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THE MORPHOLOGY OF FAINT GALAXIES IN MEDIUM DEEP SURVEY IMAGES USING WFPC2

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ABSTRACT

First results from *HST* Medium Deep Survey images taken with WFPC2 demonstrate that galaxy classifications can be reliably performed to magnitudes $I_{814} \lesssim 22.0$ in the F815W band. Published spectroscopic surveys to this depth indicate a mean redshift of $\bar{z} \sim 0.5$. We have classified over 200 galaxies in nine WFPC2 fields according to a basic morphological scheme. The majority of these faint galaxies appear to be similar to regular Hubble-sequence examples observed at low redshift. To the precision of our classification scheme, the relative proportion of spheroidal and disk systems of normal appearance is as expected from nearby samples, indicating that the bulk of the local galaxy population was in place at half the Hubble time. However, the most intriguing result is the relatively high proportion ($\sim$40%) of objects which are in some way anomalous, and which may be of relevance in understanding the origin of the familiar excess population of faint galaxies established by others. These diverse objects include apparently interacting pairs whose multiple structure is only revealed with *HST*'s angular resolution, galaxies with superluminous star-forming regions, diffuse low surface brightness galaxies of various forms, and compact galaxies. These anomalous galaxies contribute a substantial fraction of the excess counts at our limiting magnitude, and may provide insights into the "faint blue galaxy" problem.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: general — galaxies: peculiar — galaxies: structure — surveys

1. INTRODUCTION

The Medium-Deep Survey (MDS) is an *HST* Key Project which relies exclusively on parallel observations of random fields taken with the Wide Field and Planetary Cameras (WFCs). The goals of the MDS include the statistical studies of the properties of a large sample of faint stars and galaxies. The prerefurbished *HST* MDS results suggested the enormous potential of high-resolution imaging as a major tool in tackling one of the outstanding problems in observational cosmology: the nature of the abundant population of faint blue galaxies (for a review, see Koo & Kron 1992). Ground-based observations have thus far been unable to discriminate between hypotheses based on a fading population of dwarf galaxies (e.g., Broadhurst, Ellis, & Shanks 1988; Cowie, Songaila, & Hu 1991; Babul & Rees 1992) and those based on galaxy merging (Rocca-Volmerange & Guiderdoni 1990; Broadhurst, Ellis, & Glazebrook 1992). Recent high-resolution CFHT images (Colless et al. 1994) suggest that many of the most active star-forming systems identified spectroscopically are multiple, lending weight to the merger hypothesis. Furthermore, prerefurbishment MDS observations (Griffiths et al. 1994) indicate a deficit of large galaxies (half-light radius $\gtrsim 1''.0$) and an excess of compact galaxies at or near the *HST* resolution limit. Although progress has been made in this area, the conclusions must remain preliminary, particularly in view of the small samples examined to date.

After the successful refurbishment mission, MDS observations have continued with WFPC2, and the main purpose of this *Letter* is to demonstrate that the full high-resolution potential of *HST* for faint objects has now been realized. For the first time it is possible to explore the *morphological* nature of faint galaxies.

In this short *Letter*, we show that morphologies can be studied with a precision adequate for classification on the normal Hubble scheme to a limiting magnitude of $I_{814} \sim 22.0$ mag.[1] Cruder information (e.g., scale lengths) can be determined to considerably fainter limits. Unlike the prerefurbished images, our morphological classifications for the current sample are not based on parametric fits to the objects, nor do they rely on any deconvolution technique.

The MDS team is in the process of correlating the morphological properties of *HST*-selected galaxies with redshift and star formation rates derived from ground-based follow-up spectroscopy and photometry. In this *Letter*, we present a first analysis of the classification of ~ 200 galaxies to $I_{814} = 22.0$ mag in nine MDS fields taken early in the cycle 4 observing cycle. Redshift surveys of other fields to this depth have been undertaken by Lilly (1993) and Tresse et al. (1993) and indicate a median redshift $\bar{z} \simeq 0.5$ with a high fraction of objects within the range $0.4 < z < 0.7$. Consequently, we expect our sample to be representative of the field galaxy population at a look-back time of $\simeq$5–7 Gyr ($H_0 = 50$ km s^{-1} Mpc^{-1} assumed throughout).

2. OBSERVATIONS AND SAMPLE SELECTION

MDS observations in cycle 4 of the *HST* General Observation program began on 1994 January 24 and are scheduled when suitable opportunities arise and primary observations permit. Typical MDS observations range from 600 to 2000 s per exposure and may consist of 1–20 exposures of the same field. Parallel exposures may be registered or not, depending on the needs of the observer using the primary *HST* instrument. In some cases, up to 12,000 s have been accumulated in a single pointing. Following *HST* refurbishment, the improvement in spatial resolution and read noise of WFPC2 have resulted in 4–5 times better sensitivity for the faintest galaxies, which are smaller in size than the extended halo of the aberrated WF/PC PSF.

Cycle 4 MDS observations use preferentially two filters: F606W, somewhat redder and broader than Johnson *V*, and F814W, close to Kron-Cousins *I* (Burrows 1994). These filters have been chosen to maximize the sensitivity for typical galaxies at intermediate redshifts ($z \sim 0.5$). Magnitudes in these filters are referred to as V_{606} and I_{814}, respectively.

A typical WFPC2 MDS field contains 50–400 detectable sources within the three WFCs to a limiting magnitude of $I_{814} = 24$–26 depending on the total exposure. Clearly, the precision with which morphological properties can be ascertained is a function of both size and apparent magnitude. For this initial study, we inspected nine WFC fields with F814W exposure times greater than 2000 s observed in the first 2 months of the MDS cycle 4 program. In order to facilitate comparison with extant ground-based data we have constructed a sample of 213 sources with magnitude $I_{814} < 22.0$ in an aperture of 3".0 diameter. This catalog of faint sources was constructed by smoothing the WFC images from the nine deepest MDS fields to an effective 1" "ground-based" resolution and applying the Cambridge Automated Plate Measurement (APM) image detection algorithm with typical isophotal surface brightness limits. The aim was to compile a catalog that is very similar to those used in ground-based surveys, but returning to the original WFC images for the morphological classifications. The number-magnitude counts for this selection agree closely with published ground-based work and indicate completeness to $\sim I_{814} \simeq 23.5$. However, morphological classification was only performed to $I_{814} = 22.0$, the current limit at which statistical redshift distributions are available (Lilly 1993; Tresse et al. 1993).

[1] For a typical galaxy in our sample, Kron-Cousins I and I_{814} are related by $I_{814} - I = 0.1$ mag (Holtzman et al. 1994). For comparison with the redshift sample of Lilly (1993), $I_{814} = I_{AB} - 0.38$.

3. MORPHOLOGICAL CLASSIFICATION OF FAINT FIELD GALAXIES

3.1. *Quality of Morphological Classification*

Most of the galaxies seen in the WFPC2 images have a familiar "normal" appearance. The morphological information available for these galaxies depends mostly on their SB distribution and total exposure time. The limiting SB of observable features is comparable to that on deep ground-based plates, but with the overwhelming advantage of 0".1 resolution. For a 2000 s integration in F606W, the single-pixel SB sensitivity is 25.0–25.5 mag arcsec^{-2}, depending on the level of the sky background. Photon noise from the sky is generally the largest contribution to the noise, except at the ecliptic poles. The limit extends $\sim$1 mag fainter for the longest exposures obtained thus far in cycle 4. This sensitivity is sufficient to see structural features such as grand-design spiral arms, bars, and rings, at least out to moderate redshifts (0.4–0.7). On the other hand, small-scale details such as flocculent spiral structure are hard to detect because of the limited number of resolution elements.

For galaxies with isophotal diameters $\gtrsim 3''$, the level of detail visible is sufficient for a fairly accurate morphological classification. This is illustrated in Figure 1 (Plate L8), where F814W and F606W images are shown side-by-side for 10 galaxies with $19 < I_{814} < 22$. At smaller sizes (1"–2" diameter), morphologies are harder to establish (cf. Fig. 2 [Pl. L9]) but it is still possible in many cases to distinguish spheroidal, spiral and irregular galaxies from compact or low surface brightness examples. Possibly merging systems (multiple nuclei, close companions, etc.) can be readily identified at this limit.

3.2. *Summary of Classifications*

The distribution of types for the galaxies in our sample are summarized in Table 1 as classed independently by two of the authors (J. P. H. and R. S. E.). R. S. E. classed several galaxies as "nucleated diffuse sources" and placed these in the unknown category, whereas J. P. H. was willing to assign these as S0s or, in some cases, early-type spirals. J. P. H. was able to

TABLE 1

DISTRIBUTION OF MORPHOLOGICAL TYPES

Type of Galaxy	Distribution (%)
Early (E/S0)	17
Spirals (Sa–Sm)	39
Irregulars	1
Unclassified & Peculiar	20
Mergers	10
Compact Objects	13

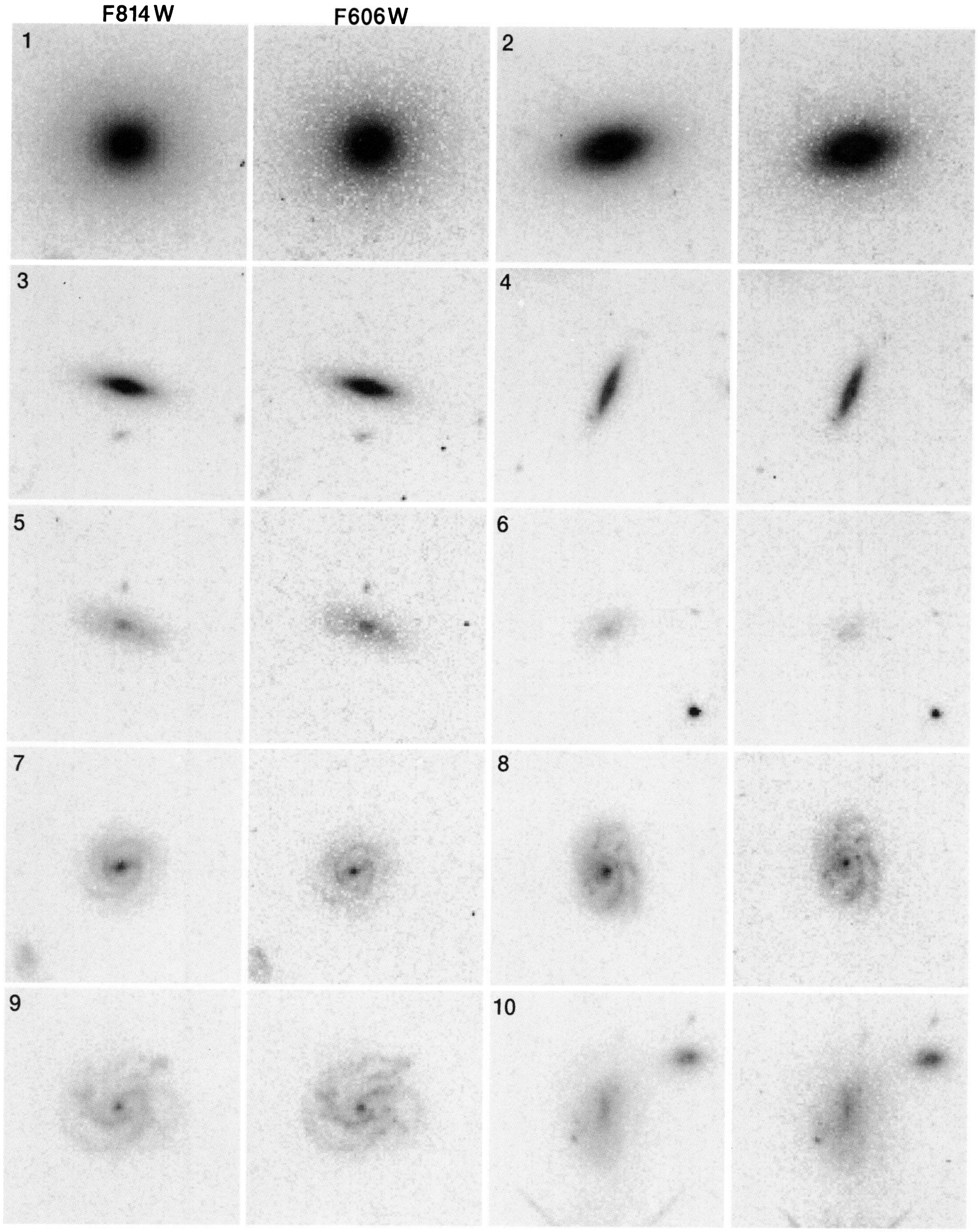

FIG. 1.—Galaxies of large angular size (isophotal diameter $\gtrsim 3''$) for which detailed classification is possible. Galaxies are arranged two per row, with the first and third columns contain the I_{814} images, the second and fourth the corresponding V_{606} images. Each box is 10" wide. Galaxies are ordered according to their morphological type: in order, E0, E4, S0$^+$, Sa, SAa, Sb, SBbc(r)R, Scd, SXcd, and IBm. Total magnitudes range from 18.8 to 22.5. The faintest level of detail visible in the figure corresponds to a surface brightness of $I_{814} = 23.6$ mag arcsec^{-2} and $V_{606} = 24.8$ mag arcsec^{-2}.

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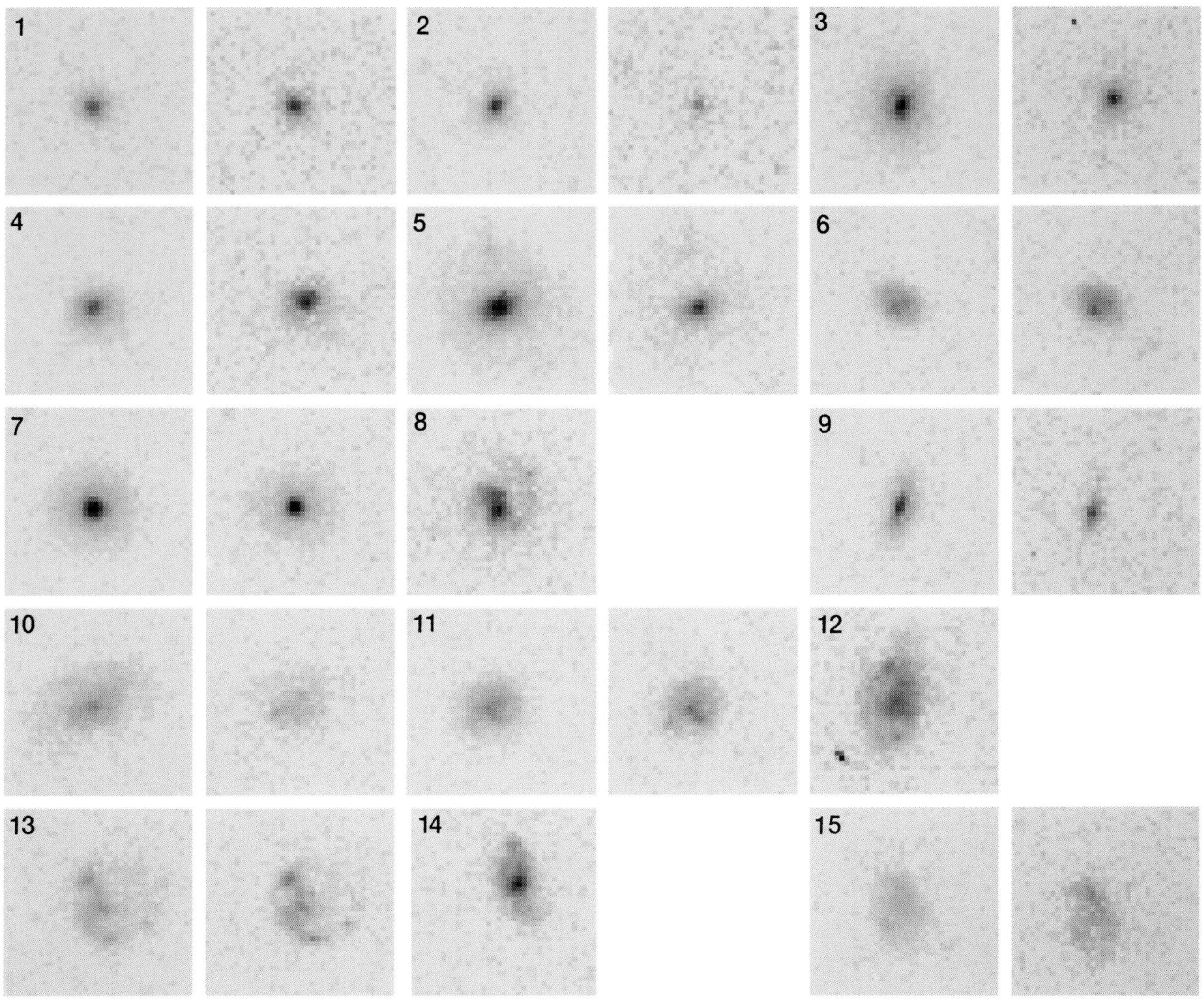

FIG. 2.—Galaxies of smaller angular size (1″–2″.5), for which an approximate classification is nonetheless possible. The arrangement is similar to that of Fig. 1, with three galaxies per row. Each box is 4″ wide. Magnitudes range from I_{814} = 21.5 to 23.5 mag. The stretch is the same as in Fig. 1. Types are E (*first row*), S0 and SB0 (*second row*), S0a–Sa (*third row*), Sb–Scd (*fourth row*), and Sdm–Sm (*fifth row*).

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subclassify spirals into early and late-types and found roughly equal proportions.

At our $I_{814} = 22.0$ limit, the galaxy counts already exceed the no evolution prediction by a factor of 50%–100% so it is instructive to compare the results in Table 1 with the expected mix for a standard model based on local luminosity functions (LFs), *k*-corrections and morphological mix (cf. King & Ellis 1985). We adopted separate Schechter LFs for early- and late-type systems (Loveday et al. 1992), with absolute normalizations chosen to match the observed mix in the $B < 16.5$ sample of Peterson et al. (1986). As expected, an I_{814}-selected sample with a mean redshift $z \simeq 0.5$ introduces only a small bias to later types from that observed in B locally. The mix predicted for $I_{814} < 22.0$ in the absence of evolution is E+S0: 24%, Sp: 71%, Irr: 5%. This is a reasonable approximation to the distribution of *normal* objects observed. However, there appears to be a far higher proportion of unclassifiable, abnormal and compact sources than could reasonably be found in local samples. A more detailed exposition on this point is under preparation (Ellis et al. 1994).

4. GALAXIES WITH UNUSUAL PROPERTIES

Although a high proportion of the galaxies appear normal, we are struck by the large number which are unusual in appearance, SB distribution or other properties. Examples are shown in Figure 3 (Plate L10), where the galaxy numbers used below are given. In order to compare with local samples, we note that in the subset of 191 $B < 17$ galaxies from the sample discussed by Peterson et al. (1986), for example, only 12 were classed as "peculiar" and a further 4 as "Irr." Even allowing for misclassed Sds in that sample, the total proportion of non-regular systems is only 13% (cf. 44% in Table 1).

4.1. *Merging, Interacting, and Paired Galaxies*

Among the objects in the sample, 20 are in pairs/triplets with separation smaller than 3″. For a typical density of 12 objects/WFC chip, this separation corresponds to a random pairing probability of 5%. For a purely random distribution, about 7 objects would be expected to be in pairs. Thus, about half of these pairs might be true physical associations.

At least two systems deserve specific mention. The first, No. 1, is a string of small galaxies lying ~3″ from one another, which looks very much like Hickson's group No. 34 (Hickson 1993). The other, No. 2, is a pair of galaxies with a separation of 1″.4, with a third, fainter galaxy at approximately the same distance.

In addition, more than 15% of the galaxies in the sample have one or more satellites, or close neighbors (less than 2″.5 away), which are too faint to be included in our sample. Magnitudes for these satellites range between $I_{814} \sim 23$ and the detection limit of ~26 for the deeper exposures. The four examples shown in Figure 3 (Nos. 3–6), span the observed ranges in separation and magnitude difference between primary galaxy and satellites. A more precise evaluation of the statistical properties of satellite galaxies will require a larger, more objectively defined sample.

Finally, several galaxies appear to have evidence of interaction and perhaps merging, in the form of multiple nuclei or broken-up appearance within a common envelope. Shown in Figure 3 are the most unusual ones: No. 7 has two equally bright nuclei; No. 8 has a barely visible bridge connecting the large irregular and its faint companion; and No. 9 has a low surface brightness envelope.

4.2. *Galaxies with Prominent Bright Knots*

In a few cases, very bright knots—presumably star-forming regions—dominate the galaxy light. Perhaps the most striking is galaxy No. 10, which shows an extended red object surrounded by four compact bluer knots arranged on a circle of $\simeq$0″.7 radius. The three knots to the lower right are connected to a fainter component by a low-level arc of emission. Spectroscopy at the William Herschel Telescope has shown that this galaxy has a spectrum similar to that of a classical H II region, with a redshift of $z = 0.6881 \pm 0.0003$; the blue components thus seem to be supergiant H II regions undergoing starbursts (Glazebrook et al. 1994).

Two other peculiar galaxies, Nos. 11 and 12, consist of several luminous knots within a common envelope, with morphological characteristics somewhat reminiscent of those in Arp 56, Arp 143, and Arp 145 (Arp 1966). The first is one of the apparently largest galaxies in any of our fields, with a total isophotal diameter of 6″.5 at 23 mag arcsec^{-2} and a total integrated $I_{814} \sim 19.3$ mag. The central nucleus reaches a surface brightness in I_{814} of 19.4 mag arcsec^{-2}, which is somewhat high for an irregular galaxy. Individual peaks have magnitudes between $I_{814} = 22.5$ and 24.0, and sizes ranging from barely resolved to 0″.5. The large knot to the upper right, which could be a separate companion galaxy, has $I_{814} = 22.2$ mag and a diameter of 1″.2.

These objects may be illustrative of the triggering of starbursts in galaxies by minor mergers (e.g., Mihos & Hernquist 1994).

4.3. *Nucleated Faint Galaxies*

A number of galaxies, especially prominent in the magnitude-limited sample, have a fairly smooth light distribution, as typical of intrinsically faint spirals, with a small nucleus at their geometric center. Whether these are nearby dwarfs or distant face on early-type spirals or S0's remains unclear. The light distribution in the nuclear component appears to be consistent with the stellar PSF, that is, the nucleus is completely unresolved. Examples are Nos. 13–16 in Figure 3. The nucleus typically accounts for 5%–20% of the total flux, for a flux of $I_{814} \sim$ 24–25 mag. The bulge component of a typical spiral galaxy of this angular size is expected to be at least partially resolved, since nearby galaxy bulge and disk sizes are usually within a factor 3 of one another (see for example Kent 1985). In at least one case, No. 16, several separate point sources can be seen along the major axis of the galaxy.

4.4. *Compact Galaxies*

Beyond the primary samples discussed here, we note a class of galaxies which can be called "compact," characterized by small angular size, high central SB, and lack of extended emission at the level of 24 mag arcsec^{-2} or brighter (cf. category 13 of Arp & Madore 1987). Their light distribution appears both less centrally peaked and less extended than for typical elliptical galaxies, for which a very high central SB is coupled with a relatively slow drop beyond the half-light radius. We have identified 16 such objects, with typical half-light radii of 0″.15–0″.3 and $I_{814} \lesssim 24$ mag. However, since their identifying characteristics are not unlike those of point sources, some of these may in fact be stars. For 10 of these objects (half-light radii $\lesssim$ 0″.25) this possibility cannot be ruled out with certainty, while the other six are definitely resolved. Examples are Nos. 17–18 in Figure 3. These galaxies may be similar to the

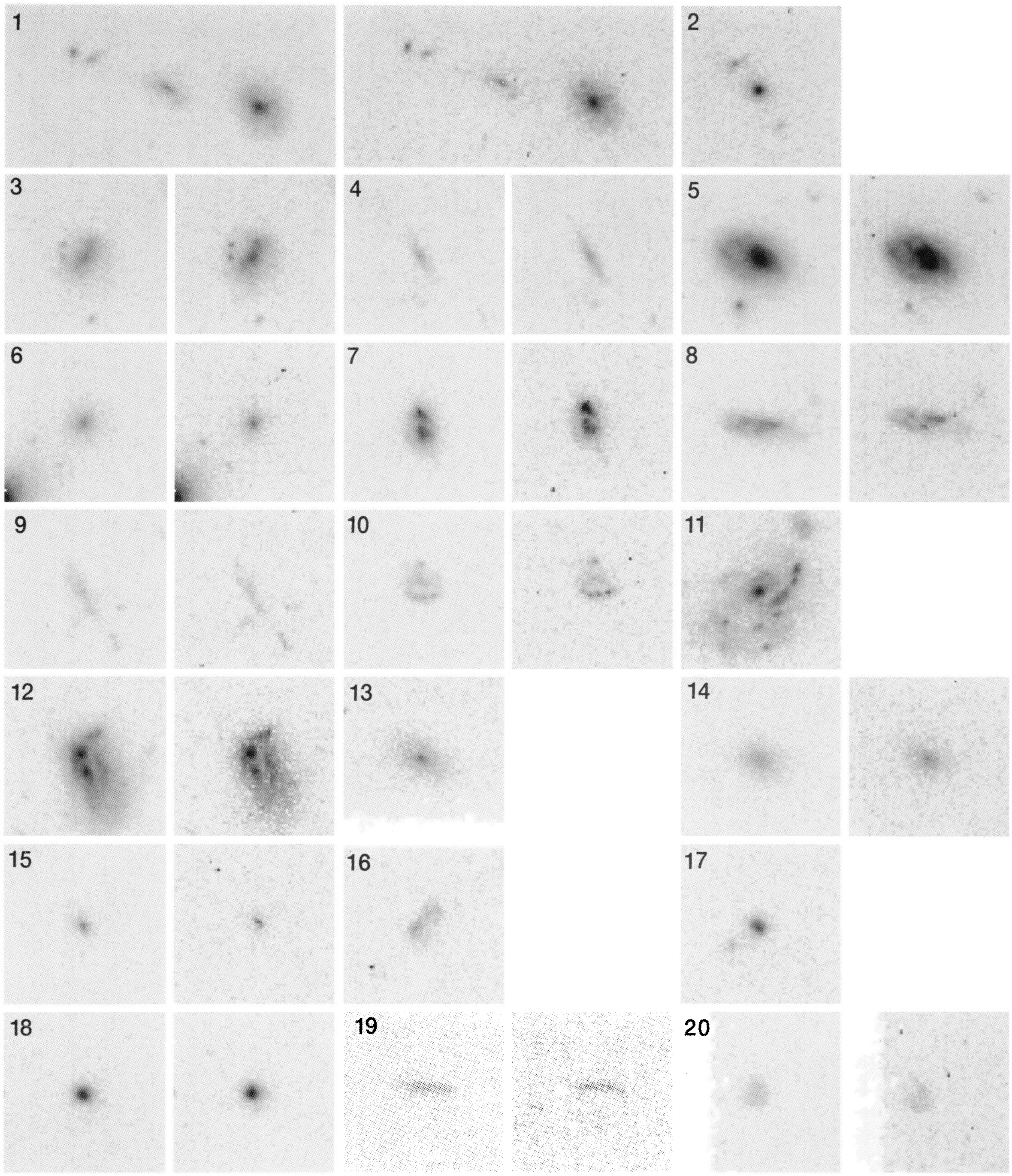

FIG. 3.—A collection of unusual and/or peculiar galaxies. The same arrangement and stretch has been used as in Figs. 1 and 2, except that the box size is now 6″.4, and object No. 1 (actually a system of four or five galaxies) spans two boxes. Galaxy numbers refer to the description in the text.

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low-redshift blue compact dwarfs studied by Kunth, Maurogordato, & Vigroux (1988) and Thuan (1987).

4.5. *Low Surface Brightness Galaxies*

Finally, our sample includes about 10 galaxies with very low central SB and relatively large angular size. These galaxies are perhaps generally classifiable as late spirals or irregulars, but are characterized by a central SB of 21.0–22.5 mag arcsec^{-2} in I_{814}, which corresponds approximately to 23.0–24.5 mag arcsec^{-2} in *B*. This population could consist of either low- and intermediate-redshift dwarfs, with a somewhat lower than expected central luminosity, or of luminous high-redshift spirals (cf. Bothun 1990). For example, the galaxy No. 19, with $I_{814} = 23.0$, size $1''.6 \times 0''.5$, and peak SB 21.9 mag arcsec^{-2}, could be a bright spiral with $M_I = -21.2$ at redshift $z = 1$, with its SB dimmed by the $(1 + z)^4$ effect, or a dwarf with $M_I = -16.2$ and intrinsically low SB at a redshift $z = 0.1$. There are also some examples of unclassifiable galaxies of low SB which have tubelike shapes.

5. CONCLUSIONS

Examination of the first WFPC2 images from the *HST* Medium Deep Survey has demonstrated that galaxy classifications can be reliably performed down to $I_{814} \lesssim 22$ mag. We have initially classified over 200 galaxies in nine WFPC2 fields according to a basic morphological scheme. The majority of these faint galaxies appear similar to regular Hubble-sequence examples observed at low redshift. To the precision of our classification scheme, the relative proportion of spheroidal and disk systems of normal appearance is as seen in local samples. Clearly the bulk of the normal population was unchanged at $z \simeq 0.5$. The increased fraction of later type galaxies observed may partly be explained by the smaller *k*-dimming of these galaxies in these deep samples.

A major result, however, is the large proportion (40%) of compact or abnormal objects of various kinds. These promise to reveal the true origin of the count excess discussed by many workers. Anomalies include apparent interacting pairs whose multiple structure is only revealed with *HST*'s angular resolution, galaxies with superluminous starforming regions, diffuse low surface brightness galaxies of various forms, and compact objects. In order to understand the role that these peculiarities may play in galaxy evolution and, in particular, resolving the "faint blue galaxy" question, spectroscopic follow-up is now required. In this way, morphological fractions can be determined for field populations *as a function of redshift*. The present data, representing only a minor fraction of that destined to form the MDS archive, already shows the promise that lies ahead.

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