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Understanding the Astrophysics of Galaxy Evolution: the role of spectroscopic surveys in the next decade

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Abstract

Over the last decade optical spectroscopic surveys have characterized the low redshift galaxy population and uncovered populations of star-forming galaxies back to $z \sim 7$. This work has shown that the primary epoch of galaxy building and black hole growth occurs at redshifts of 2 to 3. The establishment in this same decade of the concordance Λ CDM cosmology shifted the focus of galaxy population studies from constraining cosmological parameters to characterizing the processes which regulate the formation and evolution of galaxies. In the next decade, high redshift observers will attempt to formulate a coherent evolutionary picture connecting galaxies in the high redshift Universe to galaxies today. In order to *link galaxy populations at different redshifts*, we must not only *characterize their evolution in a systematic way*, we must *establish which physical processes are responsible* for it. Considerable progress has already been made in understanding how galaxies evolved from $z \sim 1$ to the present day. Large spectroscopic surveys in the near infrared are required to push these studies back towards the main epoch of galaxy building. Only then will we understand the full story of the formation of L_* galaxies like our own Milky Way. A large near-IR spectroscopic survey will also provide the calibration needed to avoid systematics in the large photometric programs proposed to study the nature of dark matter and dark energy. We provide an outline design for a multi-object 0.4 to 1.8 micron spectrograph, which could be placed on an existing telescope, and which would allow a full characterization of the galaxy population out to $z \sim 2$. We strongly recommend a serious further study to design a real instrument, which will be required for galaxy formation studies to advance to the next frontier.

1 Current state of observations of high-redshift galaxies

Over the past decade and a half, our observational understanding of galaxy evolution has grown enormously. Steidel and collaborators demonstrated that colour selection techniques allow so-called Lyman Break galaxies (LBGs) to be isolated efficiently at redshifts ~ 3 , thus breaking the $z = 1$ redshift barrier that had dogged the field for many years. Spectroscopy then confirmed the redshifts and showed that LBGs had moderate mass ($10^9 - 10^{10} M_\odot$) and metallicity (0.3 solar), that they were forming stars very rapidly, and that supernovae were driving significant outflows. Since then, the race to claim the record for the highest redshift object has absorbed many in the field. Today, this record stands at $z = 6.96$. These distant objects appear as tiny smudges in the deepest HST imaging data obtained and have low masses. At $z \sim 5$ the integrated mass density in stars was less than 10 percent of its present day value. Although galaxies at $z > 6$ may hold the key to understanding the re-ionization of the Universe, their story is not central to our understanding of the formation of the main components of typical spirals and ellipticals in the nearby Universe.

Today, we know that typical L_* galaxies assemble at $z = 2$ to 3. These are the redshifts where star formation and black hole accretion activity peaked. Lyman Break galaxies were initially viewed as the obvious progenitors of present-day L_* galaxies. However, it is now clear that although the Lyman break technique is extremely powerful, it does not pick up *all* high redshift galaxies. Franx and his collaborators found a significant population of very red galaxies (DRGs) that did not satisfy the LBG colour selection. Some are red because they were dusty, but a significant fraction are red because star formation had already switched off some time previously. DRGs are more massive than LBGs ($> 10^{10} M_\odot$) and denser than elliptical galaxies in the local Universe.

The Great Observatories, HST, Chandra and Spitzer, also spent considerable effort on deep surveys, as did ground-based observatories such as the JCMT. Each new survey successfully found galaxies at $z \sim 2$ and triumphantly announced the discovery of a "new population" with its own acronym. These now fill the literature on high redshift galaxies with a bewildering menagerie: XBONGs (X-ray bright optically normal galaxies) from Chandra, DOGs (dust-obscured galaxies) from Spitzer, UVLGs (ultra-violet luminous galaxies) from GALEX, not to mention LBGs, DRGs, BXs, BzKs and BMs from ground-based optical and near-IR surveys.

This situation is symptomatic of a subject that is still in its infancy. Over the next decade, high redshift observers will attempt to unify these different galaxy classes, in order to formulate a coherent evolutionary picture connecting galaxies in the high redshift Universe to galaxies today. Just as evolutionary biology progressed from Linnaean taxonomy to a more mature phase where the theories introduced by Charles Darwin were used to connect and to unify the different species, so too must the field of galaxy evolution progress beyond the naming of the animals. As we will describe, large spectroscopic surveys of galaxies in the near infrared are critical if we are to make this transition successfully.

2 Current state of the theory of galaxy formation

The scientific development of the last decade which most impacted galaxy formation theory was the establishment of the Λ CDM concordance model of cosmology, in which the Universe consists of 70% dark energy, 25 % dark matter and 5 % ordinary matter. Before this happened, it was thought that galaxies might provide strong constraints on cosmological parameters. Considerable attention was devoted to the abundances, masses and ages of high-redshift galaxies, because these properties constrain the epoch of structure formation, and hence parameters such as Ω and H_0 . The precise cosmological parameters provided by the cosmic microwave background, supernovae and low redshift large-scale structure data have now made such approaches obsolete.

For the galaxy formation theorist, the era of precision cosmology means that the challenge now shifts to understanding the formation of the galaxies themselves. The evolution of the main matter component of the Universe, the dark matter, can be modelled to high accuracy by running N-body simulations on large supercomputers. The same does not hold for the baryons. It has become increasingly clear that the processes that regulate cooling, condensation and star-formation at the centers of dark matter halos are extremely complex. It is likely that we will never be able to model them “ab initio” using direct simulations in the way we now model dark matter evolution. One of the main problems hampering progress is the enormous dynamic range in scale that must be considered when treating star and galaxy formation.

Some of these processes, such as the effect of supernova explosions on the interstellar medium of the galaxy, have been discussed for many years. Others are just now coming to be appreciated. The discovery that the centers of essentially all luminous nearby galaxies harbor a supermassive black hole with mass tightly related to that of the surrounding bulge, has revolutionised current thinking about how giant elliptical galaxies form. Rather than being simply an end-product of galaxy formation, supermassive black holes are thought by many to play an active role in regulating the formation process. In the most extreme form, “feedback” from an accreting black hole is supposed to blow all the gas out of the galaxy and its surrounding dark matter halo, thus shutting down star formation and terminating growth. Except in the cores of rich galaxy clusters, the observational evidence for such violent AGN feedback remains sparse, and the models suggesting its feasibility are necessarily schematic. Nevertheless, AGN feedback is currently one of the hottest topics in galaxy formation theory.

The main reason for this is that the Λ CDM cosmological model provides robust predictions for the dark matter halos of typical giant ellipticals and for the mass of baryons they should contain. Simple physics predicts that in the absence of compensating effects, the gas should cool and form many more stars than are observed. *It is this tension between theoretical predictions and what is observed in the real Universe, that will continue to drive both observational and theoretical progress in the field of galaxy evolution for the foreseeable future.* Considerable theoretical effort will be needed to develop more accurate sub-grid models to describe star formation, chemical enrichment, and supernova and AGN feedback. Such sub-grid models must be included in larger scale simulations of the evolution of galaxy populations so that comparison with observations can determine the extent to which the effort has been successful.

3 From taxonomy to evolutionary science: the role of large galaxy surveys

The main goal in galaxy formation for the next decade will be to *connect* galaxy populations observed at different redshifts within the framework of a single, consistent picture of galaxy evolution. We will now argue that large near-infrared spectroscopic galaxy surveys are crucial if this effort is to succeed.

In order to understand galaxy evolution, it is critical to select galaxies using photometric passbands that sample the light emitted by the population of long-lived stars, i.e. longwards of the rest-frame 4000 Å break, but shortwards of wavelengths where emission by thermally-pulsating giant (TP-AGB) stars or by dust becomes important. In contrast to the light emitted at ultra-violet wavelengths or far-infrared wavelengths, which is dominated by (direct or reprocessed) radiation from short-lived O and B stars, or radiation at X-ray or radio wavelengths, which is influenced by processes occurring in the immediate vicinity of the black hole, the rest-frame optical light from a galaxy is normally stable over relatively long timescales. A survey selected in the *rest-frame* optical will allow us to characterize different transient phenomena (e.g. starbursts and AGN) occurring in

the galaxy population at a given epoch. It will also allow us to connect galaxy populations observed at different epochs and to estimate galaxy stellar masses, the quantity that is likely most tightly correlated with dark matter halo mass and so the best link to the underlying cosmological model.

A survey must be large ($\sim \text{few} \times 10^5$ galaxies) in order to disentangle *covariances* in the physical properties of galaxies. One reason it is so difficult to understand how galaxies form is because almost all galaxy properties are correlated. Galaxy mass correlates with morphological type, with colour, with metallicity, with star formation rate, with gas content and with local and large-scale environment. The correlation of property A with property B does not establish that B regulates A. With a large survey, one can control many properties at the same time, i.e. one can look at how property A depends on property B if properties C through F are all held fixed. Accurate measurement of the correlation function out to the scales needed to constrain dark matter halo masses typically requires samples of 10^4 galaxies or more. These techniques became standard analysis procedure with the advent of the Sloan Digital Sky Survey; imaging and spectroscopy of well over half a million galaxies at $z \sim 0.1$ have given us a detailed view of the astrophysical processes at work in the low-redshift Universe. The next step is to establish the evolutionary sequence that produced today's population of galaxies. Deep optical surveys have made substantial progress in studying evolution at $z < 1$ but new efforts at longer wavelengths are needed to cover the principal epoch of galaxy growth which lies at $z > 1$.

Two steps must be accomplished if one is to use a large survey to connect galaxy populations at different redshifts: 1) The evolution of galaxies must be *characterized* in a systematic way. This can be done to some extent using photometric surveys. 2) We must then establish which physical processes are responsible for the observed evolution. This requires large spectroscopic surveys in the near infrared.

4 Imaging and spectroscopy: what can be accomplished

4.1 Imaging only

One cannot begin to study the evolution of galaxies unless one has some idea of the redshift at which they lie. With broad-band imaging data alone, one must resort to photometric redshifts. The standard method is to fit the photometry to a set of template spectra, drawn from population synthesis models or using the observed SEDs of low-redshift galaxies. The problem lies in the appropriate choice of templates. The galaxy population evolves strongly, so templates constructed from low-redshift galaxies do not necessarily match very well at high redshift. If one uses models, then one has to worry whether these are a good representation of real galaxies, how to introduce corrections for dust, and so on. The best results are obtained if one has a large training set of redshifts derived from real galaxy spectra. The typical errors on photometric redshifts using spectroscopic training sets and state-of-the-art techniques such as neural nets, are $\sigma(\Delta(z)/(1+z)) = 0.06$ at $z > 1.5$ for redder galaxies with strong 4000 Å breaks. The errors are larger for blue galaxies, which have featureless spectra dominated by emission lines that vary strongly from object to object.

Despite these limitations, the current generation of large imaging surveys (e.g. COSMOS) has been able to characterize how the luminosity functions of different galaxy populations (e.g. red/blue sequence galaxies, morphologically early/late type galaxies, radio-loud and X-ray detected AGN) evolve out to redshifts ~ 1 . The photo- z errors are too large to allow identification of large-scale structure in redshift space, but with high quality imaging, characterization of the underlying dark matter density field becomes feasible through weak gravitational lensing. By stacking many galaxies with similar properties and measuring the tangential distortion of background galaxies, one can directly measure the mean mass profile of the galaxies' dark matter halos. This provides extremely

powerful constraints on galaxy formation models, and the next generation of large imaging surveys (Pan-Starrs, DES, LSST) will bring real advances in understanding here. If we are to realize the full power of the lensing techniques, however, we need to stack the galaxies according to a variety of different *physical* properties, and to calibrate accurately the photo- z 's of the background sources. This is where near-infrared spectroscopy will be crucial.

4.2 Imaging and optical spectroscopy

Galaxy redshifts out to $z \sim 1.4$ can be obtained from optical spectra. At higher redshifts, the doublet [OII] λ 3727 is no longer accessible with standard optical spectrographs and one enters the so-called “redshift desert”.

Over the past 5 years, surveys such as DEEP2 and VVDS have amassed a few tens of thousands of optical spectra of galaxies at $z \sim 1$. We have learned that the standard Hubble sequence is still largely in place at these redshifts, but that there has been significant evolution in both late- and early-type galaxy populations. At $z \sim 1$ the total stellar mass in red sequence galaxies is only about a third of the present-day value, and the mean star formation rates of blue sequence galaxies are larger by a factor of 7 to 10 in the mean. Spectral information has been critical in attempts to elucidate what is *causing* this evolution.

Accurate redshifts have allowed the construction of group and cluster catalogues and reliable estimates of local galaxy density. From this, we have learned that the relation between galaxy color and environment evolves very strongly out to $z = 1$. Locally there are no massive star-forming galaxies in very rich environments, but at $z = 1$ these are apparently quite common.

The kinematics of galaxies at $z = 1$ were also studied using the higher resolution spectra provided by DEEP2. From this we learned that galaxies that look like ordinary spiral galaxies in the HST images frequently have velocity fields that are dominated by dispersion ($V/\sigma < 1$) rather than rotation. These are currently hypothesized to be galaxies where the infall of cold, clumpy gas has produced turbulent, disordered velocity fields.

Emission lines in the optical spectra of these intermediate redshift star-forming galaxies provided valuable information on the physical conditions in their interstellar media. The evolution of the mass-metallicity relation with redshift was studied in detail, the main result being that the mean gas-phase metallicity of star-forming galaxies appears to drop quite strongly with redshift at fixed stellar mass, once again supporting the idea that the blue galaxy population at high redshifts might be experiencing a rather high rate of gas accretion.

Rather little is currently known about the stellar metallicities and element abundance ratios of high redshift galaxies. Stellar absorption lines do contain important information, but individual high-redshift spectra generally have too low S/N to permit metallicity determinations. However, one can get quite far by stacking the spectra of many similar galaxies.

Studies of stellar absorption lines in high redshift galaxies are just beginning. One very exciting development has been the identification of a population of extreme post-starburst galaxies at redshifts $z \sim 1$. These galaxies have extremely strong Balmer absorption lines, but weak or absent emission lines, indicating that they must have experienced a very significant burst of star formation in the past gigayear. One pressing question is whether these galaxies are in some way connected with the population of galaxies with actively accreting black holes at the same redshift. Progress on that question has suffered because the emission lines needed to diagnose the presence of an AGN ($H\alpha$ and [NII] λ 6548) are already redshifted into the near-IR part of the spectrum at $z \sim 1$, and hence are inaccessible with current instruments.

4.3 Why we need near-IR spectroscopic surveys in the next decade

The reason is very simple. As we push out to redshifts $z \sim 2$ when typical spiral galaxies and ellipticals were in their most active formation phase, optical spectra sample the rest-frame ultraviolet part of the galaxy SED which is dominated by light from the most massive, short-lived stars. There are very few strong stellar absorption lines at these wavelengths, particularly in the near-UV, and no important nebular emission lines apart from Ly α , which is difficult to interpret due to complex radiative transfer effects. It is therefore difficult to measure even the most basic galaxy properties – redshifts and velocity dispersions. The UV does provide an important snapshot of a galaxy’s recent star formation activity, but to realize its full diagnostic power data at longer wavelengths are required to constrain the effects of dust attenuation. The UV also contains a large number of interstellar absorption lines that can provide important diagnostics of the kinematics and ionization state of the ISM, but optical data is needed to relate the properties of these absorbers to the star formation, AGN activity, and metallicity of their hosts.

If we are to understand the full story of the formation and evolution of our home galaxy, the Milky Way, and its peers, we require large near-IR spectroscopic surveys.

5 Cosmology and spectroscopy

In the next decade observational cosmologists will attempt to constrain the nature of dark matter, dark energy and the (perhaps inflationary) processes which generated structure. Large-scale spectroscopic surveys on large telescopes will be critical to achieving reliable results in all these areas.

The distribution of dark matter is closely related to its nature, and can be constrained through dynamical studies of clusters and satellite systems, by the statistics of intergalactic absorption in the spectra of high redshift objects, and by gravitational lensing of distant galaxies. The first requires large galaxy samples with precisely measured velocities; the second requires high S/N spectra of many faint objects to achieve good statistics with a high sampling density on the sky; the third needs large spectroscopic samples to the faintest possible limits in order to calibrate the photo-z error distribution as a function of true redshift.

Dark energy can be constrained by precise measurements of the cosmic expansion history and of the linear growth of cosmic structure. Spectroscopy of large samples of faint galaxies are mandatory to control for systematics in all currently proposed schemes to make these measurements. Large-scale photometric surveys aiming to measure baryon acoustic oscillations or lensing statistics again require a precise calibration of photo-z errors as a function of true redshift. Methods based on cluster evolution need spectroscopy to measure cluster velocity dispersions and to characterize the evolution of cluster galaxies, in particular, the prevalence of AGN activity. Supernova-based methods require a good understanding of the evolution of the parent galaxy population (metallicities, SFRs, dust contents) to constrain systematic variations in progenitor properties and supernova environments.

The process which generated structure in the early Universe can be constrained by measuring the linear power spectrum of density fluctuations. The cosmic microwave background is the prime tool for such studies, but degeneracies which arise in analyses of CMB data alone can be broken with sufficiently precise data on the late-time matter distribution. Again gravitational lensing estimates of the relevant quantities will need exquisite photo-z error characterizations, while direct estimates from the galaxy distribution will require a detailed understanding of bias effects which can only be robustly investigated through large spectroscopic surveys.

6 A large near-infrared spectroscopic survey for the next decade

As outlined above, the desideratum is a survey which obtains the spectra of a few times 10^5 galaxies from the visible into the near IR at each of a sufficient number of redshift slices that one can follow the evolution of all interesting populations. The SDSS main sample contained 300,000 galaxies brighter than L_* within a volume of $\sim 0.05 \text{ h}^{-3} \text{ Gpc}^3$. One basically wishes to produce a set of samples comparable in size to this from redshift about 2 to the present, covering the epoch during which most of the baryonic matter was assembled and most of the stars in the universe were formed.

At redshift 2, the effective wavelength of the R band is at about 1.8 microns, the red edge of the H band; working longward of this is possible but technically very much more difficult, and the survey we envision covers the range 1-1.8 microns with infrared technology and 0.4-1 micron with optical technology. As stressed above, one really needs both in order to study both stellar mass from the observed IR, rest-frame optical, and star-formation rate from the observed optical, rest-frame near UV, in the same objects, and we cannot really understand the properties of galaxies without both. We stress here the infrared coverage; the optical is much easier and has already received a great deal of attention. A reasonable set of redshift shells to focus our thinking might be something like:

Boundaries	0.6-0.8	0.8-1.05	1.05-1.35	1.35-1.65	1.65-1.95
Mean z	0.7	0.9	1.2	1.5	1.8
Area/ $.05\text{Gpc}^3$	140	100	70	60	60
λ_r	1.07	1.19	1.38	1.57	1.76
AB(r, L_*)	20.8	21.3	22.0	22.4	22.9

The AB row is the AB magnitude at rest-frame r (6300\AA) for a simple evolutionary model corresponding to a bluish L_* galaxy today, and λ_r is the corresponding observed wavelength in microns. The brightness of the target galaxy obviously depends on its star formation history, but this is a pessimistic estimate for most relevant objects.

There are about 300,000 galaxies brighter than an evolution-corrected L_* in each cell, 1.5 million in all. Whether one would really like to restrict the sample to intrinsically bright galaxies (for example by color selection) is debatable; the sample would be roughly twice as large if one simply went to a photometric limit in the smallest region corresponding to the L_* cut at redshift 2. This would sample galaxies up to 2 magnitudes below L_* at lower redshifts over a somewhat smaller volume, which would certainly be extremely valuable.

What instrumentation is required to do this? It certainly does not exist at the present time, but is, we believe, technically feasible (though certainly not easy.) While expensive, it is very much cheaper than yet another large general-purpose telescope, and it would scientifically be of enormously more importance.

The surface density of targets is very high. Of order a million galaxies in 100 square degrees is 10^4 galaxies per square degree. We will see that for a plausibly realizable setup, reasonable spectra should be obtainable in of order four hours. Thus for 3 million galaxies, a 1000-object spectrograph or array would require of order 3000 pointings of 4 hours each, 12,000 hours. Accounting for reasonable weather and avoidance of very bright moon, this is about 2200 nights, about six years. Clearly there are economic trades between number of fibers and survey duration, and they need to be carefully made.

The most severe problem with infrared spectroscopy in this wavelength region is the very bright sky background, which, however, is confined to a large number of very bright OH airglow lines. The lines are quite closely spaced, so one needs to go to quite high spectral resolution to make use of the dark wavelength regions between the lines to reach faint distant objects. The OH spectrum and intensities are very well known; how dark the sky is between the lines is not so well known, and appears to be completely dominated by scattering arising from fundamental grating physics, with

a small zodiacal contribution. With reasonable assumptions about the quality of VPH gratings, the calculated background brightness is of order $19.5\text{AB}/\text{arcsec}^2$ except at the longest wavelengths, where it rises to about a magnitude brighter because of the extremely strong lines there. One must work at a resolving power in excess of about 4000 in order that some reasonable fraction (at least $\sim 60\%$) of the spectrum is reasonably uncontaminated by the OH emission.

The technological problems are not the same over the whole wavelength region 1-1.8 μm , and it might well be advantageous to split it in two, 1-1.34 μm and 1.34-1.8 μm . In the short segment, ordinary optical materials can be used, and it is not necessary to cool the spectrograph; in the long region, one can use silicon to enormous advantage as a refracting material, and it is necessary to cool the spectrograph. In both, doped HgCdTe detectors have to be used. In the optical and shortwave IR regions spectrographs very similar to the SDSS ones or those proposed by Hopkins for WFMOS could be built. The longwave spectrographs are more problematical, but the UVa group (Skrutskie and Wilson) are building a high-resolution H-band instrument, which is a reasonable (but larger and more complex) model for this instrument. It is probably best economically and strategically to use a separate fiber set for each of the three spectrographs rather than split the light, given the very high target density; multiple visits to each field are necessary in any case.

If we suppose we have available for the survey a 6.5-meter telescope with a reasonably wide field with a cassegrain F/5 focus (such as the MMT), things scale quite well to the SDSS spectrographs. We have thought mostly about fiber systems, which make dealing with the large multiplex capability possible, though we will need object-sky pairs for chopping. 150 micron fibers (SDSS used 180) translate to about 1.0 arcseconds, probably nearly ideal for the redshift range in question (this is about 6 kpc over most of the range, similar to the footprint of the fibers for the SDSS main sample). We need about 3000 pixels in the wavelength direction, and could use one and a half 2K^2 arrays or contract for a somewhat larger chip. If we use 300 fibers, the interfiber spacing is equal to the fiber footprint, so each spectrograph will accommodate 150 object/sky pairs, and we need 7 spectrographs. Sensitivity calculations indicate that one can obtain a S/N of about 7 per resolution element with this setup at AB=23 in four hours through most of the IR band, falling to about 3 at the reddest end. Rebinning to $R\sim 1000$ and taking the missing data due to the OH into account gives $S/N \sim 11$ over most of the range degrading to 5 at the reddest end. With the noise performance now being reached with IR detectors, one exceeds the read noise limit in short enough times that the chopping will be efficient.

How much would this cost? A reasonable guess scaled from the APOGEE camera for the longwave IR spectrograph is about \$1.5M, the shortwave one a bit cheaper, say \$1M. The visible could be covered by a WFMOS survey if that is to happen, but if covered here, about \$2M (double spectrograph to cover the whole range). If we adopt \$3.5M per spectrograph, we calculate a total cost of about \$30M for 1000-object capability on an existing 6.5-m telescope. Needless to say, this survey's worth is severely compromised unless there are corresponding deep optical and IR imaging surveys, deep enough to obtain multicolor structural parameters for, and choose, the spectroscopic targets... but the area is small enough that this can be accomplished with existing equipment.

The closest competitor to the instrument proposed is FMOS on Subaru, with 400 fibers (200 pairs), which is currently being commissioned. FMOS has a fifth the number of objects on a slightly larger telescope which is a public facility; clearly a survey of the scope needed is impossible using it.

This is clearly *not* a detailed instrument proposal. It was intended to motivate further study to produce a real instrument without which galaxy evolution studies in the coming decade or two will, we strongly feel, be severely impaired.