THE HST MEDIUM DEEP SURVEY: GALAXY MORPHOLOGY AT HIGH REDSHIFT

R. E. GRIFFITHS, K. U. RATNATUNGA, S. CASERTANO, M. IM AND L. W. NEUSCHAEFER
JHU, Homewood Campus, Baltimore, MD 21218, USA

R. S. ELLIS, G. F. GILMORE, R. A. W. ELSON, K. GLAZEBROOK AND B. SANTIAGO
Institute of Astronomy, U. Cambridge

R. A. WINDHORST, S. P. DRIVER, E. J. OSTRANDER AND S. B. MUTZ
ASU, Tempe, AZ

D. C. KOO, G. D. ILLINGWORTH, D. A. FORBES AND A. C. PHILLIPS
Lick Obs., UCSC

R. F. GREEN
NOAO, Tucson, AZ

J. P. HUCHRA
Harvard-Smithsonian CfA, Cambridge, MA

AND

A. J. TYSON
AT&T Bell Labs., NJ

1. ABSTRACT

With HST and WFPC2, galaxies in the Medium Deep Survey can be reliably classified to magnitudes $I_{814} \lesssim 22.0$ in the F814W band, at a mean redshift $\overline{z}$ ~0.5. The main result is the relatively high proportion (~40%) of objects which are in some way irregular or anomalous, and which are of relevance in understanding the origin of the familiar excess population of faint galaxies. These diverse objects include compact galaxies, apparently interacting pairs, galaxies with superluminous starforming regions and diffuse low surface brightness galaxies of various forms. The 'irregulars' and 'peculiar' galaxies contribute most of the excess counts in the I-band at our limiting magnitude, and may explain the 'faint blue galaxy' problem.

M. Kafatos and Y. Kondo (eds.), Examining the Big Bang and Diffuse Background Radiations, 219–227.

At least half of the faint galaxies, however, appear to be similar to regular Hubble-sequence examples observed at low redshift. Furthermore, 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. Little or no evolution in the properties of these galaxies has been observed.

2. 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. The goals include the statistical studies of the properties of a large sample of faint stars and galaxies. The pre-refurbished 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, and Koo in these proceedings). Ground-based observations have thus far been unable to discriminate between hypotheses based on a fading population of dwarf galaxies (e.g. Broadhurst, Ellis and Shanks 1988; Cowie, Songaila and Hu 1991; Babul & Rees 1992) and those based on galaxy merging (Rocca-Volmerange and Guiderdoni 1990; Broadhurst, Ellis and Glazebrook 1992). The very first MDS observations (Griffiths et al. 1994a) indicated a deficit of large galaxies (half-light radius $\gtrsim 1\farcs0$) and an excess of compact galaxies at or near the HST resolution limit.

Morphologies can now be studied with a precision adequate for classification on the normal Hubble scheme to a limiting magnitude of $I_{814} \sim 22.0$ mag. Cruder information (e.g. scale lengths) can be determined to considerably fainter limits. Unlike the pre-refurbished images, morphological classifications for the WFPC2 objects are not based on parametric fits, 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. Redshift surveys of other fields to this depth have been undertaken by Lilly (1993) and Tresse et al. (1993) and indicate a median redshift $\overline{z} \simeq 0.5$ 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 lookback time of $\simeq$5–7 Gyr ($H_0 = 50$ km s^{-1} Mpc^{-1} assumed throughout).

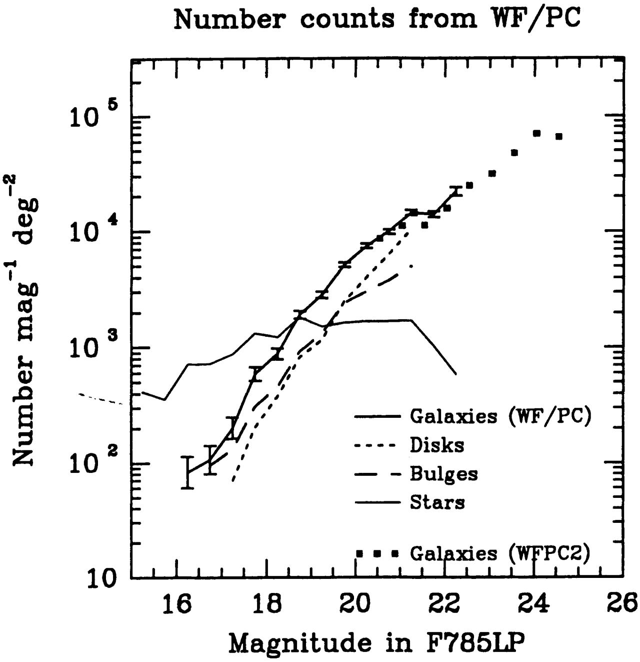

Figure 1. Total number counts for spirals, bulges and stars; from Casertano et al. (1995)

3. OBSERVATIONS

Typical MDS observations range from 600 to 2000 seconds 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 seconds have been accumulated at 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. In Cycles 1–3, 146 fields were observed with the WFC in a total exposure time of 240 hours. To September 30 1994, Cycle 4 MDS observations had been made in 113 fields, with a total of 84 hours in the two predominant filters: F606W, somewhat redder and broader than Johnson V, and F814W, close to Kron-Cousins I. Of these fields, 46 were exposed to both filters, and 12 had at least three exposures in each. The 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 Wide Field Camera (WFC) to a limiting magnitude of I_{814} = 24–26 depending on the total exposure. The precision with which morphological properties can be ascer-

https://doi.org/10.1017/S0074180900110101 Published online by Cambridge University Press

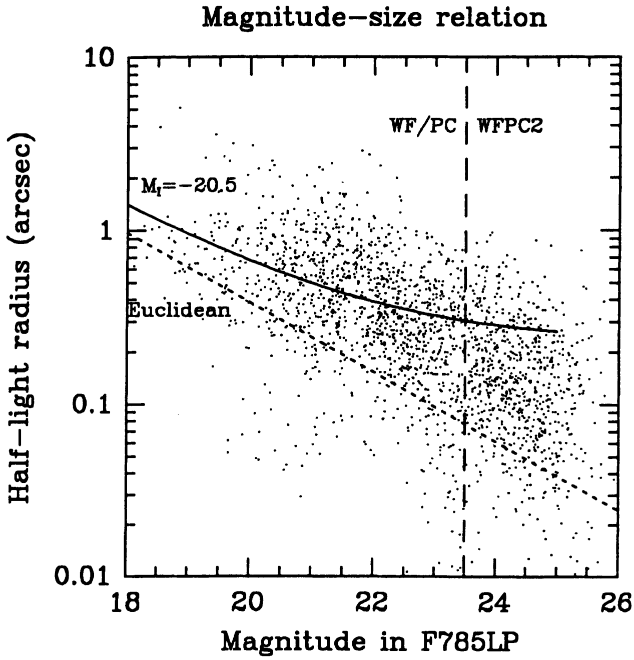

Figure 2. Half-light radius vs. mag. for galaxies in WF/PC and WFPC2 data. The Euclidean line is the extrapolated median for low-z galaxies; the predicted median for $M_I = 20.5$ is also shown – adapted from Casertano et al.(1995)

tained is a function of both angular size and apparent magnitude.

The cycle 1–3 HST MDS object catalog (11,000 objects) is available via the STScI's Electronic Information System, STEIS, in the directory observer/catalogs/mds. The 64x64 pixel images of all objects will be available on the HST archive in early 1995. Super-sky flat fields for WF/PC and WFPC2 are available on STEIS (Ratnatunga et al. 1994a).

4. SUMMARY OF EXTRAGALACTIC RESULTS

(i) Hubble-type morphological classification can be achieved to $I_{814} = 22$ (Griffiths et al. 1994b, Forbes et al. 1995, Driver et al. 1995, Glazebrook et al. 1995). Spectroscopy is in progress for large subsets of these galaxies

(ii) Statistical properties of galaxies are measured to I = 24 with WF/PC and 25 with WFPC2 (figs. 1 – 4). For the pre-refurbishment WF/PC images, the structural parameters of about 13,000 objects are presented by Casertano et al. (1995), using data taken from about 112 fields. Sizes, magnitudes, colors and crude classifications are based on two-dimensional model fitting to undeconvolved images (Ratnatunga et al. 1994b). Number counts

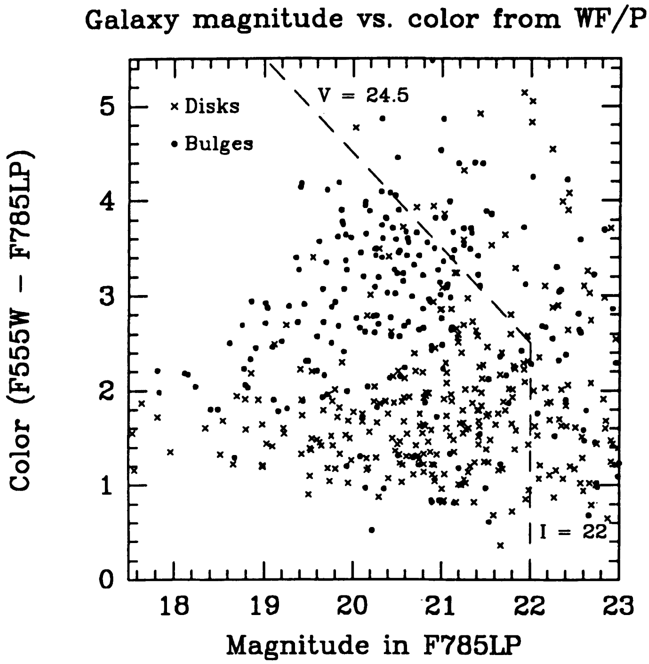

Figure 3. The color-magnitude diagram for galaxies in WF/PC data; completeness lines are drawn at I = 22 and V = 24.5. The 'bulges' appear redder towards fainter magnitudes; from Casertano et al. (1995)

in the range $18 < I < 22$ exceed the ground-based numbers by about 50%, a range over which many ground-based objects may have been misclassified as stars. The ellipticals become redder for $I_{814} > 20$ mag, but the spirals show no trend of color with magnitude, indicating that they are intrinsically bluer at higher redshift when K-corrections are taken into account.

(iii) The local universe is dwarf-rich. The marginal distribution of size vs. magnitude can be compared with the predicted distributions based on various galaxy evolution models such as the no-evolution model, the merger model, and the dwarf-rich model (fig. 5). The mild-evolution or no-evolution models predict luminous galaxies of large angular size at high redshift: such objects are not seen in the data, which are instead consistent with the dwarf-rich models and a dwarf luminosity function with a steep faint-end slope. The MDS results also rule out models in which the faint, excess number counts are caused by large, low-surface brightness galaxies (e.g. Ferguson & McGough 1995) since we do not see the predicted numbers of large objects. The median half-light radius for all galaxies to $I_{814} = 24$ is 0.4 arcsec (Im et al. 1995a).

(iv) The excess number counts are not explained by 'giant' spirals or

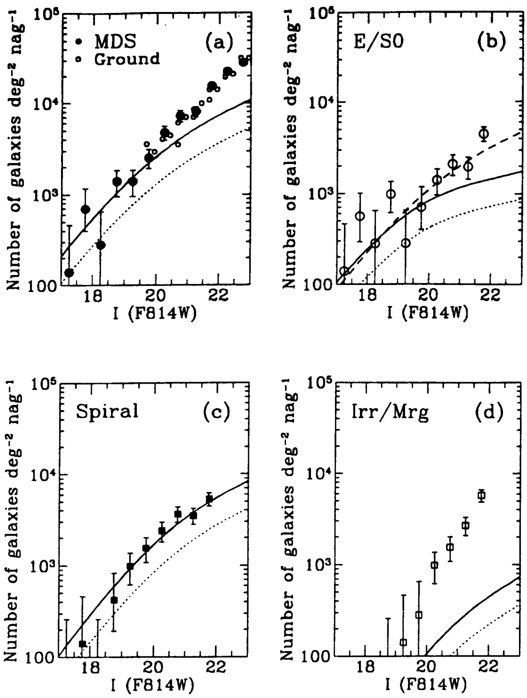

Figure 4. Number counts for spirals, ellipticals and Irregulars/Peculiars in WFPC2 data; from Glazebrook et al. (1995) and Driver et al.(1995)

ellipticals, which are observed to have little or no evolution in terms of number counts (Glazebrook et al. 1995), size vs. redshift (Mutz et al. 1994), or structural parameters (Windhorst et al. 1994; Phillips et al 1995): the bulk of the local (giant) population was therefore in place at half the Hubble time. Furthermore, this population has either undergone relatively little merging (about 10%), or else the mergers have been of the 'minor' kind (with gas-rich dwarfs) and have not caused major disruptions (Driver et al. 1995). For those galaxies which do show evidence of merger activity, photometry shows bluer colors and thus increased star formation (Forbes et al. 1994)

(v) Spiral galaxies are, however, bluer in the past when their K-corrections are taken into account; their apparent (V-I) color does not change between I=18 and I=22 (fig. 3). The microJansky radio population is linked to these spiral galaxies with enhanced star formation, especially those showing evidence of interaction (Windhorst et al. 1995)

(vi) WF/PC data show that elliptical galaxies have a higher angular correlation than spirals, but this difference in correlation amplitude is smaller than that observed in local samples (Neuschaefer et al. 1995). The two-point correlation function (all galaxies, irrespective of morphology) shows

https://doi.org/10.1017/S0074180900110101 Published online by Cambridge University Press

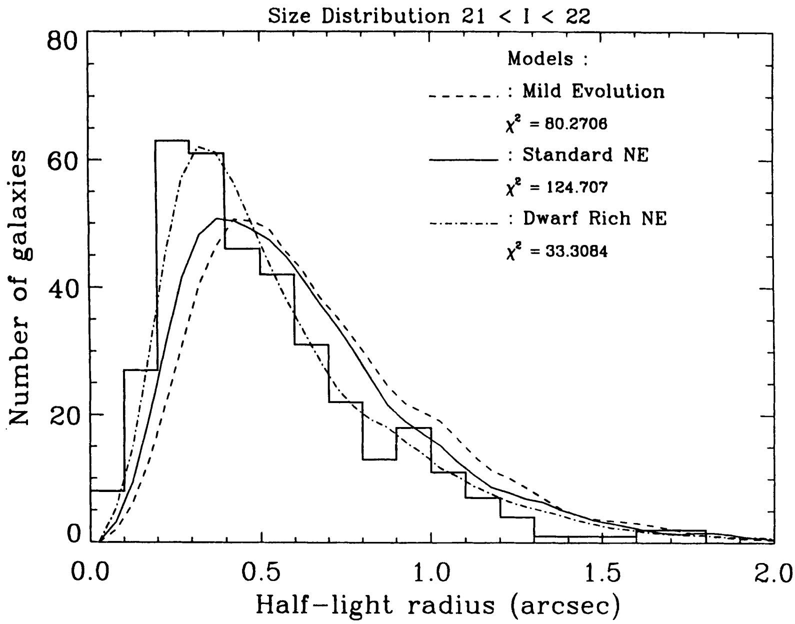

Figure 5. Number counts vs. size, compared with galaxy evolution models; from Im et al.(1995a)

a constant slope down to arcsec scales, with no substantial evidence for the excess galaxy pairs that might result from a high merger rate

(vii) The excess number counts in V and I are explained by the high fraction of compact objects and irregulars/peculiars. The irregulars show a steeply rising number count with magnitude (Glazebrook et al. 1995 Driver et al. – see fig. 4). Multiple cores are evident within 40% of them, and a third of these show evidence of being mergers.

(viii) The irregulars/peculiars also include minority populations which are diverse morphologically, including low surface brightness galaxies (some nucleated), and galaxies with superluminous starburst regions or knots (e.g. the peculiar object at $z = 0.7$ – Glazebrook et al. 1994)

(ix) The small, predominantly 'dwarf' population is dominated by objects with exponential profiles but with the axis ratios of ellipticals (Im et al. 1995b). The axis ratio distribution of faint bulge-like galaxies is like that of local ellipticals, showing no evolution in their properties. The axis ratio distribution of large disk-type galaxies ($r_{hl} > 0''.6$) is similarly consistent with local samples, but the same is not true for the small galaxies with exponential profiles – these have an axis ratio distribution which is like the ellipticals

(x) At I = 22, 15% of all galaxies have 'satellite' galaxies which are fainter than their 'parents' by at least 1 or 2 mags. Such observations may represent evidence in support of the 'minor merger' hypothesis (e.g. Mihos and Hernquist 1994)

5. CONCLUSIONS

Parallel HST operations have steadily improved in efficiency through observing Cycles 1–4, and parallel observations with WF/PC and WFPC2 have been highly successful in providing a database which is extremely useful for achieving the goals of the Medium Deep Survey: the measurement of field galaxy properties to I=22 and fainter, number counts as a function of morphology, studies of the evolution of galaxies to at least z =0.5–0.7, and study of morphology as a function of environment. The detailed morphological studies include the search for compact and multiple nuclei, the frequency of mergers, interactions and groups, and the frequency of irregularities, starburst knots, bars, arms and rings, etc.

A picture is emerging whereby the familiar problem of the excess number counts is being solved in terms of the evolution of low-luminosity systems which have a space density which is higher than expected. This is manifested by a large number of irregular and peculiar galaxies in WFPC2 data, some of which seem to be merger remnants. Ground-based spectroscopy is underway to elucidate the properties of each of the classes of these enigmatic galaxies.

References

Babul, A., & Rees, M. J. (1992), *Mon. Not. R. Astr. Soc.,* **255**, 346

Broadhurst, T., Ellis, R. S., & Shanks, T. (1988), *Mon. Not. R. Astr. Soc.,* **235**, 827

Broadhurst, T., Ellis, R. S., & Glazebrook, K. (1992), *Nature,* **355**, 55

Casertano, S., Ratnatunga, K. U., Griffiths, R. E., Neuschaefer, L. W., & Windhorst, R. A. (1995), "Structural Parameters of Faint Galaxies: Results from a Catalog of Galaxies from the HST Medium Deep Survey with WF/PC", *Astrophys. J., in press*

Cowie, L. L., Songaila, A., & Hu, E. M. (1991), *Nature,* **354**, 460

Driver, S. P., Windhorst, R. A. & Griffiths, R. E. (1995) "The properties of Irregular field galaxies found in HST Medium Deep Survey images", *Astrophys. J., submitted*

Ferguson, H. C. & McGough, S. S. (1995), *Astrophys. J., in press*

Forbes, D. A., Elson, R. A. W., Phillips, A. C., Illingworth, G. D., & Koo, D. C. (1995), "The Nuclear Colors and Morphology of Field Galaxies at Moderate Redshift", *Astrophys. J. Lett., in press*

Glazebrook, K., Lehar, J., Ellis, R., Aragon-Salamanca, A., & Griffiths, R. (1994), "An unusual high redshift object discovered with HST: peculiar starburst galaxy or new gravitational lens", *Mon. Not. R. Astr. Soc.,* , **270**, L63

Glazebrook, K., Ellis, R. S., Santiago, B. and Griffiths, R. E. (1995) "The Distribution of Faint Galaxy Morphologies to I = 22", *Nature, submitted*

Griffiths, R. E., et al. (1994a), "The HST Medium Deep Survey with WF/PC: I. Methodology and Results on the Field Near 3C273", *Astrophys. J.,* **437**, 67

Griffiths, R. E., et al. (1994b) "The Morphology of faint galaxies in Medium Deep Survey Images using WFPC2", *Astrophys. J. Lett.,* **435**, L49

Im, M., Casertano, S., Griffiths, R. E., Ratnatunga, K. U. & Tyson, J. A. (1995a) "A Test of Galaxy Evolutionary Models Via Angular Sizes", *Astrophys. J., in press*

Im, M., Casertano, S., Griffiths, R. E., & Ratnatunga, K. U., (1995b) "The Axis Ratio Distribution of Faint Galaxies and their Morphological Properties", *Astrophys. J., submitted*

Koo, D. C., & Kron R. G. 1992, *Ann. Rev. Astr. Astrophys.,* **30**, 613

Lilly, S. J. 1993, *Astrophys. J.,* **411**, 501

Mihos, J. C., & Hernquist, L. (1994), *Astrophys. J.,* **425**, L13

Mutz, S. B., et al. (1994) "The Θ-z relation for HST bulges and disks out to $z \simeq 0.8$", *Astrophys. J. Lett.,* **434**, L55

Phillips, A. C., Bershady, M. A., Forbes, D. A., Koo, D. C., Illingworth, G. D., Reitzel, D. B., Griffiths, R. E., & Windhorst, R. A., (1995) "Structure and Photometry of an $I < 20.5$ Galaxy Sample from the HST Medium Deep Survey", *Astrophys. J., in press*

Neuschaefer, L. W., Casertano, S., Griffiths, R. E. & Ratnatunga, K. U. (1995), "Galaxy Clustering Statistics in HST Medium Deep Survey Images", *Astrophys. J., submitted*

Ratnatunga, K. U., Griffiths, R. E., Casertano, S., Neuschaefer, L.W., & Wyckoff, E. W. (1994b), "Calibration of the HST Wide Field Camera for Quantitative Analysis of Faint Galaxy Image Parameters", *Astron. J., in press*

Ratnatunga, K. U., Griffiths, R. E. and Casertano, S. (1994b), "Maximum likelihood estimation of galaxy Morphology: faint HST WFC images", in *The Restoration of HST Images and Spectra II,* eds Hanisch, R. J., White, R., Proc. Space Telescope Science Institute Workshop, p. 333.

Rocca-Volmerange, B. and Guiderdoni, B. (1990), *Mon. Not. R. Astr. Soc.,* **247**, 166

Tresse, L., Hammer, F., Le Fevre, O., & Proust, D. (1993), *Astron. & Astrophys.,* **277**, 53

Windhorst, R. A., et al. (1994) "The HST Medium Deep Survey: Deconvolution of WFC field galaxy images in the 13H+43deg field", *Astron. J.,* **107**, 930

Windhorst, R. A., et al. (1995) "The nature of microJansky radio sources: Deep HST imaging of an ultradeep VLA 8.4 GHz survey field", *Nature, in press*