Quantifying Morphological Evolution from Low to High Redshifts

Roberto G. Abraham
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 OHA, United Kingdom

Abstract. Establishing the morphological history of ordinary galaxies was one of the original goals for the Hubble Space Telescope, and remarkable progress toward achieving this goal has been made. How much of this progress has been at the expense of the Hubble sequence? As we probe further out in redshift space, it seems time to re-examine the underlying significance of Hubble's tuning fork in light of the spectacular and often bizarre morphological characteristics of high redshift galaxies. The aim of this review is to build a morphological bridge between high-redshift and low-redshift galaxy populations, by using quantitative morphological measures to determine the maximum redshift for which the Hubble sequence provides a meaningful description of the galaxy population. I will outline the various techniques used to quantify high-redshift galaxy morphology, highlight the aspects of the Hubble sequence being probed by these techniques, and indicate what is getting left behind. I will argue that at higher redshifts new techniques (and new ideas) that place less emphasis on classical morphology and more emphasis on the link between morphology and resolved stellar populations are needed in order to probe the evolutionary history of high-redshift galaxies.

Keywords: galaxies: evolution — galaxies: morphology — galaxies: general — cosmology: observations

1. Introduction

In an influential series of lectures delivered nearly two decades ago, Kormendy (1982) described how morphological considerations supply the basic framework for our understanding of galaxies, but also noted that

“.... morphology is more generally a ‘soft’ science, which is best viewed as preparation for more quantitative work. Its most important use may be to provide a list of specific questions which provide direction for this work.”

In the same series of lectures, Kormendy espoused the view that physical morphology (a scheme in which morphological components such as lenses, bars, disks and halos are superposed in order to build up a coherent classification for galaxies) provides a promising avenue toward the ultimate goal of a taxonomy of galaxies that is physically interpretable.
In this review I will try to take Kormendy’s ideas a little further and argue that with the advent of deep imaging data from the *Hubble Space Telescope* (HST), coupled with advances in objective galaxy classification and measurement, the subjective art of morphological classification has begun to yield to the quantitative science of physical morphology. The new perspectives offered by observing distant galaxies *in situ* allows physical morphology to go straight to the heart of issues central to our understanding of galaxy evolution. In this review I will focus on several of these key issues, posed in the form of the following three questions: (1) At what redshift is the Hubble sequence observed to be in place? (2) Does the Hubble sequence contain its own “ground state”, or do entirely new classes of galaxy emerge at early look-back times? (3) What drives morphological evolution (i.e. which components of galaxies form first)? Data that offers insight into the first of these questions now exists, and will be reviewed in §2. The second question is presently wide open, so in §3 I will describe the measurement of promising physical parameters that should at least help constrain the possibilities. In §4 I will focus on the third question, and describe the role of resolved stellar populations in reconstructing the physics of galaxy formation at high redshifts.

2. At What Redshift is the Hubble Sequence in Place?

2.1. What are we really measuring?

The impressive physical correlations along the Hubble sequence are discussed extensively in several recent reviews (Sandage & Bedke 1994; Roberts & Haynes 1994; van den Bergh 1998; Abraham 1999d). The physical significance of the Hubble sequence is a testament to the genius of Hubble, and to the hard work of subsequent generations of astronomers who have elaborated and refined Hubble’s original system over the past 75 years (e.g. Sandage 1961, 1981; de Vaucouleurs et al. 1976, 1991; van den Bergh 1960, 1976). But before going on to consider recent evidence for evolution of the Hubble sequence as a function of redshift, it is first necessary to shed some light on a fact that will shock nobody working with HST data, but might come as a surprise to those focusing on morphology in the low-redshift Universe. *The Hubble sequence is a wholly unsuitable basis for the study of high-redshift galaxies.* As a result of this, most workers analyzing deep HST data have adopted private galaxy classification schemes (such as the ten-bin MDS system, or the ubiquitous three-bin early/late/peculiar system adopted by many groups) that attempt to preserve the spirit of Hubble’s tuning fork (Hubble 1926, 1936), but ride roughshod over the details. This seems to me to be a reasonable strategy, for three reasons:
1. **The Hubble sequence is not robust at low signal-to-noise levels.** Because the bulges of galaxies generally correspond to regions of high surface brightness, one of the three central parameters of the Hubble sequence (bulge-to-disk ratio) is far more robust than the other two parameters defining the system (pitch angle and resolution of spiral arms). As a result, classifications of high-redshift galaxies are generally based on apparent bulge-to-disk ratio, with little (and often no) regard to the visibility of spiral arms. This is true regardless of the detailed mechanics (visual inspection, profile fitting, neural nets, decision trees, etc) of the classification process. Studies of spiral structure at high redshifts are in their infancy (see §2.3). In fact, it can be argued that classifications of high redshift galaxies have more in common with Morgan’s Yerkes system (Morgan 1958, 1959), based on central concentration of light, than with Hubble’s original system.

2. **Some archetypal high redshift galaxies do not exist in the Hubble sequence.** Recent work from deep HST imaging surveys has shown that much of the faint galaxy population is comprised of a diverse set of morphologically peculiar galaxies entirely outside the Hubble system. These may be tidally distorted counterparts to conventional tuning fork galaxies, or entirely new classes of objects. It seems to me deeply unsatisfactory to simply bin one-third of the galaxy population (at $I = 25$ mag) together into a catch-all “peculiar” category, but that is the current state of the art. Another concern is that Hubble sequence is intended to describe only luminous galaxies, which is appropriate for bright local surveys where most detected systems are near $L_\star$. However, deeper magnitude-limited surveys may (depending on the faint-end slope of the luminosity function) probe much farther down the luminosity function so that typical systems are substantially fainter than $L_\star$. Therefore some component of a perceived evaporation of the tuning fork towards higher redshift could be alternatively interpreted as the evaporation of our local $L_\star$ window function.

3. **Even for local galaxies, the consistency between visual morphological classifications is poor.** The results from controlled comparisons between independent morphological classifications of local galaxies made by expert morphologists (Naim et al. 1995) are depressingly bad. The upshot of this is that one must have rather serious doubts about observer-to-observer consistency in visual classifications at any redshift even though there is little doubt in my mind that an individual expert morphologist can make classifications that are internally highly consistent. When
combined with the complications (quantified below) introduced by a variable rest-wavelength of observation for high-redshift galaxies, these factors force me to conclude that objective machine-based classifications are essential for progress in this field.

In light of these considerations, when I review in the next section the results from studies intended to probe evolution along the Hubble sequence, it is important for the reader to bear in mind that what is really being probed is evolution in the early–late axis of the tuning fork, indirectly traced by bulge-to-disk ratio. In the local Universe this parameter is correlated with, but does not define, position along the tuning fork.

2.2. THE EARLY–LATE AXIS OF THE TUNING FORK

The clearest evidence for morphological evolution to \( z \sim 1 \) does not come from work on the Hubble Deep Field, but from the deep HST imaging follow-ups to the CFRS and LDSS redshift surveys (Brinchmann et al. 1998; Lilly et al. 1998). The statistical completeness of the underlying redshift surveys (Lilly et al. 1996; Ellis et al. 1996) are very well understood, and at \( z < 1 \) cosmological bandshifting serves mostly to synchronize observed \( I \)-band data closer to rest wavelength \( B \)-band, where galaxy morphology is most familiar. The morphologically segregated (on the basis of machine classifications) \( I_{AB} < 22.5 \) mag number–redshift distributions from Brinchmann et al. (1998) are shown in Figure 1, along with the predictions of simple no-evolution and mild-evolution models. These authors conclude that there is little evidence for substantial evolution in the early-type population, some evidence for modest evolution in the spiral population (consistent with mild luminosity evolution at 0.5–1 mag level by \( z = 1 \)), and a spectacular over-abundance of systems categorized as peculiar. These results seem quite convincing, although the apparently good agreement with the models should not be over-interpreted, as the absolute normalization of the local luminosity function is probably known only to within a factor of two.

These results are in good agreement with earlier findings obtained by other groups studying the morphologically segregated number-magnitude

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1 Recent years have seen great advances in the usefulness of objective, machine-based morphological classifications designed to probe position along the early–late axis of the tuning fork (Doi, Fukugita, & Okamura 1993; Naim et al. 1995; Abraham et al. 1996a; Odewahn et al. 1996). Even the comparatively simple two-parameter system with which I am most familiar is able to classify galaxies with an accuracy comparable to that achieved by the visual classifications of independent observers (Abraham et al. 1996b; Brinchmann 1998).
Figure 1. Morphologically segregated number counts from Brinchmann et al. (1998) (Brinchmann et al. 1998), based on data from the CFRS/LDSS collaboration. The solid-line bins show counts as a function of redshift for irregular/peculiar/merger systems (top), spirals (middle), and ellipticals (bottom). Morphological classifications have been made from WF/PC2 images using an automated technique based on central concentration and asymmetry of galaxian light (Abraham et al. 1996a). The model curves have been corrected for “morphological K-corrections”, accounting for the effects of observing the galaxies at bluer rest wavelengths as a function of redshift. Superposed on the observed histograms are the predictions of no-evolution (dashed) and 1 mag linear evolution to $z = 1$ (dot-dashed) models. At $z \sim 1$ approximately 40% of the galaxy population is morphologically peculiar.
relations from the Medium Deep Survey (Glazebrook et al. 1995; Driver, Windhorst, & Griffiths 1995; Abraham et al. 1996a). The redshift distributions lay to rest earlier concerns that the luminous peculiar population at $I < 23$ mag is severely contaminated by “morphologically K-corrected” very high-redshift systems, and allows calculation of the size function for subsets of the data (Lilly et al. 1998). It is not clear whether these trends are consistent with models based on hierarchical growth (although at a basic level the results do appear consistent with the semi-analytical prescription of Baugh, Cole & Frenk 1996). If there is a peak of star formation activity at $z \approx 1-2$ (Madau 1998), either the evolutionary behaviour of massive regular galaxies beyond $z \approx 1$ must change dramatically from that observed for $z < 1$, or perhaps the trends delineated from the optical photometric data are underestimated because of complications such as dust extinction (Meurer et al 1997). Intriguingly, there seems to be no change in the space density of large spiral systems to redshift $z = 1$, in apparent contradiction of the predictions of hierarchical models, although attempts are being made to reconcile the sizes of “big disks” with theory (Mao, Mo, & White 1998).

Beyond $I \sim 22 - 23$ mag, the HDF is required for reliable morphological classifications. Various authors (Abraham et al 1996a; Mobasher et al 1996; Odewahn et al 1996; Driver et al 1998) have used the HDF to extend the earlier Medium Deep Survey morphological source counts to fainter limits, finding that the fraction of the peculiar systems increases to at least $I_{814} = 25$ mag, and finding some evidence for a turn-over in the early-type counts beyond $I = 24$ mag (Abraham et al 1996a). Another striking result from the HDF is the small angular size of the faintest sources, implying physical extents of only 2-4 $h^{-1}$ kpc. In a recent analysis, Bouwens et al (1998) suggest that such sizes cannot be reconciled with the expected redshift and surface brightness dimming of typical $z < 1$ sources and thus claim substantial physical growth and merging must have occurred for the galaxy population during the redshift range 1 < $z < 3$. In another recent paper, Driver et al. (1998) have used photometric redshifts to extend the CFRS/LDSS number-redshift distributions to $I = 26$ mag. These authors confirm both the earlier claims of a deficit of early-type systems beyond $I = 24$ mag, and the rapid rise in the proportion of morphologically peculiar systems with redshift. Driver et al. (1998) also note that beyond $z = 2$ very few well-ordered spirals are seen (see the review by Windhorst in these proceedings), in agreement with the basic point made by van den Bergh et al. (1996). Beyond $z = 1$ a comparison with physical models becomes problematic. In addition to the uncertain normalization of the local luminosity function, at least three other factors come into play: (1)
Evolutionary $K$-corrections become very uncertain, especially for sub-$L_*$ systems; (2) The appropriate cosmology is unknown (e.g., the possible presence of $\Omega_\Lambda$); (3) The importance of dust is unknown.

On the basis of all these results, it seems to me that one can safely place the epoch at which the early–late axis of the Hubble sequence is well-established to be somewhere around $z \sim 1$. At this redshift most luminous spirals and ellipticals are in place, but at least 30% of luminous galaxies lie off the sequence, and the sequence as a whole cannot really be considered a reasonably complete description of the luminous galaxy population.

2.3. **The Tines of the Tuning Fork**

I will now consider the redshift at which the “orthogonal” axis of the tuning fork, namely the bifurcation into barred and unbarred systems, is established. As described earlier, studies of spiral structure at high redshifts are in their infancy. While simple quantitative measures of overall galactic structure are adequate for placing even faint HDF galaxies within a one-dimensional early–late classification sequence, much higher signal-to-noise data are needed to probe spiral structure. Another fundamental complication is that the fraction of *local* barred spirals is poorly established; there is clearly a continuum in apparent bar strength, and the strength required to merit classification as a barred galaxy is highly subjective. These difficulties can be sidestepped by using quantitative measures of bar strength on appropriate subsamples of very high signal-to-noise data spanning a broad range in redshift space, so that no reference to visually determined estimates of the local bar fraction is needed.

Abraham et al. (1999b) combine data from the Northern and Southern HDF fields in order to define a sample of luminous $I < 23.2$ mag low-inclination spirals with redshifts less than $z \sim 1$, where band-shifting effects are negligible and where signal-to-noise levels are high enough for unambiguous bar detection. Bar strength is quantified using a simple measure, $(b/a)_{\text{bar}}^2$, corresponding to the *physical* axial ratio of a bar under the assumption of an elliptical bar embedded within a round, thin disk. Where these assumptions are not a good approximation, the estimator still yields a perfectly quantitative, objective parameter that appears to closely track visual estimates of bar strength. For reasonably low-inclination systems ($< 60$ degrees), spirals classed locally as SA in the sample of Frei et al. (1996) are cleanly-separated from systems.

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2 Note that I am excluding low surface brightness systems from consideration at this stage, although constraints on the putative existence of these in the HDF are now very severe, as discussed in §3.
Figure 2. The bar strength estimator \((b/a)_{\text{bar}}^2\) plotted as a function of spectroscopic redshift (filled symbols) or photometric redshift (open symbols) in the northern (triangles pointing upward) and southern (triangles pointing downward) Hubble Deep Fields. Note the marked gradient in the proportion of barred systems with redshift, beginning at \(z \sim 0.5 - 0.6\). Taken from Abraham et al. (1999b).

classed as SB. The results obtained by applying this statistic to the HDF data are shown in Figure 2.

This figure reveals a striking decline in the proportion of barred examples beyond a redshift \(z \sim 0.5\). This cannot be due to uncertainties in using photometric redshifts for the Southern HDF data, as the same effect is seen in both HDF samples and at \(I < 23.2\) mag the Northern HDF is spectroscopically complete at the 90% level. Similarly, this result cannot be due to bandshifting effects: the redshift range considered corresponds to the rest-frame optical, and the effect is most striking at redshifts close to rest-frame \(B\)-band, where the barred spiral fraction is best established in the local Universe. This is confirmed from an analysis of the northern HDF, where deep NICMOS observations allow the construction of a sample imaged at a uniform rest-frame (Abraham et al. 2000). Formally, the redshift distributions of the barred and unbarred samples selected on the basis of \((b/a)_{\text{bar}}^2\) in Figure 2 are inconsistent at the 99.8% confidence level from a Kolmogorov-Smirnov test.

Figure 2 would seem to bring forward the epoch at which the conventional Hubble system is observed to be in place, from \(z \sim 1\) (based the early–late axis of the tuning fork, as described in the previous
subsection) to $z \sim 0.5$. The physical mechanisms responsible for the absence of barred spirals at high redshifts is unclear. Obvious possibilities include dynamically hotter (or increasingly dark-matter dominated) high-redshift disks, and an enhanced efficiency in bar destruction at high redshifts (Sellwood 1999; Combes 1999).

2.4. Summary

Hubble’s tuning fork appears to provide a good description of the morphologies of luminous galaxies out to redshifts $z \sim 0.5$, at which point the proportion of strongly barred spirals begins to drop off. By a redshift $z = 1$ around 30% of galaxies within two magnitudes of $M_*$ lie off the early–late axis of the classification sequence.

3. Alternative Metrics of Galaxy Morphology

Early results from deep NICMOS observations of the Hubble Deep Field (Thompson et al. 1998; Bunker et al. 1999) have lain to rest the possibility that most high-redshift morphologically peculiar systems are simply late-type spiral galaxies whose peculiar appearance is due to their being imaged in the rest-frame ultraviolet. The bizarre appearance of most of these galaxies is intrinsic, and classification schemes which encompass the diversity in the forms observed are needed to realistically capture the appearance of galaxies in the distant Universe. However, an appropriate classification scheme for such systems should not just be descriptive. The ultimate goal of galaxy classification is to mirror an underlying physical order in the systems being studied, and alternative approaches to galaxy classification that are appropriate for studying distant galaxies should therefore take into account not only the practical limitations on resolution and signal-to-noise, but also our improved understanding of the physical basis for galaxy formation.

I would argue that central concentration (or bulge-to-disk ratio) is a useful (albeit crude) probe of the relative importance of thermally supported versus rotationally supported structures, and can be used to test rather directly the predictions of hierarchical formation models. Measures of bar strength capture (again, rather crudely) information regarding the dynamical state of the disk, and probe the importance of secular processes in building up galaxies. Similarly, on the basis of a close correspondence to underlying physics, I would argue that bulk asymmetry and mean surface brightness should be considered fundamental morphological characteristics of high-redshift galaxies.
3.1. Asymmetry

Locally, most morphologically peculiar systems show dynamical evidence for tidal disruption, and it is tempting to assume that a large fraction of the diverse peculiar galaxy population seen on deep images are actually mergers in progress. Few of the high-redshift peculiar systems in the Hubble Deep Field resemble the classical appearance of local merging systems, but the usual signatures of mergers (e.g., tidal tails) are no longer visible at \( z > 2 \), and at these redshifts the effects of bandshifting on morphology can be rather extreme. Merging starburst systems seem to provide at least qualitatively reasonable counterparts to many faint peculiar galaxies (Hibbard & Vacca 1997). On the other hand, synchronization in the colours of some morphologically peculiar systems (e.g., in the “chains” first identified by Cowie, Hu, & Songaila 1995) seems difficult to explain as the product of mergers (Abraham 1999c), and many morphologically peculiar systems do not resemble archetypal starbursts on deep NICMOS data probing rest-frame optical light (Bunker et al. 1999). Therefore a crucial issue in high-redshift studies is to distinguish between intrinsically asymmetric protogalactic systems and mergers in progress, and perhaps at a higher level to consider whether such a distinction is even meaningful in the context of hierarchical formation scenarios. I don’t think I can describe the situation more clearly than I did in my Les Houches lectures:

“When should an amorphous blob of components be regarded as single morphologically peculiar galaxy, as opposed to a system of interacting proto-galaxies? de Vaucouleurs used to dismiss the notion of considering mergers to be fundamental morphological units with the observation that ‘car wrecks are not cars’. But when the road is littered with wrecks, and when the by-product of a wreck is another working car, it may be time to re-assess the wisdom of restricting morphological classification to regular-looking systems”.

Studies of asymmetry at high redshifts may shed light on this issue. Conselice et al. (1997) and Takamiya et al. (1999a,b) find strong correlations between color and symmetry in both local and high-redshift galaxies. Intriguingly, Conselice et al. (1999) also demonstrate that at least some interacting systems can be distinguished from other classes of morphologically peculiar systems on the basis of position on a color-asymmetry plane. Using imaging data from the LDSS/CFRS survey, Le Fèvre et al. (1997; 1999) show how objective measures of bimodality can parameterize the growth in the merger rate with redshift, finding evidence for a sharp increase in the merger rate with redshift. It is worth noting however that this study was restricted to relatively low redshifts \( (z < 1) \) and, like all such studies to date,
Figure 3. Figures from Driver (1999), showing the utility of the bivariate brightness distribution for establishing the bulk characteristics of “local” (0.3 < z < 0.5) galaxy samples while explicitly accounting for selection effects. In both panels open circles are early-type galaxies, asterisks are spirals, and peculiars are shown as triangles. [Left:] Absolute magnitude versus photometric redshift for galaxies with I < 27 mag in the HDF. The region enclosed by dashed lines corresponds to the volume-limited sample shown in the next panel. [Right:] The bivariate brightness distribution for the HDF volume-limited sample defined on the left. The lines indicate the selection functions for the HDF survey data. Note the clear absence of a dominant population of luminous low surface brightness systems, the clear trend for morphology to be correlated with both surface brightness and luminosity, and the strikingly large area within which systems that are absent could have been detected.

may not account fully for the evolution in the background counts needed in order to translate observed close pair counts to a physical merging fraction (R. Carlberg, private communication). I suspect that the ultimate clarification of the nature of the morphologically peculiar systems in general, and the most distant Lyman-break systems (Steidel et al. 1997; Giavalisco, Steidel, & Macchetto 1996) in particular, must await the completion of at least the first round of dynamical studies on these objects. These studies are needed to provide the basic physical framework upon which future morphological work can be built.

3.2. Mean Surface Brightness

Including surface brightness as a classification criterion makes sense on several levels. Firstly, the majority of galaxies in Universe are low-surface brightness dwarfs whose morphologies lie off the Hubble sequence. Clearly the the visibility of such systems is a strong function of the limiting surface brightness of the observations, and an understand-
ing of the surface brightness of a given population allows the calculation of reasonably unbiased selection functions that are necessary to calibrate the faint-end slope of the galaxian luminosity function. Another reason why surface brightness might be considered a fundamental morphological parameter is because of the rather tight correlations between surface brightness, luminosity, and central concentration. These allow two (or more) of these parameters to be used in decision-tree based galaxy classification strategies that capture much of the variance in the Hubble sequence (Doi, Fukugita, & Okamura 1993; Abraham et al. 1994). Finally, mean surface brightness can be viewed as a crude tracer of angular momentum (Heavens & Jimenez 1999).

The utility of including surface brightness as a classification criterion is probably best illustrated in a recent paper by Driver (1999), the results from which are shown in Figure 3. This work exploits the extraordinarily deep limiting surface brightness of the HDF observations to construct a volume-limited sample of the nearby Universe that is largely immune to the surface brightness selection effects whose putative importance has been the source of so much recent debate (Bothun, Impey, & McGaugh 1997 and references therein). Driver concludes that luminous low-surface brightness galaxies are relatively rare (< 10% of the galaxy population), and that dim galaxies at all luminosities contribute only very modestly to the both the luminosity density and mass budget of the Universe, in basic agreement with the results of Ferguson and Babul (1998).

A disadvantage of using surface brightness as a classification criterion is that its physical interpretation is closely coupled to assumptions regarding star-formation history (and hence mass-to-light ratio). However, similar objections can also be raised regarding the use of asymmetry, and to some extent central concentration, as fundamental parameters. In fact the parameter most strongly correlated with position on the Hubble sequence for local Sa–Scd spirals is rest-frame colour, and by inference star-formation history. In the next section I will argue that the connection between morphology and star-formation history should be made explicit when probing the high-redshift Universe.

4. The Morphology–Star-formation Connection

The notion that morphology is a transient property of galaxies is a key idea in hierarchical models for galaxy evolution. This suggests that the

\footnote{It is interesting to note that the mean surface brightness of early-type dwarf galaxies decreases with luminosity, while the mean surface brightness of late-type dwarfs increases with luminosity.}
Figure 4. Internal colour analysis of a $z=0.517$ spiral in the HDF. A $V-I$ colour map for the galaxy is shown at top left, and refers to an area $4 \times 4$ arcsec sampled at the drizzled pixel scale of 0.04 arcsec and limited to contiguous pixels contained within the $\mu_B=26.0$ mag arcsec$^{-2}$ isophote. The pixel-by-pixels colours in the four HDF bands are compared to the predictions of exponential star-formation history spectral synthesis models for the redshift in question. The arrows on these plots show a $E_{B-V} = 0.1$ mag reddening vector calculated from the extinction model of Calzetti (1997). Model tracks for solar metallicity are shown in the bottom two panels. Red points refer to pixels within a 5 pixel radius of the center of the image. The corresponding age, star formation timescale, and dust maps are determined using the maximum-likelihood formulation. Corresponding best-fit maps for age, star-formation history e-folding timescale $\tau$, and $E_{B-V}$ are shown at top-right, middle-left, and middle-right. Figure taken from Abraham et al. (1999a).
best way forward may be a marriage of stellar population-based studies (which focus on stellar content that is preserved during morphological transformations) with Kormendy’s notion of a component-based approach to morphology. Ideally, such an approach should avoid the use of both integrated colors (which fly in the face of stellar population work and ignore the greatest advantage of HST, namely its ability to resolve distant systems), and profile fits (because distant galaxies clearly aren’t as smooth and axially symmetric as their local counterparts, and the locally-defined canonical fitting laws may no longer work).

An example of this approach is shown in Figure 4, which comes from the pilot study described in Abraham et al. (1999a). In this paper the spatially resolved colours of a sample of bright $z < 1$ galaxies of known redshift in the Hubble Deep Field are analyzed by matching resolved four-band colour data to the predictions of evolutionary synthesis models (Bruzual & Charlot 1993). This procedure quantifies the the relative age, dispersion in age, ongoing star-formation rate, and star-formation history of distinct components. The central idea behind this approach is conceptually similar to that used when applying color–magnitude diagrams to establish the epoch of formation for galaxy clusters (Bower, Lucey, & Ellis 1992): dispersion in color probes the history of star-formation. By assuming a simple extinction law, the presence of dust can be tested for and its effects incorporated into the color modeling. On the basis of this study, Abraham et al. (1999a) concluded that $\sim 30\%$ of early-type galaxies with $I < 23$ mag show evidence of star formation which must have formed at least $5\%$ of the stellar mass of the galaxy within the past third of the galaxian age at the epoch of observation. This result is largely independent of assumptions with regard to metallicity and is in agreement with recent spectroscopic observations of field ellipticals (Schade et al. 1999), and contrasts with the strikingly low dispersion in the color-magnitude relation of HST-selected ellipticals in distant rich clusters (Ellis et al. 1997; Stanford, Eisenhardt, & Dickinson 1998).

This methodology can also be used to analyze the relative histories of bulge and disk stars in spiral galaxies. For example, the established view is that galactic bulges form at high redshifts through early dissipation-less collapse (Eggen, Lynden-Bell, & Sandage 1962; Carney, Latham, & Laird 1990). This is based principally on the irrefutable evidence for old stellar populations concentrated in the bulge of our own Galaxy (Baade 1957; 1963) and contrasts with more recently-developed hierarchical galaxy formation models (Kauffmann et al 1993, Baugh et al 1996) where elliptical galaxies form from the merger of early disk systems which can, in turn, continue to accrete gas to form a two component spiral galaxy. A safe prediction of the hierarchical models is that spiral
bulges should, on average, contain older stars than their associated disks which form by subsequent accretion. Moreover, statistically at a given redshift, bulges should be older and redder than field ellipticals which predominantly form from the merger of previously created spirals. Importantly, these conclusions should remain valid regardless of the particular cosmological model or initial power spectrum which governs the rate of assembly of massive galaxies. As such, a comparison of the relative colors of ellipticals and spiral bulges offers a remarkably simple, but powerful, test of hierarchical assembly models (Ellis & Abraham 1999; Peletier et al. 1999). Of course a third alternative for the origin of stellar bulges proposes their manufacture via various instabilities of pre-existing disks (see §2.3, and the recent review by Combes 1999). The point here is that the establishing the relative importance of the three bulge formation processes as a function of redshift is clearly another area where morphology and stellar population studies unite to provide basic tests of galaxy formation models. Abraham et al. (1999a) concluded that median ages of bulge stars are significantly older than those in galactic discs, and exhibit markedly different star-formation histories. This is really only the tip of the iceberg — high-redshift resolved multi-color studies of this kind should be pushed into the infrared in order to probe more directly the formation of stellar mass.

5. Conclusions and Future Directions

In this review I have emphasized the transition from the established morphologies of the local Hubble sequence to the peculiar forms of the most distant Lyman break galaxies. While I have tried to highlight lines of continuity as a function of redshift, one must be careful not to invent lines of continuity where they do not exist. The framework of the Hubble sequence seems to be a fairly recent phenomenon. It has begun to break down by $z = 0.5$, and by $z = 1$ it provides a rather poor general description of the luminous galaxy population. At higher redshifts less emphasis should be placed on classical morphology, and more emphasis on quantifying the visibility of fundamental morphological components, and on their resolved stellar populations.

The redshift range $0 < z < 1$ is a particularly interesting for establishing how the Hubble sequence is built up. The size functions for the various classes needs to be more firmly established, on account of their fundamental role in testing theory. The connection between the formation of the Hubble sequence and the sharp drop-off in the integrated star-formation history of the Universe needs to be understood. Emphasis also needs to be placed on developing quantitative
methods for the parameterization spiral structure, perhaps along the lines of the useful system developed by Elmegreen & Elmegreen (1982). How does the density enhancement from spiral structure relate to the overall star-formation rate? Another valuable contribution would be the development of a really robust method for distinguishing between S0 and elliptical systems at high redshifts, in order to settle conclusively the origin of the Butcher-Oemler effect (Dressler et al. 1994; Ellis et al. 1997; Andreon 1998).

At higher redshifts the proportion of morphologically peculiar systems that are mergers in progress needs to be established. New metrics, such as global asymmetry and mean surface brightness, should be combined with dynamical studies in order to investigate this. Perhaps these metrics could also help answer another intriguing question: what is the highest redshift at which really archetypal spiral and elliptical galaxies can be detected? On the basis of photometric redshifts and optical HDF data, I can just about convince myself that there are reasonable looking disk+bulge systems at $z = 1.5$, as well as centrally concentrated early-type systems at $z = 3$. NICMOS observations of the HDF may allow these issues to be investigated at an appropriate rest wavelength.

Generally speaking, morphological work needs to be pushed further to the infrared. We need to establish the role of dust, and the importance of “old” stellar populations at high redshift. Resolved stellar population work in particular really should be done in the near infrared in order to probe directly the buildup of stellar mass without being biased by the presence of relatively recent star-formation activity dominating the observed rest-frame ultraviolet flux. It is interesting that, in many ways, the motivation for these sorts of programs is similar to the motivation for multi-colour imaging surveys of local galaxies that are now underway. For example, compare the results presented in §4 with the scientific rationale for the Ohio State University Bright Spiral Galaxy Survey (presented at the last South Africa morphology meeting) given by Frogel, Quillen & Pogge (1996). As with so many other areas of astronomy, our understanding of the distant Universe is limited by our poor understanding of our own neighborhood.

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References

Abraham, R.G., Valdes, F., Yee, H.K.C. & van den Bergh, S. 1994, ApJ, 432, 75
Abraham, R. G, Tanvir, N. R., Santiago, B. X., Ellis, R. S., Glazebrook, K. & van den Bergh, S. 1996a, MNRAS, 279, L47
Abraham, R.G., van den Bergh, S., Glazebrook, K., Ellis, R.S., Santiago, B. X., Surma, P., & Griffiths, R. 1996b, ApJSupp, 107, 1.
Abraham, R. G., Ellis, R. S., Fabian, A. C., Tanvir, N. R. & Glazebrook, K. 1999a, MNRAS, 303, 641
Abraham, R. G., Merrifield, M. R., Ellis, R. S., Tanvir, N. R. & Brinchmann, J. 1999b, MNRAS, 308, 569
Abraham, R. G. 1999c, To appear in proceedings of IAU 186, Galaxy Interactions at Low and High Redshifts. Preprint: astro-ph/9802033
Abraham, R.G. 1999d. In Formation and Evolution of Galaxies: a Perspective [Proceedings of the 1997 Les Houches Physics Summer School], eds. Le Fèvre et al (in press, astro-ph/9809131)
Baade, W. 1963, Evolution of Stars and Galaxies, (Cambridge: Harvard University Press).
Baade, W. 1957 in Stellar Populations, ed. O’Connell, D., p3 (Vatican Obs)
Baugh, C. M., Cole, S., Frenk, C. S. 1996, MNRAS, 282, L27
Bouwens, R., Broadhurst, T., Silk, J. 1998, ApJ, 506, 579.
Bower, R. G., Lucey, J. R., & Ellis, R. S. 1992, MNRAS, 254, 589
Bothun, G., Impey, C. & McGaugh, S. 1997, PASP, 109, 745
Brinchmann, J. et al. 1998, ApJ, 499, 112
Bruzual, G., & Charlot, S. 1993, ApJ, 378, 471
Bunker, A. 1999, astro-ph/9907196
Calzetti, D. 1997, AJ, 113, 162
Carney, B., Latham, D., & Laird, J. 1990. In ESO Proc., “Bulges of Galaxies”, eds. Jarvis, B., Temdrup, D.,
Combes, F., DeBasis, F., Friedli, D., Pfeiffer, D.1990, A&A, 233, 82
Combes, F., 1999. astro-ph/9908145
Conselice, C. J. 1997, PASP, 109, 1251
Cowie, L. L., Hu, E. M., & Songaila, A. 1995, AJ, 110, 1576.
de Vaucouleurs, G., de Vaucouleurs A., & Corwin, H. G. 1976. Second Reference Catalog of Bright Galaxies (Austin: University of Texas Press)
de Vaucouleurs, G., de Vaucouleurs A., & Corwin, H. G., Buta, R., & Fouqu/e, P. 1991. Third Reference Catalog of Bright Galaxies (New York: Springer Verlag)
Driver, S. P., Windhorst, R. A. & Griffiths, R. E. 1995, ApJ, 453, 48
Driver, S. P., Fernandez-Soto, A., Couch, W. J., Odewahn, S. C., Windhorst, R. A., Phillips, S., Lanzetta, K. & Yahil, A. 1998, ApJLett, 496, L93
Doi, M., Fukugita, M., & Okamura, S. 1993, MNRAS, 164, 832
Dressler, A., Oemler, A., Butcher, H. R. & Gunn, J. E. 1994, ApJ, 430, 107
Driver, S.P., Windhorst, R.A. & Griffiths, R.E. 1995, ApJ,453, 48
Driver, S. P., Windhorst, R. A., Ostrander, E. J., Keel, W. C., Griffiths, R. E., Ratnatunga, K. U. 1995, ApJ, 449, L23
Driver, S. P., Fernandez-Soto, A., Couch, W. J., Odewahn, S. C., Windhorst, R. A., Lanzetta, K., & Yahil, K. 1998 (ApJ(Letters), in press, astro-ph/9802092.

Eggen, O., Lynden-Bell, D., & Sandage. A. 1962, ApJ, 136, 748

Ellis, R. S., Colless, M., Broadhurst, T., Heyl, J., Glazebrook, K. 1996, MNRAS, 280, 235

Ellis, R. S., Colless, M., Broadhurst, T., Heyl, J., & Glazebrook, K. 1996, MNRAS, 280, 235

Ellis, R. S., Smail, I., Dressler, A., Couch, W. J., Oemler, A., Butcher, H., Sharples, R.M. 1997, ApJ, 483, 582

Elmegreen, D. M. & Elmegreen, B. G. 1982, MNRAS, 175, L19.

Hibbard, J. E., & Vaccia, W. D. (1997) AJ, 114, 1741

Heavens, A. F. & Jimenez, R. 1999, MNRAS, 305, 770

Hubble, E. 1926, ApJ, 64, 321

Hubble, E. 1936, The Realm of the Nebulae. (New Haven: Yale University Press)

Kormendy, J. 1982, in Morphology and Dynamics of Galaxies, Eds. L. Martinet & M. Mayor (Sauverny: Geneva Observatory).

Kormendy, J. 1992, in Proc.IAU Symp.153, “Galactic Bulges”, p.209, Kluwer, Dordrecht, eds. Dejonghe, H., Habing, H.

Kormendy, J. & Bender, R. 1997, ApJ, 464, L119

Le Fèvre, O. et al. 1997, in The Hubble Space Telescope and the High Redshift Universe (Singapore: World Scientific).

Le Fèvre, O. et al. 1999. MNRAS, in press.

Lilly, S. J., Tresse, L., Hammer, F., Crampton, D., Le Fèvre, O. 1995, ApJ, 455, 108

Lilly, S. J., Le Fèvre, O., Hammer, F., & Crampton, D.1996, ApJ, 460, L1

Lilly, S. J., Schade, D., Ellis, R. S., Le Fèvre, O., Brinchmann, J., Tresse, L., Abraham, R., Hammer, F., Crampton, D., Colless, M., Glazebrook, K., Mallen-Ornelas, G., Broadhurst, T. 1998. ApJ, 500

Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106

Mao, S., Mo, H. J., & White, S. D. M. 1998, MNRAS, 297, 71

Meurer, G. R., Heckman, T. M., Lehnert, M. D., Leitherer, C., & Lo wenthal, J. 1997, AJ, 114, 54

Mobasher, B., Rowan-Robinson, M., Georgakakis, A., & Eaton, N. 1996, MNRAS, 282L, 7

Morgan, W. W. 1958, PASP, 70, 364

Morgan, W. W. 1959, PASP, 71, 394

Naim, A., et al. 1995 , MNRAS, 274, 1107

Norman, C. A., Sellwood, J. A., & Hasan, H. 1996, ApJ, 462, 114

Odewahn, S. C., Windhorst, R. A., Driver, S. P., & Keel, W. C. 1996. Nature, 383, 45.

Roberts, M. S. & Haynes, M. P. 1994 AnnRev.A&A, 32, 115-52
Sandage, A. 1961, *The Hubble Atlas of Galaxies*, (Washington, D.C.: Carnegie Institution of Washington)
Sandage, A. & Visvanathan, N. 1978 ApJ, 223, 707
Sandage, A. & Tammann, G. A. 1981. *A Revised Shapley-Ames Catalog of Bright Galaxies*, (Washington, D.C.: Carnegie Institution of Washington)
Sandage, A. & Bedke, J. 1994 *The Carnegie Atlas of Galaxies*, Carnegie Institution of Washington, Washington, D. C.
Schade, D. et al. 1999, ApJ, in press.
Schade, D., Lilly, S. J., Crampton, D., Hammer, F., Le Fèvre, O., Tresse, L. 1995, ApJ (Lett), 451, L1
Sellwood, J., 1999. astro-ph/9909093
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M. & Adelberger, K. 1996, 462L, 17
Takamiya, M. 1999, ApJSupp, 122, 109
Thompson, R. et al. 1998. astro-ph/9810285
van den Bergh, S. 1960, ApJ, 131, 558
van den Bergh, S. 1976, ApJ, 206, 883
van den Bergh, S., Abraham, R. G., Ellis, R. S., Tanvir, N. R., Santiago, B. X. 1996, AJ, 112, 359.
van den Bergh, S. 1998, *Galaxy Morphology and Classification*, (Cambridge: Cambridge University Press)
Whitmore, B. C. & Gilmore, D. M. 1991, ApJ,
