galaxy (0.10" on the PC chips), any galaxy which did not lie above the 25.0 814 mag arcsec^{-2} survey limit through a radii of at least 0.5" (.25" for the PC galaxies) was eliminated from our galaxy list, as such galaxies are not well resolved.

2.2. Data Analysis

The zeropoints for each field were taken from the PHOTFLAM value given in the image headers. The zeropoint, in the STMAG system (the space telescope system based on a spectrum with constant flux per unit wavelength set to approximate the Johnson system at V), is then

$$\mathrm{ZP_{STMAG}} = -2.5\log(\mathrm{PHOTFLAM}) - 21.1.$$

For the 814 filter, the PHOTFLAM was 2.5451 x 10^{-18}, corresponding to a zeropoint of 22.886, and for the 300 filter PHOTFLAM was 6.0240 x 10^{-17}, with a zeropoint of 19.450. Due to filter variances, conversion to the Johnson/Cousins U and I band was done using the conversion given in O'Neil, *et.al.* (1998) of $814 - \mathrm{I} = 1.43 \pm 0.05$, $300 - \mathrm{U} = 0.04 \pm 0.05$. See Appendix A of O'Neil, *et.al.* for more information on the magnitude systems and conversion between the systems.

The peak intensity for each galaxy was found and ellipses were fit around that point to obtain the intensity in each annulus using the IRAF ELLIPSE routine. In the cases where no obvious peak intensity existed in the galaxy (the more amorphous background galaxies) the physical center of the galaxy, estimated by centroiding with respect to outer isophotes, was chosen. In the cases of interacting (or overlayed) galaxies, the competing galaxy was masked when possible, allowing for a surface brightness profile to be obtained. On rare occasions, although two galaxies appear to be merging, the merger appears close enough to being complete that the galaxies were treated as one and a surface brightness profile was fit to the entire object, with the center having been chosen by the galaxies' peak intensity.

The average, sky-subtracted intensity within each (annular) ellipse was found and calibrated with the photometric zeropoint. The seeing (based on the stellar PSF) gives a radius of 0.1" for the Planetary camera (galaxies starting with 731, 281, m1, and 141), and 0.2" for the Wide Field camera (all other galaxies), typical of WFPC2 data, inside of which the surface brightness profiles cannot be trusted. Surface brightness profiles were then plotted against the major axis (in arcsec). Two different functions were then fit against the deconvolved profiles – an exponential profile and a $r^{1/4}$-type profile. The exponential profile is of the form

$$\Sigma(\mathrm{r}) = \Sigma_0 \, e^{\frac{-r}{\alpha}} \qquad (1)$$

where Σ_0 is the central surface brightness of the disk in linear units ($M_\odot$ /pc^2), and α is the exponential scale length in arcsec. This can also be written (the form used for data analysis) as

$$\mu(\mathrm{r}) = \mu(0) + (\frac{1.086}{\alpha})\mathrm{r} \qquad (2)$$

where $\mu(0)$ is the central surface brightness in mag arcsec^{-2}. The $r^{1/4}$-type profile is

$$\Sigma(\mathrm{r}) = \Sigma_0 \, e^{(\frac{r}{R_e})^{1/4}} \qquad (3)$$

where Σ_0 again is the central surface brightness of the disk in linear units and R_e is the exponential scale length in arcsec. In mag arcsec^{-2}, this equation reads

$$\mu(\mathrm{r}) = \mu_e + 3.33\left[\left(\frac{\mathrm{r}}{\mathrm{R_e}}\right)^{1/4} - 1\right] \qquad (4)$$

where μ_e is the effective surface brightness in mag arcsec^{-2} and R_e is the effective (1/2 light) radius in arcsec. Profiles were fit to the data only between r = 0.2" (0.1" for the PC data) and r_{25}, with the best fit profile being determined by the data's χ^2-fit to the profiles.

Isophotal, rather than aperture, annuli were fit to the galaxies for a number of reasons. First, many of the galaxies in this study are not face on. As such, aperture magnitudes do not accurately describe the light intensity of the galaxy. Second, most of the galaxies do not lie in isolation in empty fields, but are in fact background objects behind foreground galaxies. As such, it is not uncommon to have a star, galaxy feature, or even another galaxy within close proximity of the studied object. Since isophotal annuli follow the shape of the galaxy, accurate information can be obtained to fairly high radii (major axis), while aperture annuli will encompass the unwanted region more quickly. If it were possible to make a perfect mask of the unwanted region, this would not matter. But since is is extremely difficult to completely mask out all pixels affected by, say, a star, aperture magnitudes often have to be restricted to small radii to avoid contamination from nearby objects. The results of the above two affects are this – for an inclined object, the isophotal and aperture magnitudes are different at small radii and converge to the same value at high radii, while galaxies with nearby stars, CCD flaws, etc. may never converge, as the large aperture annuli may me contaminated.

To offer a comparison between the two magnitudes (isophotal and aperture), Table 2 provides the aperture magnitudes (in the F814W band) and total isophotal magnitudes for all the galaxies in this study. Table 2 is laid out as follows:

Column 1: The Galaxy name.
Columns 2 – 6: Aperture magnitudes at radii of 0.5", 1.0," 2.0 ", 3.0" and 4.0".
Column 7: The total isophotal magnitudes of each galaxy.
Column 8: The radius at the 25.0 mag arcsec^{-2} isophote, which is the same radii at which the isophotal magnitudes (Column 7) were determined.

Not surprisingly, the isophotal and annular values are within 0.1 magnitude for the majority of the galaxies. Of the 31 galaxies with magnitude differences greater than 0.1 mag, 27 have inclinations greater then 60° . The remaining four either have inclinations of ∼55° and/or are extremely small (r_25=0.5"), and none have isophotal/aperture differences greater than 0.2 magnitudes. The isophotal magnitudes thus do give an accurate value for each galaxies and are therefore used throughout the rest of this paper.

Galaxy structural types were assigned to three categories based strictly on profile fit and not on any morphological criteria. These categories are:

- Class A: Pure $r^{1/4}$-type profile
- Class B: Good exponential fit with possible up or down turn in the inner regions – a subset of these galaxies will later be fit with a combine Bulge + Disk model.
- Class C: No adequate fit to the profile

This classification system is similar to that used by Driver *et.al.* (1995a, 1995b), but we emphasize that these classifications were based only on χ^2-fit to the surface brightness profiles and not on morphological inspection of the image. For some $r^{1/4}$ profiles it is actually the fit to the outer part of the profile which drives the χ^2 to its best value. The very inner part of the profile is sometimes not well fit. This is mostly a problem for the smallest galaxies where the deconvolution effects may still linger.

For the data in this survey the average sky brightness through the 814 filter was 23.0 mag arcsec^{-2}. Galaxies with a central surface brightness as faint as 25.0 mag arcsec^{-2} (15% of the sky background) were detected, and an accurate (error $\leq$ 0.25 mag arcsec^{-2}) radial surface brightness profile was typically found to 25.5 mag arcsec^{-2} (10% of the sky background).

Galaxy inclination was found by using the IRAF ELLIPSE software to determine the major and minor axis at each isophote. The inclination angle is then

$$i \ = \ \cos^{-1}\left(\frac{\mathrm{r_{minor}}}{\mathrm{r_{major}}}\right). \tag{5}$$

which we estimate to be accurate within ± 5° .

2.3. Galaxy Identification

Once it was determined that a significant number of background galaxies could be seen in the WFPC2 LSB galaxy images, an intensive search was undertaken to identify as many background galaxies as possible. The search was undertaken by enlarging each WF and PC image, within the IRAF environment, by a factor of four and scanning the images by eye for non-stellar objects. By examining both the 814 and 300 images available for each field a minimum of four times, a list was compiled of all possible non-stellar objects which had a minimum radius of 5 pixels. All objects on the list then had their appearance checked against their image in one of the uncombined frames to insure no errors had occurred during the image processing phase (e.g. image registration errors). Remaining objects were considered potential galaxies and left on the list. It should be noted that because of the high noise in the 300 frames, all galaxy identification was ultimately done in the 814 frames. Many of the galaxies could not even be found in the 300 frames even after being clearly identified in the 814 frames.

We did attempt to utilize the FOCAS software to examine each image for objects at least 4 pixels in radius and at least 2σ above the sky background. Unfortunately, though, FOCAS proved remarkably inept at identifying the majority of the background galaxies. Many of the galaxies found in the survey fields have a non-spherical, amorphous appearance. If the galaxy was bright enough FOCAS *usually* identified the object as a potential galaxy candidate. As the galaxies became fainter, though, FOCAS relied on the objects having a core with contiguous pixels brighter than the given threshold (2σ, typically) and usually missed both the fainter and the more interesting background galaxies (e.g. 284-15). Thus although our 'by eye' method of searching for galaxies is more tedious than the usual automatic scanning methods, the non-conventional appearance of these galaxies made our method more accurate in detecting all the objects to a central surface brightness of approximately 25.0 mag arcsec^{-2} (10-15% of the sky brightness), giving us a more complete list of galaxies in the studied regions than would otherwise have been possible. The difficulty FOCAS had in identifying galaxies which were either very faint or 'non-conventional' in appearance has also been shown to hold true in nearby ($z \leq 0.02$) LSB galaxy searches, for identical reasons (see O'Neil 1997; O'Neil, Bothun, & Cornell 1997a; O'Neil, *et.al.* 1997b). This has significant implications for the yield of LSB objects found by the Sloan Digital Sky Survey (SDSS) if reliance is made solely on automatic image detection software.

After the initial list of potential galaxies was compiled, all the candidates were visually inspected to determine the likelihood that they are true background galaxies and not a part of the foreground LSB galaxy or random noise. For example, discrete blobs within an LSB galaxy do not generally have exponential or $r^{1/4}$ profiles. This led to a set of visually qualitative indicators used to assess the probability that a faint image was indeed that of a distant galaxy. Each galaxy's structural appearance, surface brightness profile, and location within the frame was examined, and a rating was given to the galaxy in each category.

For structural appearance, the galaxy was given a 3 if it looked like a typical galaxy, a 1 if it had a completely unconventional appearance, and a rating of 2 if it lay in between. The surface brightness profiles of the galaxies were examined similarly. If the galaxy had a nice exponential or $r^{1/4}$-type of profile, it was given a rating of 3. If its profile was fairly close to exponential or $r^{1/4}$, or if it had a rounded profile, it was given a rating of 2. If the profile was noisy, or contained a number of 'bumps', it was given a rating of 1. Finally, if the surface brightness profile of the galaxy appeared to simply be a lot of noise or was near the

25.0 814 mag arcsec^{-2} limit, it was given a 0, possibly indicating that the image, in fact, is not that of a real galaxy. In the third category, location, the galaxy's position in the mosaicked WFPC2 image was examined to determine the likelihood that the 'galaxy' was simply a region of higher than average surface brightness within the foreground LSB galaxy. Again, a rating of 3 indicated the background galaxy was considerably removed from the location of the foreground galaxy to make the possibility of it actually being a part of the foreground galaxy extremely small. A rating of 0 was given if, upon inspection of the foreground galaxy it became clear the 'background galaxy' was likely a surface brightness enhancement within the foreground galaxy (i.e it clearly lay within the foreground galaxy's nucleus or as a part of a spiral arm). Ratings of 1 and 2 were given to the galaxies which lay in between these two extremes. The three scores were then averaged and rounded to one significant figure, and a final rating was given to the galaxies (Column 5 in Table 3). Any galaxy which had an average score of 0 was dropped from the list, while a score of 1 indicates the identification of that object as a background galaxy is questionable, a rating of 2 indicates that it is likely the object is a background galaxy, and finally, a rating of 3 means the galaxy is clearly a background galaxy.

3. The Data

139 potential galaxies were identified in the four fields and surface photometry was performed on each of these candidates. All information derived from the WFPC2 images on the galaxies is given in Table 3 which is organized as follows:

Column 1: Galaxy names which correspond to our internal field sequencing convention. None of these galaxies have been previously identified.

Column 2 & 3: RA and Dec of the galaxy, in J2000 coordinates, as found using the STSDAS METRIC task.

Column 4: Galaxy type.

Column 5: Scorecard rating.

Column 6: The χ^2 fit to the exponential profiles, assuming the data has uniform error bars of $\pm$ 0.05 mag arcsec^{-2}. (As the fits were only carried out from r = 0.2" through r_{25}, this value is fairly accurate.)

Column 7: The χ^2 fit to the $r^{1/4}$-type profiles, again assuming the data has uniform error bars of $\pm$ 0.05 mag arcsec^{-2}.

Column 8: The total integrated isophotal magnitude of the galaxy through the 814 filter. Magnitudes are corrected for galactic extinction (treating the 814 filter as a Johnson I band filter and the 300 filter as a Johnson U band filter) but not for inclination or redshift (since that is unknown). Magnitudes are within 0.1 unless otherwise noted.

Column 9: Isophotal colors for the galaxies in 814 − 300. If the galaxy couldn't be found in the 300 a minimum color is given, assuming the galaxy would have been detected if it had a minimum radius of 5 pixels and a brightness at least 2σ above the sky value. Again, colors are corrected for galactic extinction (treating the 814 filter as a Johnson I band filter and the 300 filter as a Johnson U band filter) but not for inclination of redshift. Colors are within 0.2 magnitudes unless otherwise noted.

Column 10: The total integrated magnitude of the galaxy is calculated using

$$\mathrm{mag}(\alpha) \;=\; \mu(0) \;-\; 2.5\log(2\pi\alpha^2) \tag{6}$$

where α is the exponential scale length in arcsec and μ_0 is the central surface brightness in mag arcsec^{-2}. If an exponential profile was not fit to a particular galaxy's surface brightness profile this column is left blank.

Column 11: The central surface brightness of the galaxy in mag arcsec^{-2}, when it was possible to obtain this from the profile fit. Surface brightnesses are within 0.1 mag arcsec^{-2}, unless otherwise noted. In the case of $r^{1/4}$ profile galaxies, this is the effective surface brightness.

Column 12: The inclination corrected central surface brightness in mag arcsec^{-2}.

$$\mu_c(0) \;=\; \mu(0) \;-\; 2.5\log(\cos(i)), \tag{7}$$

where the inclination used is listed in column 11. Note that this is a geometric path length correction which assumes no dust.

Column 13: The inclination angle (in degrees) as found by the fitted ellipses (equation 5). The angle is accurate to $\pm\,5°$.

Column 14: The exponential scale length in arcsec. For the galaxies with a $r^{1/4}$-type profile the value listed in this column is for R_e (equation 4). α is not given for galaxies whose surface brightness profile is too irregular for a linear fit. α (or $r^{1/4}$) are to within 0.1" unless otherwise noted.

Column 15: The major axis radius in arcsec as measured at the μ_{814}= 25.0 mag arcsec^{-2} isophote. If the surface brightness profile errors exceeded 0.25 mag arcsec^{-2} before μ_{814}= 25.0 mag arcsec^{-2}, then the largest accurate radius is given. r_{25} is to within 0.1" unless otherwise noted.

Comments about particularly interesting galaxies are contained in Appendix A.

After identification of the background galaxies in the WFPC2 images, the Las Campanas images were inspected to determine if any of these galaxies could now be identified in the multi-filter ground based images in order to obtain additional color information. Twenty-seven of the background galaxies were reliably identified in the ground based Las Campanas images, and the colors of these galaxies through the B, V, and I filters were found. The results are listed in Table 4. Column 1 gives the galaxy name, while column 2 gives the total integrated V magnitude for the galaxy. Columns 3 and 4 give the B − V and V − I colors for the galaxies. If a galaxy could not be identified in one of the filters, a minimum color was found, assuming the galaxy would have been identified were it at least 3 pixels in radius and had an intensity 3σ above the sky. Finally, column 5 lists the radius at which these colors were determined. As with the WFPC2 images, the radii chosen insured the errors were less than 0.25 mag.

4. Surface Brightness Biases and Galaxy Types

4.1. The Early Type Galaxies

Figures 3, 4, 5 are images of selected galaxies in this survey that fall into one of our structural categories. Numerically, the majority of these serendipitously discovered galaxies (102 or 73%) were fit with an exponential profile, 27 of the galaxies (20%) were fit by an $r^{1/4}$-type profile, while the remaining 10 galaxies, or 7%, could not be fit by any profile, either because of their amorphous appearance or location in the frame. Figure 2 shows example surface brightness profiles for all categories. Our overall result is thus fairly consistent with many previous analyses of the Hubble Deep Field (i.e. Abraham, *et.al.* 1994; Abraham, *et.al.* 1996; Driver, *et.al.* 1995a, 1995b; Oemler, Dressler, & Butcher 1997). This result will be discussed further in the next section, and can be seen in Table 5.

In Figure 6 we plot effective radius (in arcsec) versus effective surface brightness (in mag arcsec^{-2}) for our sample of $r^{1/4}$ galaxies. The model running through the data shows the expected trend in these quantities if we take a standard elliptical (R_e = 5 kpc, M_B = -21.0 (i.e. Kormendy 1977) and redshift it, it's angular size decreases according to

$$\delta = \frac{R_e\, H_0\, q_0^2\, (1 + z)^4}{zq_0 + (q_0 - 1)\left(\sqrt{2q_0 z + 1} - 1\right)} \tag{8}$$

(Weinberg 1972). Additionally, its surface brightness is dimmed according to I_e(observed) $= \frac{I_e}{(1+z)^4}$, or equivalently $\mu_e(\text{observed}) = \mu_e + 2.5\log(1+z)^4$. Figure 6 shows the above plots for q_0 = 0.05, 0.55, & 1.05. Overlayed onto the plot are the points where the standard galaxy would lie were it at a redshift of 0.5, 1.0, 1.5, 2.0, 2.5, & 3.0 (left to right). Although the data are limited, they do conform well to this model indicating that $r^{1/4}$ galaxies do lie somewhere between z = 0.5 and z=2.5, and begin to drop out of the survey beyond a redshift of z$\sim$3.0 due primarily to the effects of cosmological dimming. While the variation around the model is undoubtedly a result of the evolution of real stellar populations (e.g. Schade, *et.al.* 1999), the mean trend is consistent with the Tolman test for the expansion of the Universe (see Wirth 1997; Sandage & Perelmutter 1990). In this case, the large observed range in μ_e represents a large range in redshift and not an intrinsic range in surface brightness perhaps due to differences in star formation rates among these galaxies. Note that there is one very deviant point in this diagram which is both of large angular size and very low surface brightness. Spectroscopic follow-up of this galaxy (m2-8) might be interesting.

4.2. Recovering Freeman's Law

The galaxies which fall into classification B (53 galaxies, or 38%) are those whose surface brightness profile is *well fit* by an exponential profile (equation 2). These galaxies have a median central surface brightness of $\langle \mu_{814}(0)\rangle$ = 22 mag arcsec^{-2} and a median scale length of 0.7". Recall that the average surface brightness of the background 814 sky was 23 mag arcsec^{-2}. Hence, our median value of $\langle \mu_{814}(0)\rangle = 22$ mag arcsec^{-2} is 1 mag arcsec^{-2} brighter than the sky background. This is identical to selecting galaxies from the ground where the Freeman value of 21.65 in the blue is approximately one magnitude brighter than the blue sky background, as observed from the Earth. This in fact, is the essence of the original argument of Disney (1976) which was later quantified by Disney & Phillips (1983) and McGaugh *et.al.* (1995). The recovery of the 814 WFPC2 HST equivalent of Freeman's law shows the remarkable uniformity of this selection effect as applied to galaxy detection on any detector. This, of course, means that the serendipitous detection of true LSB galaxies with HST WFPC will be as difficult as it has been from the ground (see Impey & Bothun 1997).

A few of these disk galaxies show distinct spiral structure, ranging from the sharp, well-defined spiral arms of 144-13, through the very faint, yet still obvious arms of 284-2 and 731-1, to the extremely clumpy, yet still visible arms of 734-13 and 283-2 (Figure 4). Furthermore, about one-third of these galaxies have significant luminosity excess in their central regions and the rest are pure disk systems or with with central luminosity excesses too small to resolve. On the surface, this suggests that the disk galaxies span a similar range in B/D ratio at z $\sim$ 1 as they do at z=0, a point consistent with other studies (e.g. Wirth *et.al.* 1994).

4.3. Bulge/Disk Deconvolution

A feature of galaxy evolution, hitherto rather un-probed, is the redshift evolution of the bulge-to-disk (B/D) ratio for disk galaxies. This question is of key interest in understanding the origin of S0 galaxies and whether or not they have always been present or they are an evolutionary end product of normal astration processes in disk galaxies (see Bothun & Gregg 1990; Andreon 1998). The identification of relatively blue disk galaxies at moderate redshifts, which nonetheless have significant B/D, would indicate a population of disk galaxies that likely do not have a long timescale for disk formation. For a reasonable star formation rate, the astration timescale in such disks may well be half a Hubble time. By z=0, such objects would have the characteristics that define the SO class.

Simard *et.al.* (1999) have studied this issue by constructing a magnitude versus size relation for a sample of distant, high surface brightness galaxies. They find strong evidence that a wide range of bulge-to-total (B/T) luminosities exist and that galaxies in their sample define regions in the magnitude-size plane that are not occupied by local galaxies. This suggests that significant evolution in B/T may well occur. To first order, evolution in B/T should also correlate with color evolution but a large enough data set to look for this statistical signature is not yet available.

In principal, our data is sufficiently deep that we can perform bulge/ disk deconvolutions on our surface brightness profiles. Using the procedure of Schombert & Bothun (1987) we have attempted to derive B/D ratios for those exponential disks which show a clear excess of light at small radii above the exponential. In general, this attempt was only made on galaxies where r_{25} exceeded one arcsecond. In many of these cases, it was not possible to find an acceptable fit because the excess light was not well described by an $r^{1/4}$ law. This is an important point. Wirth *et.al.* (1994) defined a light concentration index as a means of quantitatively distinguishing early galaxies from later galaxies. However, the mapping of this light concentration index onto a conventional bulge and disk structural scheme may be both complex and ambiguous. The excess light, or the light which causes a high value for the light concentration index could well be a bulge, or an extended nuclear starburst, or another exponential disk with a short scale length. Indeed, in our sample we have found examples of these so called "exponential bulges" (e.g. Carollo 1999; Seigar & James 1998; Moriondo *et.al.* 1998) in which the composite profile is best fit as the sum of two exponential disks.

Approximately 25% of our sample exhibited a surface brightness profile morphology that made them candidates for B/D deconvolution. In most cases, the deconvolution failed to converge, again largely because the excess light about the exponential disk could not be well fit by an $r^{1/4}$ law. In some cases, the deconvolution failed because the disk fit was too noisy. However, we were able to adequately fit 7 profiles with a standard bulge+disk. These profile fits are shown in Figure 7 and the fitting parameters are shown in Table 6. It is clear from inspection of the figures that the bulge+disk fits are not particularly good (in the strict chi^2 sense) but these are the only 7 objects for which such a fit was even approximately decent. While it would be silly to generalize on the basis of only 7 galaxies, we do note that these B/D deconvolutions define a fairly large range in B/D ratio and include several objects which do have large B/D. We estimate the uncertainties on our formal values of B/D at $\pm$ 30%.

This large range in B/D is consistent with the large range in B/T seen in the Simard *et.al.* (1999) sample. The overall low frequency, however, at which a bulge+disk fit could be found, indicates that, relative to nearby galaxies, these distant galaxies are structurally noisy. That in itself may be an important conclusion from this study. That is, the vast majority of the detected, presumably distant, galaxies have a luminosity distribution that can not be deconvolved into simple bulge + disk components.

Finally, we call attention to the case of 283-10 as an example of a structurally ambiguous object (see also Andreon 1998). In the top panel of Figure 8 we show the surface brightness profile with an exponential disk fitted to the outer regions. The exponential fit is reasonably good and the clear excess luminosity at r $<$ 1.0" indicates a bulge component. The middle panel shows the best fitting bulge+disk model. The overall fit is not very good and the resulting B/D ratio is $\sim$ 2.0 $\pm$ 0.2. This is a high value of any disk system and, if real, would be a good example of an S0 galaxy, similar to say NGC 7814 (see Bothun *et.al.* 1992) or NGC 5866 both of which have approximately a 25% contribution to the total V-band luminosity from the disk component. But, should we believe this deconvolution? In the bottom panel we show a pure $r^{1/4}$ fit on the data. The fit is not great but most of the deviation is occurring at radii larger than 2.0 arcseconds. So what is the nature of 283-10? Is it a structurally noisy elliptical galaxy? Does it have a small disk and is therefore an S0? Or is it a disk dominated system with a strong nuclear excess of light that is not related to a bulge? Clearly, the answer is ambiguous and this one object is a strong testimony to the difficulty of performing accurate structural analysis of distant galaxies.

4.4. Structurally Noisy Galaxies

As is well known (i.e. Abraham, *et.al.* 1994; Abraham, *et.al.* 1996; Driver, *et.al.* 1995a, 1995b; Oemler, Dressler, & Butcher 1997, Smail *et.al.* 1999) the frequency of galaxies with "irregular", "amorphous", or "peculiar" appearance seems to rapidly increase with redshift. Similar results are seen here to the extent that we can equate the 49 galaxies which have surface brightness profiles too irregular to classify (e.g. Category C) with morphologically peculiar objects. These galaxies typically exhibit a fairly clumpy appearance, perhaps indicative of some kind of asymmetric star formation activity/ dust distribution (e.g. Smail *et.al.* 1999) or tidal encounter with another galaxy (see Patton *et.al.* 1997). Indeed most deep galaxy surveys reveal an unusually high number of galaxies at z $\geq$0.5 to be interacting (i.e. Oemler, Dressler, & Butcher 1997; Pascarelle, *et.al.* 1996; Abraham, *et.al.* 1996; Driver, *et.al.* 1995a). The probability that at least a few of the galaxies in this group have experienced a merger is fairly high and some examples of this appear as overlayed galaxies in our images. For instance, of the galaxies in category C that are large enough to produce reasonable surface photometry, most exhibit exponential surface brightness profiles with small overlayed 'bumps' which could be individual regions of star formation, perhaps triggered by a merger or strong interaction. Interestingly, the median central surface brightness for category C galaxies ($\langle\,\mu_{814}(0)\rangle = 22.7$ mag arcsec^{-2}) is lower than category B galaxies and hence they should be selected against. However, their lumpy appearance (e.g. surface brightness enhancements) greatly aids in their visual detection. This suggests that part of the reason for the apparent increase in galaxies of "peculiar" morphology is simply they are easier to recognize against the background sky noise than galaxies with more smooth appearance but lower than average surface brightness.

4.5. Inclination, Size, Colors and Redshift

The median inclination of the galaxies in this survey is 50° , close to the expected value of 60° in random phase space. The distribution of inclination is shown in (Figure 9). A significant fraction of the galaxies (39, or 28%) have $i \geq 65°$. These galaxies would fall into Cowie, *et.al.* 's (1995) classification of 'chain galaxies,' since many also show the bright knots (of star formation?) inherent in the chain galaxy classification. Two good examples of this phenomenon are 734-9 and 284-15. 734-9 is an edge-on galaxy, with $i = 75°$. In addition to its well defined central bulge, 734-9 clearly shows a number of the knots of star formation discussed in Cowie, *et.al.* . Due to their placement and the clear central bulge of the galaxy, these 'knots' appear to be relatively transparent, edge-on spiral arms. Each galaxy in the apparent galaxy group that creates 284-15 is also fairly edge-on, ranging from $58° \leq i \leq 77°$. The close proximity and edge-on nature of these three galaxies indicates they are interacting, and are possibly simply the bright regions of the same galaxy. Because the same localized spots occur in the galaxies with $i \leq 65°$, and because many local galaxies have been found with inclinations equally as high (e.g. Dalcanton & Schectman 1996; O'Neil, Bothun, & Cornell 1997a), it is likely these galaxies do not belong to a new galaxy classification but instead are the same (albeit more inclined) as the other galaxies in this survey.

Lacking the detailed color information to properly infer photometric redshifts (e.g.

Connolly, Szalay, & Brunner 1998,), we can only estimate redshifts by using the measured scale lengths. The average scale length is $\langle \alpha \rangle = 0.7''$, with a range from $0.1'' \leq \alpha \leq 3.1''$. Assuming these are typical disk galaxies, with 1 kpc $\leq \alpha \leq$ 5 kpc (H_0 = 100 km/s/Mpc) (van der Kruit 1987; Grøsbol 1985), gives a probable redshift range of 0.2 – 1.0 for q_0 = 0.05 – 1.0.

Figures 10 and 11 show the two color diagram for the background galaxies that could also be identified in the ground-based images and the relation between measured scale length and V−I color. Comparing these colors with those from galaxies with known redshifts in the Hubble Deep Field indicates the background galaxies have redshifts lying between 0.5 $\leq z \leq$ 1.5, though the possibility exists, from this comparison, that the galaxies lie considerably farther away (i.e. Phillips *et.al.* 1997; Lowenthal *et.al.* 1997; Madau *et.al.* 1996). However, in this case their disk scale lengths would exceed 5 kpc. The three galaxies with B−V $\leq$ 0.55 and V−I $\leq$ 1.0 all have r_{25} values of 1 – 1.5" and are most probably low luminosity irregular galaxies at relatively low redshift. The majority of points, however, are of small angular size and red color (with one prominent exception), suggesting a probable redshift of $0.5 \leq z \leq 1.5$. To first order, the relatively noisy correlation between observed angular scale length and color does suggest that the redder objects are simply farther away. This would place them at the distance of many of the galaxies identified in the medium-deep HST WFPC2 surveys and, as will be discussed in the next section, the morphology of these galaxies is similar to that of the WFPC/WFPC2 deep and medium-deep surveys.

5. Comparison with Other WFPC2 Surveys

Extensive work has been done to morphologically classify the galaxies found in both the deep (HDF) and medium-deep (MDS) WFPC2 surveys (i.e. Marleau & Simard 1998; Oemler, Dressler, & Butcher 1997; Driver, *et.al.* 1995a; Driver, *et.al.* 1995b; Griffiths, *et.al.* 1994). On average, the morphological mix of galaxies for both the HDF and MDS is given as: A type galaxies (E/S0) 16% - 41%; B type galaxies (Sabc) 31% - 53%; C type galaxies (Sd/Irr/Pec) 15% - 47% (Table 5). Considering only those galaxies for which a surface brightness profile could be found, the galaxies in this survey are distributed as 21% A type, 41% B type and 38% C type, a distribution similar to the majority of HDF and MDS classification schemes. Again, we emphasize that our classification scheme is based strictly on profile fit to surface photometry. The issue now becomes whether this distribution of A, B and C types is representative or whether the results are driven by volume selection effects. If Figures 6 and 11 are indirect volume sampling indicators then it seems clear that unless the disk galaxies selected here have intrinsically large scale length, the volume involved selecting type A galaxies is considerably larger than selecting type B galaxies. This strongly suggest that the absolute volume density of type A galaxies, as observed outside of clusters, is quite low in comparison to that of type B galaxies. If this is correct, then this situation seems to be unchanged with respect to what we observe at z=0.

Support for this view comes from the results of other surveys which show that the morphological mix deduced in a survey does seem to be dependent on the magnitude limit of that survey. This, of course, is the selection function and its currently unclear if going to fainter limits means more full sampling of the galaxy luminosity function (and its evolution with time) or going to a large volume (hence longer look back times). Spectroscopic follow-up surveys (e.g. Morris *et.al.* 1998) tend to be more consistent with the volume effect although this may be a direct reflection of surface brightness bias in the spectroscopy. The morphological mix listed above is from surveys with limits of $m_I \sim 21.75$ or brighter, while the galaxies in our survey have a limit of ~ 24, with a significant portion lying between $22 \leq m_I \leq 24$. Driver, *et.al.* (1995b) analyzed the morphological mix of galaxies in the HDF with $23.0 \leq m_I \leq 24.5$, and show that the percentage of E/S0 galaxies in this sample is considerably lower (16%) than in the brighter sample, with most of the difference lying in the Sd/Irr category (47%). Thus it's likely that any difference between our sample and previous WFPC2 galaxy surveys lies in the fact that our sample is considerably fainter than previous studies. As disk galaxies are more prevalent at lower absolute magnitudes, this would be consistent with our technique selecting objects further down the luminosity function.

In contrast, using an automated, 2-dimensional photometric decomposition algorithm, Marleau & Simard (1998, MS) analyzed galaxies in HDF down to $m_{814} = 26.0$ ($m_I \sim 24.5$) and found only 8% of the galaxies to be bulge dominated (A type). The first reason given by MS to explain the discrepancy between the morphological classifications in their survey and that of previous HDF morphological classifications is that the subjective nature of the visual classification used by most groups analyzing the HDF data biases towards finding more early-type galaxies (this, of course, is a surface brightness selection bias). This bias within the visual classification system effects primarily small ($r \leq 0.31$") round galaxies which are typically labeled as E/S0 galaxies. As the algorithm run by MS does not have such biases it found a considerably lower percentage of A type galaxies. On the other hand, our classification system is structurally based and hence similar to that used by MS and we do not find such a low percentage of early type galaxies. The second argument put forth by MS is that many of the galaxies in their survey lay at $z \geq 1$, considerably farther than the majority of the galaxies examined by other groups. However, it is unclear if MS are viewing morphological evolution in galaxies as being responsible for their low percentage of early types. If, instead, the faintest galaxies observed by MS, are in fact not at $z \geq 1$ but are simply low luminosity galaxies, then the 8% number they find is quite similar to what is found in the nearby Universe, if you sample far enough down the galaxy luminosity function.

6. Conclusions

While using the HST WFPC2 to image four low surface brightness galaxies in the direction of the Virgo cluster we discovered 139 potential background galaxies shining through the LSB galaxies. We performed surface photometry on each of these images and classified them into various structural types depending on the form of the surface brightness profile. Our overall results are the following:

1. The combination of angular sizes and limited color information is consistent with these galaxies occupying the redshift range $0.5 \leq z \leq 2.5$. This places the galaxies at the same distance as many of the galaxies discovered in the Hubble Deep Field and the Medium Deep Survey.

2. The value of $\mu_I(0)$ found for the "disk" galaxies is approximately one magnitude brighter than the F814W sky background. Although the detector is much different, this is

a manifestation of the kind of surface brightness selection bias that leads to Freeman's Law - i.e. values of $\mu_B(0)$ that are approximately one mag brighter than the terrestrial blue sky background.

3. The percentage of $r^{1/4}$ galaxies found in this survey is similar to that found by others (e.g. $\sim$ 28%). There are, however, indirect suggestions in the data that the volume over which $r^{1/4}$ galaxies are selected is significantly larger than the volume over which disk galaxies are selected. This suggests that the space density of $r^{1/4}$ galaxies in the general field from z =0 to z $\sim$ 2.5 is low; that is, this population may be largely confined to galaxy clusters.

4. Rather few of the galaxies can be reliably deconvolved into a bulge + disk. Even those that could did not have particularly good fits. To first order, this indicates that the structural components of disk galaxies have not fully formed at these redshifts. Interestingly, the small sample of bulge+disk fits that we did obtain show a large variation in the bulge-to-total luminosity ratio and we did detect some disk galaxies with significant B/D. Such objects could be visually classified as ellipticals. We have also highlighted one object, 283-10, as an excellent example of how difficult the classification exercise can be.

5. It seems clear that surface brightness information, when coupled with broad-band colors, can help to better quantify the rate of "morphological" evolution of galaxies. However, the recovery of Freeman's Law from this data, together with the known cosmological dimming effect, $(1+z)^4$, means that the biases against selecting intrinsically LSB objects at high redshift are severe. There may well be large numbers of such objects, as is the case at z=0 (e.g. O'Neil & Bothun 2000), that simply can easily escape detection. This demands that caution must be taken when using the number density of galaxies, as a function of redshift, as a cosmological probe.

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7. Appendix A: Few Good Galaxies

Having found 139 previously uncatalogued galaxies, we cannot go into detail about each one. A few of the galaxies, though, are worthy of mention, due to their unusual shape or surface brightness profile. Images of these, and all the galaxies in this survey, can be found at http://guernsey.uoregon.edu/~karen. These unusual galaxies are listed below:

731-5: This appears to be two galaxies nearing the end of their merger, with one galaxy (the chosen core in the surface brightness profile) considerably brighter than the other. Both galaxies likely had well-formed cores before the merger began.

731-6: This galaxies is fairly small and diffuse, and was only found due to its bright central core ($\mu_{814}(0)\sim$ 21.5 mag arcsec^{-2}), The galaxy lies in a particularly noisy region of the image and therefore is difficult to classify.

732-3: This is a fascinating galaxy, having a clear spiral core surrounded by a diffuse halo which has its own spiral arm (Figure 5a).

733-10: The core (peak intensity) of 733-10 lies far from the galaxy's physical center. Although it is, of course, impossible to know the cause of this, the fact the core is highly non-spherical lends credence to the conclusion that this galaxy has recently experience a strong tidal influence, either by a passing galaxy or by a galaxy which has recently merged with 733-10.

734-10: These highly elliptical ($i = 80°$) galaxies may be interacting, though their ellipticity makes that determination difficult.

283-3: This object has a star overlaying the galaxy between r = 0.7" ad 1.3". The star was masked in the surface brightness profile, leaving an artificial depression.

283-9, 283-10: This pair of galaxies consists of a large, bright, and presumably elliptical galaxy (283-10) and a much small galaxy. The excess of gas between the galaxies makes it appear as if they're interacting tidally. Due to the large discrepancy in size between the two galaxies, it is likely 283-9 will be, or is being, ripped apart by, or pulled into 283-10.

284-7: 284-7 has an usual, V-shaped morphology, with a bright central core. This galaxy may actually be two small overlapping galaxies, or we could be seeing star forming knots embedded in a larger, but much fainter, galaxy.

284-15: Based on their close proximity to each other, this system appears to be three separate, interacting galaxies. All three galaxies are highly inclined ($i = 58°$, 77° , 69° , respectively), and all have remarkably similar position angles.

142-8: This appears to be two (or three) galaxies interacting galaxies. 142-8 contains two bright cores and has a highly elliptical appearance ($i = 73.3°$). It may be the result of a recent merger, or the non-centralized knot of star formation may be due to the close proximity of its companion.

m2-21: At $r_{major} = 0.85$", m2-16 has two bright circular regions. These may be foreground stars, or even a foreground galaxy, or they may be star forming regions in the galaxies. If the spots are regions of heightened star formation, then, because they are far from the galaxy's peak intensity, they were most likely externally triggered.

m3-9: This galaxy has previously been given a stellar classification due to its round shape. The high resolution of the WFPC2, however, enabled us to view the galaxy's faint disk and thereby determine its true nature as a galaxy.

The four images which constitute the full field of the WFPC2 are strongly vignetted in the lower columns and rows due to the aberration of the primary beam dividing the light from sources near these edges. The increased noise affects the faint end of the surface brightness profiles of the following galaxies: 284-8, 284-24, 733-1, 733-14, 734-1, 734-2, 734-8, 141-5, 143-15 and 143-16, m2-30, m4-1 and m4-2.

References

Abraham, R..G. *et.al.* 1996, ApJS, 107, 1
Abraham, R..G. Valdes, F., Yee, H., van den Bergh, A. 1994, ApJ, 432, 75
Andreon, S. 1998 ApJ 501,533
Barger, A.J. *et.al.* 1998 AJ, in press
Balogh *et.al.* 1999, preprint
Bothun, G., *et.al.* 1992 PASP 104, 1220
Bothun, G., & Gregg, M. 1990 ApJ 350, 83
Carollo, C. M. 2999 ApJ 523, 566
Cohen, J, *et.al.* 1996 ApJ 471, 5
Connally, A.J., Szalay, A.S., & Brunner, R.J. 1998 ApJ 499, 125
Cowie, Lennox L., Songaila, Antoinette, Hu, Ester M., & Cohen, J. G. 1996 AJ 112, 839
Cowie, L., Hu, E., & Songalia, A. 1995, AJ, 110, 1576
Dalcanton, J. & Schectman, S. 1996, ApJ, 465, 9
Disney, M., & Phillipps, S. 1983 MNRAS 205, 1253
Disney, M. 1976 Nature 263, 573
Driver, S., *et.al.* 1995a, ApJ, 453, 48
Driver, S., *et.al.* 1995b, ApJL, 449, 23
Ellis, R., *et.al.* 1996 MNRAS, 280, 235
Griffiths, R.E., *et.al.* 1994 ApJ 437, 67
Grøsbol, P. 1985 A&AS 60, 261
Hammer, F, *et.al.* 1997 ApJ 481, 49
Hogg, D., *et.al.* 1999, preprint
Impey, C., & Bothun, G. 1997 ARA&A 35, 267
Impey, C., Bothun, G., Malin, D. 1988, ApJ, 330, 634 (IBM)
Kormendy, John 1977 ApJ 218, 333
Krist, J. 1996, *Tiny Tim Manual* http://scivax.stsci.edu/krist/tinytim.html
Lilly, S. J., Le Fevre, O., Crampton, David, Hammer, F., & Tresse, L. 1995 ApJ 455, 50
Lowenthal, J. 1997 ApJ 481, 673
Madau, Piero, 1997 IAUS 186, 188
Madau, Piero, *et.al.* 1996 MNRAS 283, 1388
Marleau, F. R. & Simard, L. 1998 AAS 192, 2503 (MS)
McGaugh, S., Bothun, G., & Schombert, J. 1995 AJ 109, 2019
Meurer, G., Heckman, T., Lehnert, M., Leitherer, C., & Lowenthal, J. 1997 AJ 114, 54
Moriondo, G. *et.al.* 1998 A&AS 130, 8
Morris, S. *et.al.* 1998 ApJ, in press
Oemler, A., Dressler, A., & Butcher, H 1997, ApJ, 474, 561
O'Neil, K. Bothun, & Impey 1999, ApJ, preprint
O'Neil, Bothun, Impey, & McGaugh 1998, AJ, 116, 657
O'Neil, K, Bothun, G. & Cornell, M. 1997a, AJ, 114, 2448
O'Neil, K, Bothun, G. Schombert, J., Cornell, M., Impey, C. 1997b, AJ, 113, 1212
O'Neil, K. 1997, Ph.d. dissertation, University of Oregon, Eugene
Pascarelle, S. M., Windhorst, R. A., Driver, S. P., Ostrander, E. J., & Keel, W. C. 1996 ApJ 456, 21
Patton, D. *et.al.* 1997 ApJ 475, 29
Phillips, A., *et.al.* 1997 ApJ 489, 543
Ratnatunga, *et.al.* 1999 AJ 118, 86
Remy, M. *et.al.* 1997 *1997 HST Calibration Workshop* S. Casertano, *et.al.* eds.
Sandage, A., & Perelmuter, J-M. 1990, ApJ, 361, 1
Schade, *et.al.* 1999, preprint
Schombert, J. & Bothun, G. 1987 AJ 93, 60

Seigar, M. & James, P. 1998 MNRAS 299 672
Silva, D. & Bothun, G. 1998 AJ 116, 85
Simard, L., *et.al.* 1999 ApJ 519, 563
Smail, *et.al.* 1999, preprint
Steidel, C., *et.al.* 1999, preprint
Steidel, C., Giavalisco, M., Pettini, M., Dickinson, M., Adelberger, K, 1996 ApJ 462, 17
Thomsen, B., & Frendsen, S. 1983, AJ, 88, 789
Van Der Kruit, P. C. 1987 A&A 173, 59
von Dokkum, P., *et.al.* 1998 ApJ in press
Weinberg, S. 1972 *Gravitation and Cosmology: The Principles and Applications of the General Theory of Relativity* John Wiley & Sons: New York
Wirth, G., Koo, D., & Kron, D. 1994 ApJ 432, 464
Wirth, G., *et.al.* 1997 PASP 109, 344

FIGURES

Fig. 1.— HST WFPC2 mosaicked images of V1L4 (a), V2L8 (b), V7L3 (c) and Malin 1 (d) taken through the 814 (I band) filter. The images are 2.6 arcminutes across.

Fig. 2.— Representative sample of surface brightness profiles for the three categories. Figure 2*a* are all category A, Figure 2*b* are category B, and Figure 2*c* are category C.

Fig. 3.— Examples of some of the more interesting (morphologically) background galaxies discovered during our study. The galaxies shown are 732-3, 733-10, 282-3, and 142-31 (a - d, respectively).

Fig. 4.— Examples of spiral background galaxies discovered during our study. Images a - e are 731-1, 284-2, 144-13, 283-2, and 734-13, respectively.

Fig. 5.— Examples of merging background galaxies discovered during our study. Figure 5a shows 731-5, while Figure 5b shows 734-10. In Figure 5c is 283-9 at the top, and 283-10 at the bottom. Figure 5d shows the three galaxies which comprise 284-15.

Fig. 6.— A plot of the effective radius (in ") versus $\mu_{e_{814}}$ (in mag arcsec^{-2}) for the sample of $r^{1/4}$ galaxies. The lines are for q_0 =0.05 (solid line), 0.55 (dashed line), and 1.05 (dash-dotted line), the circles are the actual data, and the crosses are for the standard galaxy (R_e=5.0 kpc, $\mu_{e_{814}}$ 21.0 mag arcsec^{-2}) with z = 0.5, 1.0, 1.5, 2.0, 2.5, & 3.0 (left to right). (See Sandage & Perelmuter 1990, Thomsen & Frandsen 1983 for more information on this procedure.)

Fig. 7.— Surface brightness profiles for the 7 galaxies which were successfully fit with a standard bulge + disk profile.

Fig. 8.— Surface brightness profile of 283-10 with a pure exponential fit (*a*), a bulge + disk fit (*b*), and a pure $r^{1/4}$ fit (*c*).

Fig. 9.— Histogram showing the inclination (in degrees) for all the galaxies in this survey.

Fig. 10.— Two color diagram for the background galaxies that could also be identified in the ground-based images.

Fig. 11.— Scale length (in ") vs. V−I color for the background galaxies that could also be identified in the ground-based images.

TABLES

Table 1:

Field	**RA**	**Dec**	**Date**
V2L8	12:31:27.1	14:37:14.1	01/05/96
V7L3	12:29:06.2	12:53:34.7	03/08/97
V1L4	12:34:52.3	14:12:21.3	03/10/96
Malin 1	12:37:08.8	14:18:45.9	03/10/96