Thirty Meter Telescope

Infra-Red Multi-object Spectrograph (IRMS)

Operational Concept Definition Document (OCDD)

IRMS OCDD – *v0.8*

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Revision History

Version	Date	Last edited by	Remarks
0.5	05-04-2014	Mobasher	First draft completed and circulated among Science Team
0.6	06-18-2014	U	Incorporated major revisions from Figer (Sec 3.2), Crossfield (Sec 3.1), U (Sec 2.2), Akiyama (Sec 3.3), and comments throughout from Nobunari/U
0.7	06-26-2014	U	Incorporated major comments from Armus; Revised table of contents
0.8	08-21-2014	U, Mobasher	Inserted several missing sections, including brown dwarf science, KBOs under Solar System(?), Galactic Center and Globular Clusters, Nearby Galaxies(?), Galaxy clusters(?)

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1. Introduction

Among the top priorities of ground-based astronomy for new initiatives in the new millennium emerged the need for a 30-meter class optical telescope that would complement the James Webb Space Telescope (JWST) in tracing the evolution of galaxies and the formation of stars and planets. In order to achieve diffraction-limited imaging and unprecedented light-gathering power, the Thirty Meter Telescope (TMT) features an adaptive optics system that will explore unprecedented scales of spatial resolutions and sensitivities at the optical and near-infrared wavelengths. To fulfill the vast science goals outlined by the TMT Science Advisory Committee, three early light instruments have been selected; one of these is the InfraRed Multi-object Spectrometer (IRMS).

The present operational concept design document (OCDD) describes the technical detail and presents the science cases for IRMS. Instrument specifications, expected sensitivities, and the AO interface are presented to facilitate the science user's planning of an observation. An exposure time calculator has been developed to aid the proposal process and simulate observation results. This document discusses the comparison and improvement over a similar instrument MOSFIRE on the Keck telescope, and presents synergy with the JWST. A variety of science cases from cosmology to exoplanets are illustrated in detail to demonstrate the advances and contribution that IRMS will make toward understanding the universe.

2. Instrument Overview

2.1. Technical Detail

The IRMS is a near diffraction-limited multi-slit near-infrared spectrometer and imager. As one of the first-light instruments on the TMT, it is modeled closely after the MOSFIRE instrument on the Keck Telescope and will be fed by the Narrow-Field Infrared Adaptive Optics System (NFIRAOS). See schematic of the instrument in Figure 2.1.

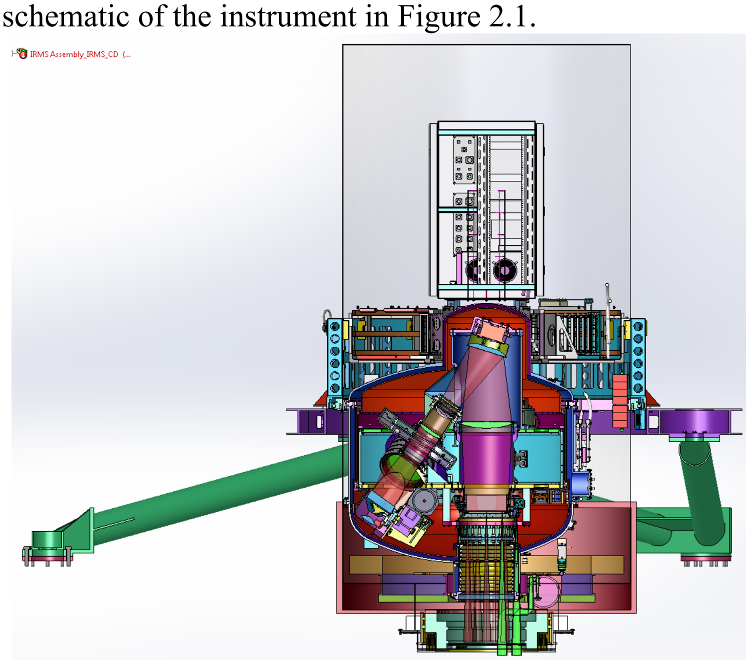

Figure 2.1 Schematic of cross-section of IRMS.

IRMS will provide near-infrared imaging and multi-object spectroscopy at Y (0.97–1.12 micron), J (1.15–1.35 micron), H (1.46–1.81 micron), and K (1.93–2.45 micron) bands. Operating with NFIRAOS on the TMT, it can be used as a diffraction-limited imager and multi-slit spectrograph with moderate resolution. It has a circular field-of-view (FoV) of 2.27 arcmin in imaging mode, and elliptical FoV of 2.0'x0.6' in spectroscopy mode. The spatial scale is 0.06" per pixel, or 0.08" per pixel in the dispersion direction. The spectral resolution R is 3270 for 3 pixel or 0.24" wide slit, or R = 4660 for 2 pixel or 0.16" wide slit. IRMS has a multiplex capability of up to 46 slits using a slit mask system on a cryogenic configurable slit unit. Each slit width can be adjusted arbitrarily, with minimum slit width of 0.16". The IRMS detector will be 2048x2048 Teledyne Technologies Hawaii-2RG with a long wavelength cut-off at 2.5 micron. These specifications are summarized in Table 1.

Table 1 Summary of IRMS Specifications

Wavelength Coverage	0.9 – 2.5 μm
Spectral Resolution	R ~ 3000 – 4000
Spatial Scale	0.06"
Field of View	2.1' x 2.1'
Filters	Y, J, H, K
Detector	2048 x 2048 H2RG and ASIC
Multiplex	Cryogenic configurable slit unit (Minimum slit width: 0.16", up to 46 slits)

2.2. The AO System

The IRMS will be fed by the Narrow-Field Infrared Adaptive Optics System (NFIRAOS) on the Nasmyth platform. IRMS will implement one 2x2 Shack Hartmann wavefront sensor capable of sensing tip/tilt/focus. NFIRAOS is expected to provide a factor of 3 improvement in enclosed energy within a 160 mas slit for the IRMS spectrograph at the edge of its 2' FoV (Hickson and Pfrommer, 2010). Example on-axis (top) and off-axis (bottom) PSFs are illustrated in Figure 2.2; the latter ones have been incorporated in the ETC to provide conservative estimates in sensitivity calculations. The IRMS+NFIRAOS operation will be designed to sample the diffraction limit of the TMT in the infrared.

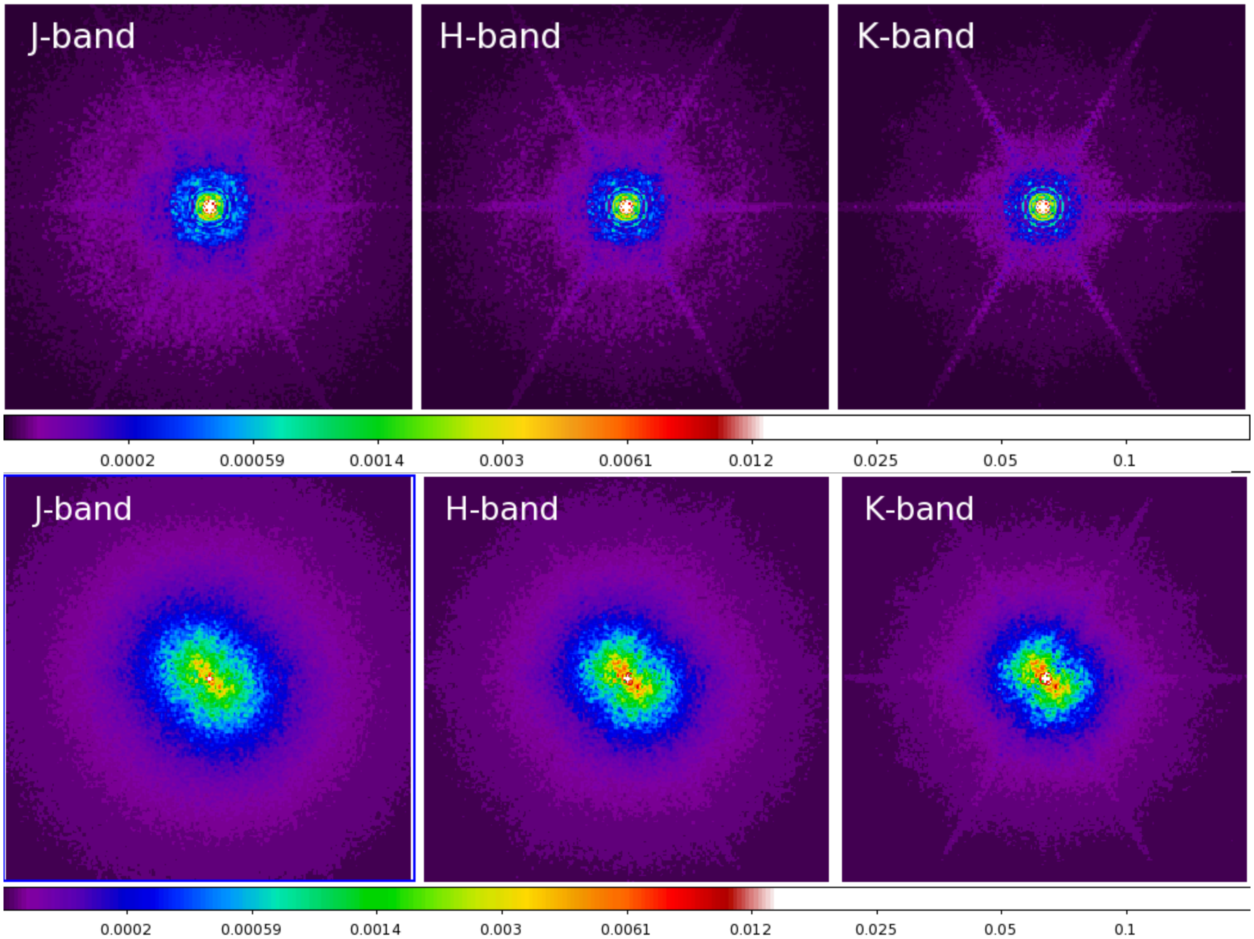

Figure 2.2 Left to right: example on-axis (top) and off-axis (bottom) PSFs for J-, H-, and K-band. Shown here in matched logarithmic scale and color bar (courtesy of L. Gilles and the NFIRAOS Team).

The IRMS+NFIRAOS combination will be used in three different modes:
1. Stand-alone: used to monitor the health of the instruments and to obtain calibration images (arcs, dark frames etc).
2. On sky with NGS: both imaging and spectroscopic modes will use this capability. The guiding and corrections will be provided by the high resolution NGS WFS in NFIRAOS.
3. On sky with LGS: this mode is more flexible as it provides a much better sky coverage than the one with NGS. This will serve both imaging and spectroscopic capabilities.

2.3. Exposure Time Calculator

The IRMS exposure time calculator (ETC) has preliminarily been adopted from that of MOSFIRE[1] given the similarities in their technical specifications. The MOSFIRE ETC was written by Gwen Rudie to facilitate the computation of exposure time for an observation given a desired signal-to-noise ratio (SNR), and vice versa. The principle modes involve computations of SNR based on a specific line of interest ("Line Flux") or on the full continuum band ("Magnitude"). The user may also indicate whether AO mode was to be used for the intended

[1] http://www2.keck.hawaii.edu/inst/mosfire/etc.html

observations, and the appropriate AO PSF will be chosen. The inputs to the ETC include the wavelength bands, slit width, angular extent, line flux or full band magnitude information, the desired SNR or an input exposure time, etc. as demonstrated on the left side of the ETC's graphical user interface (GUI) in Figure 2.3.

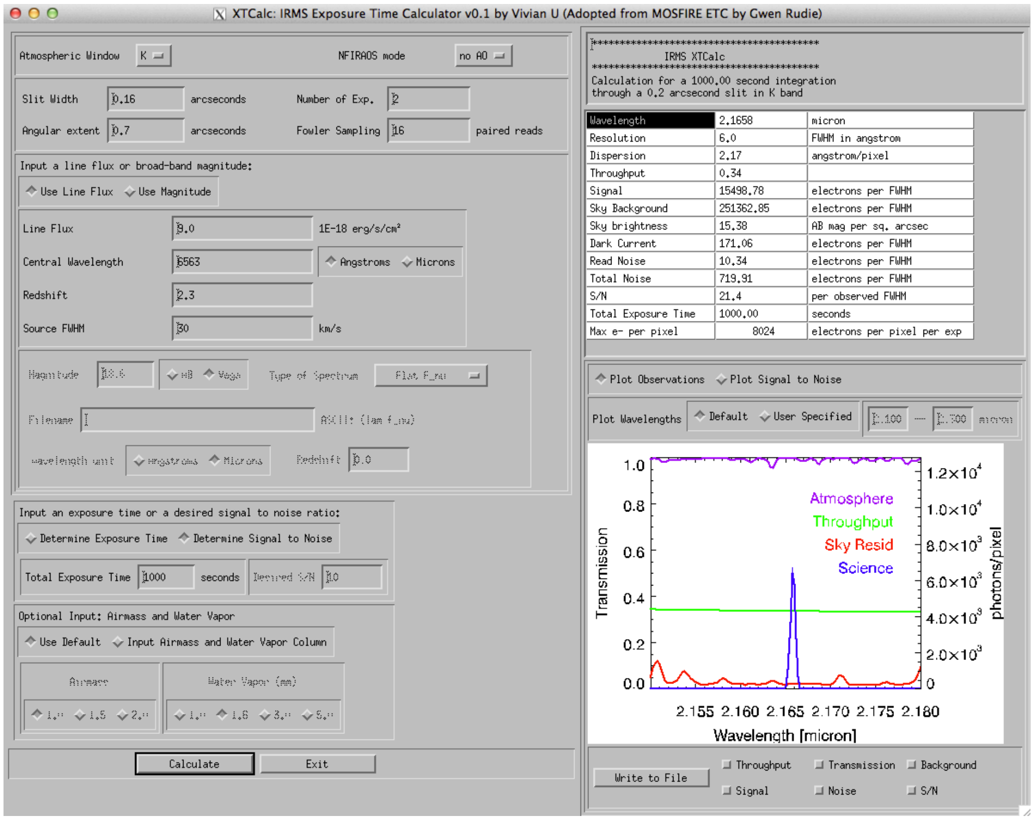

Figure 2.3 A screenshot of MOSFIRE exposure time calculator GUI.

2.3.1. Installation Guide

The IRMS ETC is primarily a GUI widget coded in IDL. The tarball can be downloaded from http://tinyurl.com/irms-etc. This guide walks you through running the code on a working IDL installation with the astronomy library 'ASTROLIB'. However, it should also be able to run with IDL virtual machine which does not require an IDL license. For more details please refer to the installation guide of the MOSFIRE ETC.

After you download and unzipped the tar file, check and make sure that the mandatory directories are present: the bin directory contains the main codes of the ETC that must be compiled prior to starting up the ETC; the mosfire, Mauna_Kea_sky, MosfireSkySpec, MosfireSpecEff, and NFIRAOS directories all contain relevant data files regarding MOSFIRE and TMT/AO characteristics on which the IRMS ETC are based.

Be sure to set the 'MOSFIRE_XTCALC' environment variable to the path where you put the directories. Start up an IDL session, and start running the ETC by first compiling the following:
IDL> .r events_XTcalc.pro

```
IDL> .r XTcalc_irms.pro
IDL> .r run_XTcalc.pro
IDL> run_XTcalc
```

2.3.2. Changes to the MOSFIRE ETC

For the IRMS ETC, we have adopted the MOSFIRE ETC code but incorporated the following changes to account for differences between observations from the two instruments and telescopes: the effective area of the telescope (e.g. a factor of ~8 larger), the slit width (e.g. a factor of ~4 narrower), pixel scale (e.g. a factor of ~3 finer), dispersion pixel size (e.g. ~60% smaller), and detector readnoise (e.g. a factor of 3 lower). Estimates of the Mauna Kea sky background, throughput curves, and linearity limits have been temporarily adopted from MOSFIRE, while the atmospheric transparency spectra were taken from the Gemini Observatory website. Once an observed throughput spectrum is taken with IRMS and the reflectance of the TMT mirrors measured, this will need to be updated in the ETC.

As IRMS will operate behind NFIRAOS, improvement on the sensitivity based on adaptive optics needs to be taken into account. Point spread function (PSF) models from NFIRAOS have been simulated by the TMT AO team for the J, H, and K bands and have been incorporated in the calculations to the first order. In AO mode, a fixed off-axis PSF (see Figure 2.2) is convolved with the line or spectrum of interest before SNR or required exposure time is computed. In future implementation of the ETC, different AO models reflecting the degree off-axis of the target and effect from slit orientation may be incorporated.

2.4. Sensitivity

The sensitivity of IRMS is demonstrated from the current version of the ETC. The effective collecting area of TMT is 630 m^2; slit width is 0.16"; and the pixel scale is 0.06"/px. A detector readnoise of 5 electrons/px and dark noise of 0.03 electrons/sec have been adopted in the sensitivity calculation. The diffraction limit is 0.021" at J-band, 0.027" at H-band, and 0.036" at K band. With the NFIRAOS wide-field mode enabled, the ensquared energy inside the aperture degrades from the center of the FoV (0.70, 0.75, and 0.80 at J-, H-, and K-band, respectively) to the 2' edge (0.43, 0.52, and 0.6 at J-, H-, and K-band, respectively) in the imaging mode; with slit width of 0.16", the ensquared energy is 0.65, 0.73, and 0.80 at J-, H-, and K-band, respectively in spectroscopy mode. Imaging throughput is ~0.25-0.35 while the spectroscopy throughput is ~0.21-0.23 at the three near-infrared bands.

As an example, we illustrate here the signal to noise of an H-alpha line at a redshift z = 2.3. With a resolution FWHM of 6.0 angstrom, dispersion of 2.17 ang/pixel, and a throughput of 0.34, an observation with exposure time t = 1000 seconds in non-AO mode would yield a signal-to-noise ratio of 21.4 per observed FWHM for this line. This is a factor of ~3.5 improvement in S/N over an equivalent MOSFIRE observation. See Figure 2.4 for the expected spectrum.

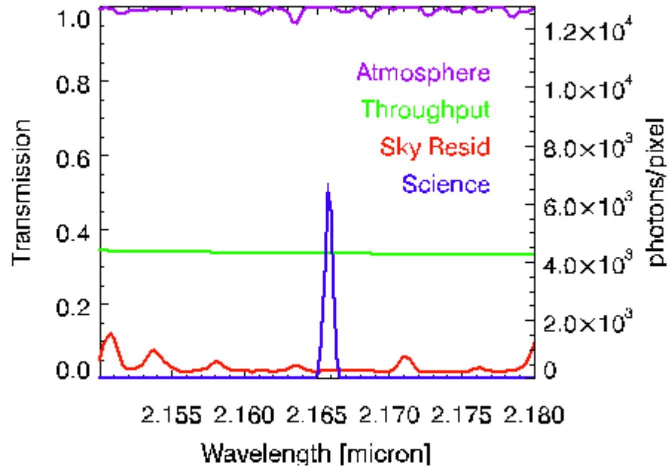

Figure 2.4 Example sensitivity of an H-alpha line found at z = 2.3.

In spectroscopy mode, a comparison of the sensitivity between IRMS (AO and non-AO modes) and MOSFIRE for J and K bands is presented in Figure 2.5. In these calculations, the total integration time is assumed to be 5 hours, with 0.16" slit width for IRMS and 0.7" for MOSFIRE. These curves reflect the AB magnitude of a flat spectrum and AO is assumed to be on-axis in AO mode.

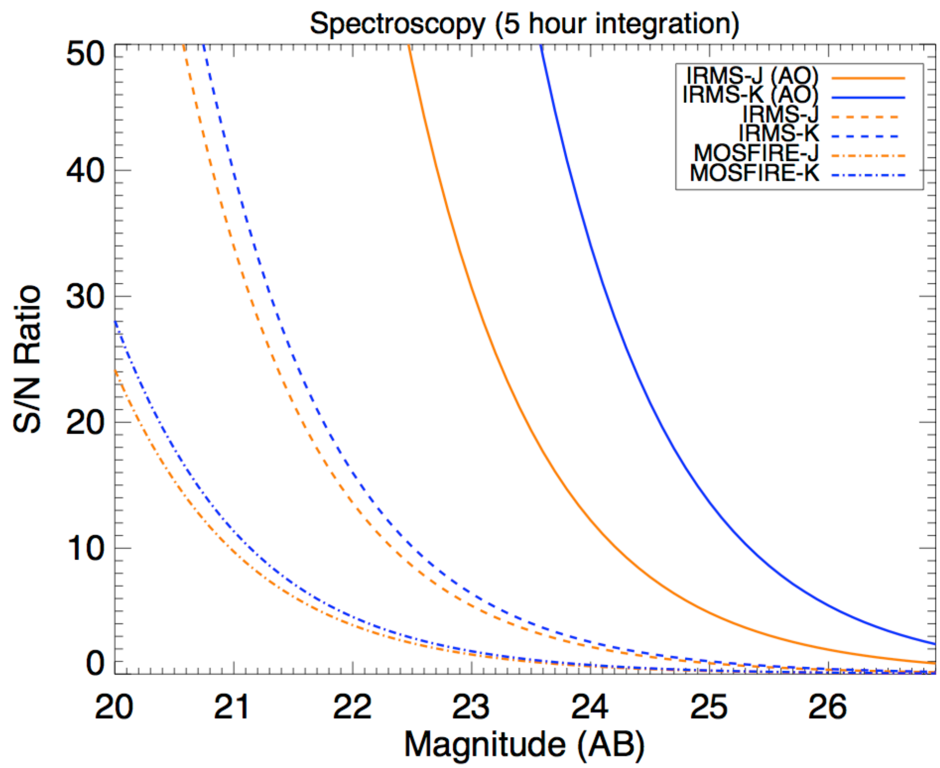

Figure 2.5 Sensitivity comparison for a 5-hour integration between IRMS (AO and non-AO modes) and MOSFIRE for J and K bands.

2.5. Comparison with MOSFIRE on Keck

MOSFIRE is a multi-slit near-infrared instrument designed for the f/15 Cassegrain focus on the Keck I telescope. It provides near-infrared (0.9 – 2.5 microns) multi-object spectroscopy over a

FoV of 6.1' x 6.1' in the YJHK bands. Like IRMS, it also uses a cryogenic slit mask unit with 46 deployable slits. Using a single Teledyne Hawaii 2RG HgCdTe detector with 2K x 2K pixels, MOSFIRE will capture most or all of an atmospheric window in a single exposure for any slit placed within a 6' x 3' field, and the instrument will employ a single, fixed diffraction grating used in multiple orders (3, 4, 5, and 6) for dispersion in the K, H, J and Y bands, respectively (see MOSFIRE website). The spectral resolution R = 3270 for 0.7" slit, and R = 4770 with 0.48" slits. MOSFIRE works in the seeing-limited regime without adaptive optics, and samples 0.18" in imaging mode.

Like MOSFIRE, IRMS can be configured as a long slit spectrograph or as an imager that would cover the entire NFIRAOS field of regard, albeit with spatial sampling of only 33-60 mas (roughly 2-4 times larger than the diffraction limit at 2 microns). It could also be used in a seeing-limited mode (for either imaging or spectroscopy) by flattening the deformable mirrors in NFIRAOS and turning off AO correction. While its FoV (2' x 2') is smaller than that of MOSFIRE (6' x 6'), its spatial sampling is one-third the size (0.06" versus 0.18"). The plate scale of IRMS is 0.45"/mm, 267 mm for 2' FoV, and 355 microns for 0.16" slits, while that for MOSFIRE is 1.38"/mm, 300 mm for 6.1' FoV, and 507 microns for 0.7" slit.

2.6 Synergy between JWST and TMT/IRMS

The combination of TMT and JWST will significantly change the landscape for ground and. space astronomy, the same way the Keck and. Hubble telescopes did. While NAFARIOS makes TMT a powerful imager with the ability for high spatial resolution in the 1-2 micron range, the JWST is unique in spectroscopy at lambda > 2 microns. One important feature of ground-based infrared spectroscopy/imaging is the contribution from sky background. Figure 2.6 shows the clear advantage of the JWST regarding the sky background and hence, sensitivity at longer wavelengths (>~2 microns). Another advantage of TMT/IRMS over JWST is a flexibility in ToO mode for transient targets. In the following, we list specific characteristics of JWST vs. the combination of TMT/IRMS:

JWST:
Ability to cover all sky
0.6-27 micron wavelength coverage
Stable diffraction limited at > 2.2 micron
Has high dynamic range
Low sky background at L2

TMT/IRMS:
Larger telescope with ~21 times larger light collecting area
A factor of 5 superior angular resolution
Superior R > 3000 at 1-2.2 micron
High spatial resolution capability
Upgradable
ToO mode for transient targets

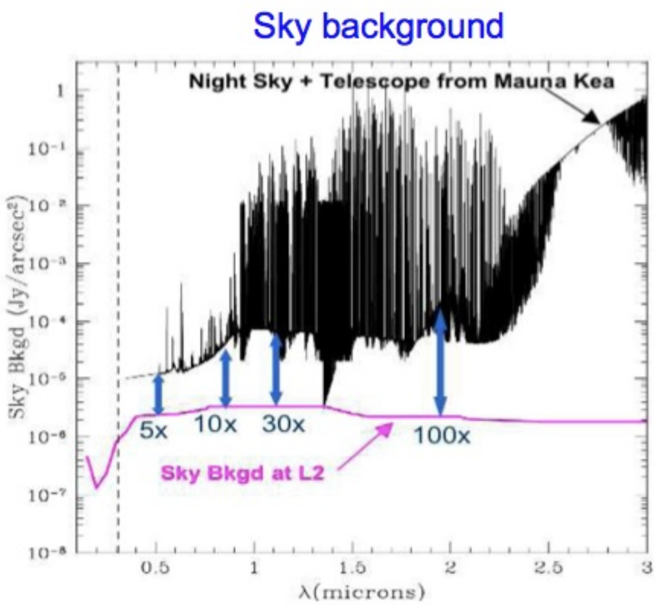

Figure 2.6 Comparison of the sky background between the site of TMT (Mauna Kea) and the L2 orbit where JWST would be located.

3. Science with the TMT/IRMS

3.1. Solar System and Planetary Astronomy

Over the last decade the science of planetary astronomy has been revolutionized, thanks to new dedicated missions within the solar system and extensive transient programs searching for extra-solar planets (exoplanets). Detailed study of the atmosphere and composition of the solar system planets have been performed by analyzing their soils and chemicals through robotic missions. Far from home, NASA missions (Kepler, TESS) and ground-based surveys will identify many thousands of transiting planets by the time of TMT's first light. In conjunction with these efforts, the field has seen considerable success in the use of multi-object spectrographs to probe the composition and thermal structure of exoplanet atmospheres. However, these are challenging observations. Since planets are faint, spectroscopic efforts are limited to planets exhibiting large transit depths and/or those with high infrared brightness temperatures. By measuring the number and abundance of terrestrial planets in or near the habitable zone of a wide variety of stars and by determining the properties of stars that harbor planetary systems, one could understand the formation and evolution of these systems and if they could harbor life. With large numbers of observationally-favorable systems known in the TMT era, IRMS will help move the field from the domain of bulk population statistics to detailed spectroscopic follow-up measurements of the composition, size, period, and host stars of individual planets.

(a). Characterizing Exoplanetary Atmospheres

The Outstanding Questions:

- What is the atmospheric composition of rocky exoplanets?
- What is the atmospheric composition of gas-dominated exoplanets?
- How did transiting exoplanets form and reach their current short-period orbits?

Present state of knowledge:

The study of exoplanets and their atmospheres places the origin, formation, and evolution of Earth and the Solar System in a broader context. The last several years have seen rapid strides in this direction through the study of transiting planets, which pass in front of and behind their host stars. The latest new frontier to emerge is the study of molecular chemistry in the atmospheres of the brightest nearby exoplanets, which is performed by looking at emission from the planet and/or at the transmission of starlight through the limb of the planet's atmosphere. Currently, there are tight constraints on the atmospheres of only a handful of planets. One successful approach has used broadband infrared photometry with *Spitzer* (e.g., Knutson et al. 2008; Stevenson et al. 2010), but significant atmospheric degeneracies remain even for those planets with the highest-quality photometry (e.g., Madhusudhan & Seager 2010). Spectroscopy offers a much more powerful method to constrain atmospheric structure and composition (e.g., Fortney et al. 2010; Madhusudhan et al. 2011), and to probe the planet's formation and evolution (e.g., Oberg et al. 2011; Lopez et al. 2012).

These studies have now been extended to probe the atmospheres of very small planets. A recent prime example is the 6.5 M_E with 2.4 R_E and GJ 1214b, (the first of many discovered ``super-Earths") whose properties lie between those of the Solar system's terrestrial and hydrogen-dominated planets. Ground-based, multi-object spectrographs have been instrumental in measuring the transmission spectrum of this family of planets (see Fig. 3.1).

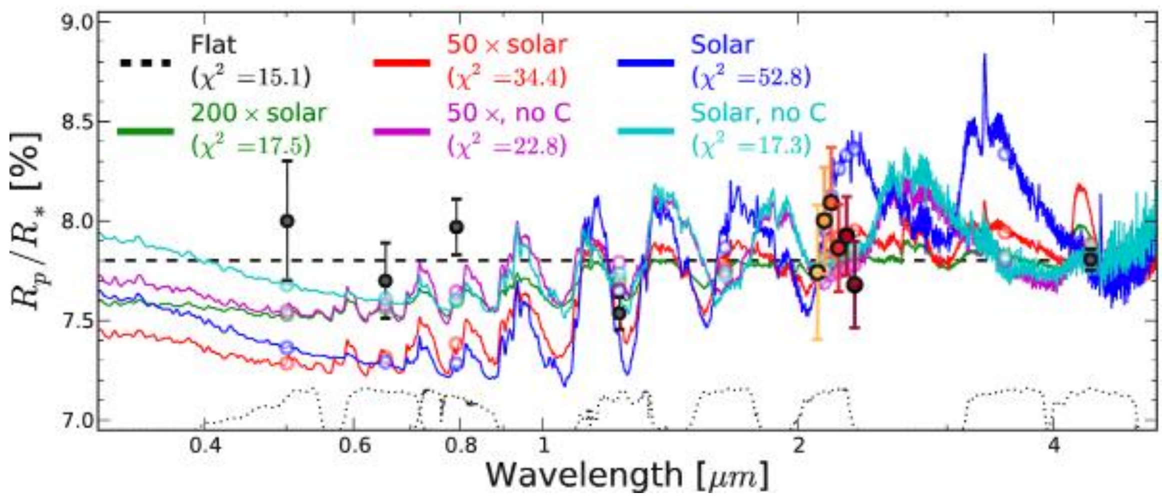

Figure 3.1 Transmission spectrum of the 700K "hot Neptune" GJ 3470b. Colored points with error bars are MOSFIRE measurements from Crossfield et al. (2013); black points are the measurements of Fukui et al. (2013) and Demory et al. (2013). The solid lines show the model transmission spectra described in Sect. 5. The ensemble of measurements rule out equilibrium-chemistry models with solar composition (blue) and 50× solar abundances (green) at 5.4σ and 3.8σ, respectively. A methane-depleted atmosphere (pink), a very highly enriched atmosphere (200× solar, light blue), and a simple flat spectrum suggestive of high-altitude haze (dashed) all remain plausible. These scenarios are discussed in Sect. 5. The dotted lines at bottom show the filter profiles (from Fukui et al. (2013), 2MASS, and Spitzer/IRAC) used to compute the band-integrated model points (shown as colored open circles).

These techniques are continuing to evolve, which enables the study of even smaller planets. For example, Figure 3.2 shows recent detection with MOSFIRE of a transiting planet smaller than the Earth (0.87 R_E; Crossfield et al., in prep). However, these latest data are rather noisy; thus detection of such planets are near the edge of the current state-of-the-art, and atmospheric characterization of such planets lies well beyond current capabilities.

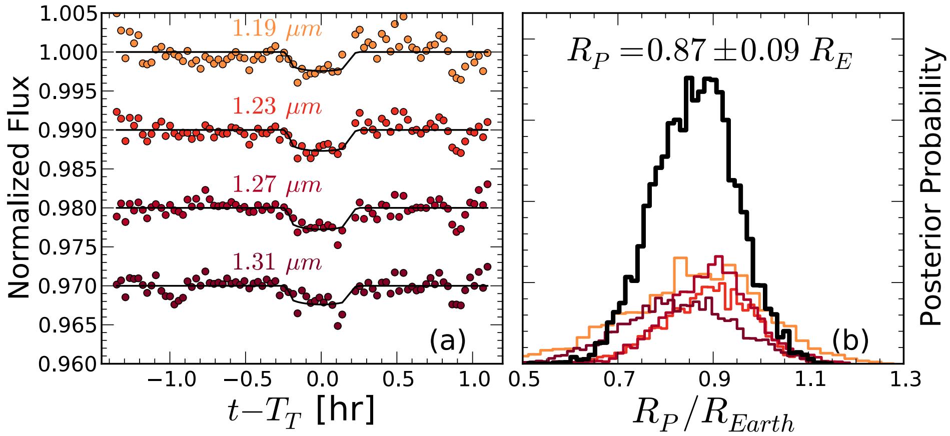

Figure 3.2 Current state-of-the-art transit observations with MOSFIRE, the direct predecessor to the IRMS. Transits of planets as small as 0.87 R_E can be detected around the most favorable stars, as shown by (a) the dip at t=0 in the spectrophotometric light curves and (b) the marginalized distributions of radii measured at each wavelength, which are all consistent with a sub-Earth-sized planet. By collecting more photons and incorporating ``lessons learned'' from MOSFIRE, IRMS will have increased sensitivity that enables it to study even smaller planets.

Need for TMT/IRMS

The IRMS will be the latest in a growing list of multi-object spectrographs that are used to perform high-precision characterization of transiting planet atmospheres, including MMIRS at Magellan (Bean et al. 2011), GMOS at Gemini (Gibson et al. 2012), and Keck/MOSFIRE (Crossfield et al. 2013). IRMS has two advantages over these earlier instruments: a tenfold increase in collecting area, and an instrument with a design appropriate to address the exoplanet science. For example, studies with MOSFIRE are already elucidating minor design changes that can be made to IRMS to enhance its exoplanetary science return (e.g., wedge-shaped optical filters instead of plane-parallel substrates; Crossfield et al. 2013). IRMS will be able to observe quite bright targets in seeing-limited mode: the collecting area per pixel is approximately the same as that of MOSFIRE, which has observed targets as bright as K=8.0 (Vega mag; see Fig. 3.1). New surveys for transiting planets anticipate finding hundreds of new Earth- and super-Earth-sized planets in the coming years (Irwin et al. 2009, Chazelas et al. 2012, Snellen et al. 2012, and NASA's recently-approved TESS mission), ensuring a wide array of new targets amenable to study with IRMS.

Technical requirements

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
   The spectroscopy case is stronger (multi-object is better, long-slit is also useful), but imaging (i.e., time series photometry) in a single bandpass will also be useful in some cases. Dithering is possibly useful for sky and fringing subtraction based on Subaru MOIRCS experience.

2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
   No AO is needed or desired.

3. What is the expected target source density over the FoV of the detector?
   One transiting exoplanet, and 1-2 reference stars whose brightness is comparable to that of the planet's host star.

4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
   We need exquisite precision, since we are making measurements at the 1e-4 (0.01%) level. But this is a relative measurement, so we only need stability, not uniformity. To compare target spectrum with comparison spectra and achieve 0.1% or better precision, we hope uniformity (or calibration capability) of the detector better than 0.1% accuracy.

5. What spectral resolution and wavelength coverage does the science require?
   The normal R~3000 mode is fine. Wavelength coverage should be a minimum of one band (Y,J,H,K) per shot, but ideally we would add the ability for multi-band observations (e.g., J+H+K at R~1000) as seen on Subaru/MOIRCS and Magellan/MMIRS.

6. What is the required spatial resolution?
   Seeing-limited only. But I like the small pixels, because they will let us observe even fairly bright exoplanet host stars. Spatial resolution is not as critical as large FoV.

7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)
   I would like to strongly advocate for an internal flat-field calibration system. With MOSFIRE's current dome-flat setup, nominal "flat field frames" exhibit telluric water absorption lines. If one's target spectrum shifts by >1 pixel between calibration and science observation, calibration with these dome-flats leads to spurious features in the spectra. Also, we should aim to provide a well-calibrated linearity correction as a function of pixel position & wavelength. For additional calibrations other than flats and darks, we request a calibration capability for non-linearity of detectors (possibly before installing on TMT).

8. Is the proposed observation affected by the slew time or the read out time?
   Yes: our targets are bright so we will be limited to short integrations. To minimize down time, we want the readout time (and other overheads) to be as low as possible. Here, doing as well as MOSFIRE should be our absolute minimum requirement.

9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
   No "depth" requirement in the usual sense, but over a 3-hour transit of a bright source we might take 500 or more 10-second exposures.

10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

As noted above targets even as bright as K=8 (Vega mag) should be observable with short integrations. Nonetheless saturation is possible for the brightest targets. It would be nice if we can allow observations with intentional instrument/telescope defocus, to spread light over more pixels and permitting more efficient observations of bright targets. Also, precise non-linearity calibration is important to use detectors efficiently.

Instrument Requirements

- Spectroscopy: R~3000 (allows observation of bright sources).
- Wavelengths: minimum of one band (Y,J,H,K) per shot. Goal: ability for multi-band (e.g., H+K or J+H+K, as seen on Subaru/MOIRCS and Magellan/MMIRS).
- Detector: Need fast readout modes (to allow observations of bright targets). Need well-calibrated linearity corrections on a per-pixel basis for each band.
- Optics: Designed to avoid the strong fringing seen at OH emission lines in wide-slit (10") MOSFIRE data. Designed to allow observations with intentional instrument/telescope defocus, spreading light over more pixels and permitting more efficient observations of bright targets.
- Goal: no more than 2 pixels of tilt in the projection of the slit onto the detector (e.g., as seen from sky emission lines).
- Field of View: 2.1' x 2.1' typically offers 1-2 simultaneous reference objects of comparable magnitude (e.g., GJ 1214).
- Calibration: Standard. Goal: internal flat-field calibration (telluric water lines are imprinted on MOSFIRE dome flats)
- Instrumental stability: No more than 1 pixel of drift in X or Y per 4-hour observation (MOSFIRE achieves ~3 pixels per 4 hours).
- NFIRAOS mode: No AO needed or desired.

(b). Kuiper Belt Objects

Placeholder: A science case regarding the finding and characterizing of new, ultra-faint KBOs? Check with the Solar System ISDT!

Observational Questions

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?
4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
5. What spectral resolution and wavelength coverage does the science require? W
6. What is the required spatial resolution?
7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)

8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

3.2. Stellar Astronomy

(a). Massive Stars and Young Star Clusters

Massive stars are powerful probes for studying a wide range of astrophysical processes, e.g., star formation and the chemical evolution of galaxies. Given their youth, they reflect the chemical abundances of the gas-phase material out of which they are formed. Unlike lower-mass stars, they are highly likely to be located near their birthplace (de Wit et al 2005). Therefore, they are ideal tracers of the Galaxy's gas-phase component and its metallicity. They are also relatively bright and can be seen at large distances in the Galaxy.

High mass stars are produced in lower proportion than low mass stars. The ratio d(logN)/d(log m), referred to as the Initial Mass Function (IMF) slope, is typically negative (G~-1.35 – the Salpeter value; Salpeter 1955). This apparent universal rule implies that a very large star formation event would be needed to produce the most massive stars. Such events are rare, and large volumes in space need to be probed in order to find even a handful of starburst clusters that could harbor at least a few of the most massive stars known. As an example, a Salpeter IMF predicts only a few stars with initial masses between 150 and 200 Msun for a cluster mass of $\sim 10^4$ Msun.

Massive stars make the greatest contribution to the enrichment of the Inter Stellar Medium (ISM), primarily when they collapse as type II Supernovae (SNe). Although the theory of stellar evolution is among the best studied topics in astrophysics, there are still a number of unknowns in the sequence. For example, it is not clear as what the initial mass range of a star should be in order to end up in a singularity or what is the fate of the red and blue supergiant stars resulting from intermediate and massive stars respectively. Detailed study of the life cycle of high mass stars and their association with the mass loss process (from AGBs) allows an understanding of dust formation process and enrichment of the ISM.

Outstanding Questions

- How universal is the Initial Mass Functions of star formation and does it change with time?
- What is the abundance distribution of elements in our Galaxy?
- How can we fill in the missing links in the life cycle of massive stars?

Present State of Knowledge

Massive stars collapse as SN when they run out of nuclear fuel. Theory predicts a certain relationship between the end-product and the mass of the progenitor star (Hegar et al 2003). Recent models show that high mass stars lose so much mass during their short life that they have insufficient mass (and gravity) to produce the expected singularity. In this scenario, the black holes can only be formed by stars within a relatively narrow mass range (for example, between 20 Msun and 40 Msun and around 80 Msun for solar metallicity- Woosley et al 2002). By estimating cluster age, one can determine the maximum mass of a star which has recently exploded as a SN and provide a lower limit to the progenitors initial mass (Figure 3.3), directly testing models that relate progenitor mass to the equation of state of the end product.

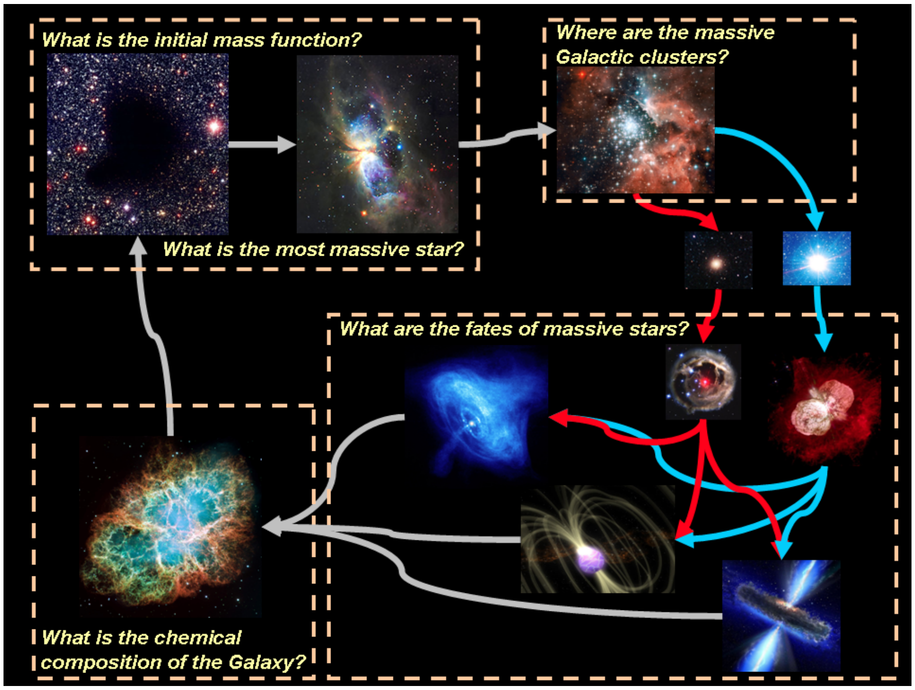

Figure 3.3. Star clusters and life cycle of massive stars. The fundamental questions to be addressed by TMT/IRMS observations are in yellow text. Note the uncertainty between the progenitor mass and the end state, as indicated by overlapping lines connecting neutron stars and black holes to intermediate mass stars that become red supergiants (red lines) and more massive stars that become blue supergiants (blue lines). It is not clear which of these lines are accurate.

Understanding the chemical evolution of the Milky Way is fundamental in our quest for uncovering the history of our Galaxy and other spiral galaxies. While previous observational studies measured abundances along the disk of galaxies towards their center (Smartt et al 2001; Daflon et al 2004), recent studies indicate azimuthal abundance gradients in the inner Galaxy (Davies et al 2009- Fig 3.4). High mass stars within massive clusters are ideal tracers of Galaxy's gas-phase component associated with various physical structures. For example, the ratio of alpha elements to iron is a reliable measure of star formation rate in galaxies. While the dominant source of enrichment in the ISM is through type II SNe (core collapse of massive stars), Fe-peak elements are resulted from Type Ia SNe (thermonuclear explosion of low mass stars). Therefore alpha-elements are enriched on short time scales (~Myr) while Fe-peak abundances are increased over much longer time scales (~Gyr). The observed abundance gradients in disk systems (both in the galacto-centric and azimuthal directions) is attributed to changes in their star formation rate (Luke et al 2006). Ultimately, a global knowledge of the Galaxy's 2-D chemical abundance pattern is needed to better constrain evolutionary models of disk galaxies.

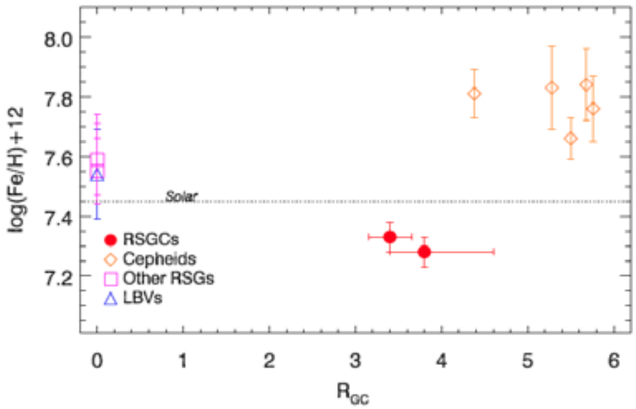

Figure 3.4. The trend of Fe/H abundance in the inner 6kpc of the Galaxy (Davies et al 2009).

One of the parameters needed in any study of the evolution of galaxies is the shape of their IMF, its higher mass limit, and the universality of both. The IMF slopes measured so far, appear to be close to the Salpeter value (eg. Kroupa 2002- Fig 3.5) while, there has been evidence for a different IMF in other clusters (Kim et al 2006) and claims for a very flat IMF in clusters of massive young stars in the central parsec of the Galaxy- Figure 3.3- (although this claim requires the present-day mass function not to have been affected by dynamical evolution in the presence of supermassive black holes).

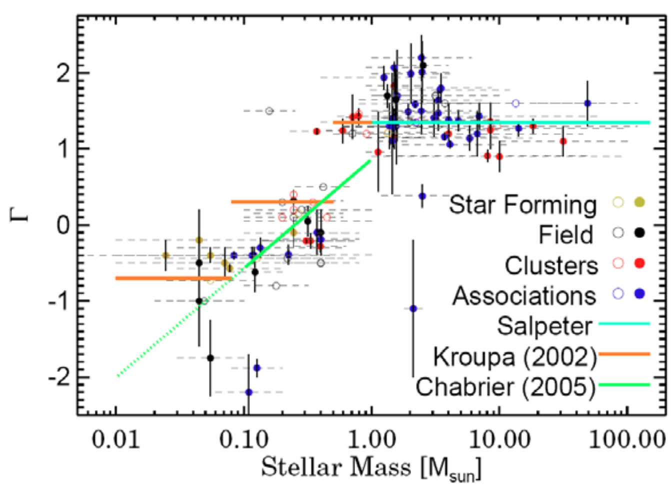

Figure 3.5 Estimates of the IMF slopes as a function of mass (Bastian et al 2010). The relative lack of values at the high mass end is evident.

Determination of the IMF requires: (1). identification of targets (i.e. star cluster) which contain coeval stars; (2). The star clusters should be close enough for their members to be resolved; (3). To estimate the high mass end of the IMF (~150 Msun), the clusters should be massive (~10^4 Msun). Such stars do not live for long and must be observed when they are young (but not so young that they would still have traces from their gas-phase cloud). This needs stellar samples at larger distances and for massive stars.

The Need for TMT/IRMS

Measurement of the IMF requires high spatial resolution imaging and spectroscopy of stars in young clusters. These are typically located within the Galactic disks and hence, this must be done in the infrared wavelengths. Furthermore, to test the universality of the IMF, one needs to measure them in clusters at larger distances.

The Combination of the TMT and IRMS provides highly efficient near-infrared spectroscopy with high spatial resolution (using the AO capability of the IRMS) allowing measurement of the radial velocity of the star clusters and their kinematic distances. From the spectroscopy of the stars, one could measure their age, using stellar evolutionary models. This, combined with the mass of the stars measured from their infrared luminosity function provides a measure of the IMF slope and its upper mass limit.

Using a statistically significant sample of massive stars in young stellar clusters, one could probe the chemical abundance in the ISM. This requires multi-object spectroscopy of stars and star clusters adequately sampling the Galactic Plane. Due to the high line-of-sight extinction, such surveys need to be performed at near-infrared wavelengths. The infrared spectra will then be fitted by model atmosphere predictions to measure the chemical abundance. The result is 2-D maps of the distribution of the chemical abundance in the Galaxy.

IRMS on TMT would be a powerful tool for discovering new massive clusters in the Galaxy. Such a combination would easily verify the presence of massive stars in clusters within ~8kpc down to a mass of 10 Msun with only a few minutes of exposure time. This would identify and characterize the stellar content, metallicity, age and mass of the identified massive star clusters in the Galaxy.

Observational Questions *PLACEHOLDER*

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?
4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
5. What spectral resolution and wavelength coverage does the science require?
6. What is the required spatial resolution?
7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)
8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

Instrument Requirements

- Spectroscopy: R ~ 3000, 4000
- Wavelengths Coverage: 1.6-2.5 micron to measure FeII lines in H and K bands
- FoV: 2.1' x 2.1' with ~20 galaxies within the field
- Photometric Calibration: needs calibration to 5% accuracy to measure metallicities and age diagnostics
- NFIRAOS mode: needs high spatial resolution observations with multiplexing facility
- Dither mode: need dithering to have a good measure of the sky background
- Given the small FoV, correction for sky background (which is important at infrared wavelengths) reduces

(b). Brown Dwarfs

Placeholder for the BD science case (answers from A. Burgasser – detailed case to be followed up) :

Observational Questions

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
   Both; imaging is an key precursor for verifying targets for spectroscopy that may have moved (large distance stuff is not an issue, but nearby solar neighborhood has yearly proper motions equivalent to slit width). Also key for flux calibration of targets (absolute spectrophotometry and variability).

2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
   Given the factor of 2.5 increase in distance/16 increase in volume, yes. It is also key for studying resolved spectra of close binaries.

3. What is the expected target source density over the FoV of the detector?
   Targeting nearby cool dwarfs means one (or two if binary) targets in FOV; targeting planetary mass objects in young clusters can get to hundreds (so possibly multiple slit configurations).

4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
   Since this is not wide field camera of TMT, probably not mission critical.

5. What spectral resolution and wavelength coverage does the science require?
   R ~ 3000 is good (perhaps high) for classification, spectral line/band analysis, and space kinematics. It would be nice to broach 6000 for resolved binary orbits. there is also a case for low resolution - R ~ 100-300? - to hit really faint late T and Y dwarfs; is there a low

resolution spectrograph planned for TMT. This of course depends on how you're planning the set up. If in cross-dispersion, slipping in a mirror would be a wonderful add-on.

Resolution	*Science*
6000	*RV variability, resolved binary/planet orbits, abundance analysis*
3000	*spatial kinematics (e.g., cluster members), line/band analysis (physical properties),* *"low-res" spectral modeling*
100-300	*classification/identification of deep targets (free-floating planets in young clusters,* *T < 300 K in Solar Neighborhood, halo substellar subdwarfs)*

6. What is the required spatial resolution?
   For deep pointings, we can get by with native telescope resolution (~0."1); for AO it would be great to subsample the AO PSF, so 0"01.

7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)
   Reasonably precise wavelength calibration. Someway to observe brighter standards for transmission calibration (neutral density filter?).

8. Is the proposed observation affected by the slew time or the read out time?
   No.

9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
   Deeper is better.

10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?
    This is going to be a major problem for calibration; faint A stars are highly reddened and not as useful (although maybe we can move on to using DB stars).

(c). Galactic Center and Globular Clusters

Placeholder for <u>M. Rich</u>

Bulge of M31; kinematics and abundances

Problem: R~4000 is low; very hard to get [Fe/H] without J band (which has poor correction) and would want higher resolution for OH lines in H band.

Calibrating the subdwarf content of the halo using globular clusters

Idea is to obtain YJHK spectra of faintest hydrogen burning stars, brown dwarf candidates, in globualr clusters and NGC 6791 (old metal rich open cluster). Measure indices and attempt to calibrate halo field dwarf metallicities. This problem may have been addressed before First light though..

Galactic Center: Problem- R~4000; where is science?

There may be interesting science in exploring the kinematics and abundances of clump and MS turnoff stars in hte Galactic Center cluster. The ability to explore larger spatial scales may indeed help here.

IMBH in globular cluster cores: While primarily an IRIS problem one wants to sample kinematics covering a range in radius. Could complement IRIS studies. May also be useful (if throughput enough) to probe velocity dispersions of extragalactic globular clusters; substructure in cluster systems. Prefer R~9000

Observational Questions *PLACEHOLDER*

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?
4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
5. What spectral resolution and wavelength coverage does the science require?
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8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

3.3. Active Galactic Nuclei (AGN)

It is now known that there are tight correlations between the properties of supermassive black holes (SMBHs) and their host galaxies (e.g. mass, luminosities, velocity dispersion); what remains as an active area of research is how and when this relation was established – how galaxies and their SMBHs co-evolve, and whether SMBHs or galaxies formed first at very high redshifts. The evolution of X-ray AGN and luminous quasars space density is likely to have peaked around z~1-3 (Hasinger et al 2005, Ueda et al. 2014), the peak epoch of star formation and BH accretion activity. Luminous quasars have been found up to z~7 (Mortlock et al. 2011), and they are associated with SMBHs as large as 10^9 M_{Sun}. These appear to be indistinguishable from luminous quasars at moderate redshifts (z~2-3), suggesting that these systems were fully developed only 0.8 billion years after the Big Bang. A comprehensive study of the AGN is essential, because 1. the number density of AGN at high redshifts reveals sources responsible for the re-ionization of the universe; 2. they play major roles in the feedback process which regulates amount of gas (and hence, star formation) in massive galaxies; their very existence at the core of most galaxies makes them an essential component of any theory for formation of normal galaxies.

(a). Co-evolution of BHs and Galaxies

Outstanding Questions

When did the current relation between BH and bulge mass get established, and how does it evolve with redshift?
Are the earliest QSOs in place before their host galaxies?
How do Black Holes evolve dynamically?
How do gas inflows into the BHs affect their growth?

The Present State of the Knowledge

It has been shown that the mass of SMBHs and their host spheroids are strongly correlated (M_{BH}-sigma relation; Gultekin et al. 2009). A study of the origin of the scaling relations and their evolution with cosmic time has indicated a scenario in which BH growth may precede bulge assembly. For example, there is observational evidence that the relation between the black hole mass (M_{BH}) and total host galaxy luminosity and stellar mass may not be evolving as rapidly as the relations between the M_{BH} and spheroid mass [REFERENCE]. Such a study has been performed to z~2 (look-back time 8-10 Gyrs) finding $M_{BH}/M_{Sph} \sim (1+z)^{1.96 +/- 0.55}$ and $M_{BH}/M_{host} \sim (1+z)^{1.15+/-0.15}$ (Figure 3.6). This is consistent with the hypothesis that black holes predate formation of their host galaxies. Currently no spectroscopic data exist beyond z~2 to test this relation at the galaxy formation epoch.

Feedback process from the AGN activity is thought to be important to shaping the MBH-sigma relation and stopping the formation of very massive galaxies in the local universe (Bower et al. 2006). It is necessary to reveal in which phase of galaxy evolution AGN activity occurs. Ultra deep X-ray observations revealed that at least one third of massive galaxies at z~2-4 show Seyfert-like moderately luminous AGN activity (Yamada et al. 2009). Even larger fraction of galaxies can be associated with AGN activity, because Compton-thick AGNs, which are heavily obscured by dust and gas, can be missed even in the deepest X-ray surveys. It is possible Compton-thick AGNs outnumber less-obscured AGNs identified in the X-ray surveys (Ueda et al. 2014).

The Need for TMT/IRMS

High-resolution infrared spectroscopy with TMT/IRMS will help to extend the M_{BH}-sigma relation to higher redshifts. Since these objects are likely more clustered than their counterparts at lower redshifts, one could use the multiplexing facility of the IRMS efficiently at high-z. Although it is unlikely there would be more than one QSO per field-of-view of IRMS, if the QSOs were situated in clusters, we can then explore the environmental effects on these early QSOs for AGN and starburst-hosting galaxies. BH masses are estimated via IRMS spectroscopy by combining the FWHM of broad MgII 2798 A line and the 3000 A continuum flux from AGN (McGill et al 2008) up to $z \sim 7$-8, and by using CIII or CIV for $z > 10$. Thus, with TMT/IRMS, we should be able to reach well into the re-ionization epoch, and study the basic properties of the QSOs responsible for re-ionization.

Heavily-obscured AGN activity can be identified with high-ionization emission line seen in rest-frame optical and UV spectra of galaxies (Zakamska et al. 2003). One major problem in studying heavily-obscured AGNs is the lack of rest-frame optical spectra, which is important to identify the origin of emission lines seen in high-redshift galaxies through diagnostic diagram. The TMT/IRMS combination will be used to obtain near-IR spectra of statistical sample of galaxies at high redshifts (up to $z < 4$). This includes detection of [OIII] 5007 line, a tracer of AGN bolometric luminosity, allowing a study of the [OIII] 5007 luminosity function of AGN and hence, measurement of the distribution of accretion rates and Eddington ratio. This also allows studies of the relation between global properties of the host galaxy (i.e. SFR, morphology, environment) and the accretion rate and outflow properties.

Study of the large halo mass of high-z quasars requires measurement of Lyman alpha absorption line signatures of gas infall into these massive black holes (Broom & Loeb 2003). At high redshifts ($z > 7$-10), such observations need high- resolution near-infrared spectroscopy with the largest telescopes. An ultra-deep near-infrared spectroscopic survey of QSO candidates at high redshifts is needed to measure their redshifts, continuum and the MgII line strengths. This allows study of the evolution of line-to-continuum ratio with redshift. This also provides an unbiased sample of high-z QSOs for study of clustering of these sources.

Observational Questions

Placeholder for <u>M. Akiyama</u> (?)

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?

4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
5. What spectral resolution and wavelength coverage does the science require? W
6. What is the required spatial resolution?
7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)
8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

Instrument Requirements

- Spectroscopy: R ~ 3000-4000 (between OH atmospheric features)
- Wavelengths Coverage: 0.9-2.5 micron to detect diagnostic lines of CIII, CIV, MgII 2798, [OIII]5007, Halpha and Hbeta
- F.o.V: 2.1' x 2.1' with ~10 galaxies within the field (or 1 QSO in cluster environment with other AGN and starburst galaxies)
- Photometric Calibration: needs calibration to 10% accuracy to measure Halpha, Hbeta, [OIII]5007, CIII, and CIV line intensities and subtract the stellar continuum emission from the host galaxies. Subtraction is important to accurately measure Balmer line intensities by removing the effect of stellar absorption lines.
- NFIRAOS mode: need constant AO correction in the FoV to achieve high sensitivity spectroscopy of extended galaxies and detect AGN signature seen at their nuclei.
- Multiplexing facility of the IRMS will be used to construct a statistically significant sample of galaxies (AGN and starburst galaxies around QSOs) with different properties (SFR, inclination, mass etc).

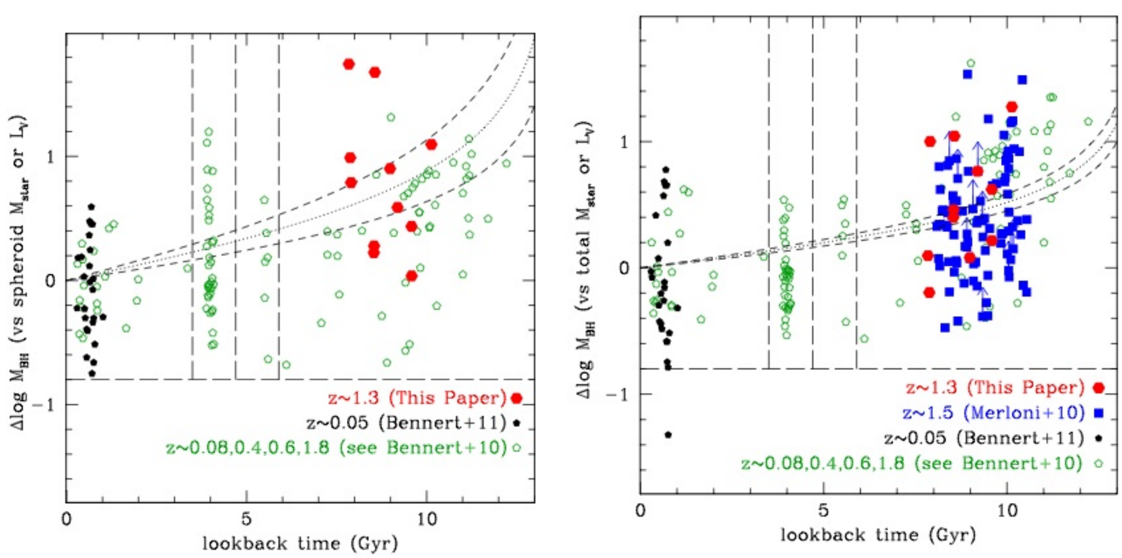

Fig 3.6. Left panel: offset in log (M_{BH}) as a function of constant M_{Sph}. The best linear fit is plotted as a dotted line corresponding to $M_{BH}/M_{Sph} \sim (1+z)^{1.96 +/- 0.55}$. Right panel: offset in log(M_{BH}) as a function of constant total host galaxy mass. The lines correspond to $M_{BH}/M_{host} \sim (1+z)^{1.15+/-0.15}$.

3.4 Inter-Galactic Medium (IGM)

The process of galaxy evolution is mainly driven by gas accretion, subsequent star formation and gas loss caused by winds from supernovae explosions. Therefore, a detailed study of this requires knowledge of the interface between the Inter-Galactic Medium (IGM) and galaxies. This requires mapping the gas distribution around star-forming galaxies to understand the exchange of baryons between the sites of galaxy formation and the intergalactic medium (the feedback process). Such study has been performed by studying the outflow/infall process in galaxies. Furthermore, using spectroscopic observations of galaxies within a few arcmins of QSO sightlines, one could measure the absorption features in the spectra of QSOs produced by the ISM in the foreground galaxies and hence, study of the physics of the ISM. This is required for a detailed understanding of the process of galaxy formation, the IGM and Circum Galactic Medium (CGM) interaction and measurement of the relative distribution of gas and dark matter around galaxies at different redshifts.

(a). Interaction of IGM with Galaxies at High-z

Outstanding Questions

How does the infall/outflow in galaxies affect their evolution and their star formation activity?
How do the Inter-Galactic Medium (IGM) and the Inter-Stellar Medium (ISM) in galaxies influence one another?
What governs the star formation activity in galaxies and how is it quenched?

The Present State of Knowledge

An essential feature of mass assembly and galaxy formation and mass assembly at high redshifts is gas inflow to galaxies. An equally important process is the feedback in which, outflow of material from galaxies transfers mass and metals to the IGM and regulates the star formation activity in galaxies by reducing their gas content. These have been measured by the spectroscopy of nebular emission lines in galaxies, quantifying non-virial motions associated with the inflow/outflow of gas.

Using a sample of star-forming galaxies at $z\sim2$-3, with optical spectroscopy from LRIS-R, it was found that the gas-phase kinematics in galaxies are closely related to their rest-frame morphology. Compact galaxies with $r < 2$ kpc are more likely than their larger counterparts to have Ly alpha in emission (Law et al 2012; Figure 3.7). Galaxies of all types drive strong outflows with the outflows from larger galaxies are less ionized and exhibit larger optical depths, corresponding to decreased efficiency in feedback to drive gas out of galaxies.

Measuring the distribution, dynamics and absorption line widths of neutral hydrogen clouds surrounding the star forming galaxies, Rudie et al (2011) studied the Circum Galactic Medium (CGM)- the interface between the interstellar medium (ISM) in galaxies and the IGM- of luminous galaxies in the range $2.0 < z < 2.8$. It was shown that most of the high column density IGM is located close to regions surrounding luminous galaxies with the majority of the excess within +/- 300 km/s. (Figure 3.8). This is the scale over which the baryonic physics of galaxy formation affect the physical state of the gas (Rudie et al (2011)).

Recently, these studies are extended to a larger population of galaxies in the range 1.5< z < 3.5 in the CANDELS fields (the MOSDEF project- Shapley et al 2013). This uses Keck/MOSFIRE combination performing near-IR spectroscopy of galaxies to measure nebular emission and absorption line features.

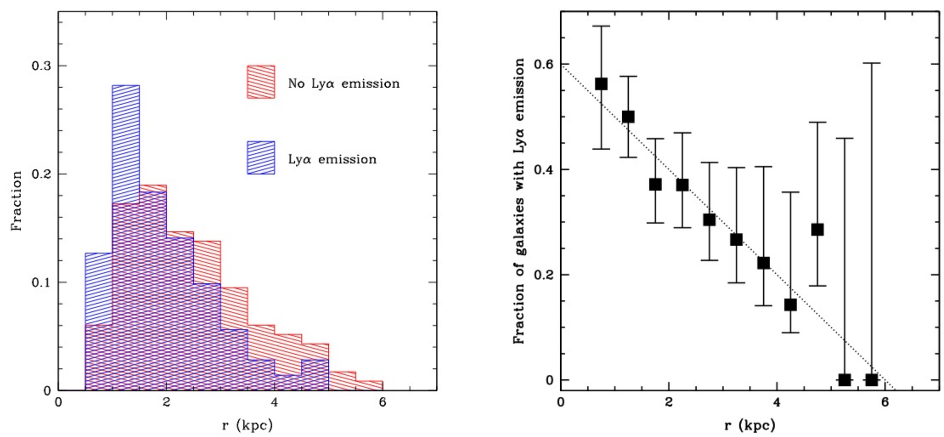

Figure 3.7. Left Panel: Distribution of semi-major radii of galaxies with/without Lyman alpha emission. The spectra are based on LRIS observations. The fraction is with respect to the total number of galaxies with and without Lyman alpha emission. Right panel: fraction of galaxies in radial bins which show lyman alpha emission. Dashed line is the least squares fit. The possibility of a zero slope fit is excluded (Figure is taken from Law et al 2012).

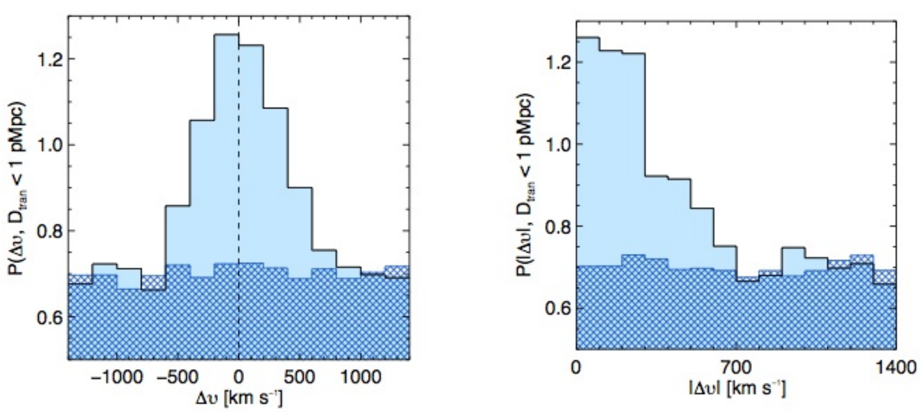

Figure 3.8. The velocity distribution for HI absorption line systems with respect to systemic velocity of galaxies, normalized by the number of galaxies in the sample. Absorbers are selected to be within < 1 Mpc of the sightline from the QSO and have log(NHI) > 1013. The solid histogram represents the distribution of HI around galaxies, whereas the hatched histogram is the average absorber density near randomly chosen redshifts in the sample used for this study (The figure is taken from Roudie et al 2011).

Need for TMT/IRMS

A detailed understanding of the physical properties of gas surrounding star-forming galaxies requires analysis of metal absorption features in their spectra and measurement of the velocity zero-point indicative of the speed of outflowing (blueshifted) or inflowing (redshifted) gas. In order to measure these, the spectra need to cover rest-frame UV (Ly a) and optical (Hbeta, [OIII]5007 and Halpha) emission lines. At $1 < z < 3.5$, these lines shift to near-IR bands, requiring infrared spectroscopy to measure their strength and relative offset. The combination of TMT and IRMS allows measurement of the extent of the inflow and outflow material from galaxies. Furthermore, the increased spatial resolution as offered by the AO capability of IRMS will allow us to separate out the spatial location of different kinematic components. The achievable spectral resolution (R ~ 3300 – 3600) will also allow measurement of the velocity gradient along the gas and the transition in the outflow/infall velocity in the intersection between CGM and IGM in galaxies. These absorption lines will measure the ionization state and metallicity of the gas and constrain the total mass in hydrogen and metals around star-forming galaxies. A correlation between these and global properties of galaxies (SFR, SFR density, size, morphology) would strongly constrain formation of galaxies and the feedback process at z=1-3.5. The multiplexing property of the IRMS allows measurement of these features for statistically large number of galaxies, allowing an extension of this study to higher redshifts and fainter galaxies by 2-3 magnitudes in depth. The very faint end of the luminosity function can be probed for the first time. This allows study of the evolution of the absorbers properties with cosmic time and will constrain the inflows/outflows from galaxies and hence, parameters responsible for the star formation and mass build-up in galaxies.

Observational Questions *PLACEHOLDER*

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?
4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
5. What spectral resolution and wavelength coverage does the science require?
6. What is the required spatial resolution?
7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)
8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

Instrument Requirements

- Spectroscopy: R ~ 3000, 4000 (between OH atmospheric features)

- Wavelengths Coverage: 0.9-2.5 micron to detect emission and absorption lines for rest-frame UV and optical wavelengths at $1 < z < 3.5$.
- FoV: 2.1' x 2.1' with ~35 galaxies within the field
- Photometric Calibration: needs calibration to 10% accuracy to measure Lyman alpha, Halpha, Hbeta and [OIII]5007 line intensities
- NFIRAOS mode: need high resolution spectra of very faint (~28 mag) sources to measure inflow/outflow velocities along the material
- Dither mode: need to follow a dithering strategy along the PA of the gas outfall/infall
- Multiplexing facility of the IRMS will be used to construct a statistically significant sample, extending the relation to fainter galaxies and objects with different properties (SFR, inclination, mass etc.).

3.5 High Redshift Universe

Today, using powerful telescopes we have been able to take images of the Universe when it was 0.4 million years old (in the form of cosmic microwave background) and images of individual galaxies when the Universe when the universe was 0.5 billion years old. There is a time between these two epochs (around 600 million years) when the Universe was dark and the stars and galaxies had not yet been formed. This is the so-called "Dark Ages", starting at recombination epoch around z~1100 during which the matter in the Universe evolved into the structures (stars and galaxies) we see today. During this time the universe was dominated by dense clouds of neutral hydrogen which absorbed and forbid escape of the radiation. This continued until the first generation of stars and galaxies were formed at z~10 (when the universe was 0.5 billion years old) and re-ionized the Inter-Galactic Medium (IGM), making the universe transparent. Present constraints from WMAP indicate that the dark ages ended around z~7-15. Figure 3.9 shows the history of our universe from dark ages to the re-ionization and formation of small scale structures (stars and galaxies)- (Robertson et al 2010, Nature 468, 49). One of the challenges in modern observational cosmology is to study the "Cosmic Dawn", the universe at the time of the re-ionization and formation of the first generation of stars and galaxies. The combination of TMT and IRMS is needed to (1). Identify the sources of re-ionization; (2). Understand the re-ionization process; (3). Study the nature of the sources responsible for re-ionization

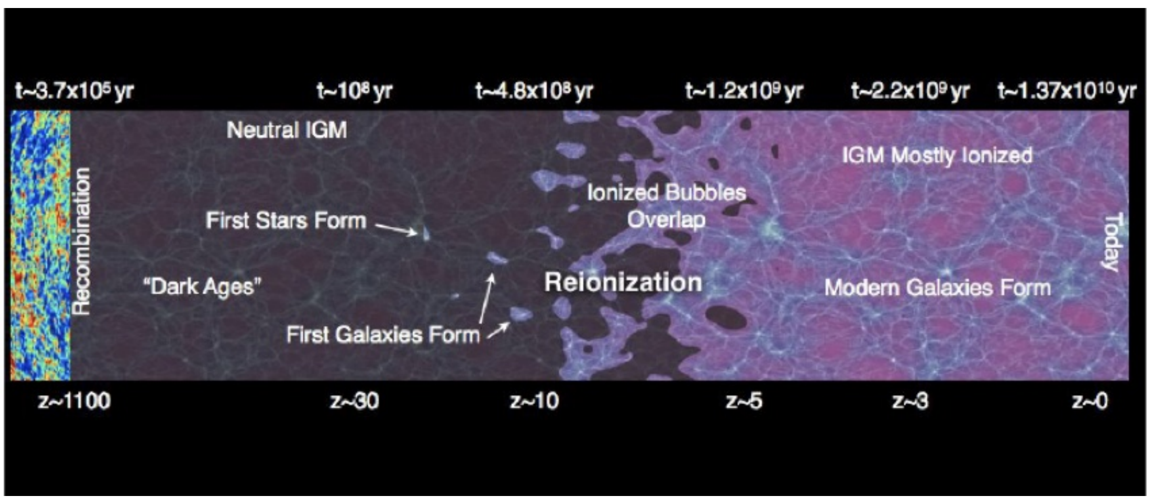

Figure 3.9. A schematic view of the evolution of the universe and the Inter Galactic Medium (IGM) from the recombination era (z~1100) and dark ages (z > 7) to the formation of the first generation of stars and galaxies and re-ionization (z~7).

(a). POPULATION III STARS

The Outstanding Questions:

- When did the first generation (population III) stars first form, and what were their observational signatures?
- How rapidly did they change to pop II stars and were they responsible for formation of primordial black holes?

Present State of Knowledge

The Cosmic Dark Ages was ended by formation of the first generation of stars- Population III stars. These stars also influenced the formation of subsequent generations of stars and therefore they played an important role in the assembly of the earliest galaxies. Finding and understanding how the first stars formed and took part in the re-ionization of the Universe, is a fundamental goal of modern observational cosmology.

To form the first generation of stars from primordial gas, the gravitational pull of luminous and dark matter must overcome the turbulent energy of the infalling gas (shocks) and the radiation pressure of the newly formed stars. Cooling of the gas is critical, but the most common cooling agents studied at $z < 8$ (UV, optical and IR atomic emission lines of metals) are not available in this pristine gas. The absence of such cooling agents restricts fragmentation to large clouds (around 100,000 times the mass of the Sun), where gravity could overcome pressure. Since the primordial gas lacks heavy elements (e.g., carbon, nitrogen and oxygen) the first stars accrete a great deal of material before nuclear burning commences, hence they tend to be extremely massive. These massive stars produce abundant high energy UV photons (shorter wavelengths than 228 A) produced by these massive stars, able to excite singly ionized helium (He+) and produce HeII1640 line. Since there are no metals, the gas cools via H, He and H2 emission lines. Subsequently, Lyman alpha 1216A and HeII1640 A lines are produced (Fig 3.10). This is one signature of population III stars (Tumlinson et al 2001; Schaerer 2003; Raiter et al 2010). As a result, POP III stars are pristine systems (zero metallicity only containing H and He), are very compact and massive (30-300 M_{Sun}), very hot and luminous (106 K; source of UV radiation) and short-lived (~3 Myrs). Because of their short life-time, they are very rare and hard to find.

It is expected that the primordial gas that gave rise to the Pop III stars was exhausted very rapidly (2-3 Myrs). The death of these first massive stars should have also produced supernovae and stellar BHs, and polluted the ISM with metals enabling subsequent generations of less massive stars to form. These low-metallicity stars are long-lived and could, in principle, be found in the halos of the Milky Way or other nearby galaxies. Current simulations indicate that the first stars formed within halos containing 10^5 M_{sun}, with the stars tens to hundreds of solar masses each, forming around 30 million years after the Big Bang.

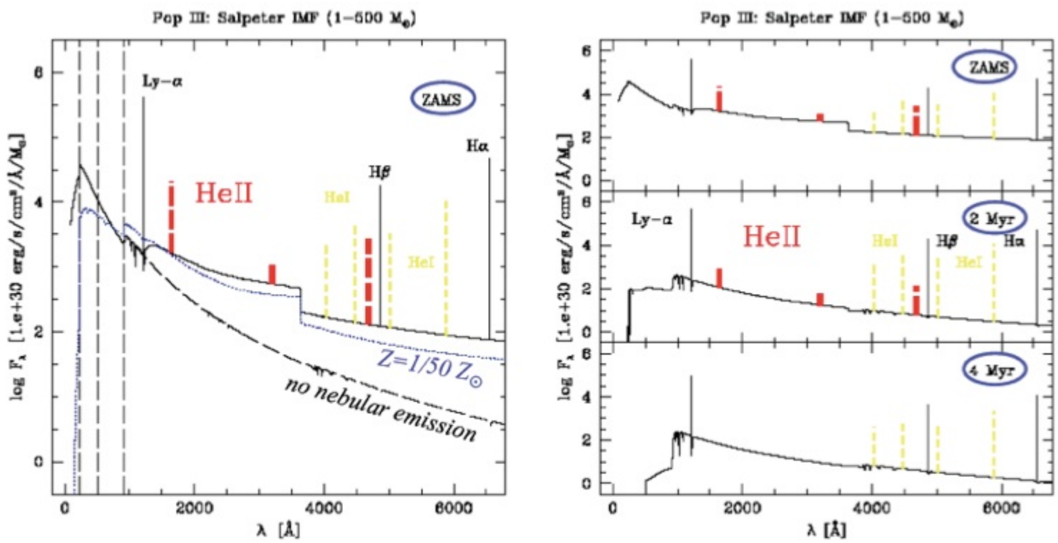

Figure 3.10. Nebular HeII emission at 1640 is considered as a sign of POP III stars. However, it is very short-lived (~3 Myrs). Lyman alpha lines are too weak due to IGM. Figure taken from Schaerer (2002).

Need for TMT/IRMS

Since the metallicity of galaxies decreases with increasing redshift, searches for the signatures of Pop III stars should focus on detecting HeII 1640 lines in the spectrum of galaxies at the re-ionization epoch (z~7-10). At these redshifts HeII 1640 lines shift to the near-IR (HK) bands. This requires high resolution infrared spectroscopy of the faintest galaxies. The target galaxies are often drop-outs and hence, lack detection in all the optical wavelengths and are m_{AB} ~ 30-31 mag faint. Although highly uncertain, the space density of galaxies dominated by Pop III stars at $7 < z < 8$ is predicted to be about 3-100 per sq. arcmin (Figure 3.11). This corresponds to 25 sources per field-of-view of IRMS.

Furthermore, to resolve these lines one needs AO capability. The combination of the TMT with IRMS+NFARIOS is the ideal way to detect and study these lines. As the HeII 1640 lines are faint and close to the sky background, one needs to perform a dither strategy to accurately estimate the sky background and to increase the S/N ratios.

The search for HeII lines become more challenging by the fact that these are short-lived (age of 4 Myrs; Figure 3.10) and are also produced by Wolf-Rayet stars, AGN and supernovae driven winds. Other diagnostic lines, such as CIII and CIV can be used to separate the contribution from these objects to the Lya+HeII lines (Leitherer et al 1996). The POP III stars could also be evolved into low-metallicty stars in the halo of nearby galaxies (including the Milky Way). Detection of these objects requires deep imaging surveys, followed up with spectroscopy to measure their metallicity. Such objects are expected to be faint, ~26 mag, requiring TMT/IRMS combination for detection of the halo stars and identification of the diagnostic lines in their spectra.

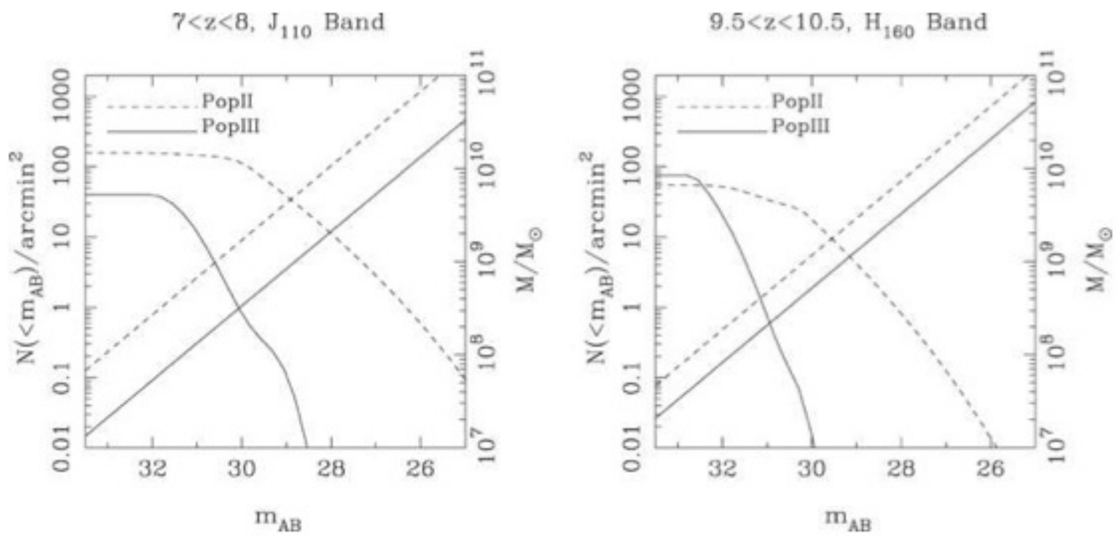

Figure 3.11. Predicted number density (cumulative) of POP II and POP III dominated sources at z~7.5 (left panel) and z~10 (right panel). (Figure is taken from Choudhury & Ferrara (2007)).

Observational Questions *PLACEHOLDER*

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?
4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
5. What spectral resolution and wavelength coverage does the science require?
6. What is the required spatial resolution?
7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)
8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

Instrument Requirements

- Spectroscopy: R ~ 4000 (between OH atmospheric features)
- Imaging: YJHK filters to detect stars in the halo of our galaxy
- Wavelengths Coverage: 1.2-1.8 micron to detect HeII 1640 at z~7-10
- FoV: 2.1’ x 2.1’ with ~25 galaxies containing POP III stars within the field
- Photometric Calibration: needs calibration to 15% accuracy
- NFIRAOS mode: need high resolution spectra of very faint (~30 mag) sources
- Dither mode: need dithering to have a good measure of the sky background

(b). Cosmic Re-ionization

The Outstanding Questions

- When did re-ionization start, and how fast did it proceed?
- What was the source of re-ionization? Was it a function of environment, and what were the dominant ionizing sources?
- How could we constrain the physical processes responsible for re-ionization?

Present State of knowledge

The re-ionization is defined as the transformation of neutral hydrogen in the Inter-Galactic Medium (IGM) into an ionized state. As the Universe became cooler due to expansion, neutral hydrogen formed some 370,000 years after the Big Bang. This continued until the first stars were formed by overdense clouds of hydrogen gas. These stars generate ionizing photons with energies greater than 13.6 eV (lambda < 912 A), the ionization energy of the hydrogen atom. Study of the connection between the first generation of stars and galaxies with re-ionization reveals details about physics of star and galaxy formation and nuclear activity. Understanding the re-ionization process needs measurement of the number of energetic ultraviolet photons produced at early times and the fraction of these who escaped to the IGM. This requires a study of the number density of early galaxies with different luminosities (i.e. the luminosity function) and their star formation activity which produces energetic photons capable of ionizing neutral hydrogen in the IGM (Figure 3.12a), while also generating the stellar mass in galaxies. An estimate of the number of ionizing photons also needs determination of the mixture of stars, gas and dust in these galaxies to measure the likelihood that ionizing UV photons could escape to the IGM (Figure 3.12b).

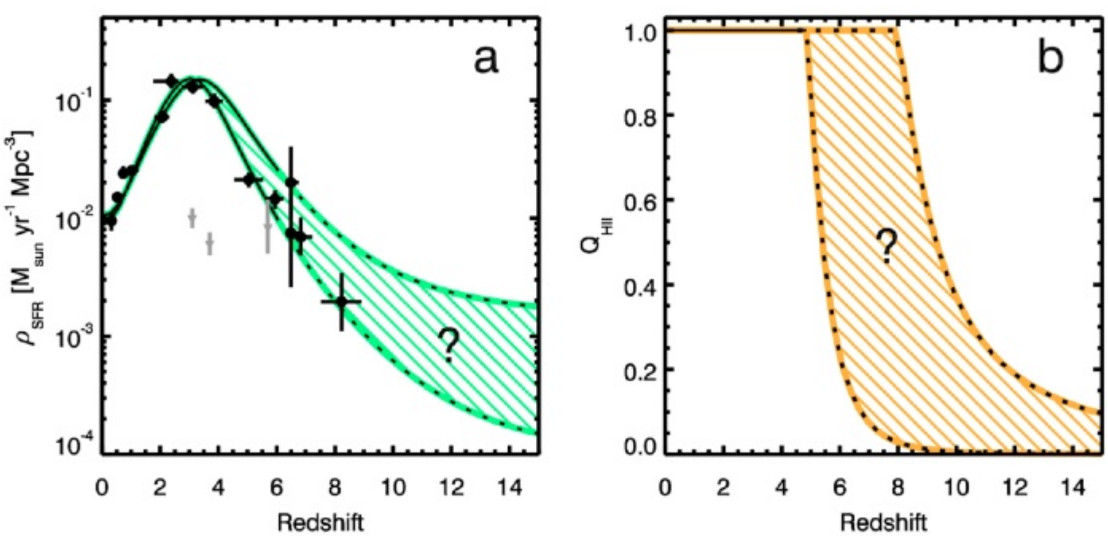

Figure 3.12. (a). The star formation history. The boundaries correspond to metal poor and metal rich populations. Fraction of ionizing photons (QHI). (b). Evolution of the ionization fraction The Universe becomes fully ionized (QHI=1) at z=4-8 (From Robertson et al 2010).

The strength of Lyman alpha emission lines is a sensitive measure of the latest time when re-ionization was complete as this can easily be absorbed by the neutral gas outside galaxies (Loeb & Rybicki 1999; Zheng et al 2010). Therefore, by monitoring the number of galaxies close to the re-ionization epoch, which exhibit Lyman alpha emission in their spectra (Fig 3.13), we could put observational constrains on the redshift at which re-ionization occurs and study its physics (Stark et al 2010). An alternative way to find fainter LAEs is to use gravitational lensing. This would be effective taking into account the FOV of IRMS.

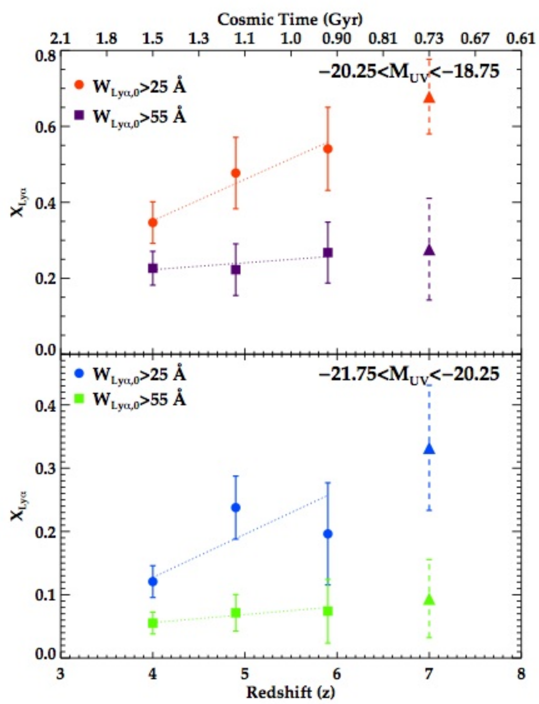

Figure 3.13. Evolution of the fraction of LBGs showing Lyman alpha emission (XLya) in the range 4 < z < 6. Luminous LBGs are shown in the bottom panel and less luminous LBGs in the top panel. The sample is divided to galaxies with Lya EWs > 25 A and > 55 A. Assuming a linear relation, this is extrapolated to z=7 (Figure taken from Stark et al 2010).

Need for TMT/IRMS

The process of re-ionization is believed to have completed by z~8. This is shown in Fig 3.12b where the fraction of ionized HII bubbles (QHII) approach 1. To measure the SFR to z~8, we need the number density of star-forming galaxies at these redshifts. The average SFR (MSun/yr/Mpc3) depends on the luminosity of the brighter galaxies at these redshifts and, more fundamentally, on the faint-end slope of the luminosity function of galaxies. The limitation here is the accuracy with which the faint-end slope is measured. Using photometric data from deep galaxy surveys (i.e. the HUDF), a steep slope of -1.8 is estimated for the faint-end of the rest-frame UV LF at z > 6 (Figure 3.14). This implies a large space density of faint star-forming galaxies at high-z. Because of the faint magnitude of these galaxies, spectroscopic redshift measurement for them is very difficult. Moreover, at the expected redshift of these objects, Lyman alpha line is shifted to near-infrared wavelengths. A combination of the TMT and IRMS is needed to measure spectroscopic redshifts for these candidates and to constrain faint-end slope of their luminosity function. Over the field-of-view of the IRMS, we expect to detect a total of ~20 star-forming galaxies at $6 < z < 8$.

Study of the re-ionization also needs accurate measurement of the number of ionizing Lya photons. This can be calculated by measuring the line intensity of Ly alpha emission lines. Furthermore, we need to estimate the fraction of LBGs with Ly a emission at the highest redshifts. The only way to make these measurements is the combination of TMT and IRMS.

Observational Questions *PLACEHOLDER*

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?
4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
5. What spectral resolution and wavelength coverage does the science require?
6. What is the required spatial resolution?
7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)
8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

Instrument Requirements

- Spectroscopy: R ~ 4000 (between OH atmospheric features)
- Wavelengths Coverage: 0.9-2.5 micron to detect emission lines to z~8
- F.o.V: 2.1' x 2.1' with ~20 galaxies within the field
- Photometric Calibration: needs calibration to 10% accuracy to measure Lyman alpha line intensities
- NFIRAOS mode: need high resolution spectra of very faint (~28 mag) sources
- Dither mode: need dithering to have a good measure of the sky background
- Given the small F.o.V, correction for sky background (which is important at infrared wavelengths) reduces

(c). Nature of the High-z Galaxies

Outstanding Questions:

What is the star formation rate and stellar mass in high-z galaxies?

What is the stellar population in $z > 5$ galaxies?
How does the strength and morphology of Lyman alpha lines change with redshift?
What are the progenitors of nearby galaxies we observe today?

Present State of the Knowledge

The first step in studying the properties of high-z galaxies is selection of an unbiased sample. The Lyman Break technique selects galaxies based on the break in their ultraviolet continuum emission due to the blanketing effect of neutral hydrogen absorption within the galaxy itself and by intervening clouds along the observer's line-of-sight. Another widely used method uses narrow-band filters to target redshifted Lyman alpha emission lines produced by hydrogen atoms excited by the UV light from young stars, selecting Lyman alpha emitters (LAEs). However, these techniques mainly select galaxies which are young enough to generate large amount of UV flux and which are relatively free of obscuring dust which would inhibit the free escape of UV photons. It is not yet clear if these techniques miss another population of galaxies. A technique has recently been developed, using age-sensitive Balmer Break features at 3646 A to select a population of old galaxies at $z > 5$ (Wiklind et al 2009), by identifying the Balmer Break feature redshifted to the near-IR and mid-IR passbands. These Balmer Break Galaxies (BBGs) are expected to be at high redshifts and yet, old.

Extensive study of the stellar population, star formation rate and stellar mass of the LBGs and LAEs has been carried out, using their Spectral Energy Distributions (SED). However, these studies are limited by the lack of data in shorter wavelengths and by the degeneracy between different physical parameters (i.e. age, dust, metallicity, redshift). Study of these systems has only been performed using their photometric redshifts, with their spectroscopic study heavily biased towards the brighter population. As a result, any measurement of the evolution of the LF and mass function to high-z is affected by this bias and by uncertainties in the photometric redshifts (Figure 3.14).

A spectroscopic study of the BBGs is even more difficult since they are old systems and hence, lack emission lines. The BBGs which yield redshifts, are often drawn from the same population as the LBGs (i.e. young or intermediate age). Because of their faint flux and difficulty in obtaining spectroscopic observations, no detailed study of the nature of galaxies at $z > 5$ has yet been performed.

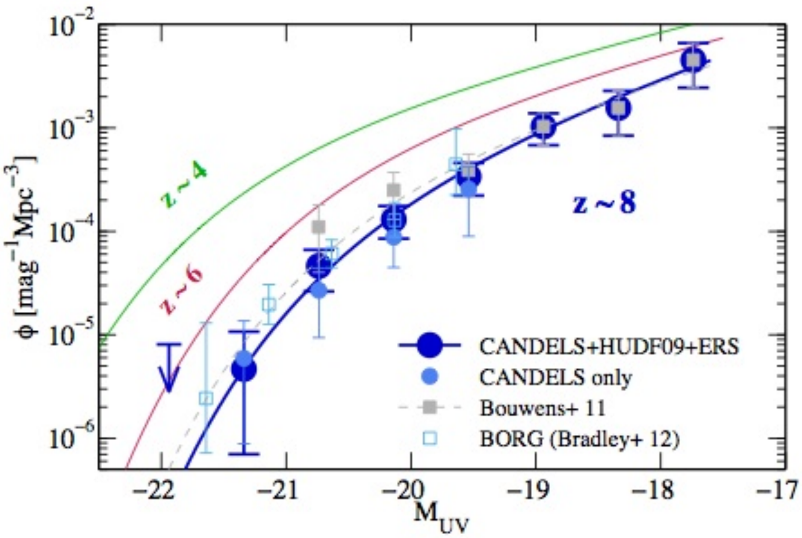

Figure 3.14. Evolution of rest-frame UV LF at z~4-8. A steep faint-end slope is found at high redshifts. The shape of the faint-end depends entirely on photometric redshifts and selection via the drop-out technique.

Need for TMT/IRMS

With the installation of near-infrared WFC3 on the HST, it has now become possible to identify LBGs, LAEs and BBGs to the highest redshifts (z~8)- (Bowens et al 2012; Finkelstein et al 2013). This limit will soon be surpassed by the James Webb Space Telescope (JWST) which would further push the frontiers of the observable universe to the epoch of dark ages. As more distant galaxies are discovered, the task of studying them becomes more challenging.

At the expected redshift of these galaxies, the UV diagnostic lines shift to near-IR wavelengths. Therefore, the TMT+IRMS combination provides an ideal tool for measuring spectroscopic redshifts, line intensities and the presence of emission/absorption lines. The spectroscopic redshifts are essential to constrain the faint-end slope of the LF of galaxies at z~6-8 (Figure 3.14) and hence, number density of high-z galaxies and study of the re-ionization. Furthermore, information about the line intensities are needed to study their evolution to the highest redshifts (Figure 3.15).

Given the old age expected for the BBGs, to measure their spectroscopic redshifts, we need to target absorption lines in their spectra. At the redshift of these galaxies ($3 < z < 7$), this requires infrared spectroscopy to deep flux levels. A measure of the number density of these objects strongly constrains the Cold Dark Matter scenario for the formation of galaxies (Wiklind et al 2010; Nayyeri et al 2013). Furthermore, measurement of spectral lines at $z > 3$, diagnostic of metallicity for LBGs and LAEs, provides an estimate for the evolution of metallicity with cosmic time. Using the near-infrared spectra, we will study the infall and outflow in these galaxies and the interaction of the interstellar medium in galaxies with the IGM. Finally, the IRMS spectra for an unbiased sample of high-z galaxies allows a study of the evolution of the lyman alpha line (its strength, EW and asymmetry) with cosmic time.

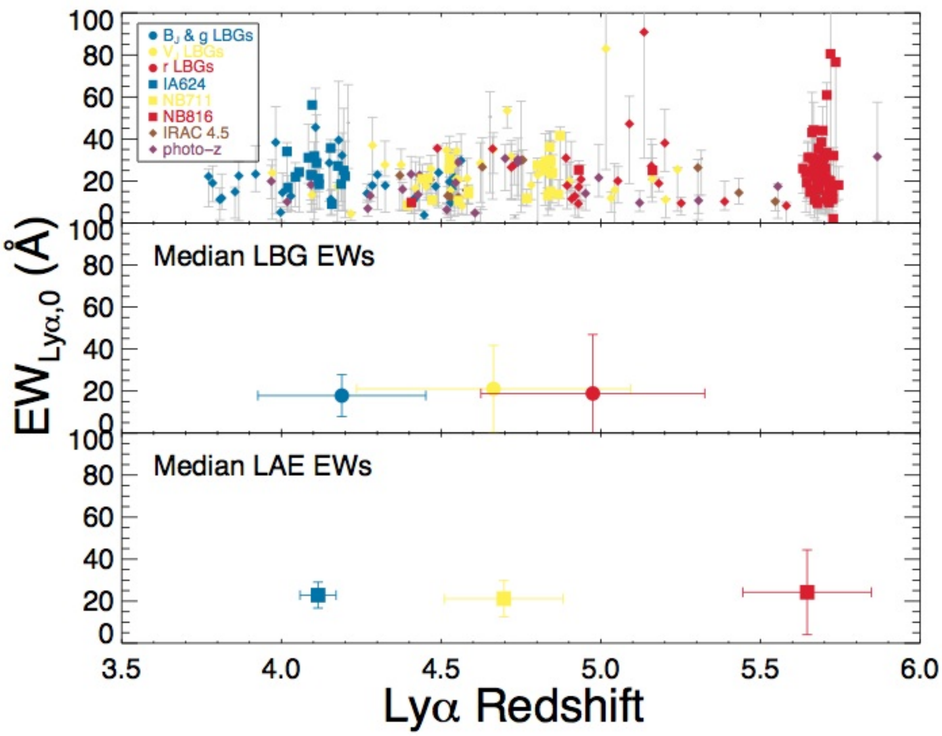

Figure 3.15. The change in rest-frame Lyman a equivalent width with redshift. The galaxies are LBGs and LAEs selected in the COSMOS field with DEIMOS spectroscopy. Top panel: LBG+LAEs selected through dropout and narrow-band imaging. Middle panel: only for LBGs; Bottom Panel: Only for LAEs. Both the LBGs and LAEs do not show any evolution in their EWs with redshift (Taken from Mallery et al 2010).

Observational Questions *PLACEHOLDER*

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?
4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
5. What spectral resolution and wavelength coverage does the science require?
6. What is the required spatial resolution?
7. For calibration, what throughput accuracy is needed? (Anything else other than flats and darks needed for calibrations?)
8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

Instrument Requirements

- Spectroscopy: R ~ 3000, 4000 (between OH atmospheric features)

- Wavelengths Coverage: 0.9-2.5 micron to detect emission lines to z~8
- F.o.V: 2.1' x 2.1' with ~20 galaxies within the field
- Photometric Calibration: needs calibration to 10% accuracy to measure Lyman alpha line intensities
- NFIRAOS mode: need high resolution spectra of very faint (~28 mag) sources
- Dither mode: need dithering to have a good measure of the sky background
- Given the small F.o.V, correction for sky background (which is important at infrared wavelengths) reduces

(d) Galaxy evolution in proto-clusters

Outstanding questions

- When is the first cluster of galaxies and the large-scale structure formed?
- Why are cluster galaxies dissimilar from field galaxies?
- How is galaxy growth accelerated in over-dense environment?
- What is the relation between QSO/AGN activity and over-dense environment?

The present state of knowledge

Based on the cold dark matter (CDM) models, the density fluctuations of dark matter grow up as time progress by merging and by accreting; and galaxy clusters would trace the particularly dense fluctuations of dark matter. Theoretical models predict the difference of galaxy evolution with its environment; galaxies residing in higher dense regions may have formed earlier and/or evolved more rapidly (e.g., Thomas et al. 2005; De Lucia et al. 2006). Actually, in the local universe, some evidences of environmental effects on galaxy evolution were found; themorphology-density relation (Dressler 1980), and the red sequence (Visvanathan & Sandage 1977).

Direct observation of protoclusters, which are galaxy overdensity regions in the high redshift universe and considered as the progenitor of galaxy clusters, is a key to understand the environmental effect on galaxy evolution. We can definitely see a few examples of protocluster beyond z=3 (e.g., Venemans et al. 2007; Capak et al. 2011). Some differences between the properties of protocluster galaxies and field galaxies already appear at z=2~3. The masses of protocluster galaxies are found to be higher than those of field galaxies (e.g., Kuiper et al. 2010; Hatch et al. 2011), and the bright-end of the red sequence is well populated by z~2 (Kodama et al. 2007). These findings indicate that the first step of galaxy evolution under high-density environments takes place at a much higher redshift, and their star formation was quenched after rapid evolution in high density regions. Theoretical works have also predicted that most of stars in cluster galaxies are formed very early (z > 3); especially, as for brightest cluster galaxies, half of their stars would be already appeared at z~5. In addition, radio galaxies and quasars also often associated protoclusters, and the activity of quasar would be triggered by the major mergers that a galaxy is experiencing during its assembly in early phase (Hopkins et al. 2006). In order to understand structure formation and galaxy evolution in high density region, we must investigate higher redshift protoclusters.

Need for TMT/IRMS

The systematic spectroscopic study with IRMS for high-z protoclusters will reveal the initial structure formation and the origin of the environmental-effect on the galaxy evolution. Protocluster galaxies, which are more strongly clustered than field galaxies, are good targets for IRMS to take advantage of its multiplexity. The major diagnostic lines in rest-frame UV and optical wavelengths shift to NIR wavelengths at z>3.

These line measurements with the aid of multi-wavelength data will provide the study of their detailed stellar population, stellar mass, age, extinction, and metallicity, which can be compared with their field counterparts at the same redshift. The line width, which can be resolved with high-resolution capability of IRMS, is useful to infer their dynamical mass. The relative offset between the lines provides the measurements of the inflow and outflow, transferring gas mass and metals associated with their star formation activity, from the galaxies to the IGM. If quasar activity was found in target protocluster, the BH mass, which can be estimated by IRMS spectroscopy from FWHM of broad MgII line and continuum flux at 3000A, is compared with star formation activity of surrounding galaxies. The LyA line will tell us the reionization history in the high dense environment of galaxies, which are though to be the major ionizing sources for reionization.

Observational Questions *PLACEHOLDER* for N. Kashikawa?

1. Imaging or spectroscopic mode? Do the proposed observations need dithering or mosaicking?
2. Do the proposed observations need the AO capability? How stable should the PSF be, if AO needed?
3. What is the expected target source density over the FoV of the detector?
4. Does the proposed project need extreme uniformity across the FoV? i.e. how accurately (as a function of position on the detector) we need the photometry.
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8. Is the proposed observation affected by the slew time or the read out time?
9. What is the required depth for the observations? (This may require use of our ETC to estimate the exposure time.)
10. Is there a possibility for saturation, given the brightness of your hypothetical targets? Do we need to take multiple short exposures and stack them?

Instrument requirements

- Spectroscopy: R ~ 3000-4000 (between OH atmospheric features). higher resolution is desirable.

- Narrow-band imaging: Once the redshift of the protocluster is determined, NB filters to detect faint cluster members.
- Wavelengths Coverage: 0.9-2.5 micron to detect emission and absorption lines for rest-frame UV and optical wavelengths out to z~8
- FOV: 2.1' x 2.1' with ~20-30 protocluster galaxies within the field.
- Photometric Calibration: needs calibration to 10% accuracy to measure Halpha, Hbeta, [OIII]5007, MgII, and LyA line intensities.
- NFIRAOS mode: need homogeneous AO correction over the protocluster region(FOV) to achieve high sensitivity spectroscopy.
- Multiplexing facility of the IRMS will be used to construct a statistically significant sample of galaxies with different properties (galaxy density, w/ or wo/AGN)

4. Set-up and Configuration Requirements

4.1. Instrument Set-up

The Instrument and the Telescope: The instrument should allow easy access for maintenance and diagnostic check. The maintenance and diagnostic checks include calibration sources (arc lamps, slit masks, flat-field lamps). Some of the calibration tasks will be located in the IRMS with others being part of the telescope.

Instrument set-up and alignment: The alignment of the instrument along the optical axis of the telescope needs to be checked. Furthermore, the IRMS focus internal to the telescope and with respect to the NFIRAOS, and the alignment of the aperture stop must be monitored.

Mask Design: This should be made flexible and efficient. The mask design software must be made portable and easy to use, on a platform which is, as much as possible, independent of the system.

Dithering Strategy: Ground-based observations in the near-infrared bands are affected by the sky background. This is particularly serious for observations requiring large exposure times or if sources are located in environments with high background density (i.e. center of our galaxy or star-forming clouds). These observations need large dither or offset motions. The dithering strategy should be designed so that the guide stars remain in the NFIRAOS field of view during the observations.

4.2. Observing Requirements

Target Astrometry: The small field of view of IRMS/NFIRAOS (2x2 arcmin2), and its slit size, requires an astrometry to better than 1 arcsec accuracy. Given that the majority of the TMT/IRMS targets are faint and not well studied before, the astrometry is challenging. As some of the targets for IRMS may not be detected prior to spectroscopy, a special camera with imaging filter in the IRMS would be helpful for follow-up observations.

The AO System: Most of the IRMS/NFIRAOS observations will be performed with laser beacons, due to the small density of guide stars. The NFIRAOS requires three tip-tilt stars to be within 2 arcmin of the science target. Furthermore, the stars should be selected to stay within the NFIRAOS field during the dither sequence. If not, additional stars are needed. The tip-tilt stars should have positions accurate to +/- 1 arcsec with photometric information reliable to +/-0.1 mag. The stars are better to be distributed across the science field of the detector and not be clustered at one point. The guide stars for NFIRAOS are faint (R~25; J~22 mag) and after detection by acquisition camera, their images will be analyzed to indicate if they are stars or faint background galaxies.
Focusing/Alignment: One should take the following steps:

- do MIRA near the mask (make sure target is highlighted).
- setup the alignment mask
- put in dark image filter and as soon as filter goes dark, execute the mask
- when mask is finished configuring for MIRA, start the MIRA

- During the MIRA execution, select the target on the Slit Alignment Tool (SAT) and set up alignment mask
- When the MIRA is finished, start moving to the target field
- Make sure that in the course of alignment all stars are located in their assigned boxes
- Adjust the integration time, make sure the alignment mask is fully configured before starting "Fine Alignment"

4.3. Calibration

The calibration before the start of the run includes dark, arc and flats. The calibrations will be taken for each configuration of the instrument and will be used in the data reduction pipeline. There is also on-the-sky Calibration depending on the spectroscopic or photometric mode of the observations. These include:

Twilight imaging flat-field, which is often used for broad-band filters. Sky flats for spectroscopy is more difficult and takes more of the telescope time. Furthermore, in the near-IR, we need to observe between the OH emission lines, which is not always possible.

To identify and remove telluric features in science spectra, we observe stars throughout the night, often before and after the science exposure and at comparable airmass.

Flux Calibration is required for some science projects. This is done using standard star observations at the beginning and end of the night. The quality of the science data would drastically improve if these standard stars are monitored throughout the night. One problem with using the existing stars for calibration of TMT instruments is that they are too bright, causing saturation of the detector. The way to get around this problem is to have a few short exposures followed by readout of the detector and recording of the data.

5. Data Reduction Pipeline

The IRMS data reduction pipeline should be flexible and efficient, allowing quick-look analysis of the data. This is needed to check the quality of the data and to allow initial detection and proper positioning of faint targets. The final data reduction pipeline must contain the following sections:

- Calibration data: while these data can be obtained for each observation separately, it is efficient to share them among different observations, if possible. Given the precious time of the TMT and high demands, the calibration process must be fast and efficient. They should be archived appropriately, to allow easy distribution of the calibration data
- Information about filters, their gain and anything which is located on the optical path of the telescope.
- To obtain empirical PSF, we need stars close to our targets. Because of the small field of view of IRMS (2' x 2'), it is unlikely for stars to be found on the same as the target beams. Therefore, knowledge about the NFIRAROS, obtained from WFS is essential. We also need a measure of how PSF varies across the field.