NGST AND THE PHYSICAL EXPLORATION OF GALAXY EVOLUTION DURING THE ERA 
\[2 < z < 5\]

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ABSTRACT

NGST offers unprecedented opportunities for charting the ‘dark ages’ beyond the limits of the deep optical surveys conducted with HST. An equally important motivation, however, is a detailed physical understanding of the later stages of cosmic history including the period \(2 < z < 5\) when most galaxies are thought to assemble and undergo dramatic changes in their star formation rate, chemical content and, ultimately, their morphological characteristics. An important question we need to resolve is the extent to which established massive systems might exist at moderate redshifts. In the context of recent observational and theoretical progress in this area, I review the role NGST could play in this redshift range taking into account the likely progress made in the next decade with the new generation of 8-m class ground-based telescopes.

Key words: cosmology, galaxy evolution & formation.

1. ‘STAR WARS’ - GROUND VERSUS SPACE IN 2007

It is a time of rapid progress in observational cosmology and it seems foolhardy to predict in detail what we might do scientifically in this area with NGST in 2007. In this brief review I have preferred to take a more strategic view of the scope and opportunities offered by NGST, both in the context of expected progress with ground-based facilities and with the goal of improving our knowledge of the physics of galaxy formation in a redshift range where sources with stellar radiation certainly exist. This contrasts with the exciting possibility of using NGST to explore the ‘Dark Ages’ before galaxies assembled where, at present, only brave theorists can guide us (Loeb, Rees, this volume).

What we can say with certainty ten years from now is that there will be an enormous increase in ground-based capability. At the last count we can expect \(13 \times 6.5\text{-}11\text{m}\) telescopes with a collective surface area equivalent to over ten Keck telescopes. History has shown that we have tended to underestimate rather than exaggerate the future impact of our new facilities. An example in faint galaxy spectroscopy will make this point clear. In the 1980’s when many of us were campaigning for new 8-m telescopes, 4-m telescopes were reaching what we considered a hard limit of \(I=22, B=24\) for absorption line galaxy spectroscopy. Skeptics used to argue that an 8-m telescope would only push back this frontier by at most a magnitude. In fact, Keck spectra of \(I=25-26, B=26-27\) galaxies are routinely being gathered representing an order of magnitude better performance than aperture scaling of old technology. This reflects the combination of many incremental advances in technology which appear first on our newest telescopes (telescope performance, image quality, detector characteristics, spectrograph throughput...) as well as personal ambitions in an increasingly competitive area. One can hardly fail to be impressed by the remarkable image quality achieved at an early stage by the active primary on the ESO VLT (Giacconi 1998) which may herald an exciting new era in high resolution ground-based imaging. For these reasons, it seems sensible to consider rather carefully the improving performance of these 8-m telescopes against that proposed for NGST.

We begin by examining the current symbiosis between HST and ground-based telescopes. In my view the complementarity between HST and a large ground-based telescopes has often been overstated. On the one hand HST is competitive with larger ground-based telescopes for many cosmological projects and, on the other hand, ground-based telescopes are increasingly encroaching into high resolution imaging territory that has traditionally been reserved for HST. Let us examine two remarks that one frequently hears:

- **HST is a small-aperture telescope** - this is a misleading comment for background-limited imaging at those wavelengths (\(0.8 < \lambda < 1.8\) microns) affected by airglow (which include those increasingly important for cosmology) since the background in space at these wavelengths is 40 times lower. Roughly speaking HST has the capability of a ground-based 6.5m telescope for this kind of work.

- **HST offers unique spatial resolution compared to ground-based telescopes** - this is certainly true in the UV/optical but recent Keck near-infrared images (Bunker et al 1998, Figure 1) show that the gain can, on occasions at least, be quite modest for many applications that have traditionally
For high dispersion spectroscopy, the gain of NGST is claimed to be quite modest, but this depends in detail on the projected performance of infrared detectors and several of the other assumptions made.

- $\lambda > 2.5$ microns: here the gains become substantial ($\simeq 10^4$) for all likely observing modes. This wavelength region is strategically important for many reasons but especially spectroscopy of redshifted diagnostic lines like $H\alpha$ beyond $z \simeq 2.5$ and for the analysis of continuum radiation from older stellar populations to $z \simeq 5$; optical/UV radiation from an early generation of young stars could also in principle be seen to very high redshifts.

In summary, NGST's gain over ground-based telescopes is greatest beyond 2.5 microns and hence, very effective in exploring the range $2 < z < 5$. Before examining the techniques we might use to explore this region, it is helpful to understand some of the controversies surrounding our present understanding of how galaxies form and evolve, noting both observational and theoretical progress.

2. PROGRESS IN GALAXY FORMATION

The now familiar way to examine recent progress in galaxy formation and evolution is via the comoving volume-averaged star formation history that has been derived observationally from the optical/IR census of galaxy luminosities selected in various ways (Madau 1997) and predicted theoretically from hierarchical cosmologies where gas cooling around cold dark matter (CDM) halos is inhibited by various feedback processes (Cole et al 1994, Kauffmann et al 1994, Baugh et al 1998). Although the redshift dependence of the star formation history remains quantitatively controversial (Blain et al 1998, Hughes et al 1998) and its interpretation is not uniquely tied to hierarchical theories of structure formation, such caveats will not be important in the following discussion. Rather than argue about the detailed form of the star formation history, I want to concentrate on more general implications supported by both theory and observations.

Foremost, what we have learnt from both theoretical and observational studies of the star formation history is that galaxy formation is an extended process, rather than the single event once imagined. But is there still room for a population of objects that collapsed monolithically at some redshift, either at beyond the current observational redshift window or, within it, perhaps shrouded in dust? The answer to this question depends on the stellar mass of high-redshift star-forming systems which is currently very poorly constrained.

Extended galaxy formation is a central assumption in hierarchical theories because of the interplay between feedback and gas cooling so it remains observationally very important to explore the physical properties of systems at high redshift. Indeed, it is worth highlighting the remarkable contrast between traditional and CDM viewpoints for the formation of giant elliptical galaxies. As ellipticals are compact objects

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{HST optical and Keck near-infrared imaging of distant gravitationally-lensed arcs from the study of Bunker et al (1998) demonstrating that ground-based telescopes are encroaching upon the hitherto unique advantage of HST's image quality. Each panel represents a 20 arcsec field.}
\end{figure}

Noting the likely improvement in ground-based technology, what then could NGST uniquely provide in comparison to the impressive array of 8-m telescopes we can expect to be in full swing by 2007? An interesting comparison of the relative performance of Gemini and NGST has been recently published by Gillett & Mountain (1998). Whilst a number of assumptions have to be made in such comparisons, two are worth bearing in mind in understanding the difference between their conclusions and those by the NGST study team. First, Gillett & Mountain assumed Adaptive Optics on Gemini would routinely deliver near diffraction-limited performance at wavelengths longer than 1 micron (a Strehl of 0.8 at K). Without AO, Gemini would deliver about 0.4 arcsec at K (matching that of Figure 1). Secondly, they assumed that NGST would be limited to fairly short exposure times because of variable cosmic ray hits. Looking at their plots (reproduced in part by permission of the authors in Figure 2) there are two regimes of importance:

- $0.5 < \lambda < 2.2$ microns: here the gain of NGST is claimed to be only appreciable for broad-band imaging. Such gains would be reduced if ground-based telescopes could find an efficient way to perform wide field OH-suppressed imaging, which seems possible given recent successes in OH-suppressed spectroscopy [http://www.ast.cam.ac.uk/~optics/cohsi/cohsi.html].
Figure 2. A comparison of the performance of NGST and an adaptive IR-optimised ground-based 8-m telescope reproduced from the study of Gillett & Mountain (1998). The panels show the relative point source signal/noise ratio for $R=5$ (imaging) and $R=10,000$ (spectroscopy). See original article for symbol explanations, assumptions and caveats. The principal gain of NGST lies in the wavelength range $\lambda > 3 \mu m$. Within the 1-2$\mu m$ range, there appears to be a significant gain only for broad-band imaging.

showing little rotation, the traditional viewpoint asserts these form via monolithic dissipationless collapse at very high $z$. In contrast, hierarchical cosmologists believe in the slow assembly of disk systems around dark matter halos and these later merge to form ellipticals. The question of whether galaxies assembled hierarchically over a large range in redshift (with perhaps a peak of activity at $z \simeq 1-2$) or collapsed monolithically clearly has a profound impact on the likelihood or otherwise of finding high redshift stellar populations (as opposed to only gas clouds).

So far, observational evidence has not convincingly come down in favour of either hypothesis. On the one hand, examples are found of high redshift radio galaxies which appear genuinely old (Dunlop 1998) and luminous cluster galaxy populations at intermediate redshifts display homogeneous ultraviolet-optical colours (Ellis et al 1997, Stanford et al 1997). Both studies indicate significant star formation must have occurred before $z \simeq 3$. But, as Kauffmann (1995) and Governato et al (1998) have pointed out, in biased models of galaxy formation we can expect accelerated evolution in dense regions. Studies of rare objects at high $z$ do not provide constraints which can be applied with confidence to the wider population.

A crucial goal is the evolutionary history of field ellipticals. Do we see a depletion of this population at modest redshift as expected in hierarchical models? Kauffmann et al (1996) claimed to find a shortage of red (V-I) objects in the CFRS redshift survey which, they claim, is consistent with the continued production rate of ellipticals from mergers in CDM models (see also Zepf 1997). However, colour alone is a very poor guide to morphology (Schade et al 1998) and utilising HST images in conjunction with deep infrared photometry, Menanteau et al (1998) have conducted a new extensive search based on HST morphology. They, similarly, find a shortage of passively evolving spheroidals to $K=20$. Moreover, in a new approach, Abraham et al (1998) have analysed the internal pixel-by-pixel colour distribution of ellipticals of known redshift in the HDF and find a sizeable proportion show a diversity of internal colours suggesting further evidence of recent activity (Figure 3).

In summary, the present evidence for established systems at high redshift includes:

1. The presence of radio galaxies with red continua and other sources with prodigious star formation rates at high redshift including the recently-discovered population of sub-mm sources (Blain et al 1998) and even the Lyman break galaxies, examples of which can be found with star formation rates approaching $100 \ M_\odot \ yr^{-1}$ (Steidel et al 1998).

2. Kinematic data which suggest damped Lyman alpha systems are well-established thick, rapidly rotating disks (Prochaska & Wolfe 1997, 1998). Alternative interpretations of this data have been presented, however, which are consistent with protogalactic clumps undergoing infall within dark matter halos (Haehnelt et al 1997).

3. The abundance of well-formed spirals at $z=1$ (Lilly et al 1998) whose stellar populations are consistent with a declining activity since at least
Evidence which suggests the bulk of the population formed late include:

1. The absence of high redshift sources in K-selected samples. The 'K-band redshift survey test' was originally proposed by Broadhurst et al (1992) and has been revisited in the framework of CDM models and the data of Cowie et al (1996) by Kauffmann & Charlot (1998). This shortfall of luminous K-band objects at high redshifts is consistent with the marked change in slope of the near-infrared counts (Ellis 1997) now confirmed to very faint H limits with NICMOS (Yan et al 1998).

2. The small angular sizes of HST images in the HDF and in other deep fields (Pascarelle et al 1997) which are highly suggestive of sub-units which later merge to form normal galaxies. Bouwens et al (1998) have simulated the appearance of a $I < 22$ sample of galaxies of known redshift when placed at greater distance in the HDF, allowing carefully for instrumental and surface brightness dimming, and concluded there has been strong size and number density evolution since $z \approx 3$.

3. The remarkably rapid and recent decline in galaxies with irregular morphology (Glazebrook et al 1995, Brinchmann et al 1998). The fate of these systems remains unclear but their delayed contribution to the luminosity evolution of the Universe gives strong support to the suggestion that star formation on galactic scales may be governed by feedback processes in addition to simple gravitational collapse of gas clouds around dark matter halos (Babul & Rees 1992).

Much of the evidence for massive systems at high redshift therefore rests on extreme objects. A valuable test of whether this is simply accelerated evolution due to bias is to examine the spatial distribution as a function of their number density. If these luminous objects are unrepresentative of the history of less massive galaxies, as CDM proponents claim, then one expects to find a high bias for the rarer galaxies. Steidel et al (1998) claim to detect the first tentative evidence of such a density-dependent bias in a correlation analysis of Lyman break galaxies selected in various ways. This serves to highlight the important connection between galaxy evolution and the large scale distribution of faint sources.

Concerning the presence or otherwise of primaeval galaxies, a topical question at the time of writing is the nature and redshift distribution of the population of sub-mm sources being found with the SCUBA array on the James Clerk Maxwell Telescope (Hughes et al 1998, Barger et al 1998). The negative k-correction for dusty sources observed at 850 $\mu$m implies luminous sources such as Arp 220...
could be detected to \( z \approx 10 \). However, where optical counterparts can be checked, the indication is that the SCUBA sources are coeval with the more modestly star-forming galaxies selected in the UV/optical (Smail et al 1998). However, even if more extensive redshift identifications confirm this is the case, an important feature of the early SCUBA results is the rapidity with which the far-IR background has been resolved into sources suggesting most of the high \( z \) dust emission is confined to a population of sources whose comoving volume density is nowhere near as high as that required to make up the UV background. Does this, in turn, mean the SCUBA sources represent a fundamentally different population from the luminous high \( z \) galaxies being found at optical wavelengths?

3. A PHYSICAL UNDERSTANDING OF GALAXY FORMATION

It is clear from the above discussions that even a complete derivation of the star formation history of the Universe from various diagnostic measurements will only represent the most basic step forward in understanding galaxy formation. Such a global measurement integrates over all luminosities and types and therefore hides most of the important physical details. Moreover, the apparent agreement between observation and theory can hardly represent a robust test of CDM, at least when it concerns testing ingredients such as feedback, merging and morphological evolution. We really need to test the more basic physical principles of any model and that means securing detailed properties of individual objects. Ultimately we wish to understand the dynamical state of forming systems and crucially their masses.

This might seem something of a tall order but NGST’s superior performance at \( 2.5 \leq \lambda < 5 \) microns can help. Examples include:

- Imaging at longer wavelengths than is possible with ground-based facilities. This allows us to trace established stellar populations at high redshift and hence to measure stellar luminosities less affected by dust and young stars.
- Detailed internal physical properties will become available through resolved, or integral field, spectroscopy including dynamical characteristics, excitation properties, dust content and star formation rates. Other articles in this volume will develop the theme of integral field spectroscopy more fully. Here I will point out some of the issues we face.

The rest-frame near-infrared luminosity can be tracked with diffraction-limited imaging to \( z \approx 5 \) or so yielding an integrated estimate of the established stellar mass. A major advantage of working in the near-infrared is that the K-band luminosity of an evolving system seems to be largely independent of its previous history (Kauffmann & Charlot 1998). However, on shorter timescales (<1 Gyr) there could be biases arising from transient populations. For example, red supergiants and AGB stars may temporarily raise the visibility of star-forming galaxies in the K-band. Calibrating these effects will require a more complete understanding of stellar populations at infrared wavelengths (Charlot et al 1996).

The motivation for IFU spectroscopy is easy to understand. Is a distant irregular (c.f. Figure 4) a well-established dynamical entity undergoing sporadic star formation (Noguchi 1998) or are we witnessing the arrival of physically-distinct sub-components with a chaotic velocity field? At the 4-m telescope level, IFU spectroscopy has proved to be extremely demanding in telescope time; only luminous or gravitationally-lensed sources have yielded interesting results (Soucail et al 1998). The problem is that there is a huge dynamical range in surface brightness in any object and this will be exacerbated at high redshift. Whilst it is tempting to restrict spectral analyses to those bright spots of star formation which conveniently provide intense emission lines, local studies already illustrate that line widths give only a lower limit on the circular velocities (Lehnert & Heckman 1996, Rix et al 1997). We really need to have good sensitivity at much larger

Figure 4. Integral field spectroscopy and multicolour HST imaging represent a powerful combination for unraveling the physical properties of a distant irregular. Upper panel shows the HDF image of a \( z = 1.355 \) galaxy with irregular morphology which is well-suited for integral field spectroscopy (each fibre segment represents a diameter of 0.15 arcsec or \( \approx 600h^{-1} \) pc). The lower panel analyses the pizex-by-pixel colour distribution for physically-distinct components (as indicated by each selected region) in the context of different star formation histories viewed at different times (solid and dashed curves). Dynamical data will be essential to resolve the question of whether such a system has recently merged or is established and undergoing stochastic bursts of activity.
radii.

4. SUMMARY

1. The design and scientific strategy of NGST should take into account the dramatic progress we can expect from ground-based 8-10m telescopes in the coming decade. In particular, it will be important to scrutinise carefully the achievements of the IR-optimised 8-m telescopes in the JHK windows.

2. Nonetheless, the clear area where NGST will excel lies longward of 2 microns and this offers the opportunity of studying the assembling galaxy population in the redshift range $2.5 < z < 5$.

3. A key goal for the future is the determination of stellar and total masses for representative subsets of the evolving population. This will necessitate mid-IR images and high resolution IFU spectroscopy to very low surface brightness limits in order to yield estimates of the integrated stellar mass and the internal dynamics.

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