The formation and evolution of galaxies II: The deep spectroscopic survey(s)

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Scientific category: DISTANT GALAXIES
Instruments: NIR/SPEC, NIR/MSPEC
Days of observation: 118

Abstract

Deep spectroscopy on NGST offers the possibility to determine the physical characteristics of faint galaxies detected in imaging surveys, and thus to make major advances in our understanding of both the phenomenology of galaxy formation and evolution and the physical processes responsible for driving the evolution. We propose four programs with different observational parameters and distinct, though related, scientific goals. (a) a very deep ($2 \times 10^6 s$) multi-object exposure at R=100 of AB=30-31 galaxies aimed at securing spectroscopic redshift identifications at the faintest possible levels and highest possible redshifts; (b) systematic spectroscopy at R=1000 in the rest-frame 3500-7000 $\AA$ range of of order 2500 galaxies with $AB \leq 27$ in the $1 < z < 5$ range, to yield uniform estiamtes of metallicities, stellar ages, star-formation rates and dust extinction levels; (c) spectroscopy at R=5,000 of order 400 galaxies to provide mass estimates and detect evidence for non-gravitational kinematics, so as to study galaxy scaling relations and gas inflow/outflow; (d) 2-d spatially resolved spectroscopy of about 20 bright and morphologically complex galaxies (AB $\leq$ 24.5 to study the physical conditions at different locations within forming galaxies.

Observing Summary:

Target	RA	Dec	m_{AB}	Configuration/mode	Days
DEEP X1	TBD	TBD	31 L	NIR/SPEC R100	23
DIAGNOSTIC X40	TBD	TBD	27 at L	NIR/SPEC R1000	25
KINEMATIC HA X40	TBD	TBD	27 at L	NIR/SPEC R5000	20
KINEMATIC CO X40	TBD	TBD	22 at N	MIR/SPEC R5000	20
SPATIAL X40	TBD	TBD	24.5 at L	NIR/SPEC R1000/R5000	30
				Grand total days	118

Scientific Objectives

OVERALL SCIENTIFIC OBJECTIVES

A fundamental question in the Origins program is: **What were the origins of the galaxies and other objects we see around us in the Universe today? In particular, what physical processes drove their formation and subsequent evolution?**. While ground-based and HST observations have already given us our first sketchy outline as to the likely history of star-formation in the Universe in the $0 < z < 5$ range, our understanding of the phenomenology of the evolution of individual galactic systems and of the dominant physical processes involved is still extremely limited. The following major questions remain which must be answered before we can claim to understand this aspect of our Origins.

- *What were the first sources of light in the Universe?* Were they stars, black holes, or something else? How and when was the Universe reionized?
- *How were galaxies assembled?* Did this proceed hierarchically by merging? What was the role of dark matter? What was the relative importance of gravity, dissipation, and energy injection on different scales?
- *How did the Hubble sequence form?* When and how did the stars in spheroids and disks form? How important was merging in determining the morphologies of galaxies?
- *How do galaxies interact with their environment?* How and when did galaxies exchange mass, metals, and radiation with the intergalactic medium? What was the origin of the metal-rich hot gas in clusters of galaxies?
- *Regarding the Universe as a single system, what are the global histories of star formation, metal enrichment, and gas consumption?*
- *What is the relationship between active galactic nuclei and their host galaxies?* Do AGN stimulate or inhibit star formation? When did massive black holes first appear?
- *How did the spatial distribution of galaxies evolve?* What are the connections between the formation of galaxies and the development of structures on larger scales? When did the cores of the great clusters form?

These are grand questions that will take a great deal of observational study to solve. In this, an important distinction should be made between determining the global evolution of the *population* and understanding the physical evolution of *individual objects*. Almost all of the observational progress to date has been on the former area. Our NGST program on galaxy evolution is directed, as much as possible, at yielding answers to the second, more fundamental but much more difficult, problem.

What observations are required for this? We would like a clear observational understanding of (a) the mass function of collapsed dark matter haloes as a function of epoch, (b) the mechanisms that regulate the formation of stars from gas within these potential wells and the flow of gas into or out of them, (c) the degree to which these haloes subsequently merge together to form larger units, and (d) how the different structural/morphological components of galaxies seen today relate to the above processes. Spectrocopic diagnostics will play an essential role in addressing these questions both through their ability to determine the physical conditions within particular galaxies and in providing the "accounting units" (such as mass or metal content or stellar mass content) which provide the means to associate, at least statistically, the members of the galaxy population observe at different epochs along the line of sight.

The redshift $1 < z < 5$ range is thought to be a critical epoch in the emergence of massive galaxies: the evolution back to $z = 1$ that has been studied from the ground and with HST is small enough that we haven't learnt very much about the origin of the Hubble sequence of typical massive galaxies similar to our own, while objects at $z > 5$ are likely to be much smaller than present day massive galaxies. Therefore, most of the action in assembling massive galaxies likely occurs in this redshift range, when there is in any case evidence that the overall star formation rate in the Universe peaks (at $z \sim 2$). *Thus, the main thrust of the spectroscopic program outlined here is aimed at securing basic spectral information for a large number of galaxies throughout the* $1 < z < 5$ *redshift range. As in the local Universe, spectroscopy of distant galaxies has the potential to yield the quantitative information on individual galactic systems that is required both for developing the correct phenomenological picture of galactic evolution and for generating the correct physical understanding of these processes.*

Spectroscopic diagnostics

Spectroscopic observations will play a decisive role in addressing many of the questions outlined above. The following quantitative information can be derived from spectroscopic measurements (see also Kennicutt 1998 for a review).

(a) *redshifts at spectroscopic levels of accuracy are required to establish physical associations between galaxies* seen projected in the same part of the sky and thus to establish the large scale environment of each system (since galactic evolution will very likely proceed at different rates and by different processes in different cluster/group environments). Accurate redshifts are also required to identify those smaller, initially discrete, units which are expected to merge together into larger galaxies in hierarchical models of galaxy formation.

(b) *measurements of* $H\alpha$ *6563 provide a measure of star-formation rate of massive stars*, i.e. essentially the number of ultraviolet ionizing photons (Kennicutt 1983), that is relatively insensitive to the effects of dust obscuration (R=100-300 is required for this measurement, Kennicutt 1998).

(c) *measurements of basic line ratios yield estimates of metallicity in the interstellar gas.* A basic indicator is the R_{23} ratio ([OII]3727+[OIII]5007)/Hβ4861 (Edmunds and Pagel 1984) derived from strong emission lines. However, there is an increasingly sophisticated literature on such studies in the local Universe - for instance including the fainter [NII]6548,6583 lines breaks the degeneracy of the above ratio at $Z > 0.25Z_0$. The ratio [OIII]4363/[OIII]4959+5007 is an even more precise metallicity indicator although very high S/N spectra are required to detect [OIII]4363 which at low metallicity has a strength only a few % that of [OIII]5007. Similarly, measurements of these lines can be used to catagorize objects as star-forming regions, AGN and LINERS (Veilleux and Osterbrock 1987). Most of these line ratios can be estimated from quite low resolution spectra, but some require $R \geq 1000$ (Kennicutt 1998).

(d) *measurements of $H\alpha/H\beta$ yield estimates of dust reddening* (e.g. Calzetti et al 1994) (Paα/Hβ is even better, though Paα is ten times fainter and at longer wavelengths, requiring spectroscopy at $\lambda \geq 5\mu$m for $z \geq 1.5$).

(e) measurements of continuum breaks (e.g. Ca HK at 4000 Å, Mg 2799 and H- at 1.6 μm) and the strengths of absorption lines such as the Balmer series can be used, with broad band colours, to *constrain the ages and star-formation histories of stellar populations in galaxies* through spectral synthesis models.

(f) *spectroscopy at $R > 5000$ can be used to estimate galactic masses*, which are obviously extremely important in tracking the build-up of massive galaxies. The best approaches are to use spatially resolved measurements of line emission in systems with ordered rotation (via a rotation curve) or measurements of velocity widths of stellar absorption features in compact systems (where uncertainties concerning non-gravitational forces makes the interpretation of gas motions uncertain). Analyses are traditionally made of the Mg feature at 5177 Å although this will weaken at young ages and metallicities. The CO bands at 2.3 microns may be more attractive (although these are redshifted past 5 microns for $z > 1.2$).

(g) *line profiles of emission lines such as Hα will indicate and quantify the exchange of material with the intergalactic medium* (i.e. outflow or inflow of gas from/onto galaxies).

(h) *Finally, spectroscopic confirmation of photometrically estimated redshifts at extremely faint levels* (and high redshifts) will be important even if the spectra are of insufficient quality or are in an inappropriate wavelength regime for detailed diagnostic analyses.

NGST will have a truly unique role in producing high quality spectroscopic data on high redshift galaxies. As outlined above, the richest part of the spectrum (and the best understood) in terms of diagnostic features is in the rest-frame 3700 - 6700 Å spectral range. This spectral domain is wholly within the core near-infrared $1 < z < 5$ micron window of NGST for the whole redshift range $1.7 < z < 6.5$, which is very well matched to the redshift range of most interest for the build-up of massive galaxies (see above). Spectral features at longer wavelengths (Paα and the CO bandheads at 2.3 microns) are also attractive to study, but they are shifted out of the $\lambda < 5$ micron waveband for $z > 1.3$ and so will be more difficult to study for a given object. Finally, the 1200-1600 Å Lyman spectral domain which is best suited to measuring redshifts in extremely high redshift galaxies is visible at $\lambda < 5$ microns for all $z < 30$.

In terms of raw sensitivity, NGST NIR/SPEC will be more sensitive than any ground-based spectrograph because of the reduced continuum background, especially at $\lambda > 2$

microns (corresponding to Hα at all $z > 2$). Furthermore, the spectra from NGST will also be free of the effects of atmospheric absorption (which define the ground-based "windows" and the sharp emission features of the OH terrestrial airglow (of particular relevance if accurate measurements of a range of features at a particular redshift are desired - one or more of them are likely to be "lost"). Equally importantly, the high spatial resolution of NGST in the near IR will, in addition to increasing sensitivity for compact objects, offer the possibility of determining physical conditions at different locations within the young galaxies at high redshift. This is especially important in the context of determining masses from spatially resolved velocity fields but it is also of great importance in the context of the origin of galactic structure and the evidence that, in some objects at least, star-formation proceeds episodically in spatially separated regions.

PROPOSED SPECTROSCOPIC OBSERVATIONS

We envisage four components of a comprehensive spectroscopic survey (aimed at yielding different scientific information) that should be undertaken with NGST, with the overall aim of understanding galactic evolution. The relative efficiency with which these can be carried out will depend to a large degree on the detailed design of the spectrographs on NGST. In what follows, we assume that there is a slit-type multi-object spectrograph capable of observing of order 100 galaxies simultaneously and an integral field-type spectrograph capable of observing a single object (or small field) at a time at the full spatial resolution of NGST. The MIR/SPEC is assumed to have only a single long slit.

(a) Spectroscopic confirmation of photometric redshifts at very high redshifts and at the faintest levels

Deep NGST images should reveal large numbers of galactic systems at unprecedented redshifts (see the associated imaging proposal). The redshifts of these can be estimated from photometric measurements in spectral regions exhibiting large scale spectral features and continuum breaks (e.g. the Lyman region for very young star-forming systems, the Balmer/4000 region for older systems, the dust-free 1.6 micron region for all ages etc.). However, for the fainter systems, these photometric redshift estimates will almost certainly be in unexplored redshift regimes, and some spectroscopic confirmation will be considered *essential*. For the faintest objects (especially those whose spectral features lie at $\lambda > 2$ microns, i.e. $z > 10$ star-forming galaxies and $z > 4$ quiescent galaxies – in many respects the "most interesting" objects NGST will detect) NGST will be the only facility capable of securing a redshift.

The aim of this part of the program is thus to obtain the deepest possible spectra in the 1-5 micron range so as to extend spectroscopic redshift determinations as far as possible into the domain of the deepest images obtained with NGST.

For this science goal there will be a trade with spectral resolution (enhancing detectability of sharp features at the cost of continuum sensitivity and possibly spectral range and multiplexing gain). A resolution of R=100 should be adequate (and will minimize the detector noise for the continuum). Even at the required depth, the covering factor of objects on the sky is small (and only a small fraction of the most interesting will be selected for this program) so the observations should ideally be carried out with a multi-object slit-type spectrograph.

As a nominal program, we propose to obtain R=100 spectra on 100 objects (assumed to require only a single "mask") at AB = 30 (for a 0.1 arcsec^2 object) and AB = 31 (for a point source) in the 1-5 micron band. The objects would be selected from the deepest field of the imaging survey (see associated proposal). With the nominal performance, this would require an exposure time of 23 days (2×10^6 seconds) for a minimum acceptable S/N $\sim$ 10 in the continuum. As discussed in the "Imaging Survey" DRM proposal (Fig 1), a sensitivity level of AB = 31 (1.6 nJy) is sufficient to detect an object forming stars at 20 $M_{solar}yr^{-1}$ at all $z < 20$ for a pessimistic cosmology ($H_0 = 65, \Omega_0 = 0.2$) and at 10 $M_{solar}yr^{-1}$ at all $z < 40$ in Omega for an $\Omega = 1$ cosmology. These scarce but very precious spectra would reach to within 3 magnitudes of the faintest objects ($AB \sim 34$) detectable on NGST images.

(b) Systematic determination of the gross diagnostic properties of a large sample of galaxies in the $1 < z < 5$ *range*

The aim of this part of the program is to acquire very homogenous moderate resolution spectra in the rest-frame $3500\AA < \lambda < 7000$ $\AA$ spectral region of a uniformly selected sample of galaxies spanning the $1.5 < z < 5$ redshift range. These will yield accurate redshifts (to establish cluster/group membership) and physical diagnostics of the stellar populations, gas metallicity, and dust extinction in each galaxy. Most of these will be small, barely resolved systems, and thus MOS integrated spectra are sufficient.

We identify a need for about 500 "galaxies" in each of 5 redshift bins within this redshift range (this "resolution" in redshift is required to follow through the apparent peak in the ultraviolet luminosity density of the Universe at $z \sim 2$ and the 500 galaxies will enable us to have of order 20 galaxies in each of six "mass" bins (spanning a range of a factor of 30 in mass) and "four" bins describing different levels of star-formation activity). This sample will have quite a wide range of brightnesses, with our science driver being to be able to observe a galaxy with AB = 27 at 3 microns - this is equivalent to a 1 Gyr old quiescent galaxy of stellar mass 3×10^9 M_{solar} at z = 5 or the brightness of a typical Milky Way progenitor galaxy at $z = 5$ in hierarchical models of galaxy formation. Assuming an area of 0.1 arcsec^2, this flux density requires 10^5 seconds of integration to yield a $S/N = 3$ in the continuum at R=1000 (this can be improved by rebinning to R=100) and $S/N = 10$ in an emission line with rest-frame equivalent width of 15 Å. The total integration time is driven by the faintest objects in the sample and so we assume that the equivalent of 500 such objects are observed (i.e. 20% of the sample). We further assume that this requires of order 20 masks (allowing for non-optimal mask design), or a total integration time of 25 days. The brighter objects can be observed in much less time.

Observations of the 3500-7000 $\AA$ spectral range in these galaxies (in principle obtainable in a single R=1000 spectrum) will yield spectrophotometric measurements of (a) Hα for SFR estimates, (b) [OII]3727, [OIII]4959,5007 and Hβ for metallicity estimates, and (c) Hα/Hβ for reddening. Spectral resolution of R = 1000 is adequate for determining these strong line rations and will distinguish broad line AGN emission lines from narrow emission lines. For many galaxies the derived diagnostics will be spatially unresolved and, in any case, they will always be averages over large regions. However, this is not a problem for the derivation of the physical properties of these galaxies since work at low redshift has shown that any bias due to averaging over large regions is small and well behaved (Kennicutt 1998). Group/cluster membership and velocity differences within groups (i.e. for estimating group masses and the likelihood of merging of galactic fragments) will also be measured.

As with the above program, we envisage the use of a slit-type multi-object spectrograph to yield spatially integrated spectra (although some extended objects may yield spatially extended spectra). The brightest objects could/will be observed from the ground, but even for these bright objects, the inhomogeneities of the terrestrial atmosphere will be a particular disadvantage in this program (on the other hand, an important issue in this program will be how to ensure spectrophotometric accuracy with NGST spectra given the variation in PSF with wavelength).

Objects will be selected from the imaging surveys. Each NGST 4x4 arcmin^2 field will contain of order 10^4 galaxies at $AB_L < 27$ over a vast range of redshift and luminosities. The desire to observe many fields to achieve statistical independence of objects at similar redshifts, arguing for sparse sampling of galaxies over many fields (see Imaging Survey proposal), must be balanced against the desire to observe all potential merger fragments in a given system (which argues for dense sampling within each field). However, photometric redshift estimation will be effective in selecting those of most interest for this survey and it is envisaged that the required number of systems can be selected from all of the 16 wide imaging survey fields (ensuring statistical independence) whilst maintaining a dense sampling of selected objects within each field.

(c) Kinematic information on gas and stars

Determining the mass function of star-forming dark matter haloes as a function of time is of paramount importance in understanding the assembly of galaxies. It is also very important to determine how closely the star-formation rate in young haloes is tied to the mass of the halo and the depth of the gravitational potential. High spectral resolution is required for kinematic measurements, especially at the low halo masses anticipated at early epochs in hierarchical models of galaxy formation, where resolutions with R $\sim$ 5,000 are required to measure velocities in the 30 kms^{-1} range. We propose to observe both Hα in emission ($2 \leq \lambda \leq 5$ for $2 \leq z \leq 6.6$) and, if possible, the strong stellar CO 2.3 μm bands which will lie at $\lambda \leq 10\mu$m for $z \leq 3.4$. These are the optimum features and lie at the wavelengths where the performance gain of NGST is maximized.

Although the sensitivity in the continuum is substantially reduced relative to the R=1000 program described above, the sensitivity for emission lines will not be greatly affected for these very low velocity systems for which the line emission will be barely resolved even at R=5,000. These galaxies are expected to be small, and so integrated measurements of line profiles will in general be made, allowing the use of multi-slit spectrographs (though the multiplexing efficiency will likely be reduced because of the limited spectral range of the spectra at these resolutions, allowing only observations of objects within a relatively narrow redshift interval, $\Delta z/z \sim 10\%$). We assume 16 masks will be observed for 10^5 seconds each, for a total of 20 days. This will yield integrated velocity measurements, and mass estimates, for of order 400 galaxies at $z > 3$. Considering again the desirability of having of order 3

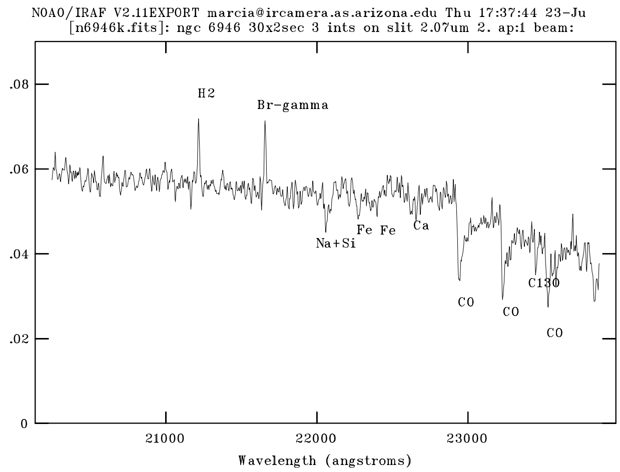

Figure 1: The 2.3 μm spectrum of the star-burst galaxy NGC 6946 from Engelbracht et al. 1996. The spectrum has a resolution $R \sim 3000$

mass bins and 3 redshift bins (recognizing that the brighter objects may have been done from the ground) this would yield a mass function with a precision of order 16%. For these observations the problems of encountering other sources of line broadening than the underlying galaxy kinematics can be alleviated by using AGN diagnostics and P Cygni profiles as indicators of line broadening.

Observations of the 2.3 μm CO bands (Fig 2) (and possibly the Ca triplet at 8600 Å) are potentially very attractive because these features are completely free of contamination from emission lines and straong enough that modest S/N is adequate. These bands dominate the near-infrared spectrum of a galaxy after only $\sim 2 \times 10^7$ years. Furthermore, the features are so saturated that the strength of the feature is almost independent of metallicity. These features are present in globular clusters with [Fe/H] ~ -2 with a strength that is within a few percent of that in solar metallicity stars. In 10^5 sec integration at $R \sim 5,000$ gives $S/N \sim 5$ at $N_{AB} \sim 22.0$, broadly equivalent to AB ~ 24 in the 1-2 μm range. While these represent the brightest galaxies known at $z \sim 3$, these observations may represent the only way to securely determine their masses. It is assumed that these observations are carried out one at a time, and 20 galaxies will be observed.

The Ca triplet at 8600 $\AA$ is also attractive as this is at $\lambda \leq 5\mu$m for $z \leq 5$, affording almost an order of magnitude gain in sensitivity over 10 microns and possibly allowing multi-object spectrocpy techniques. However, the triplet is weaker, thus requiring higher S/N, and are more prone to conatmination by emission lines and it has even been seen in emission themselves (Persson 1988).

(d) Spatially resolved spectroscopy

Finally, NGST has the capability of producing spectral data at high spatial resolution. Acquisition of this type of data is likely to be expensive because (a) by definition, each spatial element contains much less flux than the object as a whole and (b) the multiplexing advantage is much reduced since either multiple exposures with a slit-type spectrograph are required or only one object or field are observable with an integral field spectrograph.

However, for relatively bright, spatially extended objects with complex morphologies, the information content from such observations will be very high. Such objects may be amongst the most interesting objects observed with NGST since they will plausibly represent the assembly of massive galaxies. Careful analysis of the spatially resolved colours of extended morphologically peculiar galaxies in the HDF (Abraham et al, in press) show evidence for bursts of star-formation progagating through large regions of the galaxy. The addition of spatially resolved spectroscopic information from NGST will allow the diagnostics described above involving metallicity, stellar populations, reddening, kinematics to be applied to these systems at different locations, giving a vastly improved physical picture of processes occuring in them and insights into the relation of these objects to present day galaxies (e.g. identifying high metallicity bulges).

Assuming that the flux from individual components of these complex systems represent only 10% of the total, observations of order 10^5 seconds can be undertaken on galaxies at the AB = 24.5 level, representing the brighter galaxies known at $z \geq 3$. In the present program it is proposed that about 25 such galaxies be observed, again selected from the deep imaging surveys. This would require 30 days observations (assuming no multiplexing gain).

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NGST Uniqueness/Relationship to Other Facilities

The issue with spectroscopy on NGST is clearly detector performance and whether the observations are background or detector limited. If background limited, NGST clearly is superior to ground-based telescopes, particularly if the image quality is also superior.

The gain of NGST is clearly maximised for lower resolutions and longer wavelengths. In the context of multi-slit spectrographs, maintenance of image quality over extended fields on NGST is also likely to maximise the performance relative to the ground (where AO produced images may be limited to the isoplanetic area and where the difficulties of producing cryogenic multi-slit spectrographs have yet to be overcome). In the area of spatially resolved spectroscopy of single objects, the extended haloes of AO images may seriously complicate analyses.

Even when the nominal sensitivity gain is not high, NGST spectra will be far cleaner on account of the elimination of atmospheric line emission and selective absorption.

Observing Strategy

Explained in detail in context of science above.

Special Requirements

Minimum Spatial Resolution:	0.1 mas at 2 μm
Minimum Spectral Resolution:	5000 at 1-10 μm
Minimum FOV:	2? arcmin^2 at 1-5 μm
RMS offset accuracy:	15 mas
RMS repointing accuracy:	15 mas

Precursor/Supporting Observations