Galaxy Formation and Large Scale Structure

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Abstract.
Galaxies represent the visible fabric of the Universe and there has been considerable progress recently in both observational and theoretical studies. The underlying goal is to understand the present-day diversity of galaxy forms, masses and luminosities in the context of theories for the growth of structure. Popular models predict the bulk of the galaxy population assembled recently, in apparent agreement with optical and near-infrared observations. However, detailed conclusions rely crucially on the choice of the cosmological parameters. Although the star formation history has been sketched to early times, uncertainties remain, particularly in connecting to the underlying mass assembly rate. I discuss the expected progress in determining the cosmological parameters and address the question of which observations would most accurately check contemporary models for the origin of the Hubble sequence. The new generation of ground-based and future space-based large telescopes, equipped with instrumentation appropriate for studying the resolved properties of distant galaxies, offer the potential of substantial progress in this field.

1. Introduction
Despite a dramatic surge of interest in observational cosmology (Figure 1), our physical understanding of how the local diverse population of galaxies formed remains unclear. Although semi-analytical models based on hierarchical growth in a cold dark matter dominated Universe are able to reproduce many basic observables such as the joint distributions of magnitude, colour and redshift to faint limits, and the spatial distribution of sources selected in different ways at various look-back times, we seek more fundamental ways of making progress and, in particular, of finding observational tests of galaxy formation models immune from uncertainties introduced by our poor knowledge of the cosmological parameters and the power spectrum of mass fluctuations. In this brief non-specialist review, I assess the renewed enthusiasm for independently determining the cosmological parameters and emphasise how the new generation of ground-based and future space-based large telescopes, equipped with instrumentation appropriate for studying the resolved properties of distant galaxies, might then approach the question of understanding the origin of the Hubble sequence of morphological types.
Figure 1. The rapid growth in publications in Ap J and AJ containing the keyword observational cosmology. The dates of some significant events are included. Keyword statistics cannot be reliably used prior to 1975.

2. Models for the Growth of Structure

The most popular model for the origin and development of structure in the expanding Universe is the cold dark matter (CDM) model (White & Rees 1978, Blumenthal et al 1984) whose predictive power for both the assembly of mass structures and the history of galaxy formation has been exploited via both numerical simulations (Frenk et al 1985) and semi-analytical calculations (Kauffmann et al 1993, Cole et al 1994, 1999).

CDM posits that the bulk of gravitating mass in the Universe is non-baryonic in form and which detaches from the expanding plasma prior to recombination. A present-day galaxy can be regarded as a peak of radiating baryonic matter embedded within a more extensive dark matter halo. Although the growth of mass structures is governed by the merging hierarchy of dark matter halos (Press & Schechter 1985), the onset of galaxy formation depends on the interplay between gas cooling and star formation which relies on more detailed astrophysics. Further development e.g. details of the formation of the Hubble sequence remains unclear. CDM should therefore be envisioned as a theory of structure formation underpinned by a fundamental assumption - the presence of copious amount of non-interacting dark matter - upon which more detailed astrophysical ingredients must be added.

Even in the context of understanding large scale structure, the CDM picture represents a working framework rather than a specific well-defined model. Within hierarchical dark-matter dominated models are variants which differ in the assumed cosmological parameters (Ω_{mass}, Ω_{baryon}, Ω_{Λ}, H_0 etc) and the spectrum of initial fluctuations, characterised by the slope n (n=1 in most inflationary models) and absolute normalisation (the latter quoted in terms of the variance of mass fluctuations on 8h^{-1} Mpc scales, σ_8). None of these key parameters is known with certainty, including perhaps even H_0, but three combined sets consistent with much of the available data are in popular use (see Table 1) (adapted from Thomas et al 1998). Each represents a variant of the original ‘Standard’ SCDM which fails to jointly fit the absolute value of microwave background fluctuations found by COBE and the present-day number density of rich clusters (Wright et al 1992).

The key observables which have, over the past few years, been used to reject SCDM and support some or all of the others include the absolute normalisation of large scale fluctuations in the microwave background (Bunn & White 1997), the local number density of rich clusters of galaxies (White et al 1993) and the power spectrum of the local galaxy distribution (Peacock 1997). Broadly speaking, the CDM variants are underconstrained by these observables if the cosmological parameters are allowed a free range. However, structure evolution over 0< z <2, during which time the local galaxy population might have assembled, depends sensitively on the values of Ω_M and Ω_Λ and thus if it became possible to independently constrain these parameters, systematic observations
Table 1. The CDM Family

| CDM Variant   | $\Omega_{\text{mass}}$ | $\Omega_{\text{baryon}}$ | $\Omega_\Lambda$ | $H_0$ | $n$ | $\sigma_8$ |
|---------------|------------------------|--------------------------|------------------|-------|----|-----------|
| Standard SCDM | 1.0                    | 0.050                    | 0.0              | 50    | 1   | 0.61      |
| Open OCDM     | 0.3                    | 0.026                    | 0.0              | 70    | 1.3 | 0.85      |
| Lambda $\Lambda$CDM | 0.3          | 0.026                    | 0.7              | 70    | 1   | 1.30      |
| Tilted $\tau$CDM | 1.0                  | 0.050                    | 0.0              | 50    | 0.7 | 0.68      |

of distant galaxies would provide less ambiguous information on physical aspects of galaxy formation. The bottom line is that it will be hard to find a shortcut to substantial progress in understanding galaxy formation without comparable effort to nailing down the cosmological parameters.

3. Progress in Structure Formation and Cosmology

Should we believe the growing optimism that we will soon resolve many of the key variables that govern the history of large scale structure, including the elusive cosmological parameters (e.g. Tytler 1997, Turner 1999) - or are we witnessing a rerun of the enthusiasm that swept observational astronomy in the 1970’s (e.g. Gunn & Tinsley 1975, Gott et al 1976)? I have selected four basic observational initiatives and good progress can be expected for each of them in the next decade.

3.1. The Local Distribution of Galaxies

The local spectrum of mass fluctuations has, until now, been largely constrained by the abundance of rich clusters quantified via $\sigma_8$ (Eke et al 1996) (see Table 1). However, clusters of galaxies cannot be easily selected on an uniform basis in terms of their total mass. Cluster mass estimates based on galaxy dynamics are affected by substructures whose nature is poorly defined even when hundreds of velocities are available. Likewise, masses based on X-ray luminosities or temperatures rely on structural data which is in short supply. The power spectrum $P(k)$ of a large uniformly-selected galaxy redshift survey constrains the mass distribution on large scales with the disadvantage that galaxies may be biased tracers of the underlying matter. When coupled with the amplitude of angular fluctuations in the microwave background, joint constraints on various cosmological parameters become available (see Eisenstein et al 1998).

Very large, statistically-complete, redshift surveys are now underway (Gunn & Weinberg 1995, Colless 1999) motivated by the need to constrain the power spectrum and topology of the galaxy distribution as well as the peculiar velocity field, either statistically or through specific surveys targeting individual classes of galaxies (Colless et al 1999). At the time of writing the largest local survey is the Anglo-Australian 2dF Galaxy Redshift Survey (2dFGRS – Taylor 1995, Colless 1999) which has $\approx$50,000 redshifts to $b_J=19.5$ from a currently-incomplete

$^1k = 2\pi/\lambda$ is the Fourier wavenumber of a particular comoving length scale, $\lambda$ Mpc.
Figure 2. (Top) The redshift-space distribution of galaxies so far in the Anglo-Australian 2dF Galaxy Redshift Survey (Colless 1999). (Bottom) That expected in $\tau$CDM from the mock catalogue produced by Cole et al (1998). The mock catalogue incorporates many of the technical limitations of the 2dF instrument and details of the survey strategy as well as the manner in which galaxies are biased.

magnitude-limited sample within one $75^\circ \times 5\text{-}15$ declination strip in each Galactic hemisphere. An important development with these surveys is the generation of 'mock catalogues' (Cole et al 1998) based on numerical simulations incorporating bias prescriptions, observational selection criteria and the instrumental characteristics of the actual surveys (Figure 2).

Deeper surveys can, in principle, constrain the correlation function of galaxies at large look-back times, in order to track the evolution of structure. In practice however, there are formidable obstacles. Surveys such as 2dFGRS are magnitude-limited and, faintward, k-corrections increase the spread in redshift considerably so that the mean depth $\tau$ is not strongly dependent on magnitude limit (Ellis et al 1996). A $B=25$ wide-field 8-metre telescope survey is likely to have a significant volume overlap with one surveyed to $B=22$ by 2dF itself (although the galaxies sampled would of course be intrinsically less luminous).

If galaxies can be selected to lie in specific redshift intervals through judicious photometric selection (e.g. the Lyman dropout technique) then angular correlations can be more effective (Steidel et al 1996). The difficulty is relating restricted populations to those observed locally. However, this problem remains in pure magnitude-limited samples since k-corrections distort the observed mix of types each of which may have different spatial distributions. A number of groups are now undertaking multi-band panoramic surveys with a view to utilising photometric techniques to examine angular correlations as a function of inferred redshift (Brunner et al 1999, Marzke 1999, Figure 3). Such analyses will necessitate complex modelling to account for the subtle selection effects involved (Kauffmann et al 1999).

In biased galaxy formation, early star-forming systems, e.g. Lyman break galaxies, should be more strongly clustered (or biased) than their later versions forming at lower redshift. Bias can be tested within a given dataset by correlating the clustering amplitude with luminosity or preferably mass. Luminosity-dependent clustering is tentatively claimed for the Lyman break galaxies (Steidel et al 1999) and interpretation of this signal will depend on deriving the dynamical masses of individual examples (Pettini et al 1999).

In the next few years we can thus expect a huge influx of $z<0.3$ redshift survey data, the completion of several deep panoramic optical-infrared imaging surveys and detailed studies of selective populations of galaxies at $z>1$. These data will be influential in understanding biased galaxy formation and constraining the power spectrum $P(k)$ and recent growth in clustering.

3.2. Angular Fluctuations in the Microwave Background

Proponents of the two major microwave background satellites of the next decade (the Microwave Anistropy Probe (MAP, http://map.gsfc.nasa.gov) and par-
Figure 3. A new generation of faint panoramic optical and infrared imaging surveys is motivated by the desire to constrain evolution in the angular clustering of galaxies as a function of epoch. The image represents a \(13 \times 13\) arcmin\(^2\) field limited taken with four mosaiced exposures using CIRSI - a \(4 \times 1024^2\) HgCdTe array (Beckett et al 1998). Analyses of angular correlations for IR-selected samples partitioned according to photometric redshift will necessitate consideration of both k-correction and luminosity-dependent biases.

Figure 4. Angular spectrum of fluctuations in the microwave background as constrained by various experiments (see legend) leading to the suggestion of a ‘Doppler peak’ whose angular scale constrains the spatial curvature \(\Omega_M + \Omega_\Lambda\) to be flat (after Efstathiou et al 1999)

particularly the Planck Surveyor \(\text{http://astro.estec.esa.nl/Planck/}\) promise precision measurement of all cosmological parameters and characteristics of the initial power spectrum. Is such optimism simply a reflection of the fact that the theoretical modelling is well ahead of the observational data?

A good assessment of the immediate opportunities can be found by considering evidence for the location of a possible ‘Doppler peak’ in the spectrum of angular fluctuations delineated by various experiments (Figure 4). The sought-after feature is the sound horizon at recombination and its angular scale measures the angular diameter distance at \(z \approx 1100\) and hence the spatial curvature representing the sum of the contributing energy densities \(\Omega_M + \Omega_\Lambda\). Efstathiou et al (1999) \(^2\) analysed the extant data and found:

\[
\Omega_M + \Omega_\Lambda \equiv 0.88 \pm 0.06 (1\sigma)
\]

Considerable progress is expected in the next few years in confirming or otherwise this result which, at the moment, involves combining measurements made with different instruments. The Boomerang project \(^3\) should be the first to trace the fluctuation spectrum through the putative Doppler peak with a single instrument.

3.3. Supernovae and The Cosmic Deceleration

The traditional apparent magnitude redshift relation for brightest cluster galaxies led to conflicting claims on the cosmic deceleration parameter \(q_0\) \(^4\) (Gunn & Oke 1974, Kristian et al 1977). Uncertain corrections for luminosity evolution in giant ellipticals even led to early claims for a cosmic acceleration (Gunn & Tinsley 1975)! A more recent infrared study (Aragón-Salamanca et al 1998)

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\(^2\)See also the independent analyses by Lineweaver (1998) and Tegmark (1998).

\(\text{http://astro.caltech.edu/~lgg/boom/boom.html}\)

\(^3\)The deceleration parameter \(q_0 = -\frac{\ddot{R}}{R\dot{R}^2}\), where \(R(t)\) is the scale factor, is no longer commonly used as it maps onto \(\Omega_M\) and \(\Omega_\Lambda\) in a redshift-dependent manner.
introduced a further correction for the assembly of stellar mass from mergers since $z \simeq 1$. First-ranked cluster members are evidently complex evolving systems whose properties will have to be understood in considerable detail before any believable constraints on the cosmic deceleration emerge.

It is thus only reasonable to be skeptical about recent claims (Garnavich et al 1998, Perlmutter et al 1999) for a cosmic acceleration based on the apparent magnitude - redshift relation for distant Type Ia supernovae (SNIa, Figure 5). May their poorly-understand progenitors not evolve in some as yet undiscovered way with redshift?

There are, however, fundamental differences between the first-ranked cluster galaxy and SNIa campaigns. Foremost, supernovae are thermodynamical events not a restricted class of objects drawn in a (possibly biased) manner from a wider statistical population. Secondly, the information obtained for each distant SN event is impressive and includes (i) time-dependent spectra for day-by-day comparison with that of local examples constraining possible compositional and energetic differences, (ii) light curves in various photometric bands useful for clarifying correlations between the rest-frame peak luminosity and light curve shapes, and (iii) the morphological properties of the host galaxies and the location of the SN event within them. With larger samples, analyses can be executed for subsamples representing, e.g. the most luminous examples, those found in dust-free environments or with old stellar populations. The absence of an increased scatter in Figure 5 at large redshift is highly significant. If progenitor evolution, host galaxy dust or other systematic effects were distorting the curve towards a non-zero $\Lambda$, then such effects would have been orchestrated to be similar across a wide range of environments and galaxy evolutionary histories.

The SNIa data do not yet span a sufficiently large redshift range to independently constrain $\Omega_M$ and $\Omega_\Lambda$ and thus measures deceleration over a particular redshift range, effectively $\Omega_M - \Omega_\Lambda$. Contrary to popular perception, the strongest result is the rejection of the matter-dominated Einstein-de Sitter model not the presence of a non-zero cosmological constant (the latter being only a $3\sigma$ effect with the current data). Only by combining the SN constraint with that of spatial curvature derived from the location of the microwave background Doppler peak is strong evidence for a cosmic acceleration inferred (Figure 6, Efstathiou et al 1999).

What are the weak points in the SNe analyses? Notwithstanding the near-constant scatter with redshift referred to above, uniformly distributed dust extinction (arising within all host galaxies at $z > 0.5$ or in the intergalactic medium
Figure 6. The location of the Doppler peak in the microwave background (which constrains $\Omega_M + \Omega_\Lambda$ - Figure 4) can be combined with complementary constraints on $\Omega_M - \Omega_\Lambda$ from the Type Ia supernova data (Figure 5) (Efstathiou et al 1999). The resulting solution supports a spatially flat ($\Omega_K = 1 - (\Omega_M + \Omega_\Lambda) = 0$) Universe with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

... progenitor evolution (c.f. Riess et al 1999) remain a concern. Fortunately, we can expect to address both convincingly in the next few years via much larger samples from which carefully-selected subsets can be compiled, and by extending the analysis beyond $z \approx 1$ where the effects of a non-zero $\Lambda$ should decrease in comparison with that of a uniform absorbing medium. The challenge, as always, lies in designing the most effective facility to conduct the necessary survey. Considering the impact of the SNe Ia results, it is surely high time to consider more ambitious instrumentation dedicated to locating them and their multi-band follow-up.

4. Gravitational Lensing and the Mean Mass Density

The synergy achieved between the SNe and microwave background data is, at first sight, reassuring (Ostriker & Steinhardt 1995). However, the conclusions lead cosmology into difficult territory. What is the physical origin of a non-zero $\Lambda$ and why is its energy density anywhere near that of the gravitating mass? (Steinhardt et al 1999)?

Not only do we seek verification via at least one further constraint on Figure 4 but also, in understanding galaxy formation, the relative distribution of baryonic and non-baryonic matter and precise constraints on $\Omega_M$ are important goals. The most fundamental assumption of CDM is the presence of non-baryonic matter and, short of its direct detection, comparing the baryonic and non-baryonic components is an essential test. Mass distributions on cosmological scales can be constrained with ambitious wide field imaging surveys utilising the weak gravitational lensing of background field galaxies (Narayan & Bartelmann 1996, Mellier 1998, ).

Gravitational lensing is a fascinating phenomenon. However, even its most ardent supporters would admit it has yet to provide convincing constraints on the distribution of non-baryonic matter on scales upward of 1 Mpc. Work has concentrated where the signals are strongest, i.e. the cores of rich clusters. Here weak shear and strong lensing (multiply-imaged arcs) studies have confirmed high M/L ratios consistent with $\Omega_M \approx 0.3$ inferred already from dynamical and X-ray studies (Smail et al 1997, Allen 1998).

Powerful techniques have now been developed to derive the projected distribution of lensing mass from the weak shear seen across the field of a CCD detector. The methods assume that, statistically, the intrinsic ellipticity and redshift distribution of the background sources are well-behaved (Kaiser & Squires 1996, Kaiser et al 1998, Schneider et al 1998). In practice, the techniques are limited by instrumental and seeing corrections, particularly for ground-based data. Comparative studies utilising different techniques for the same rich cluster ob-
Figure 7. The extension of weak gravitational lensing as a probe of mass distributions outside rich clusters is an imminent prospect with panoramic imaging cameras. The image shows Kaiser et al’s (1999) mass reconstruction in a field containing two X-ray clusters. Dark material connecting such systems may be revealed through weak lensing techniques.

served independently with different telescopes (Erben et al 1999) suggest mass distributions can be extracted reliably to sensitivity levels equivalent to those needed to see coherent shear from larger-scale structures outside rich clusters. Potential targets for weak lensing studies therefore now extend to individual filaments whose existence is inferred from redshift surveys or otherwise (e.g. Kaiser et al 1998, Figure 7).

There is great potential because lensing offers a bias-free probe of mass fluctuations on various scales (Jain & Seljak 1997). CCD cameras with upwards of 8000^2 pixels make surveying for mass structures independently of their baryonic fraction a practical prospect provided the systematics can be controlled. Correlation studies of the shear drawn from many randomly-chosen independent fields can provide a global measure of the mass power spectrum on a particular scale (the ‘cosmic shear’ - Mould et al 1994) whereas ultimately one can hope to define projected mass maps and interpret these statistically for \(\Omega_M\) by correlating with similar data from redshift surveys (Figure 2).

In conclusion, there are four observational programmes each of which already offers complementary constraints on the cosmological parameters and power spectrum of mass fluctuations. More importantly, the future prospects for each are excellent. By eliminating the cosmological uncertainties which underpin all theories for structure formation, we can hope to move forwards to a physical picture of how galaxies form and evolve.

5. The Origin of the Hubble Sequence

Although originally introduced for taxonomic purposes, the Hubble sequence of morphological types defines an axis along which there are strong physical trends. For stellar populations the sequence represents the locus of the ratio of the current star formation rate to a long-term average (Struck-Marcell & Tinsley 1978). There are near-monotonic dependences in gas content, rotational support, bulge/disk ratio and central density (de Vaucouleurs 1977, Efstathiou & Silk 1983). Most importantly, there are suggestive variations in the population mix as a function of environment (Dressler 1980, Whitmore et al 1993).

The challenge to infer the evolutionary history of this sequence has been revolutionised by Hubble Space Telescope’s (HST) ability to resolve kpc scale structures at most redshifts of interest. However, surprisingly little progress has been made in equivalent 2-D spectroscopic follow-up of these distant sources with ground-based telescopes. This is one of the key areas of importance in the next decade.
Figure 8. The redshift-dependent comoving volume-averaged density of star formation derived from the luminosity density of ultraviolet light, Hα-emission and bolometric far-infrared flux (Madau 1999). Data points with error bars refer to UV-based measures with no extinction correction (left panel) and that corrected with a constant value at 1500Å (right panel). The dotted line shows the fiducial value necessary to produce the observed background light. No star formation diagnostic is immune from difficulties and comparisons for the same sources suggest further complications arise from the timescales over which a given diagnostic applies.

5.1. Monolithic and Hierarchical Theories of Galaxy Formation
The continuous merging of dark matter halos and delayed onset of star formation in the hierarchical picture has led to a profound challenge to classical views for the origin of the Hubble sequence. Prior to CDM, the traditional viewpoint (e.g. Eggen et al 1962, Sandage 1986) associated the high stellar density, low specific angular momentum and homogeneous old stellar populations of spheroidal galaxies with rapid dissipationless collapse at high redshift. Dissipative collapse of gas clouds at later epochs would lead to rotationally-supported disks destined to become local spirals. Giant ellipticals forming at high redshift via ‘monolithic’ collapse prompted numerous searches for luminous primaeval galaxies (Djorgovski 1996).

In hierarchical pictures however, the first stellar systems will be small and numerous, reflecting the abundance of appropriately-sized halos at early times. Rapid merging of these initial systems delivers a population of young bulges. Continued gas cooling produces stable disks around these bulges some of which will later merge to form large spheroidal galaxies (Baugh et al 1995).

The differences between the monolithic and hierarchical pictures are greatest for the spheroidal galaxies. Merger-driven morphological evolution occurs earlier in the denser environments (Kauffman 1995) and thus strong differential effects are also expected in the sense that field spheroids will always be younger and more inhomogeneous than their clustered equivalents. Although evidence continues to accumulate suggesting that many local ellipticals formed via the merger of disk galaxies (Schweizer 1997), this does not necessarily imply all spheroids formed recently.

5.2. Cosmic Star Formation and Mass Assembly Histories
The completion of extensive redshift surveys (Lilly et al 1995, Ellis et al 1996, Cowie et al 1999) and the identification of representative samples of Lyman break galaxies at various epochs (Steidel et al 1996, 1999) has led to analyses of the comoving density of star formation as a function of look-back time (Madau et al 1996, Madau 1999, Figure 8). Does this ‘Madau plot’ which indicates an extended history of star formation differentiate between hierarchical and monolithic galaxy formation as has been claimed (Baugh et al 1998)?

In quantitative detail, the star formation history is susceptible to major changes through unaccounted obscured sources, dust extinction on the detected
ones, incompleteness arising from sources fainter than the survey limit, and inaccuracies or inappropriate comparisons associated with different diagnostics used, each of which has its own limitations. Although in broad agreement with the CDM predictions (Baugh et al 1998), detailed comparisons depend more on how feedback and star formation are implemented in the semi-analytical models rather than on structure formation in a cold dark matter Universe (c.f. Jimenez et al 1999). Although Figure 8 has been central in motivating optimum strategies for finding distant sources, we now seek a more fundamental way to address the physical foundations of galaxy formation theories. Ultimately this implies tracking the evolution of the assembling mass.

5.3. Field Spheroidals

The continuous formation of field spheroidals from merging spirals contrasts markedly with the traditional picture of monolithic collapse at high redshift. This seems one of the simplest ways to differentiate two very different pictures of morphological evolution. However, in practice, a demise with redshift in the abundance of field ellipticals has been remarkably difficult to verify. Although field ellipticals can be readily discerned to $I=22-23$ in typical WFPC-2 images (and $I=24-25$ in the higher signal to noise Hubble Deep Fields), morphological number-magnitude counts (Glazebrook et al 1995, Driver et al 1996, Abraham et al 1997) give ambiguous results because of uncertainties associated with the local luminosity function. Regardless, the evolution expected in hierarchical CDM is a strong function of the cosmological model, with little evolution to $z \approx 1-2$ expected in open or $\Lambda$-dominated versions (Kauffmann & Charlot 1998b).

Optical-infrared colours offer an alternative route to constraining the assembly history. In the monolithic case we would expect to find a sizeable population of intrinsically red systems beyond $z \approx 1$; in fact few are found (Zepf 1997, Barger et al 1999). Menanteau et al (1999) selected a large sample of morphological spheroidals and demonstrated a marked paucity of examples with colours compatible with passively evolving systems formed at $z > 3$. The drawback is that only a modest amount of ongoing star formation occurring in objects which collapsed at higher redshift would be needed to move passively-red systems into the colour range observed (Jimenez et al 1999).

Ideally we seek a characteristic that demonstrates that field ellipticals are bluer and more inhomogeneous than their clustered counterparts from which the associated mass assembly rate could be derived. Figure 8 shows the internal colour distribution of two rather different field spheroidals located in the HDF (Abraham et al 1999a). Across a large sample of such systems, evidence is accumulating that field ellipticals are more inhomogeneous in their observed properties than those found in clusters in qualitative agreement with the predictions of hierarchical models. The patchy colour distribution of a significant fraction of field spheroidals at $z > 0.3$ may be consistent with merger-driven evolution and the challenge is now to quantify this in terms of both the observed merger fraction and the mass assembly history. Inevitably, more detail is needed on the metallicity and timescales of secondary star formation implied in the HST images.
The internal V-I colour distribution for two spheroidals of known redshift in the Hubble Deep Field (Abraham et al 1999a). Such analyses indicate a greater degree of internal inhomogeneity, possibly consistent with secondary star formation induced by mergers, for field ellipticals than for their clustered equivalents.

Figure 10. A morphologically irregular galaxy in the HDF with the integral field unit for the Gemini CIRPASS spectrograph superimposed. Each fiber would sample a 0.15 arcsec diameter portion of the galaxy enabling detailed internal studies.

5.4. Faint Blue Irregulars
Deep HST images confirmed that the bulk of the faint blue excess first located in faint galaxy counts arises from galaxies of irregular morphology (Glazebrook et al 1995, Ellis 1997). Such systems also contribute significantly to the increasing star formation density to $z \approx 1$ (Brinchmann et al 1998). But what is the physical origin of these systems and why are so few found today?

Pixel-by-pixel simulations which attempt to recover the appearance of local galaxies as viewed at various redshifts taking into account instrumental and redshift-dependent effects (Abraham et al 1998, Brinchmann et al 1998) suggest that only a small fraction of the HST irregulars might be late-type spirals viewed at rest-frame UV wavelengths (a claim now supported by the NICMOS images, Figure 10).

The demise of these abundant peculiar systems with active star formation remains an outstanding question. High resolution infrared images are needed to quantify the established stellar mass (Broadhurst et al 1992, Kauffmann & Charlot 1998a) as well as resolved dynamical data to address the possibility that many merge to form more regular systems.

This will be an enormous challenge. Merging statistics based on projected imaging data (Patton et al 1998, LeFevre et al 1999) are difficult to interpret in the context of hierarchical models because merger timescales are needed to convert pair fractions into merger rates. Will spectroscopy help in resolving this impasse? Possibly not in individual cases such as Figure 10, but the redshift-dependent mass distribution and star formation timescales of young peculiar will be an important step forward in understanding the role of feedback which apparently delays the formation of these systems.

5.5. Disks, Bars and Bulges
Numerical simulations have yet to make much headway in addressing the quantitative evolution of internal features in galaxies, e.g. stellar disks, bars and bulges, yet we can expect exquisite observational data on these to $z \approx 1$ and beyond in coming years. Theorists prefer to delay disk formation to late epochs in order to avoid spiral destruction through mergers as well as an inexorable transfer of angular momentum from the stellar disk to the outer dark matter halo (Weil et al 1998).
Rotation curves are now available for almost a hundred distant spirals to $z \approx 1$ (Vogt et al 1999) yet the associated Tully-Fisher relation shows little sign of any evolution. Structural decomposition of HST images indicate both increased disk surface brightnesses and bluer colours consistent with a higher star formation rate (Lilly et al 1998). All available data are consistent with the notion that spirals had their current space density and structural forms established at $z \approx 1$. Is this in conflict with theory? Again, in open or $\Lambda$-dominated models, the conflict might not be so severe. Moreover, observations could be reconciled with predictions if disks were still growing whilst their star formation rates declined (Mo et al 1998). However, neither the observational data nor the model predictions are sufficiently refined to be sure what is happening at the moment.

Stellar bars and bulges offer a further clue to the growth history of spiral galaxies. CDM models predict bulges should be the very oldest components having formed at early times from mergers of the first collapsing systems and therefore have intrinsically red colours (Cole et al 1999). However, bulges selected from a sample of HDF spirals reveal a remarkable range of colours with few as red as ellipticals of the same redshift (Ellis & Abraham 1999, Figure 11) suggesting either many formed more recently or a continuous infall of gas or satellites introduced recent star formation in their cores. Bulges may also form sequentially from stellar bars, both features representing stages of instability in a well-established disk embedded in a significant stable dark matter halo (Combes 1999). A paucity of barred systems has been claimed in the HDF (Abraham et al 1999b) although the sample size remains small.

Whereas there is naturally much interest in surveying galaxies with $z > 2-5$, progress in understanding the astrophysical processes which govern galaxy formation and evolution will also require extensive studies of selected galaxies with the redshift range $0 < z < 2$ during which period it seems the Hubble sequence of types became established. HST has shown the way with exquisite optical imaging data. The challenge will be to complement this with near-infrared and spectroscopic data of appropriate resolution from ground-based telescopes and move away from the traditional ‘number counting’ approach which serves only to determine the integrated properties of the galaxy population.

6. **Instrumental Themes**

The above scientific overview is intended to set the scene for some of the 3-D applications discussed at this meeting. A few common instrument themes are relevant in connecting the various scientific questions:
• **Wide Field Imaging:** The Schmidt telescope revolution which influenced this field in the 1970’s has been replaced by its digital equivalent - panoramic CCD cameras on 2.5-4m telescopes with $\sim \text{deg}^2$ fields. Already such surveys are being extended into the near-IR. Multicolour surveys promise great progress in the cosmological arena through supernova searching, weak lensing and photometric redshifts aimed at tracking the growth of galaxy correlations. There are substantial challenges in each application, however. The Type Ia SN programme is hindered by the need for more detailed astrophysical information spanning a wide wavelength range (at both high and low $z$) rather than gross statistics. Weak lensing as a probe of large scale structure and $\Omega_M$ requires exquisite correction of instrumental effects and may, ultimately, only be possible in space. Photometric redshifts are largely untested in the all-important $1 < z < 2$ range and redshift-dependent effects will have to be understood before extracting meaningful signals on correlation evolution.

• **Wide Field Spectroscopy:** Now is also an exciting time for wide field spectroscopic surveys. Although the prime spectroscopic products of the Sloan and 2dF surveys will be maps of the $B < 20$ galaxy distribution for power spectrum analyses, we can also hope to utilise the galaxy spectra to investigate the astrophysical origin of bias through luminosity or star-formation rate dependencies. The spectroscopic surveys will deliver data that is much richer than a simple redshift. Just as the Schmidt surveys formed the basis for springboard projects using other facilities so the 2dF survey is already proving useful for spinoff projects from faint radio surveys to weak lensing behind known filamentary structures. 2dF also has the potential to probe much fainter than $B \simeq 20$ and this raises the important question of an 8-m equivalent device capable of exploring to $z \simeq 1$ and beyond.

• **Resolved Spectroscopy:** HST has shown us the tantalising beauty of resolved galaxies at high redshift. At face value it seems the Hubble sequence of galaxy types was laid down by some process soon after redshift 2. Optical surveys are biased however, being sensitive only to sources with recent or ongoing star formation. We seek to extend our viewpoint of these galaxies with high resolution images in the near-infrared, where more representative stellar populations can be analysed, and through far-infrared and sub-mm detections sensitive to obscured regions. A major question is whether the optical/near-infrared should remain the fulcrum of activity in unravelling galaxy evolution. Our investment in this area is now unparalleled through HST and a new generation of 8-m telescopes equipped for high resolution work. Yet surprisingly little resolved spectroscopy has been done at moderate look-back times. Together with upcoming facilities at mid-IR and sub-mm wavelengths, we can expect to unravel the details of galaxy evolution over $0 < z < 5$ via studies of assembling mass as well as the history of star formation.

5At the moment there is no contest as the field of view of Hubble Space Telescope is very uncompetitive but a wide field modest aperture space telescope would be overwhelmingly powerful in this area.

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Acknowledgments. I am grateful to my collaborators and students at Cambridge and elsewhere for allowing me to present work done with their assistance. I thank Joss Bland-Hawthorn and Wil van Breugel for their encouragement and patience with this article.

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Supernova Cosmology Project

$z (\Omega_M, \Omega_\Lambda) = (0, 1) (0.5, 0.5) (0, 0) (1, 0) (1.5, -0.5) (2, 0)$

$\Lambda = 0$

(apparent brightness vs. redshift $z$)
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