The Contribution of Late-type/Irregulars to the Faint Galaxy Counts from HST Medium Deep Survey Images

Simon P. Driver, Rogier A. Windhorst
Department of Physics and Astronomy, Arizona State University,
Tempe, AZ 85287-1504

and

Richard E. Griffiths
Bloomberg Center for Physics and Astronomy, The Johns Hopkins University,
Baltimore, MD 21218-2695

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ABSTRACT

We present a complete morphologically classified sample of 144 faint field galaxies from the HST Medium Deep Survey with $20.0 \leq m_I < 22.0$ mag. We compare the global properties of the ellipticals, early and late-type spirals, and find a non-negligible fraction (13/144) of compact blue $[(V - I) \leq 1.0$ mag] systems with $r^{1/4}$-profiles. We give the differential galaxy number counts for ellipticals and early-type spirals independently, and find that the data are consistent with no-evolution predictions based on conventional flat Schechter luminosity functions (LF’s) and a standard cosmology.

Conversely, late-type/Irregulars show a steeply rising differential number count with slope $(\frac{\delta \log N}{\delta m}) = 0.64 \pm 0.1$. No-evolution models based on the Loveday et al. (1992) and Marzke et al. (1994b) local luminosity functions under-predict the late-type/Irregular counts by 1.0 and 0.5 dex, respectively, at $m_I = 21.75$ mag. Examination of the Irregulars alone shows that $\sim 50\%$ appear inert and the remainder have multiple cores. If the inert galaxies represent a non-evolving late-type population, then a Loveday-like LF ($\alpha \simeq -1.0$) is ruled out for these types, and a LF with a steep faint-end ($\alpha \simeq -1.5$) is suggested. If multiple core structure indicates recent star-formation, then the observed excess of faint blue field galaxies is likely due to evolutionary processes acting on a steep field LF for late-type/Irregulars. The evolutionary mechanism is unclear, but $60\%$ of the multiple-core Irregulars show close companions. To reconcile a Marzke-like LF with the faint redshift surveys, this evolution must be preferentially occurring in the brightest late-type galaxies with $z \gtrsim 0.5$ at $m_I = 21.75$ mag.

Subject headings: galaxies: elliptical — galaxies: spiral — galaxies: irregular — galaxies: luminosity function — galaxies: evolution

1 Introduction

The majority of explanations for the excess of faint blue galaxies (“FBG’s”, see Broadhurst, Ellis & Shanks 1988, hereafter BES) observed in deep ground-based CCD images (e.g. Tyson 1988; Lilly et al. 1991; Driver et al. 1994; Neuschaefer & Windhorst 1995) involve Irregular/dwarf \footnote{Here we broadly define dwarf galaxies to have $M_B \geq -18.0$ mag for $H_o = 50 \ km \ s^{-1} \ Mpc^{-1}$, i.e. galaxies like the LMC and fainter.}
populations (Kron 1980; Lacey 1991). In some models, these dwarfs have rapidly evolved through isolated starbursts (Cowie et al. 1991; Babul & Rees 1992) or via general luminosity evolution (Phillipps & Driver 1995), while in other models, strong merging (Broadhurst, Ellis & Glazebrook 1992; Rocca-Volmerange & Guiderdoni 1991) or tidally induced star formation (Lacey et al. 1993) are proposed. Other models have suggested that no evolution is necessary, and that the abundance of FBG’s may be due to a combination of cosmological effects and/or an underestimation of the local space density of Irregular/dwarf galaxies (Koo, Gronwall & Bruzual 1993; Driver & Phillipps 1995; McGaugh 1994). Whichever process is occurring (and perhaps a combination of several), one needs high-resolution studies of well a selected galaxy sample in the magnitude range over which the FBG excess is observed to address their true nature. Ground-based studies are always limited in resolution due to atmospheric seeing, because the median scale-length of faint field galaxies is \( \sim 0.3'' \) (Griffiths et al. 1994b, GR94b; Casertano et al. 1995, CRGINOW). Giraud (1992) found evidence for both merging, isolated starbursts, and possibly post-starburst remnants. The studies of Burkey et al. (1994) and Colless et al. (1994) also find a significantly increased fraction of close companions for \( 19 \leq m_I \leq 22 \) mag. The Colless et al. sample was limited by ground-based seeing to a resolution of 0.5"—1.0" FWHM. The superb resolution provided by the refurbished HST now allows morphological details to be seen to much higher resolution and fainter limits (Griffiths et al. 1994a, GR94a; Forbes et al. 1994; Glazebrook et al. 1995a, GL95a) and in particular allows us to study the morphology, light-profiles and contours of individual galaxies to a resolution of \( \sim 0.1'' \) FWHM in the flux interval over which the excess FBG’s are observed (i.e. \( m_B \geq 22 \) mag; BES, Driver et al. 1994). Here we present a complete sample of HST field galaxies with \( I \)-band magnitudes in the range \( 20.0 \leq m_I < 22.0 \) mag (or \( 22.0 < m_b < 23.5 \)), from which we extract a complete sub-sample of galaxies that are irregular in appearance. In §2 we summarize the new HST WFPC2 data and its method of data reduction. In §3 we present the detection and photometry algorithms used to construct the current catalog. In §4 we discuss the morphological classification, and in §5 we compare the global properties of each galaxy class. In §6 we present a discussion of the detailed morphology of the Irregular HST galaxies.
2 The HST WFPC2 data

The HST Medium Deep Survey (MDS) collects data in parallel with other HST instruments (FOC, FOS, FGS) using the WFPC2 to randomly image a field 4′—14′ away from the primary target (depending on the primary HST instrument being used). A more detailed description of the MDS project is given by GR94b, and a summary of the Cycle 4 HST data reduction methods is given by Ratnatunga et al. (1995). The MDS pipeline data reduction was carried out using the MDS WFPC2 super-skyflats (Ratnatunga et al. 1994). This results in a uniform calibration accuracy of ±0.1 mag (Holtzman et al. 1995). The actual zero magnitude points for 1.0 ADU/sec are: $K_{I_{814W}} = 21.67 - 0.009(F606W - F814W)$ mag and $K_{V_{606W}} = 22.84 - 0.076(F555W - F814W)$ mag. (Note that $(F606W - F814W) \approx 1.4$ and $(F555W - F814W) \approx 1.8$ mag for faint field galaxies, GR94a, GR94b). The fields were selected from the MDS database to have comparable exposure times in both the wide V (F606W) and I (F814W) filters. Table 1a shows the positions and exposure times for the data used in this study, along with Galactic foreground extinction in $V_{606}$ and $I_{814}$, taken from the reddening values in Burstein & Heiles (1982). We adopted an extinction $\propto 1/\lambda$ (Osterbrock 1989) and a ratio of $A_V/E(B - V) = 3.2$. The removal of cosmic rays was achieved using the CRREJECT facility in IRAF’s IMCOMBINE, which compares individual orbits to reject cosmic-rays and creates a final stack via a sigma-weighted average. In general, we did not have a sufficient number of undithered orbits per field to apply the optimized CR rejection routines of Windhorst, Franklin & Neuschaefer (1994). Additional low-level cosmic rays and bad pixels were therefore cleaned by replacing pixel values 3σ above or below the local median sky-background with the mean from adjacent pixels. The WFC pixel scale is 0.0996″ per pixel, and so each of the three WFC CCDs corresponds to a 1.3′ × 1.3′ region. This gives a total sky coverage of 0.00845 sq deg. Data from the PC was not used in this survey due to its poorer surface brightness (SB) sensitivity and its much lower sky coverage.

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3There is a potential bias introduced by the position of the primary HST target and the desire for long integrations. However, most primary targets are themselves randomly detected (i.e. QSO’s or stars at relatively high galactic latitude), so any such bias is expected to be small.
A complete catalog of Irregular HST galaxies to $m_I = 22$ mag

In order to define a complete sample of Irregular HST galaxies, and study their morphology in an unbiased way, it was necessary to first construct a complete sample for all galaxy types from the MDS images. We therefore required that the magnitude limit was not so faint that the Irregulars become unresolvable by HST. Typical field Irregulars are expected in the range $20.0 < m_I < 22.0$ mag and $0.5'' \lesssim r_{\text{half-light}} \lesssim 1''$ for $z \leq 0.3$, assuming $-14.5 \lesssim M_I \lesssim -19.5$ mag, $(B-I) \simeq 1.5$, and $r_{\text{hl}} \simeq 1-3$ kpc (for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$, and $\Lambda = 0$). This observed range is equivalent to a $B$-band magnitude range of $22.0 < m_B < 23.5$ (Driver et al. 1994), at which level the observed density of FBG’s is a factor of $\sim 2 - 3$ over the standard cosmological predictions (Tyson 1988; see our Figures in §5). The expected surface density of galaxies of all types in this $I$-band range is $\sim 20$ objects per WFPC2 field (Tyson 1988; Driver et al. 1994; Table 1b here).

3.1 Image detection and photometry

Prior to the image detection phase, a median filter of $127 \times 127$ pixels was used to create a smoothed sky-image for each WFPC2 frame, representing any large-scale variations in the sky (gradients of $\sim 2\%$ typically remained after applying the MDS supersky flats). This sky-image was subtracted from the original frame to give an extremely flat sky-background ($<< 2\%$). We divided each CCD frame into nine sections and measured the sky background within each section, using a Gaussian fit to the peak of the ADU-histogram, which reduced the WFPC2 gradients of $2-3\%$ to $\lesssim 0.5\%$ of sky.

The initial object detection was done with the isophotal detection routine ‘IMAGES’ in the RGASP package (Cawson 1983), searching for objects with 4 connected pixels ($0.04''^2$) with a signal $2 \sigma$ above the mean sky-background (where $\sigma$ is the measured noise in the local sky-background). Detections with centroids within 26 pixels ($2.6''$) of the CCD frame edge were rejected to prevent any edge bias. This reduces the usable area per CCD image to $66^2$ pixels or $1.1' \times 1.1'$. For the photometry stage we used a variable size circular aperture centered on the initial detection position and a global sky-background for each CCD image (because any significant large-scale structure in the sky background was already removed to $\leq 0.5\%$ or $\sim 28.5 \text{ mag/arcsec}^2$). The size of the aperture, $r_{\text{ap}}$, was based on the following relationship:
\[ r_{ap}^n = r_{iso}^n + r_{min}^n, \]  

(1)

as described in Driver (1994) and in Jones et al. (1995). This equation essentially satisfies the conditions that the aperture radius is comparable to the isophotal radius \( r_{iso} \) for objects with large isophotal areas (i.e., bright), and comparable to a fixed minimum \( r_{min} \) for objects with small isophotal radii (i.e., faint). The following optimal values for pure exponential disks were determined via simulations (Driver 1994): \( n=1.5 \) and \( r_{min} \approx 1'' \approx 3 \) scale-lengths (CRGINOW).

These simulations showed that this technique includes at least 95% of the light for exponential disks as well as bulge-dominated galaxies. All detections with an aperture flux \( m_I \leq 22.0 \) mag were re-evaluated individually to exclude any contamination due to nearby objects within the initial aperture. The final catalog was then defined to be all galaxies within the total flux range of \( 20.0 \leq m_I < 22.0 \) mag.

### 3.2 Completeness of the HST WFPC2 sample

Figure 1 shows the logarithm of the signal-to-noise ratio versus \( I \)-band magnitude for the isophotal detection stage (Fig. 1a) and the photometry stage (Fig. 1b) as a test of our sample completeness. The majority of detected galaxies are well above the signal-to-noise limit set by the detection criterion (i.e. \( 2\sigma \) above sky over 4 contiguous pixels). Fig. 1b also follows the predicted slope of \(-0.6\) in a Euclidean Universe (shown as dashed line) very closely for optimal aperture radii (i.e. the radius which just encompasses the object). Galaxies with central SB \( \mu_I \geq 23.26 \) mags arcsec\(^{-2}\) (i.e., whose extent is greater than 5'' in radius, see Table 1b) would escape detection. Since no objects are seen close to the quoted signal-to-noise limit (\( \approx 4.0 \) in Fig. 1a), the sample is essentially 100\% complete down to a limiting total magnitude of \( m_I = 22.0 \) mag. A discussion of the completeness of WFC images much closer to the HST detection limit is given by Neuschaefer et al. (1995). Note that the total volume surveyed for low-SB galaxies is still very small due to the limited WFC2 field-of-view. The catalog may therefore be statistically mis-represented for these types (Disney 1976). Table 1b shows the number of detections per WFPC2 CCD along with the magnitude zero points and SB detection limits. The number of detections agrees well with that expected (§5.1).
3.3 Morphological Classification of the WFPC2 galaxies

The morphological classification of the HST galaxies was achieved from the consensus of three independent eyeball classifiers (SPD, RAW and Roger Rouse - RR). To assist in the classification, greyscale plots were made from 1σ below sky to 5σ above sky, as well as major-axis profiles in both SB vs. r and SB vs. r$^{1/4}$. These were used to classify all objects in both V and I. Simulated light-profiles of perfect de Vaucouleur-laws and exponential disks were also plotted on the same scales as a reference. The following rules were followed for the classification of our HST galaxies, based on the Hubble Atlas of Galaxies (Sandage 1961):

(1) Visually compact objects showing a predominately linear profile in SB vs. r$^{1/4}$ were classified as E/S0. This includes compact systems which show no evidence for a disk, irrespective of their colors.

(2) Objects which are linear in r$^{1/4}$ in the inner region and linear in r in the outer region were classified as Sa, Sb or Sc, depending on the ratio between the linear sections and the steepness of the respective profiles (see e.g., Windhorst 1994a, 1994b). Note that the Sabc’s are lumped together into a single galaxy class for the purpose of classifications in this paper. This class thus includes those systems that have a well defined bulge and disk.

(3) Objects with a flat light-profile, a profile which rises from the center, an erratic profile, or a profile which is a poor linear fit to either SB vs. r or SB vs. r$^{1/4}$ were classified as Sd/Irregular or Peculiar. Peculiar galaxies are those which exhibited a strong central core (initially linear in SB vs. r$^{1/4}$), but with a highly disturbed outer disk. This is an attempt to distinguish between genuine Irregulars and early-type galaxies undergoing some form of interaction, etc.

Note that major-axis light-profiles were used rather than azimuthally-averaged profiles to prevent any irregular structure being smoothed out. In all cases, the grey-scales plots were used as a secondary check to determine whether a nearby companion might be disturbing the light-profiles. Both the V and I light-profiles and grey-scale plots were used for optimal classification. Figure 2 shows a selection of major-axis profiles to illustrate the range of Hubble types and light-profiles seen in our HST sample. A representative galaxy for each Hubble class was chosen with $m_I \sim 21.5$ mag to allow a direct comparison of the appearance and light-profiles of the fainter objects.

Comparing the results between the independent classifiers, we find complete agreement for 91/144 objects and agreement to one Hubble class for 45/144 objects. The remaining 8 objects...
were typically unusual cases where one classifier identified the major component of a clump and the other classified the entire system as “Peculiar” or Irregular. In these cases the classification of the objects was openly discussed, and a consensus classification was assigned. No attempt was made to separate stars from compact ellipticals, as the two populations sometimes appear indistinguishable by visual examination of their HST light profiles (see Ratnatunga et al. 1995 for an automated method of star-galaxy separation). Currently, a full spectroscopic follow-up of the entire sample is in progress (Driver et al. 1995b) to determine redshifts and luminosities. This will allow an accurate separation between compact ellipticals and stars, and enable us to confirm the eyeball classifications and determine how many high-SB galaxies are masquerading as stars at faint magnitudes.

3.4 Reliability of the WFPC2 Classifications

Figure 3 shows a simple test of our classification by plotting the concentration index (C.I. = core SB minus total magnitude) versus total magnitude. Here, the core SB is defined as the flux within 0.2″ radius in units of magnitudes per square arcsecond. The C.I. is a measure of the concentration of galaxy light, where a lower index reflects a greater amount of light contained in the core, which is expected to correlate well with morphological type (Forbes et al. 1994). This should not be confused with the more conventional definition of the C.I. (e.g. Kent 1985), which requires better resolution and signal-to-noise than we have. In reality, the core SB is both resolution and distance dependent. However at moderate redshifts the Θ − z relation for HST bulges and disks is flat enough (Mutz et al. 1994) that the C.I. is to first order distance independent.

Figure 3 shows that the E/S0 sample (i.e. compact systems including a small number of stellar-like objects) separates very well from the bright spirals. However, the transition from early to late-type spirals is less well-defined by this technique, although there is still a distinct correlation between galaxy type and the C.I..

As a final check we compare our morphological classifications to those of GL95a and GR94a. Both of these surveys are also based on HST MDS data. The survey of GL95a covers several fields in common with this study, yet uses entirely independent methods for data reduction and image detection. Comparing the classifications for the 92 galaxies in common, we find that 25 agree exactly, 44 within one Hubble class, and 8 within two Hubble classes. The remaining 14 objects are unusual in some way, and represent cases where a decision had to be made as to whether to classify
the major component of a clump or the entire system. In their magnitude limited sample, GR94a find a mixture of 19% E/S0, 44% Sa-Sm, 13% Irregulars/Mergers, and 25% Peculiar/Unclassified, whereas we find: 32% E/S0, 53% Sa-Sd, and 15% Irr/Peculiar. The agreement clearly depends on the distribution of the Peculiar/Unclassified class of GR94a amongst our classes, but they note that a significant number (i.e. about half) of their “unclassified objects” were classified as S0’s by one of their two classifiers. If so, this would suggest very good agreement between the two samples. Overall, we consider the agreement between this study and those of GL95a and GR94a to be good, providing a consistent picture of the field galaxy mix at faint magnitudes.

Nevertheless, we recognize the need to develop an automated classifier for faint field galaxies. Given the good agreement with the other independent eyeball classifiers of GL95a, we consider our sample to be a suitable representative control set and thus a good training set for Neural Network classifiers. Such automated classifications methods are essential, as the MDS database of WFPC2 images has by now accumulated over 200 fields containing several thousand galaxies. Finally, we note that a full spectroscopic survey is underway, which will help confirm the reliability of these classifications, although we point out that faint E/S0’s and Sa’s, as well as faint Sb’s and Sc’s, are hard to distinguish spectroscopically at moderate redshifts (Keel & Windhorst 1993; Windhorst et al. 1994a, b).

3.5 The WFPC2 Galaxy Catalog down to $I \leq 22$ mag

Table 2 shows the full WFPC2 catalog which contains the basic parameters for the 144 MDS field galaxies from which we draw our Irregular galaxy sample. The random error in the listed magnitudes is ±0.06 mag. The largest error comes from the limited accuracy in the sky-subtraction. Given that large-scale residuals in the sky are of order 0.5%, an average aperture radius of 16 pixels (see Column 15 of Table 2) yields random errors of $\sigma_I = 0.06$ and $\sigma_V = 0.10$ mag for an object with $I = 22.0$ and $V = 23.3$ mag (and a mean sky value of $\mu_I = 21.7$ and $\mu_V = 22.3$ mag arcsec$^{-2}$). For the $(V - I)$ color, this implies a random error of ±0.12 mag.

More information about the objects in Table 2, such as their scale-lengths, is given by and Ratnatunga et al. (1995). A discussion of the scale-lengths of MDS galaxies is also given by Mutz et al. (1994) as function of redshift, and by CRGINOW and Im et al. (1995a) as function of apparent magnitude.
The classifications in Table 2 are listed according to Hubble class as defined above. For the remainder of this paper, the Hubble classifications that we assigned to the individual WFPC2 galaxies were binned into three classes: E/S0 (compact), Sabc (early-disk), and Sd/Irr (late-disk) plus Peculiar galaxies. The Sd’s were grouped together with Irr’s so as to obtain roughly equal numbers in each of the three categories.

4 Global properties of the Late-type HST galaxies

Without complete redshift information, we cannot distinguish between genuine Irregular galaxies of low intrinsic luminosity at lower redshifts and normal galaxies which have developed an irregular appearance, perhaps due to merging or a violent asymmetric burst of star formation at moderate to large redshifts. The rather low mean redshifts observed in the field galaxy redshift surveys (BES; Colless et al. 1990, 1991, 1993; Cowie et al. 1991; Lilly et al. 1991) imply that only limited luminosity evolution can have occurred in the intrinsically brighter galaxy populations. Hence, those galaxies with highly irregular appearance are more likely to be intrinsically low-luminosity systems with inherent irregular morphology, or intrinsically low-luminosity systems undergoing some evolutionary process, or a combination thereof. For the purposes of this paper, however, we exclude the ”Peculiar” galaxies and consider only the ellipticals, early- and late-type spirals plus what we believe to be the genuine Irregulars based primarily on their low apparent central SB and flat light-profiles. The mean apparent central SB for each of these types is: $\mu^E_I = 18.5 \pm 0.2$, $\mu^{Sa}_I = 19.9 \pm 0.2$, $\mu^{Sb}_I = 20.5 \pm 0.2$, $\mu^{Sc}_I = 20.8 \pm 0.3$, $\mu^{Sd}_I = 21.2 \pm 0.3$ and $\mu^{Ir}_I = 21.8 \pm 0.2$ mag/arcsec$^2$. Note that our central SB was measured as the core SB within the central (0.2") ellipse from the RGASP PROF package (Cawson 1983). Quoted rms errors are based on the number of objects binned into each group.

Figure 4 shows the integrated ($V-I$) color versus magnitude for the full sample with the equivalent histogram overlaid. There is little or no distinct trend in color with apparent magnitude nor with morphological type. This is mainly due to the rather small wavelength baseline between the F606W and F814W filters (which however overlap little in wavelength). No Irregulars are seen with colors redder than $(V-I) \simeq 1.5$ mag, and no spirals exhibit colors redder than $(V-I) \simeq 2.0$ mag. The shaded area shows the distribution of Irregulars only, and is not found to be significantly
bluer than that of the overall sample \([V - I] = 1.2 \pm 0.1\) mag. For each individual type the observed mean colors are: \((V - I)_E = 1.4 \pm 0.2\), \((V - I)_{Sa} = 1.2 \pm 0.2\), \((V - I)_{Sb} = 1.1 \pm 0.2\), \((V - I)_{Sc} = 1.0 \pm 0.3\), \((V - I)_{Sd} = 1.1 \pm 0.3\) and \((V - I)_{Irr} = 1.0 \pm 0.2\) mag.

Note that the mean color for the entire sample agrees well with that determined by GR94b when converted to a common filter system (Bahcall, et al. 1994). Figure 5 shows the predicted color versus redshift for the various galaxy types. The local colors for each Hubble type were taken from the models in Windhorst et al. (1994b): \((V - I)_{E/S0} \simeq 1.4 \pm 0.2\), \((V - I)_{Sabc} \simeq 1.1 \pm 0.2\), and \((V - I)_{Sd/Irr} \simeq 1.0 \pm 0.2\) mag. K-corrections for galaxy types E/S0, Sa, Sb, Sc, and Sd/Irr were derived from the present day spectra of Guiderdoni & Rocca-Volmerange (1987, 1988) for the WFPC2 \(V_{606}\) and \(I_{814}\) filters (Myungshin Im 1995, private communication). Based on their likely zero-redshift SED’s, the Hubble classes are expected to have a range in observed \((V - I)\) color of

\[
0.9 < (V - I)_{E/S0} < 2.7, \quad 0.7 < (V - I)_{Sabc} < 2.2, \quad \text{and} \quad 0.3 < (V - I)_{Sd/Irr} < 1.8\]

mag, depending on their exact redshift distribution. Our observed \((V - I)\) color range is generally consistent with these expectations: the only major exception is the surprising abundance of very blue E/S0’s with \((V - I) \lesssim 1\) mag. This may imply an error in our method of classifications (i.e. a preponderance of Blue Compact Dwarf systems mis-classified as E/S0’s), or that the E/S0 population has evolved (Charlot & Bruzual 1991), and/or a strong color-luminosity relation for E/S0 galaxies. Blue E/S0 systems are known to exist in other samples studied with HST (e.g. compact narrow emission-line galaxies, c.f. Koo et al. 1995, see also Im et al. 1995b), but are not normally noted in significant numbers in ground-based field surveys. However, they could have been missed as E/S0’s in typical ground-based seeing. Our sample of E/S0’s has a preponderance of \(r^{1/4}\) light-profiles, even though a non-negligible fraction has rather small scale-lengths \(r_e \lesssim 0.3''\), CRGINOW. A spectroscopic follow-up is needed to reveal the nature of these blue E/S0 classifications.

Figure 6 shows the change in morphological mix from the bright to the faint end of our magnitude range, and shows a distinct increase in the ratio of late-type galaxies to bright spirals plus ellipticals. The percentage mix changes from 36% E/S0, 50% Sabc, 14% Sd/Irr at \(m_I = 20.25\) mag to 28% E/S0, 35% Sabc and 31% Sd/Irr at \(m_I = 21.75\) mag (+6% Peculiar). There is thus a rapid increase in the number of galaxies with late-type morphology towards progressively fainter magnitudes. Our high resolution HST images thus confirm the initial claims that late-type galaxies are responsible for the excess of faint blue objects observed in deep CCD surveys (see §1). The bright end of our
sample compares well to that observed by Shanks et al. (1984), who found 43% E/S0, 45% Sabc and 12% Sd/Irr. Note that galaxies classified as Peculiar (i.e. obvious mergers or images with a bright core coupled with irregular structure) also become more prevalent at fainter magnitudes. This may be a reflection of the increasing volume surveyed at fainter magnitudes making the catalog more complete for rarer types. Alternatively, it could represent an epoch at which brighter field galaxies merged more frequently (Burkey et al. 1994). Clearly, with only 7 galaxies it is impossible to draw substantial conclusions for the Peculiar types other than that they may represent evolution in a small fraction (7 of ∼ 110) of the brighter field population, which appears to become more frequent at fainter magnitudes.

5 The Morphological Galaxy Counts Observed with HST

5.1 The observed counts as a function of galaxy type

Figure 7 shows the more conventional differential galaxy number counts versus I-band magnitude plots for: (a) the total galaxy sample; (b) the elliptical/compact galaxies (E/S0’s); (c) spiral galaxies (Sabc’s); and (d) late-type galaxies (Sd/Irr). The counts of the total sample are linear, suggesting that the sample is indeed representative and complete down to at least I=22 mag, as inferred from Figure 1. However, the slope is slightly steeper (0.43 ± 0.05) than that observed by other groups in the I-band (Tyson 1988; Driver et al. 1994; Burkey et al. 1994, Neuschaefer & Windhorst 1995). This may suggest that the ground-based samples suffer from partial incompleteness or star-galaxy confusion (Neuschaefer & Windhorst 1995, CRGINOW), or more likely that the discrepancy is a reflection of the limited magnitude range covered by our high S/N sample (the ground-based slopes are typically measured out to fainter magnitudes, where the counts are expected to flatten). The individual counts of ellipticals (E/S0’s — Fig. 7b) and early-type spirals (Sabc’s — Fig. 7c) have flatter and comparable slopes of 0.31 ± 0.05 and 0.34 ± 0.05, respectively. The counts of the late-type galaxies, however, exhibit a much steeper and rather unexpected slope of 0.64 ± 0.1 (Fig. 7d), consistent with the Euclidean value. GL95a independently find a similar trend for the fractions of morphological types over a comparable magnitude range. We conclude that the steep number counts of the late-type/Irregular population likely gives rise to the faint blue galaxies observed at faint magnitudes. If this trend continues, this implies that the faint galaxy number counts (and the
Extragalactic Background Light) are largely if not entirely dominated by late-type galaxies. Are these late-type/Irregulars expected, are they evolving, and if so through what mechanism?

5.2 Modelling the Morphological Galaxy Counts

To compare these observations to a series of model predictions, we must adopt a parameterization of the local space density of galaxies for each type, a cosmological model, and quantify any evolutionary processes (Driver et al. 1994). The local space density of galaxies is typically represented by a Schechter (1976) luminosity function (LF), which is derived from a local redshift survey down to some specified magnitude limit.\footnote{The problems associated with magnitude-limited surveys of this kind are discussed in further detail in Marzke, Huchra & Geller (1994) and Driver & Phillipps (1995).} Two of the most recent local redshift surveys are those by Loveday et al. (1992, LPEM) and Marzke et al. (1994b, MGHC). They find significantly different Schechter parameters for the LF of the local populations. Table 3 shows the Schechter parameters derived from these surveys corresponding to the range of galaxy types adopted in this paper (i.e. E/S0, Sabc, Sd/Irr).

Parameters for the LPEM-LF, listed in Table 3, were derived as following: $M_*$ and $\alpha$ for E/S0’s and Sabc’s come directly from the tabulated LF’s for early and late type galaxies. The $\phi_*$ values were measured from Figure 3 of LPEM. As LPEM do not segregate the early-type and late-type Spirals, we arbitrarily divide the population by absolute magnitude, assuming galaxies brighter than $M_B = -18$ are Sabc, and those fainter are Sd/Irr (c.f. Binggeli, Sandage and Tammann 1988). Hence the Sabc LF is truncated (via an exponential cut-off, i.e. $\exp[-10^{0.4(M-M_{\text{Cut}})}]$) at $M_{\text{Cut}} = -18.0$ and $M_* = -18.0$ is adopted for Sd/Irr’s. The slope and normalization for the Sd/Irr’s was then chosen such that the (Sabc+Sd/Irr) LF is consistent with the (Sp/Irr) LF shown in Figure 3 of LPEM. Parameters for the MGHC-LF were taken as the average between the appropriate classes listed in their Table 1 (as suggested by R. Marzke 1995, private communication). However, note that the $\phi_*$ for the total LF (i.e. summed over all types) listed in Marzke et al. (1995a) is twice that quoted in MGHC and, if correct, would alleviate the requirement to renormalize the models at $b_J = 18$ mag.

Table 3 shows that the level of discrepancy between these two local surveys is substantial. Hence, for the sake of completeness we shall use both sets of parameters. The cosmology we adopt
is a standard Einstein-de-Sitter model with $\Lambda = 0$, $\Omega = 1$, $q_0 = 0.5$, and we also adopt $H_o = 50$ km s$^{-1}$ Mpc$^{-1}$. K-corrections for galaxy types E/S0, Sa, Sb, Sc, and Sd/Irr were derived in §4. As our main aim is to find any evolution that may have occurred for each morphological type, we shall assume no-evolution in the model predictions. To convert the $B$-band Schechter parameters to the $I$-band, we adopt $(B-I)_{E/S0} = 2.3$ mag, $(B-I)_{Sabc} = 1.9$ mag, and $(B-I)_{Sd/Irr} = 1.4$ mag (from the models in Windhorst et al. 1994b).

5.3 The Problem of LF-Normalization in Models

An additional problem with faint galaxy models is the question of the magnitude at which to normalize the LF predictions to the observations. The optimal normalization is done at a flux level where the mean galaxy distance is sufficiently large that a homogeneous volume is sampled, but not so large that significant evolution has already taken place. Simply adopting the normalizations derived from the local redshift surveys results in a severe underestimation of the observed galaxy counts already at relatively low redshift, where little evolution is expected. This reflects the faster than Euclidean rise of the observed number counts at bright magnitudes (Shanks 1989). Either strong evolution must be occurring locally (Maddox et al. 1990), or the local redshift surveys are incomplete for galaxies of dwarf-like luminosities (Ferguson & McGaugh 1995), or our location in the Universe is unusually sparse (e.g. due to large scale structure, etc) or a combination thereof. Which of these factors is responsible is not known (see Shanks 1989 for a review).

Figure 8 illustrates the errors associated with faint galaxy models due to this normalization problem. Figure 8 compares the unnormalized no-evolution predictions derived from the two sets of Schechter function parameters listed in Table 3. Both models under-predict the counts for $m_{bj} \simeq 16$ mag, and the predictions extrapolated to fainter magnitudes differ even more significantly from our HST data. Traditionally, most faint galaxy models are normalized to the observations in the range $18 < m_{bj} < 22$ mag (Shanks 1989), which alleviates a good fraction of the discrepancy between the models and observations at fainter magnitudes. The justification is that at $m_{bj} \simeq 20.0$ mag even an $0.1L_*$ galaxy will be at a sufficiently large distance ($z>0.1$; Koo & Kron 1992) that the sampled volume is likely homogeneous and isotropic, but not so great that evolutionary processes

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5Note that if local space is underdense in galaxies, low-luminosity systems will be severely under-represented in bright magnitude-limited surveys, because of the smaller volume over which they are seen (Driver & Phillipps 1995).
have likely already occurred. It is interesting to note that if the counts are normalized at $m_{bJ} \simeq 18$ mag, the no-evolution models remain in good agreement with the observations down to $m_{bJ} \simeq 22$ mag, where the median redshifts is $z \sim 0.25$ (KK92). This suggests that we may indeed live in a sparse local region of space (for $m_{bJ} \lesssim 16$ mag), and is difficult to reconcile with a scenario of strong evolution at low redshifts (such evolution would then have to have switched off between $18 \lesssim m_{BJ} \lesssim 22$ mag, which is rather unlikely). The debate will continue as to the nature of this discrepancy, so here we will adopt the standard normalization at $m_{bJ} \simeq 18.0$ mag (which is valid until $m_{BJ} \simeq 22$ mag), as illustrated by the filled circle in Figure 8, and increase the $\phi_*$ values listed in Table 3 uniformly for all galaxy types by 0.3 dex. We do not mean to imply here that the local surveys are $\sim 50\%$ incomplete (although the Zwicky magnitudes may cause some problems at the faint end of the CfA survey), and emphasize that there is likely a combination of causes for the normalization problem. A recent LF based on a nearby galaxy sample selected in the K-band suggested a significantly larger $\phi_*$ value (Glazebrook et al. 1995) than the optical values in Table 3.

We mention in this context additional constraints from the well known source counts and the cosmological evolution of the radio source population (Windhorst et al. 1984, 1990, 1993; Condon 1989) on the LF normalization problem. The initial steep rise of the radio source counts at Jy levels (with a magnitude slope of $\sim 0.72$ !) also suggest the presence of a “local hole” in the space density of at least radio galaxies, and their strong cosmological evolution is known not to start until $z \simeq 0.3$ (Windhorst et al. 1984, 1990; Condon 1989). Hence, if field galaxies had the same space distribution as radio galaxies, LF normalization is suggested at $0.1 < z < 0.2$, consistent with our normalization at $z \simeq 0.15$. This argument is likely not valid for radio sources with 1.4 GHz fluxes $\gtrsim 10$ mJy, which undergo strong cosmological evolution and are not associated with field galaxies (Windhorst et al. 1990), but quite possibly valid for $\mu$Jy radio sources who also undergo some cosmological evolution (Condon 1989), albeit not as strong and not until $z \gtrsim 0.3$, and merge into the general population of field galaxies at the sub-$\mu$Jy level (Windhorst et al. 1993).

5.4 Model Predictions for the Morphological HST Counts

Figure 7 shows the model predictions from the LF’s of LPEM and MGHC for each morphological type with the normalizations adopted in §5.3. The LF’s of LPEM and MGHC each suggest different
amounts of evolution, when compared to our HST data in Figure 7. The prediction based on
the LPEM-LF (solid lines) appears to suggest a large amount of evolution in the E/S0’s and an
inordinate amount of evolution in the late-type spirals. Alternatively, the MGHC model (dashed
lines) implies that no-evolution is required in the E/S0 and early-type spirals. LPEM and MGHC
both note that the LPEM-LF is incomplete for early-type galaxies at the higher redshifts in the
LPEM sample, which could explain the large discrepancy between the two predictions for E/S0’s.
If true, then our HST data for E/S0’s and Sabc’s appear to be consistent with the no-evolution
prediction of the MGHC-LF (bearing in mind that the increased normalization of the models at
$mb_j \simeq 18$ mag ($m_I \simeq 16$) is still unexplained, although possible reasons are given above). The
dashed lines on Figure 7 represent the locally normalized predictions.

For late-type spirals/Irregulars, the predictions are drastically different between the two models.
This highlights the large uncertainty with which the faint end of the local field LF is known (Driver
& Phillipps 1995), and how important this part of the LF is in faint galaxy models (Driver et al.
1994; Driver 1994). LPEM find a flat faint-end slope $\alpha \simeq -1.0$, and MGHC find a much steeper
slope $\alpha \simeq -1.5$. They actually find a slope of $\alpha \simeq -1.8$ for the Sm-Im types alone, so in Table
3 we have averaged the slopes found by MGHC for Sc-Sd and Sm-Im types to generate a realistic
Sd-Im slope (R. Marzke 1995, private communication). Such a steepening of the faint end slope is
mostly dominated by the late-type population (Binggeli, Sandage & Tammann 1988 and MGHC),
and has been favored in many recent faint galaxy models (e.g. Koo & Kron 1992; Koo, Gronwall &
Bruzual 1993; Driver et al. 1994; Ferguson & McGaugh 1995; Phillipps & Driver 1995). However,
these models typically remain inconsistent with the faint redshift surveys (e.g. Colless et al. 1990,
1991, 1993; BES; Cowie, Songalia & Hu 1991; Glazebrook et al. 1995b, and references therein).

The prediction based on an LPEM-LF requires an increase in the galaxy number density at
$m_I = 21.75$ of $\sim 1$ dex, while the prediction based on the MGHC-LF requires $\sim 0.5$ dex. To obtain
a crude estimate of the amount of evolution required, we can equate these number density increases
to volume increases, and calculate the magnitude limit of these additional volumes (assuming that
galaxy numbers are preserved). The difference between this magnitude limit and that of our sample
yields an estimate of the amount of luminosity evolution required in the entire population to match
the observed counts (i.e. $N(m) \propto V(m) \propto L^{\frac{1}{2}} \Rightarrow \Delta m \propto \frac{1}{0.6} \log(\frac{V_2}{V_1})$). This yields luminosity
increases of $\Delta mLPEM \sim 1.7$ and $\Delta mMGHC \sim 0.8$ mag.
The $M_*$ value adopted for the LPEM-Late-type/Irregulars, would imply that objects with $m_I \sim 21.75$ are at $z \lesssim 0.4$ (or $\lesssim 6$ Gyrs in lookback-time). Over this timescale, a typical isolated starburst event will fade by $\simeq 1.8$ mags (see e.g. Fig. 3 of Wyse 1985 which is based on a formation starburst within a rapidly condensing gas cloud). However, if there is a significant underlying population, the total fading of the whole galaxy’s luminosity will change by considerably less, dependent on the luminosity ratio of the new to old populations $\sim 6$ Gyrs after the new burst. The implication is that for a fading of $\Delta m \sim 1.8$, a global starburst is required with strength comparable to that of the galaxy’s initial formation (or the sum of all previous starbursts). That such events have occurred in the entire late-type/Irregular population over the past 6 Gyrs seems highly improbable, although we note that the star-formation mechanisms of late-types are poorly known (see Hodge 1989, in which evidence for a wide range of star-forming timescales in local group members is discussed).

Alternatively, the MGHC-based model, requires a luminosity evolution of $\Delta m \sim 1.8$, but only for $\sim 15\%$ of the population (from consideration of luminosity conservation). This would then imply that based on a MGHC-based model we only require a major global starburst event in 15% of the late-type population over the past 6 Gyrs. Of course other evolutionary scenarios exist, but this crude calculation is indicative of the comparative amounts of evolution required to match the two local LF models to our HST observations.

Figure 9 shows the predicted $B$-band redshift distributions at $m_I \sim 21.75$ mag ($\approx m_{bJ} \sim 23.5$ mag), compared to the faint redshift surveys of Colless et al. (1993) and Glazebrook, K., et al. 1995b. The predicted redshift distributions have been scaled up to match the observed distribution. (Note that this is somewhat misleading, as neither LF model matches the $B$-band number counts at this magnitude, but it is easier to compare the rescaled predictions to the shape of the observed redshift distribution). The form of the LPEM-LF matches the overall distribution closely, while the MGHC-LF both over-predicts the number of low redshift galaxies and under-predicts the number of high redshift galaxies. Given that luminosity evolution will shift the peak of the redshift distribution towards higher redshifts, and that some evolution is required to match the steep counts, then the distribution towards lower redshifts of the no-evolution MGHC-LF is not unexpected. Of greater concern is the lack of $z > 0.5$ objects predicted by MGHC (due to the low $M_*$-values in their E/S0 and Sabc Schechter functions, see Table 3). The only way to simultaneously reconcile the
redshift distribution and the morphological counts is through an evolutionary scenario in which the intrinsically bright late-types are undergoing evolution at $z \geq 0.5$. Such models are explored in more detail in Phillipps & Driver (1995).

6 The Morphology of Irregular Galaxies in the HST Sample

Figure 10 shows $V$- and $I$-band grey scale images and contour plots for each of the 16 Irregulars and the 7 Peculiar types, as described in the caption. Qualitatively, the majority of this sample is characterized by irregular shaped outer light-profiles and in many cases a complex nucleus consisting of a number of higher SB regions. Objects 6, 18, 33, 38, 39, 44, 54, 80, 86, 95, 98, 100, 113, 122, and 126 represent the (15) genuine Irregulars, and objects 29, 65, 73, 74, 83, 104, and 128 represent the (7) "Peculiar" galaxies. The Irregulars appear to fall into two categories: (1) those which appear inert, and (2) those which contain multiple cores. Objects 6, 38, 44, 54, 113, and 126 are good examples of multiple-core objects and comprise about $\sim 40\%$ of the Irregular sample. Such complex cores may imply active star-formation, e.g. via spontaneous or merger induced starbursts. Objects 86 and 100 appear to have strong core structure but in reality this is a manifestation of their much brighter apparent magnitude. Their apparent central SB is significantly lower than that of other galaxies of comparable flux (c.f. Table 2). Both galaxies also show some evidence of merging, but the central regions appear relatively undisturbed. Objects 54, 80, 122, and 126 also show evidence for a close companion which may be responsible for their multiple core structure. If a multiple core is indicative of currently ongoing starformation (i.e. evolution), then both spontaneous (i.e. no obvious merger) and merger-induced starbursts appear to occur. Nevertheless, half the Irregular population (objects 18, 33, 39, 86, 95, 98, 100, 129) appears relatively inert with low SB-cores and with extended irregular shaped light-profiles. This suggests that both merger-induced evolution and/or active star-bursts, and a higher than anticipated density of local dwarfs contribute to the faint blue galaxy excess at $m_I \simeq 22$ mag. The density of Irregular galaxies alone (i.e. $\sim 50\%$ of the Sd/Irr population) appears to be inconsistent with the LPEM-LF.

If all the “apparently-evolving” galaxies (i.e. $\sim 50\%$) were removed from Fig. 7d, this would reduce their observed surface density by only 0.3 dex, and our HST data would still remain inconsistent with the LPEM-LF model by 0.7 dex! That is, not only is the LPEM-LF model inconsistent
with our full HST Sd/Irr sample, but it is also inconsistent with the inert looking HST galaxies alone. Such evidence argues convincingly for a MGHC-LF, where the faint end slope of the field LF is steeper ($\alpha \gtrsim 1.5$) than the often assumed value ($i.e., \alpha \sim 1.0$). Hence, it appears that a combination of evolution and a steep faint end LF is responsible for the FBG’s. The mode of evolution is still unclear, but both mergers and isolated systems with multiple cores are evident in roughly equal numbers in our HST images.

7 Summary and Conclusions

We presented a complete sample of 144 HST/WFPC2 field galaxies from the Medium Deep Survey in the magnitude range $20.0 \leq m_I < 22.0$ mag, with the goal of implementing a full spectroscopic follow-up for all galaxies listed. We have begun such a long-term program at the MMT (Driver et al. 1995b). After classification of these galaxies by eye — using both the WFPC2 $V+I$-morphology and light-profiles — we compare the global properties of Irregulars and late-type spirals to those of ellipticals and early-type spirals. We find little color difference between early and late-type spirals with mean $(V - I)$ color’s of $1.1 \pm 0.2$ mag. The ellipticals have marginally redder colors with a mean $(V - I) = 1.4 \pm 0.2$ mag. An unexpected number of blue E/S0 systems are identified with $(V - I) < 1.0$ mag. These could possibly be compact narrow emission-line galaxies (c.f. Koo et al. 1995). No Irregulars are seen with colors redder than $(V - I) = 1.5$ mag. Following the classification method of Forbes et al. (1994), we find that the galaxy types can be reasonably well separated by plotting their Concentration Index [C.I. = core SB minus total magnitude] versus total magnitude.

We present the differential $I$-band galaxy number counts as a function of morphological type, excluding those galaxies defined as "Peculiar", and conclude that the slopes for the ellipticals and early-type spirals fall at best marginally above the expected prediction from a no-evolution models based on conventional Schechter functions and a standard cosmology. This therefore implies that strong evolution in the luminous galaxy population is relatively uncommon down to $m_I = 22.0$ mag ($i.e., z \sim 0.5$), as also inferred from the faint galaxy redshift surveys and studies of Lyman-$\alpha$ absorbers at $z \lesssim 1$ (Steidel et al. 1995).

The late-types/Irregular galaxies, however, follow a near-Euclidean slope of $(d\log(N)/dm) = 0.64 \pm 0.1$, indicating either strong evolution in this population, local inhomogeneity, and/or a higher
than expected local space density of dwarf galaxies, or a combination thereof. From detailed no-
evolution predictions based on the local LF’s of LPEM and MGHC, we conclude that a flat LPEM-
LF ($\alpha \simeq -1.0$) is inconsistent with our HST data, and that a steep MGHC-LF ($\alpha \gtrsim 1.5$) coupled with a substantial amount of evolution ($\Delta m \sim 1.8$ mag in only $\sim 15\%$ of the population) is more consistent with the data. Examination of the Irregulars alone reveals that $\sim 40\%$ show evidence of interactions or multiple core structure, which suggests relatively strong and recent evolution in a large fraction of the late-type population. This work will continue with the study of a deeper field from a 24-orbit HST exposure (Driver et al. 1995a), and in a systematic spectroscopic follow-up of the entire current sample (Driver et al. 1995b).

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Tables

Table 1a — Field positions and exposures times for selected MDS fields.

| Field Name (J2000) | RA (deg) | DEC (deg) | l' | b' | Exposure time | No of Orbits | A_{606} | A_{I_{614}} |
|-------------------|----------|-----------|----|----|--------------|--------------|---------|------------|
| ueh0              | 00:53:23.2| +12:33:58 | 123.68 | -50.30 | 8700 | 6300 | 5 | 3 | 0.13 | 0.10 |
| uim0              | 03:55:31.6| +09:43:34 | 179.83 | -32.15 | 8800 | 5200 | 12 | 6 | 0.31 | 0.23 |
| uop0              | 07:50:47.1| +14:40:44 | 206.07 | 19.63  | 7200 | 4200 | 5 | 2 | 0.04 | 0.03 |
| usa2              | 17:12:23.2| +33:35:49 | 56.72  | 34.25  | 5400 | 6300 | 3 | 3 | 0.08 | 0.06 |
| ux40              | 15:19:41.2| +23:52:06 | 35.78  | 56.51  | 3300 | 7500 | 2 | 4 | 0.10 | 0.07 |
| uy40              | 14:34:48.7| +25:08:02 | 33.87  | 66.75  | 5200 | 6000 | 6 | 6 | 0.06 | 0.04 |

Table 1b — Statistics and detections for the selected MDS fields.

| Field | \(K_V\) | \(K_I\) | 2\(\sigma\)\(\mu_V\) | 2\(\sigma\)\(\mu_I\) | No of Detections |
|-------|---------|---------|---------------------|---------------------|------------------|
|       |         |         |                     |                     | WFC2 | WFC3 | WFC4 |
| ueh0i | 33.23   | 32.45   | 23.8                | 23.4                | 7    | 11   | 7    |
| uim0i | 32.53   | 31.48   | 24.2                | 23.4                | 8    | 6    | 5    |
| uop0i | 33.09   | 32.45   | 24.3                | 23.3                | 5    | 10   | 12   |
| usa2i | 33.33   | 32.45   | 25.0                | 24.3                | 6    | 7    | 14   |
| ux40i | 33.23   | 32.32   | 23.5                | 24.1                | 9    | 6    | 9    |
| uy40i | 32.53   | 31.64   | 24.7                | 23.9                | 7    | 12   | 3    |
| Total |         |         |                     |                     | 144  |       |      |

Note: \(K_V\) and \(K_I\) are the calibration constants for the V and I fields, respectively, with the exposure time and a scaling factor incorporated (i.e. observed mag = \(K - 2.5 \log ADU_{tot}\)).

Table 2 — See [http://www.phys.unsw.edu.au/~spd/bib.html](http://www.phys.unsw.edu.au/~spd/bib.html)

Table 3 — Schechter function parameters for the LF’s of different galaxy classes.
| Survey  | Type  | $M_*$ | $\alpha$ | $\phi_*$ |
|---------|-------|-------|----------|----------|
| LPEM    | E/S0  | −21.2 | +0.2     | $4.00 \times 10^{-4}$ |
|         | Sabc  | −20.9 | −0.8     | $1.00 \times 10^{-3}$ |
|         | Sd/Irr| −18.5 | −1.1     | $7.00 \times 10^{-4}$ |
| MGHC    | E/S0  | −20.5 | −0.9     | $1.14 \times 10^{-3}$ |
|         | Sabc  | −20.3 | −0.8     | $1.74 \times 10^{-3}$ |
|         | Sd/Irr| −20.3 | −1.5     | $2.50 \times 10^{-4}$ |
Figures

**Figure 1a (upper panel)** — Signal-to-noise ratio versus magnitude for the *isophotal* detection stage. **Fig 1b (lower panel)**, as Fig 1a, but for the *aperture* photometry stage. The horizontal line represents the minimum detectable signal-to-noise ratio from the detection criterion, and the vertical lines represents the selected magnitude range. Only those galaxies included in the final sample are shown here. The dashed line is the non-cosmological relation between signal-to-noise ratio versus aperture magnitude expected for a single non-evolving galaxy.

**Figure 2** — A selection of greyscale plots and major-axis light-profiles used for the eyeball classifications. The greyscale plots are plotted as log(Intensity) from $\mu_I = 21.0$ mag/arcsec$^2$ to sky. Major-axis profiles are shown as SB vs. radius ($r$) and SB vs. $r^{1/4}$. A representative galaxy for each morphological class is shown at comparable magnitudes ($m_I \sim 21.5$ mag). Only the $I$-band data is shown here, but equivalent $V$-band data was also used in the classification process.

**Figure 3** — A comparison between the morphological classification and the concentration of a galaxy’s light. The concentration index (C.I.) is the apparent central SB or core aperture magnitude minus the total magnitude. A low value of the C.I. suggests that the majority of the light is concentrated towards the center. The ellipticals form a clearly distinct population, but the late-types are less well distinguished by this method, as expected.

**Figure 4** — The $(V-I)$ color for the sample shows little or no trend with apparent I-band magnitude or morphological type, although few Irregulars and late-types are seen with colors redder than $(V-I) = 1.5$. Note the non-negligible fraction of blue galaxies classified as E/S0 which have $r^{1/4}$ light-profiles. Also shown is the histogram of the $(V-I)$ data for the entire sample and for the Irregulars alone (shaded area).

**Figure 5** — The expected relation between color and redshift for the Hubble sequence, using no-evolution, but simple K-corrections derived from the present day spectra of Guiderdoni & Rocca-Volmerange (1987, 1988) for the WFPC2 $V_{606}$ and $I_{814}$ filters (Myungshin Im 1995, private communication).
Figure 6 — The number of galaxies observed for each type as a function of $I$-band magnitude. This shows a rapid increase in the numbers of Irregular galaxies over the conventional spirals and ellipticals. The initial mix of 36% E, 50% Sabc and 14% Sd/Irr at $m_I = 20.25$ mag becomes 28% E, 35% Sabc and 31% Sd/Irr at $m_I = 21.75$ mag. Typical errors in these percentages are $\sim 5-8\%$. If this trend continues, then late-types and Irregulars will make up the bulk of the galaxy population observed at fainter magnitudes.

Figure 7 — Differential galaxy number counts for: (a) our complete HST sample; (b) for E/S0 galaxies; (c) for Sabc galaxies; and (d) for late-type galaxies (Sd/Irr). The slope of the overall counts is consistent with data from other groups (see Fig. 8) and implies that our sample is complete at least down to $I=22.0$ mag. The ellipticals and spirals (panels b and c) have shallower slopes. The model predictions are for a LPEM-LF model (solid lines) and a MGHC-LF model (dashed lines). For panels b and c, the MGHC-LF models agree well with our observed HST counts using no-evolution and a standard cosmology. However, the late-type galaxies follow a much steeper slope, indicating that either they are more local and less affected by cosmology, and/or that they are undergoing a significant amount of evolution. The model lines are assuming two alternate luminosity functions and no-evolution.

Figure 8 — The differential galaxy number counts in the $b_J$-band from various sources listed in the figure. The model lines show predictions using the non-evolving LPEM-LF (solid line) and the MGHC-LF (small dashed line). These model lines are unnormalized (i.e. as locally determined). Not only do the two models give dramatically different predictions at faint magnitudes, but also does neither model match the counts fainter than $m_{b_J} \simeq 17$ mag, suggesting local evolution, local selection effects, and/or local inhomogeneity (see text). Most galaxy models are normalized to the counts at $18.0 < m_{b_J} < 22.0$ mag (c.f. Shanks 1989, see §5.2). Here we normalize at $m_{b_J} \simeq 18$ mag, as indicated by the single solid circle, which implies a 0.3 dex increase of the local LF. The normalized Marzke-LF model is shown as a large dashed line.

Figure 9 — The predicted redshift distribution for $m_{b_J} = 23.5$ mag compared to the data of Colless et al. (1993) and Glazebrook et al. (1995). The model distributions are scaled to reflect the discrepancy between the observed and predicted number counts at $m_I \sim 23.5$ mag. The shaded areas represent the contribution from the late-type/Irregulars population.
Figure 10 — For each of the 16 Irregular and 7 Peculiar galaxies a section of six panels are shown. Each panel represents a 5×5” box. The panel columns represent: the $I$-band image; a contour plot of the $I$-band image smoothed with a 0.2” FWHM Gaussian; the smoothed $I$-band image; and the corresponding plots in the $V$-band. For the first and third columns the data is displayed from $I_\mu = 22.0$ to $I_\mu = 25.0$ mag/arcsec$^2$. In the second column, each contour represents an increase in 0.5 mag/arcsec$^2$ in SB starting at $I_\mu = 24.5$ mag/arcsec$^2$. The fourth and sixth columns are displayed from $V_\mu = 23.0$ mag/arcsec$^2$ to sky, and the contours for the fifth column are again 0.5 mag/arcsec$^2$ intervals in SB, but starting at $V_\mu = 25.5$ mag/arcsec$^{-2}$. 