GMT Science Use Case

The Stellar Content of Red Galaxies at $z > 2$

Abstract: The high mass red galaxy population presents a significant challenge to our understanding of galaxy formation and the role of feedback. The existence of massive stellar systems dominated by purely passive evolution at $z > 2$ implies an early epoch of star formation and galaxy assembly for the most massive systems. Multi-slit near-IR spectroscopy with the GMT and other ELTs can probe the stellar content of these galaxies and provide insights into their star formation and merging histories.

Motivation: Understanding the formation and assembly of massive galaxies is presently one the most active areas of extragalactic research. The discovery of a population of galaxies with large stellar masses at $z > 1$ and colors and spectra indicative of old stars was a surprise to those modeling galaxy formation in the hierarchical paradigm. There is now a sketchy picture for the early formation of massive systems involving feedback from either supernovae and stellar winds or massive central black holes. It appears that the defining event needed to understanding the properties of the passive red galaxies is a sudden and nearly total cessation of star formation at a fairly early epoch. Feedback is believed to provide the means for shutting off star formation, but the mechanism is poorly understood.

At present most of our empirical knowledge of the passive red galaxies at $z > 1$ is confined to the high mass systems and our knowledge of red systems at $z > 2$ is based almost entirely on photometry rather than spectroscopy. One of the key issues is determining the space density of purely passive systems at $z > 2$ and opposed to red systems that are obscured. Understanding the star formation rate and properties of the reddened systems is also vital and space-based mid-IR observations have played a key role here. Classical $H\alpha$ star formation rates and R23 abundances can help put these objects in context with the Lyman break galaxies and other star forming galaxies at high redshifts.

The limits of 8-10m telescopes have likely been reached in this area as 30hour and longer integrations have exhausted the potential for gains based solely on long exposure times. Larger collecting areas, and advances in background suppression are needed before further progress can be made on the observational front.

Approach: GMT provides the collecting area needed to obtain useful spectra of faint red galaxies at high redshift. The NIRMOS spectrometer designed for the GMT has a large enough field of view that it could provide fairly large samples of such objects in an efficient manner. A few night observing program could yield a sample of ~300 objects with redshifts between 1.5 and 3. This sample is large enough to allow detailed study of the full range of properties of individual objects and to detect evolution over the redshift span of the sample. Redshifts, ages and rough star formation histories could be derived from all of the spectra and the brighter objects will yield velocity dispersions and abundance indices, providing additional insight into the star formation and mass assembly history.

At present the best spectra of these objects come from deep optical spectra for objects with z < 2 using DEIMOS and GMOS on Keck and Gemini respectively, and deep GNIRS spectra on Gemini for objects z >2. In Figure 1 we show an example spectrum from GNIRS of a passive red galaxy at z = 2.24. The raw spectrum is fairly noisy and only when it is heavily binned can one see that there is real information there. The best-fit age for this object is fairly modest, but implies a formation redshift of z ~ 3.

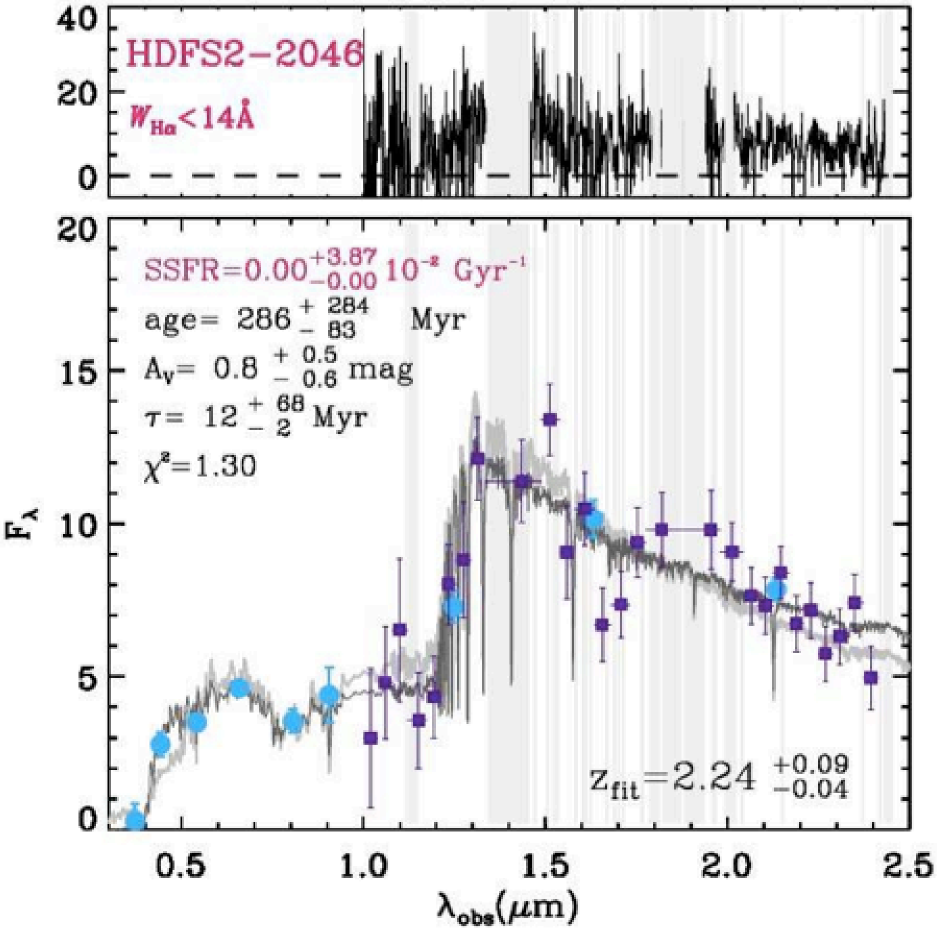

Figure 1. GNIRS spectrum of a distant red galaxy from Kreik et al. The upper panel shows the raw J, H, and K spectra, while the bottom panel shows the broad band photometry, a heavily binned version of the near-IR spectra and the best-fit spectral synthesis model. These pioneering studies have shown that there are old systems at z > 2 and that near-IR spectroscopy can provide a valuable tool for understanding their ages and star formation histories.

The field of view of NIRMOS is 5′ x 7′ and a single slit mask will contain ~ 50 targets if one adopts a fairly conservative 6 arc-second slit length. Labbe et al. have determined the surface density of distant red galaxies with redshifts above and below 2 as a function of J and K magnitudes and we tabulate these in terms of number per NIRMOS field of view in Table 1. There are more than enough targets of interest if one can reach to J magnitudes of ~24 (AB) or so. For the passive systems the J-band is the optimal window as one can detect the CaII H&K lines, the 4000A break and the Balmer series in post starburst and intermediate age objects. In principle one can detect [OII]3727 in the star forming systems at z ~ 2, but observations of Hα in the K-band are probably preferred for these objects.

Table 1. Cumulative Number of Distant Red Galaxies per NIRMOS Field of View

J(AB)	N(2 < z < 4)	N(1 < z < 2)	N(4 nights)
23.0	1	40	35
23.5	3	60	50
24.0	6	65	60
24.5	11	75	70
25.0	16	87	75
Total			**290**

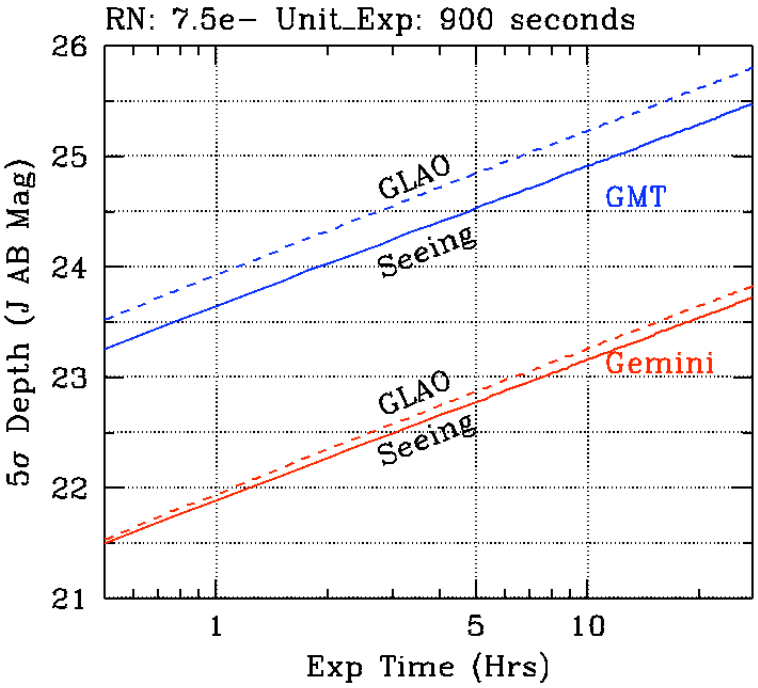

Figure 2. Predicted J-band sensitivity for NIRMOS on the GMT (blue) and an 8m aperture (red). The two curves show the 5-sigma per resolution element limiting continuum sensitivity for 0.45" seeing (solid) and GLAO (dotted) PSFs. NIRMOS on GMT provides nearly a 2 magnitude gain primarily due to the reduced impact of detector noise.

Sensitivity: The critical question in evaluating the viability and cost of a program such as this one is the expected sensitivity of the observations. We have estimated the sensitivity of the GMT using the parameters for the NIRMOS spectrograph. Figure 2 shows the expected sensitivity in the continuum along with similar numbers for a NIRMOS-like spectrograph on Gemini. The calculations all use an Rϕ product of 4000; the GMT/NIRMOS and GMOS sensitivities are based on a 0.45” wide slit for natural seeing and 0.15” slit for the ground-layer AO case. One can see that in 5 hours NIRMOS can reach a limiting magnitude between J = 24 and 25, depending on the size of the PSF.

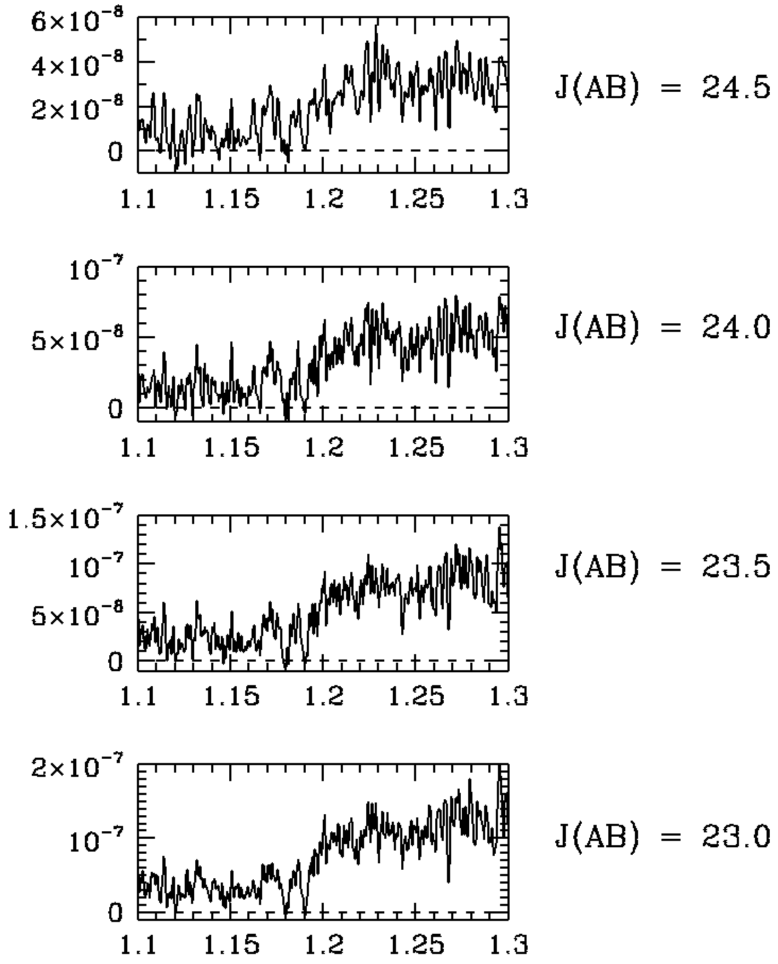

Figure 3. Simulated GMT/NIRMOS spectra of old galaxies at z = 2. These simulations are based on the basic properties of NIRMOS operating in median seeing conditions with a slit matched to the seeing. The detector read noise was set to $7.5e^-$ and the unit integration time was 900 seconds. The total integration time was 5 hours, except for the object with J = 24.5 for which we simulated a 10-hour integration. The spectra were “observed” at R = 3000 and, after sky subtraction, were rebinned to R = 1200 and lightly smoothed.

We have simulated spectra of passive red galaxies at z = 2 using the baseline properties of NIRMOS. The details of the simulations will be described elsewhere. In brief, we use the basic properties of NIRMOS along with a flux calibrated sky spectrum from Gemini.

Slit losses are included and a range of seeing and slit widths were considered. We adopted detector properties consistent with the present state of the art. The spectrograph throughput was set at 30%, conservative compared to state-of-the-art spectrographs today. The observations are simulated at a resolution of ~ 3000 and, after sky subtraction, are rebinned to R = 1200. For the present write-up we considered two cases: median natural seeing of 0.45" at J and ground-layer AO assisted seeing of 0.15" FWHM. The results are shown in Figures 3 and 4 for five-hour integrations. From these figure we conclude that J=24.5 is a reasonable limit in median seeing and that in the best seeing J = 25 is within reach.

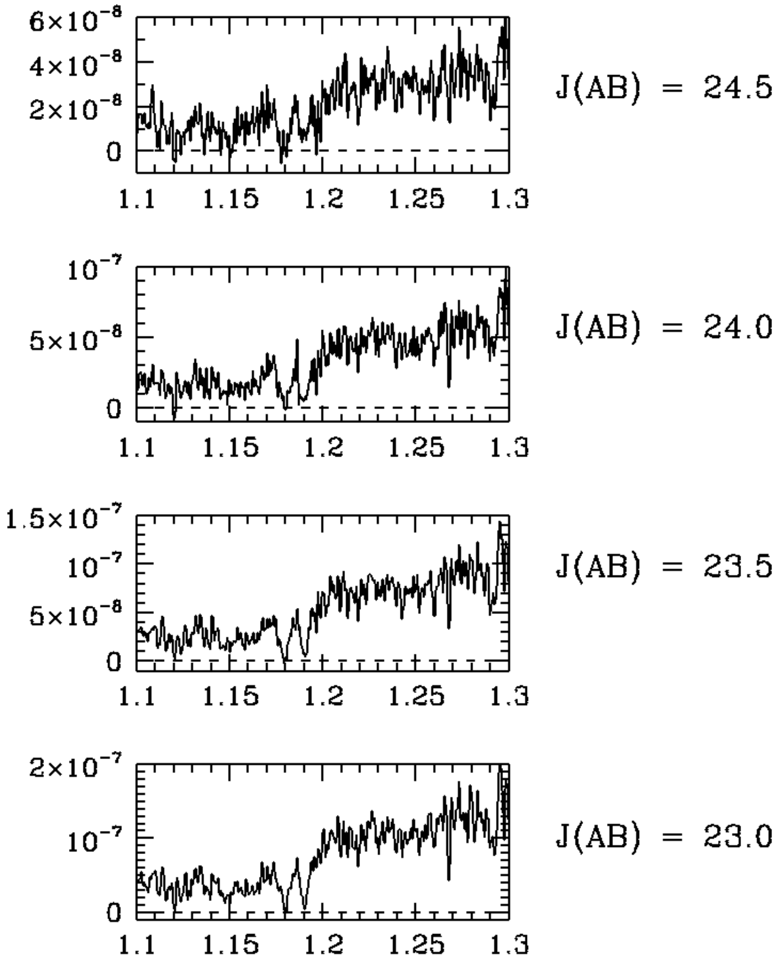

Figure 4. The same spectra simulations as in Figure 4 except in this case we used a PSF appropriate to ground-layer AO correction with FWHM = 0.15". In this case all of the objects, including the one with J = 24.5 were "observed" for 5 hours.

The star-forming segment of the population is easily recognized by strong Hα emission in the K-band. We have simulated these objects using a spectra of M82, a moderately obscuring low mass star forming galaxy in the local universe that serves as a sensible analog for bursting dwarf galaxies at high redshift. Simulated spectra of star forming galaxies at z = 2.5 with a range of line fluxes are shown in Figure 6. In this figure we compare the expected spectra with GMT/NIRMOS to spectra from a similar instrument on the Keck telescope. We compared our simulated 10m aperture spectra with real spectra of Lyman break galaxies from Erb et al. (2006). These spectra were obtained with NIRSPEC on Keck. From the figures in Erb et al. we conclude that the limiting useful line flux for a 2 hour observation is ~ 2E-17 erg/sec/cm2, similar to what we conclude from our simulations. The rough agreement between our simulations and the actual observations suggest that we our simulations have reasonable fidelity. Our simulated NIRMOS spectra suggest that we should be able to reach fluxes of ~ 5E-18 with a similar signal-to-noise ratio. The factor of 4-5 gain offered by GMT is larger than what one would expect from a simple scaling by aperture in the seeing-limited regime. The steeper gain arises from the fact that on 8 and 10m apertures near-IR spectrographs operating at sufficient resolution to work between the sky lines are detector noise limited. In the case of NIRMOS on the GMT we will be sky limited in exposure times of 600-900 seconds for resolutions of ~4000. Thus we gain like D^2 in most of the parameter space between the 10m and 22m apertures.

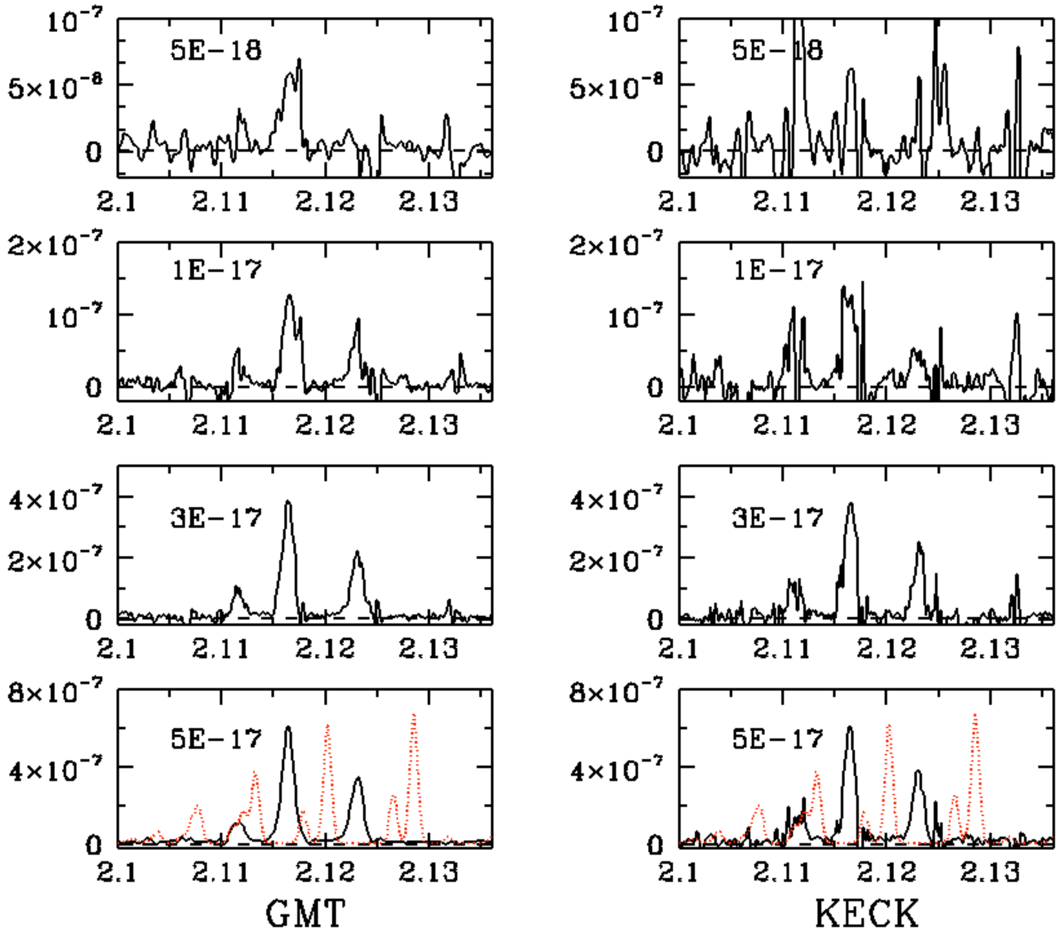

Figure 5. Simulated spectra of star forming galaxies at z = 2.4 based on spectra of M82. The left panels show simulations of 2-hour exposures with a range of line fluxes for NIRMOS on the GMT. The right hand panels show the same objects for the 10m Keck telescope using the same instrumental

parameters. In the lower panel of each set we show the sky spectrum, scaled for ease of view. The NIRMOS spectra reach line fluxes ~5 fainter than those predicted for the 10m aperture. The gain is larger than a simple D scaling because the 10m observations are detector noise limited while the GMT observations are sky limited.

Observing Strategy: Each NIRMOS slit mask can accommodate roughly 50 targets with full coverage in one complete band. If we take J(AB) = 24.5 as our limiting magnitude we can see from Table 1 that we will be able to accommodate most of the $z > 2$ red galaxies per field in a single mask and still be able to supplement this sample with red galaxies at $z < 2$ to fill the masks. Each observation is assumed to require five hours of open slit time. We expect to nod along the slit, rather than chop to blank sky, and so the overheads are modest. In a nominal 10-hour night one should be able to complete 1.5 five-hour observations. Thus in four nights we could easily complete six masks for a total sample of 250-300 targets. It is likely that one will pre-select the galaxies to split the passive and star forming galaxies and thus some of the time will be devoted to K-band spectroscopy of dusty star forming objects. Thus in a single four night run one could assemble a reasonable sample of spectra of red objects over a field area of ~200 square arcminutes. This could be used to sample the field population along several lines of sight or could be targeted at a cluster or large-scale over-density in the galaxy distribution depending on one's interests.

Target Selection: These studies require a fair amount of preparatory imaging in the near-IR and are aided by imaging in the red end of the visible. A number of sufficiently deep surveys are either completed or being planned for the near future. There is no great difficulty in providing the necessary supporting imaging observations.

Summary: We have shown that in a modest amount of observing time one could obtain high quality spectra of an interesting sample of distant red galaxies for analysis of their stellar content and star formation histories. This is an example of cutting edge cosmology-linked science that does not require a massive investment of telescope time or a large consortium of investigators. Modest sized teams from GMT founder institutions or from the NSF supported community could carry this project to completion on a time scale consistent with a PhD thesis program.