

## LECTURE 1

PERSPECTIVES IN PHYSICAL  
MORPHOLOGY

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Cambridge CB3 0HA, United Kingdom***1. INTRODUCTION**

In the first section of these lectures I outline the classical framework of the Hubble classification system. Because of space limitations I will focus on points of controversy concerning the physical interpretation of the Hubble sequence, showing how morphological ideas shape our understanding of galaxy evolution. I will then present an overview of the remarkable progress made in recent years in understanding how the local morphological composition has transformed into that seen the distant Universe, highlighting work from the *Hubble Deep Field* (HDF). Recent studies show quite clearly that the Hubble system does not provide a useful framework for describing the appearance of galaxies at redshifts  $z > 1.5$ . I argue that as a result of this work the Hubble system needs to be replaced by a system that is more objective, more physically meaningful, and which is applicable across a wider range of redshifts.

**2. CLASSICAL MORPHOLOGY AND THE HUBBLE SYSTEM****2.1. How should we judge the Hubble system?**

As Sandage points out in the superb introduction to the *Carnegie Atlas of Galaxies* [74], successful classification systems can lead to enormous advances in science. Perhaps the best example of this phenomenon is the periodic table, which played a direct role in the development of models for atomic structure.

The central idea in any *physically motivated* (as opposed to merely descriptive) classification system is that of *ranking*, in the belief that this ranking reflects an underlying order in the basic physics of the system, rather than merely reflecting the natural tendency of the human brain to impose order and organization on randomness in order to facilitate communication and memory. The choice of features upon which the ranking is defined is, in the first instance, completely subjective. In this stage of the process intuition, experience, and inspiration are paramount (see the books by Sandage [74] and van den Bergh [85] for insight into the creative processes through which galaxy classification systems are developed). But once the system is in place, subjectivity should drop away as the system is tested against the underlying physics. Therefore in my view an ideal classification should have three characteristics:

- (a) *physical significance*: The ranking imposed by the classifier should track important underlying physical processes.
- (b) *completeness*: There should be no gaping holes in the system, ie. the vast majority of objects should slot naturally into the system somewhere.
- (c) *objectivity*: The system should be sufficiently well-defined that classifications made independently by well-trained observers should be very similar.

These are the metrics we will use when judging the success of the Hubble system in the latter part of these lectures. My own verdict will be given in §2.6.

## 2.2. Physical foundations of the Hubble sequence

Figure 1 shows the familiar “tuning fork” diagram, representing Sandage’s definitive exposition [71] of the system described by Hubble in his book *The Realm of the Nebulae* [48]. I assume the reader is familiar with the basic organization of the classification system, and I will focus here on issues of physical interpretation. Because of limited space, this section only touches upon the details of the Hubble system – in particular I do not have space to describe the important extensions to the Hubble sequence developed by de Vaucouleurs [23]. The reader can consult several excellent reviews for more comprehensive descriptions of these issues [52, 74, 85]. Furthermore, I will not be able to consider alternative classification systems in this lecture – in my view the most important of these is the Yerkes system developed by Morgan [63, 64], based on central concentration of galaxian light.

## 2.3. Ellipticals

The sequence E0–E6, based on apparent ellipticity, was originally conceived of as an angular momentum sequence in young galaxies. However, it did not take long for colour-based work to suggest that ellipticals are old [7], and formed quickly in a short burst of star-formation. Furthermore, it is now known that ellipticals are pressure-supported by anisotropic velocity distributions, with rotation playing a subsidiary role (except in less luminous systems [24]). Since

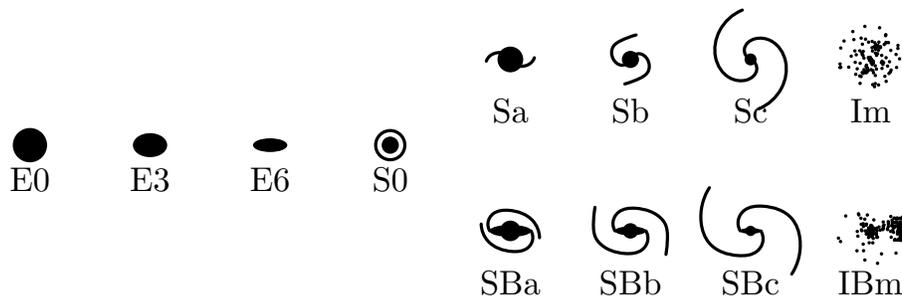


Fig. 1. — The “tuning fork” of the classical Hubble sequence [47]. As described below, the correlation between position on this sequence and the physical properties of galaxies suggests a strong underlying link between morphology and galaxy evolution.

ellipticals are known to be triaxial, the E0–E6 sequence is seriously contaminated by orientation effects.

The observational evidence supporting the view that ellipticals are old and roughly coeval is based primarily on the small scatter in the colour-magnitude diagram of low-redshift *cluster* ellipticals [72, 13]. This test has also been extended to higher redshift cluster samples with morphological classifications from the *Hubble Space Telescope* (HST) [38, 80], where the scatter remains small, suggesting that the epoch of elliptical formation in rich clusters was well in the past even at high redshifts.

### 2.3.1. Age Controversy

Although ellipticals have been considered to be old for the last 40 years, the term “early-type” to describe these galaxies (based on the original misapprehensions of Hubble) remains entrenched. Perhaps this will turn out to be a blessing in disguise, since the age distribution of elliptical galaxies, long thought a settled issue, has recently become enlivened by controversy. Ellipticals (and S0 galaxies) are predominantly found in dense environments, and consequently most local work has focussed on the properties of ellipticals in rich clusters. But hierarchical models for galaxy formation introduced the possibility that elliptical galaxies in the field are continuously formed from merging systems. In a controversial paper, Kauffmann *et al.* [50] claim observational evidence, from a colour-based analysis of data from the *Canada-France Redshift Survey* (CFRS), for a factor of three decrease in the abundance of ellipticals by  $z = 1$ . The claimed decrease is in good agreement with the predictions of semi-analytical approximations to hierarchical formation models for galaxy evolution. Kauffmann *et al.* also point out that cluster samples are ill-suited to testing the hierarchical picture as they represent accelerated regions so far as structure growth is concerned. It is quite possible that most of the rich cluster ellipticals are truly old as their homogeneously distributed colours imply. The

ultimate test of Kauffmann *et al.*'s conjecture lies in the analysis of ellipticals in field samples. The currently-available samples are too small for robust results [76, 4], although Zepf [87] claims the absence of red objects at very faint limits in the HDF is consistent with hierarchical predictions. Glazebrook *et al.* [44] have also claimed evidence for younger field ellipticals in data from the HST Medium Deep Survey, on the basis of  $I - K$  colours.

### 2.3.2. Environmental Effects

The tendency for ellipticals to be found in clusters is a manifestation of the *morphology-density relationship*, a term coined by Dressler in the first really thorough investigation of the effect [28], although the basic tendency for ellipticals to be found in rich clusters was known to Hubble, and the physical significance of this environmental effect was emphasized by Spitzer & Baade (1951). The issue has resurfaced as point of controversy in recent investigations which seek to determine whether the key correlations are between morphology and local galaxy density, or between morphology and radial distance from the centre of rich clusters [75, 86]. Obviously local galaxy density and cluster-centric radius are strongly correlated, so the distinction can be rather subtle, but resolving this issue is central to understanding whether the distribution of galaxy types is built up gradually from large scale structure by accretion from the field, or is instead primordial in origin (the *nature versus nurture* controversy).

### 2.3.3. Luminosity and the Fundamental Plane

A remarkable, but perhaps under-appreciated, feature of elliptical systems is the huge range of luminosity spanned by the class. The luminosity of ellipticals spans a dynamic range of around 50,000 (12 magnitudes), from inactive dwarf systems ( $M_V \sim -11$  mag) to giant cD galaxies ( $M_V \sim -23$  mag). In contrast, an individual classification "bin" along the spiral arm of the tuning fork encompasses a range of perhaps 3–5 mag (type Sb having the smallest dynamic range, and Sd the largest [85]). The enormous luminosity range encompassed by ellipticals masks an underlying physical order that is not obvious from the classification scheme. Ellipticals show a large scatter in quantitative photometric properties, but as Dressler *et al.* [29] and Djorgovski & Davis [26] first showed, correlations between radius, surface brightness, and velocity dispersion in ellipticals trace out a remarkably well-delineated plane in three-dimensional parameter space. Understanding the origin of this *fundamental plane* is a key component in studies of the physical morphology of early-type systems. While a large portion of the scatter in the fundamental plane is due to metallicity variations, it is important for the student to bear in mind the remarkable fact that luminous ellipticals are among the most highly enriched galaxies in the Universe (up to several hundred percent solar metallicity in their inner portions, with fairly strong internal gradients). The processes through which old systems may have undergone rapid enrichment at the time of formation are

fascinating, and well-described by Arimoto [6] and references therein.

#### 2.4. S0 Galaxies

It is interesting to note that on the basis of the early versions of the tuning fork, S0 galaxies were essentially predicted to exist by Hubble even before they were observationally established (“The transitional stage, S0, is more or less hypothetical” – Hubble 1936). The natural way in which subsequent observations entrenched S0 systems as key components in the galaxy population has been rightly hailed as a major success of the Hubble system. But are S0 galaxies, as predicted by Hubble, a truly transitional physical “bridge” between spirals and ellipticals? The evidence is equivocal, and the question remains among the most interesting in physical morphology.

As pointed out by van den Bergh (1998), *the luminosity distribution of both ellipticals and early-type spirals peaks  $\sim 1.5$  mag brighter than that of S0 galaxies*, suggesting S0 galaxies are *not* a smooth transition class between spirals and ellipticals (Figure 2). Other evidence seems to be building that suggests that S0 systems are relics of spirals. For example, the “Morphs” collaboration [30] have used HST imaging to show that much of the gradual bluing in the cluster population with redshift (the *Butcher-Oemler effect*) is due to fairly-normal looking late-type spirals that are seen in the cores of high redshift systems, but which are absent in the cores of local clusters. The elliptical fraction as a function of redshift seems constant, and the clear implication is that spirals are being transformed into S0 systems. Coming at this issue from the other direction, other studies [12, 66] have shown that some ellipticals contain boxy inner disks, and other studies have on the whole lent support to the notion that early-type galaxies can be physically differentiated on the basis of having disk components of varying strengths [54, 40, 70], possibly as a function of luminosity. An interesting synthesis of these ideas has been proposed by Kormendy & Bender (1996), who suggest that the present ranking of the early-types along the tuning fork (based on apparent eccentricity) should be replaced by a sequence in which ellipticals are ranked according to boxiness of isophotes [54]. S0 systems would then indeed form a transitional bridge between spirals and ellipticals with boxy isophotes. This proposed system is a radical alteration of the Hubble sequence, but one which preserves the spirit of the S0 class as a transitional bridge as envisioned by Hubble.

#### 2.5. Late-type Galaxies

In Figure 1 spirals are subdivided into barred and ordinary spirals — not “normal spirals”, as they are sometimes termed. In fact around  $\sim 65\%$  of spirals have recognizable bars or bar-like features in the *B*-band, according to de Vaucouleurs (1963). Along the tines of the tuning fork the spirals are further subdivided into classes ranging from early to late-type (Sa, Sb, etc) based on three criteria: (a) the dominance of the bulge; (b) the degree of winding of

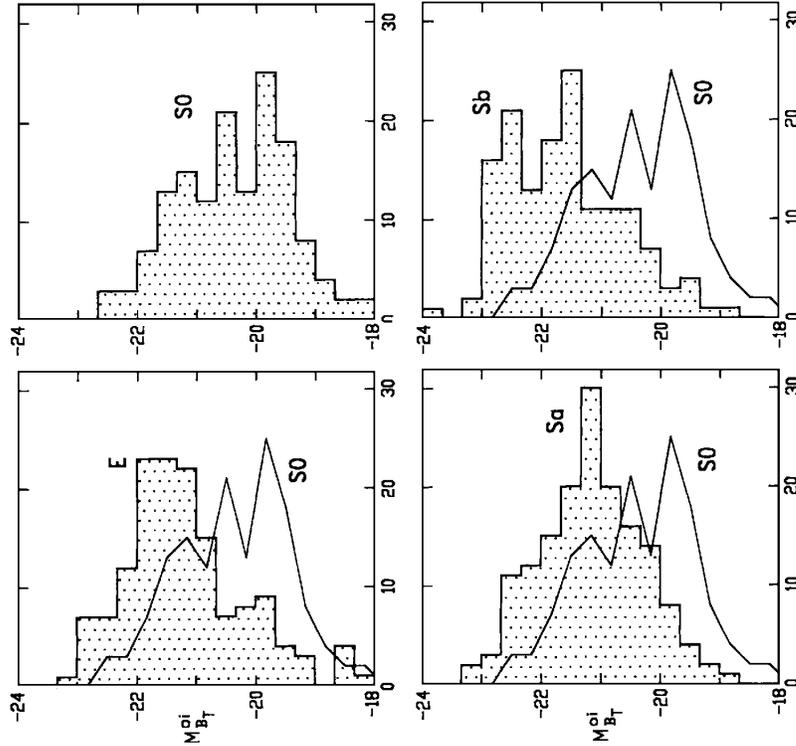


Fig. 2. — Histograms showing the luminosity distributions of elliptical, S0, Sa, and Sb galaxies in the *Revised Shapley-Ames Catalog* (Sandage 1981). The S0 distribution is repeated from panel to panel. Note how S0 systems appears to be systematically fainter than *both* elliptical and Sa galaxies, suggesting that S0 galaxies are not a morphological bridge between these. Figure taken from van den Bergh (1998).

the arms; and (c) degree of resolution of the arms <sup>(1)</sup>. A major weakness of the Hubble system is that the variety of observed spiral structure is poorly encompassed by the system [52]. Important classes are missing, such as the

<sup>(1)</sup> It is rather unsatisfactory to have the early-late spiral sequence based on three criteria, some of which may be contradictory, rather than on quantitative measures. For example, how does one classify a spiral with a smallish bulge and tight spiral structure (a combination that is not unknown). Is this designated as an early type (based on arm appearance) or late-type (based on bulge prominence), or perhaps classed as peculiar? The answer is that in these case one must look carefully through the *Hubble Atlas* for similar objects and determine what Sandage chooses to call such a galaxy – the system is subjective and ultimately defined by reference to archetypes.

flocculent spirals [39], and anemic spirals [83] (these latter systems are seen only in clusters, and exhibit faint, “ghostlike” spiral structure, suggesting they may be related to S0 galaxies). In fact this deficiency led van den Bergh [82] to propose the important luminosity class extension to the Hubble system, in which arm morphology/surface brightness is used to rank spirals. This system roughly tracks galaxy luminosity, exploiting the fact that most luminous spirals have well-developed, long spiral arms (*grand design* spiral structure), while lower luminosity systems tend to exhibit poorly developed, disconnected arms.

### 2.5.1. *Two physical regimes along the tuning fork?*

In probing the physical meaning of the Hubble sequence it is perhaps useful to mentally subdivide the sequence into two regimes: E–Sbc and Sc–Irr [85] since in the latter objects the dominant physics seems to be an almost perfect sequence of decreasing mass and luminosity with Hubble type. For very late-type galaxies, correlations between morphology and colour/star-formation history exist but are not strong – a typical Im is not significantly bluer than a typical Scd [69]. It is perhaps worth noting that while the general trends in very late-type systems are clear, there appears to be no really objective way of distinguishing between very late-type spirals (ie. types Sd and Sm) and irregular galaxies [85].

Along the earlier portion of the sequence the Hubble system remains quite successful at ranking galaxies along physical lines, although the story is more complex. In addition to ranking galaxies by bulge-to-disk ratio (partly by definition), the early part of the spiral types of the Hubble sequence order galaxies by surface HI and total mass density, total HI mass, colour, and, to some extent, mass-to-light ratio. Of these the strongest correlations appear to be with colour [69], and hence with star-formation history. To what extent these correlations would remain if one ranked galaxies simply by bulge-to-disk ratio, as proposed by Morgan [63, 64], is unknown. However, because bulge-to-disk ratio is the dominant morphological characteristic linked to star-formation history, and because this seems the strongest correlation, I would not be surprised if the correlations along the early part of the spiral sequence actually improved if the ranking was purely by bulge-to-disk ratio.

### 2.5.2. *Bulge formation*

The physics of bulge formation in spirals is of great interest. In our own Galaxy the observational evidence for early bulge formation seems established, mainly since the main tracers of bulge/halo populations (eg. globular clusters and RR Lyrae stars) are known to be old. The notion that bulges form well before the discs in the first stage of galactic collapse is the essential component in both the classic Eggen, Lynden-Bell, & Sandage (ELS) scenario [34] and more modern variants [18]. Hierarchical galaxy formation scenarios also require old bulges formed by mergers [49, 11], with visible discs built-up gradually from gas accreted onto these merger remnants. Recently, however, the issue

of the relative age of the bulge and disc in extragalactic systems has become controversial. N-body simulations indicate that bulges form naturally from bar instabilities in discs [67, 19], and recent observations now seem to indicate that bulges display the morphological and dynamical characteristics of such a formation scenario (eg. triaxiality or “peanut” shapes [55], cylindrical rotation [78], and disk kinematics [53]). Most remarkably, recent observations indicate that the inner discs and bulges in local galaxies *cannot be distinguished in terms of colour* [10, 25], which is surprising given the visual impression from “true colour” deep HST images of distant galaxies, in which bulges seem generally redder than disks [84]. Recent quantitative modelling of low-redshift spirals in the Hubble Deep Field [4] also seems to suggest that bulges are generally the oldest parts of galaxies<sup>(2)</sup>.

## 2.6. An improved Hubble system?

Most observers would agree that (locally) the Hubble system supplies a fairly complete framework for classifying galaxies in the field – it seems that over 90% of local field galaxies find a natural home within the system. Furthermore, discussion of the previous section argues rather forcefully for a close connection between the morphological bins of the Hubble system and an underlying physical order. The major criticism I would level against the ranking implicit in the Hubble sequence is that the classification of the early-type portion of the diagram (based on apparent eccentricity) seems to me rather unphysical. Furthermore the system is biased heavily in favour of luminous giant and supergiant galaxies (which dominate the galaxian mass content of the Universe, but which do not dominate in terms of total numbers seen in volume-limited samples). My own view is that both of these criticisms would be greatly alleviated if luminosity were included as a classification criterion. This is not really practical at the present time, since redshifts are rarely available for random galaxies on CCD images. But at least as an organizational structure, it seems to me that a three-dimensional system such as that proposed by van den Bergh (1998) has much to commend it (Figure 3), summarizing pictorially many of the issues dealt with so far in this lecture.

On balance, I would argue that according in terms of the first two of the three (rather strict) criteria for a useful classification scheme espoused in §2.1, the Hubble system is a resounding success. However, because of the rather depressing results from controlled comparisons between independent classifications made by expert morphologists [65], I have rather grave doubts about

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<sup>(2)</sup> However, if secular activity somehow generates bulges from disks *without* any star-formation activity (ie. by simply reorganizing existing galaxy populations without forming any new ones), then it is possible that red bulges could still be formed, provided they were built-up exclusively from the oldest disk populations in the centres of the galaxies. The plausibility of this hypothesis could perhaps be tested by hydrodynamical simulations. I am grateful to Mike Merrifield for pointing out this possibility.

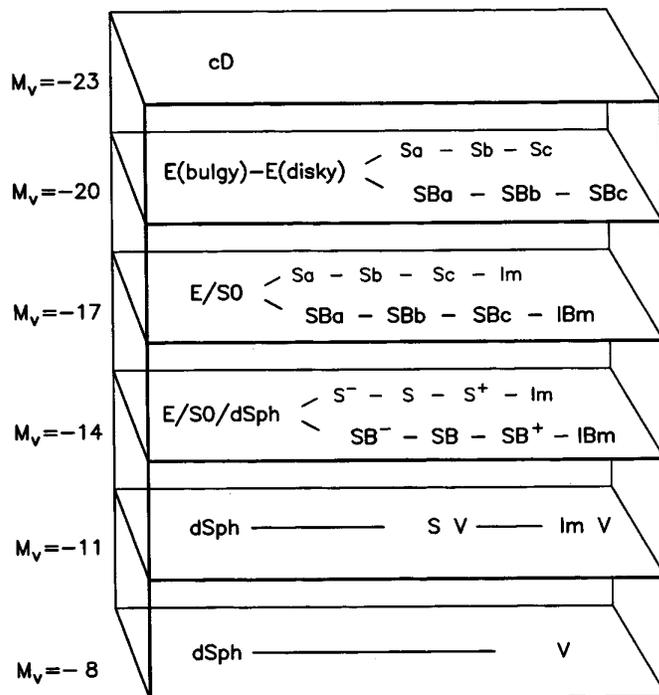


Fig. 3. — The three-dimensional tuning fork proposed tentatively by van den Bergh [85]. Note how the the early-type sequence has been replaced in all panels by more physically meaningful classifications. As one descends the luminosity scale of the three-dimensional tuning fork, the conventional forms of late-type galaxies on the Hubble sequence disappear, and become replaced by lower-luminosity systems with more ragged morphology.

the third criterion (observer-to-observer consistency in visual classifications — I have no doubt that an expert morphologist can make classifications that are, internally, highly consistent). Recent years have seen great advances in the usefulness of objective, machine-based morphological classifications [27, 65, 2, 68]. None of these automated classification schemes is able to reproduce the Hubble system in detail, although the classifications do track the system in a crude sense. At high redshifts, where low signal-to-noise and subtle selection effects play havoc with visual classifications, simple and objective classifications that can be calibrated by simulations are essential.

### 3. MORPHOLOGY AT HIGH REDSHIFTS

As one probes further into redshift space, it would be surprising if the Hubble sequence did not begin to break down as one approaches the initial epoch of galaxy formation. The interesting questions are *where* the system breaks down, and *how*. Does one class of galaxy within the system begin to gradually dominate over the others, indicating that the sequence itself contains the “galaxian ground state” as one of its classification bins? Or do entirely new classes of galaxy emerge? With the advent of HST, we are now in a position to address such questions.

Recent work from deep HST imaging surveys [45, 43, 31, 2, 3, 42] coupled with ground-based spectroscopic work, [58, 20, 59, 36] has shown that much of the rapidly evolving faint blue galaxy population [16, 51, 58] is comprised of “morphologically peculiar” galaxies. This term has been rather liberally applied to encompass a vast range in observed galaxy forms, but in fairness more precise classifications have been difficult to apply, because at high redshifts galaxies are being observed in the rest-frame ultraviolet (a “morphological K-correction”), where little is known about the appearance of the local galaxy population. However the conclusion that these systems are *intrinsically* peculiar seems secure, because the general effects of cosmological bandshifting on normal Hubble types has been determined from simulations [3]. In general the observed faint peculiar systems do not resemble the appearance of bandshifted Hubble sequence galaxies. Furthermore the redshift range probed by most deep *I*-band HST imaging corresponds to  $z < 1$  (with the exception of Lyman-limit selected systems discussed below), in which the effects of cosmological bandshifting on morphology are not yet extreme.

Perhaps the clearest evidence for the increasing importance of morphologically peculiar systems as a function of redshift has been obtained by Brinchmann *et al.* [15]. These authors applied an objective classification scheme, calibrated by simulations, to a set of  $\sim 300$  HST  $I_{814}$ -band images of galaxies *with known redshifts* taken from the CFRS [59] and LDSS [36] surveys. Because the statistical completeness of this sample is very well understood, reliable number-redshift histograms can be constructed for the various morphological types. The morphologically resolved  $n(z)$  result obtained by Brinchmann *et al.* is shown in Figure 4, and confirms that irregular/peculiar/merging systems are already greatly in excess of the predictions of no-evolution and mild-evolution models at redshifts  $z \sim 1$ . It is clear that by  $z \sim 1$  approximately 1/3 of galaxies are morphologically peculiar.

What are these peculiar systems? The answer to this question is currently unknown. These galaxies are often referred to as “irregulars” in the literature, but it is probably a mistake to regard these systems as counterparts to local irregulars. As pointed out in the previous section, luminous irregulars are virtually unknown in the local Universe, while the high-redshift peculiar systems

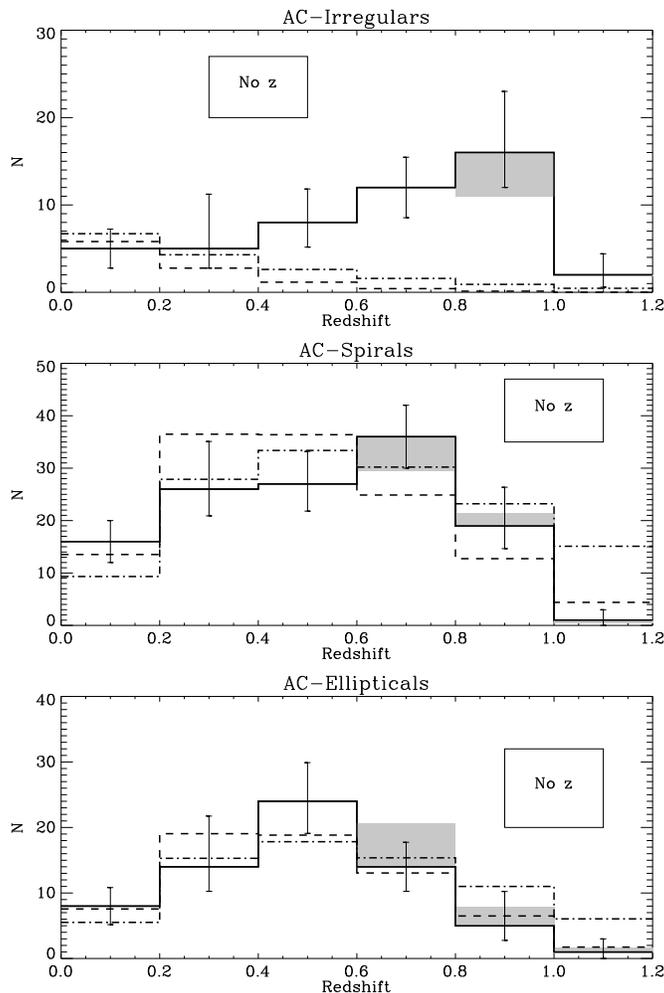


Fig. 4. — Morphologically segregated number counts from Brinchmann *et al.* (1998) [15], based on data from the CFRS/LDSS collaboration. The solid-line bins show counts as a function of redshift for irregular/peculiar/merger systems (top), spirals (middle), and ellipticals (bottom). Morphological classifications have been made from WF/PC2 images using an automated technique based on central concentration and asymmetry of galaxian light [3]. The shaded region corresponds to the size of the “morphological K-correction” on the classification, 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.

are generally both large and bright<sup>(3)</sup>

Let me conclude this section by pointing out that although (because of space limitations) my focus in these lectures is on peculiar galaxies at high redshifts, one should not lose sight of the importance of tracking systematic changes in the characteristics of morphologically *normal* systems. An interesting study has recently been completed by Lilly and collaborators [60], which seems to indicate little change in the space density of large spiral systems to redshift  $z = 1$ . The distribution of galaxian disk sizes is a sensitive probe of hierarchical formation scenarios (in which disk sizes are expected to strongly evolve with redshift). Attempts to understand the implications of this observation in the context of hierarchical models are underway [62].

### 3.1. The nature of high- $z$ peculiar galaxies

#### 3.1.1. The evolving merger rate

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. But is this assumption justified? Figure 5 shows candidate  $z > 2$  Lyman dropout systems in the Hubble Deep Field with  $I_{F814W} < 25$  mag. Clearly most are morphologically peculiar, but few resemble the classical appearance (ie. strongly bimodality, with prominent tidal tails) of “canonical” local merging systems. However, as discussed further below, the  $z > 2$  regime accessible to Lyman limit searches probes rest wavelengths where the effects of bandshifting on morphology can be rather extreme. This is made clear by Hibbard & Vacca [46], who used HST FOC ultraviolet data of local merger-induced starburst galaxies to predict the appearance of the high-redshift counterparts. The usual signatures of mergers (tidal tails, distorted disks) are no longer visible at  $z > 2$ , and merging starbursts seem to provide at least qualitatively reasonable counterparts to many faint peculiar galaxies.

Clearly the best way forward will be to incorporate dynamical information to determine directly which peculiar galaxies show distinct kinematical subcomponents. Unfortunately these observations are not currently feasible, although they may soon become possible with adaptive optics and the new generation of 8m-class telescopes. In the meantime, a promising approach to quantifying the fraction of mergers amongst the distant peculiar galaxy population may be to measure statistics which are relatively insensitive to image distortions resulting from bandshifting and surface-brightness biases, but which track probable merger activity. One such statistic is the “Lee Ratio”, a measure of image bimodality. This statistic been applied to images of galaxies in the CFRS survey [56, 57] and to HDF galaxies, with the result that around  $\sim 40\%$  of faint

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<sup>(3)</sup> It is left as an exercise for the reader to show that the selection function for a magnitude-limited survey sampling a Schechter luminosity function results in a roughly gaussian-shaped absolute magnitude distribution that peaks near  $L_*$

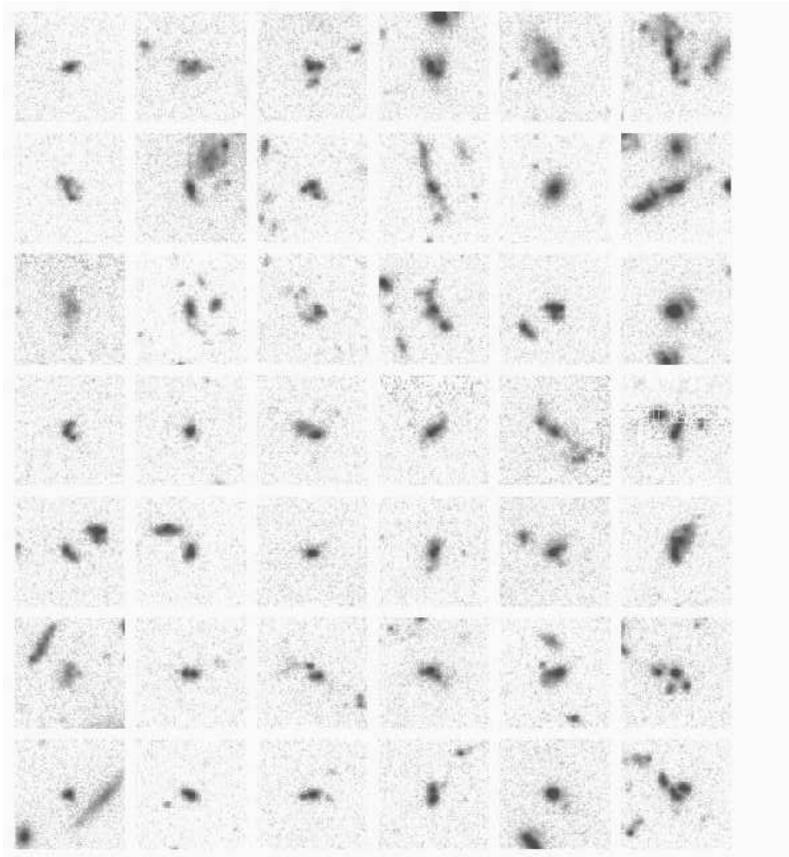


Fig. 5. — Candidate Lyman break ( $z > 2$ ) systems in the Hubble Deep Field with  $I < 25$  mag, taken from van den Bergh *et al.* (1996) [84].

peculiar systems are significantly bimodal, with an  $\sim (1 + z)^3$  increase in the merger rate.

### 3.1.2. When does a merger become a galaxy?

The observed evolution in the merger rate, coupled with the expectation from theory that mergers move galaxies up and down the Hubble sequence (cf. the lectures given by Prof. White in this volume), forces morphologists studying the high-redshift Universe to confront both philosophical and practical issues that seemed rather semantic and trivial at low redshifts. For example: when should an amorphous blob of components be regarded as single morphologically peculiar galaxy, as opposed to a system of interacting proto-galaxies? de Vau-

couleurs 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. Classification schemes which explicitly incorporate measures of asymmetry and bimodality are needed to realistically capture the appearance of galaxies in the high-redshift Universe.

### 3.1.3. Morphologies of Lyman-limit systems considered dangerous

Deep HST imaging of galaxies selected on the basis of colour to be at redshifts  $z > 2$  has provided an important breakthrough in our understanding of high-redshift morphology [81, 42]. Such surveys probe systems seen at ages corresponding to 10-20% of the present age of the Universe. So far the results appear somewhat contradictory. Early studies focussed on the compact cores of these systems, which appear well-modelled by  $r^{1/4}$  law profiles, suggestive of proto-ellipticals (Giavalisco *et al.* 1996). Deeper observations have revealed morphological characteristics among the most bizarre yet seen on deep HST data (Fig 5). Whether the morphologies of Lyman limit systems are interpreted as fairly regular or totally bizarre is a strong function of the limiting surface brightness of the observations, and whether the complex structures linking the bright knots have been resolved. Thus any interpretation of the morphologies of Lyman limit galaxies remains speculative. In the context of these lectures perhaps the best that can be done is to present explicitly the various factors that make the interpretation of the  $z > 1.5$  morphological data so subtle.

The most obvious complication is that Lyman break systems are being observed at rest wavelengths so far in the ultraviolet that even the relatively sparse ground-based  $U$ -band data of local systems provide a poor reference standard for comparison. (In fact, the handful of local systems observed with the *Ultraviolet Imaging Telescope* on the Astro-1 and Astro-2 missions provide the best calibration reference.) In any case, Lyman limit systems are at redshifts so high that the effects of evolution *must* be incorporated explicitly when making meaningful comparisons. At the epoch being observed, the Universe may simply be too young to have evolved the old stellar populations that play an important role in defining local morphology. Also, extraordinarily strong surface-brightness selection effects bias against the detection of even intermediate-aged stellar populations. These latter points are perhaps best understood from plots such as that shown in Figure 6, which illustrates the surface brightness of a surface mass density as a function of population age and observed redshift. Stellar populations with ages greater than 1–2 Gyr are strongly biased against in observations at  $z > 1.5$ , and only the youngest stellar populations (the “tip of the iceberg” in terms of stellar mass) are detectable. On the other hand, if  $\Omega$  is large then the Universe at  $z \sim 2-3$  may be sufficiently young that the populations biased against would not have time to have formed, so a large proportion of the total mass would be detectable.

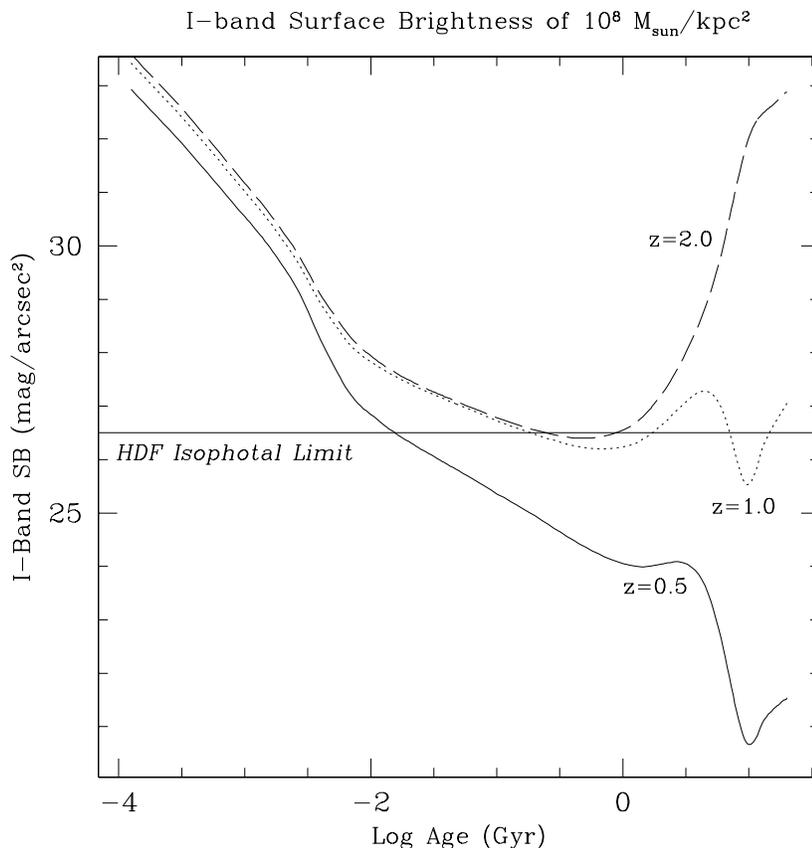


Fig. 6. — Predicted *I*-band surface brightness as a function of age for a stellar population with a projected surface mass density of  $10^8 M_{\odot} \text{ kpc}^{-2}$ . The three curves shown correspond to stellar populations with exponential star formation histories (with e-folding timescales of 1 Gyr) seen at redshifts  $z = 0.5$ ,  $z = 1.0$ , and  $z = 2.0$ . Calculations are based on the predictions of the GISSEL96 spectral synthesis package (Bruzual & Charlot 1996). Also shown is the approximate *I*-band (F814W) isophotal detection limit for the Hubble Deep Field. Note the precipitous decline in visibility of older stellar populations with redshift. Curves such as these suggest that beyond  $z > 1.5$  substantial mass could be locked in “old” (ages greater than one or two Gyr) stellar populations that would be undetectable even in red optical bands.

### 3.1.4. New classes of galaxies

The possibility that many morphologically peculiar high-redshift galaxies may be more-or-less conventional mergers (*ie.* interactions between established

galaxies) should not blind us to the likelihood that many of the observed galaxy forms probably correspond to entirely new classes of objects, or perhaps to the initial merging events forming the first generation of luminous galaxies. For example, it has been pointed out that a fairly large proportion of faint peculiar systems have knotty, linear forms [20]. Several examples are seen in Figure 5. The nature of these “chain galaxies” is controversial. Some authors suggest that they may be edge-on spiral or low surface-brightness disk systems [22]. However, I believe the evidence (at least for the most striking chain galaxies) strongly suggests that these deserve to be considered a *bona fide* new class of object. For example, the colours of the knots in some relatively low-redshift chains are remarkably synchronized — giant complexes of star-formation appear to propagate along the body of these system like a string of fireworks [5]. While intrinsically linear systems are dynamically unstable on timescales  $\sim 100$  Myr, a straight-forward comparison of the internal colours of these galaxies with spectral synthesis models suggests that the unweighted mean age of the starlight in chain galaxies is indeed of order 100 Myr, and thus comparable with the dynamical timescale. The age difference between the youngest and oldest knots in the chain is only around 30–50 Myr. If these properties prove universally true (and one needs to be cautious, as only a few chain galaxies have been examined in detail so far), then chain galaxies certainly seem to be systems with no local analogue.

How many other entirely new classes of peculiar galaxy exist at high redshifts? We will not know until such systems can be distinguished from more straight-forward mergers (perhaps through their dynamical properties), and until an inventory of the different classes of peculiar systems is undertaken over a broad range of redshifts. Until such studies are undertaken it will be difficult to disentangle the physical mechanisms responsible for the myriad spectacular forms of the distant galaxies seen on deep HST images.

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