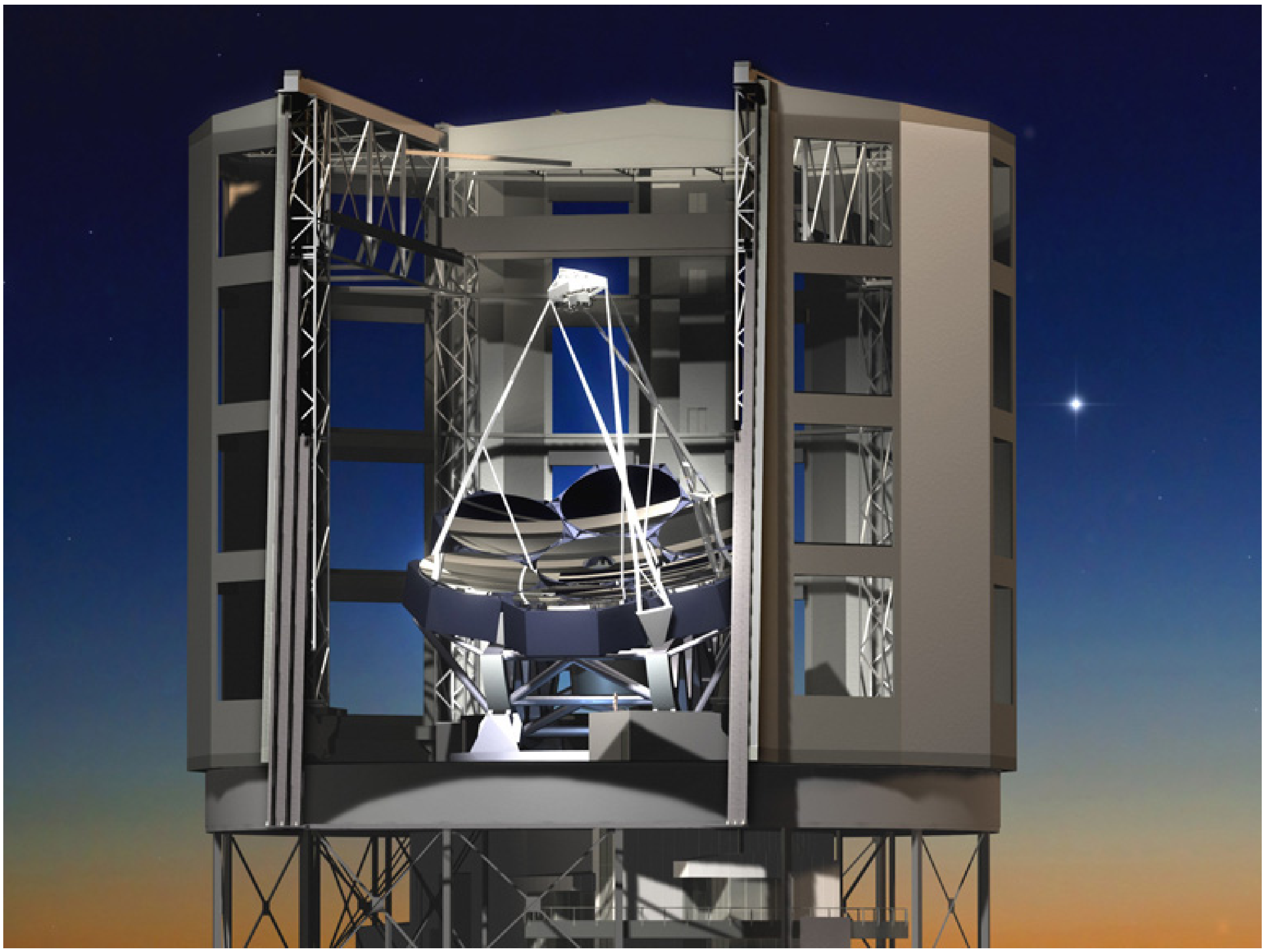
Giant Magellan Telescope
Science Case



July 10, 2006

GMT Science Case

Introduction

Astronomy is a science driven by discovery. Bereft of physical contact with the celestial objects we study, astronomers can rarely carry out the controlled experiments that are the hallmark of the scientific method. Progress in our understanding of the cosmos often proceeds from the discovery of new classes of objects or phenomena to the painstaking confrontation between observation and theory. Astronomical discovery is driven by technology and the pace of astronomical discovery can be traced largely in two dimensions: the increasing light-gathering power of telescopes, and the exploration of the full electromagnetic spectrum. The first application of the telescope to astronomy by Galileo fundamentally challenged the prevailing view of the cosmos. The first forays into other regions of the electromagnetic spectrum by Herschel, Reber, Giaconni and others revealed celestial objects and processes that were neither anticipated nor understood. The 20th century saw astrophysics develop from a rich, but largely phenomenological science into a vibrant branch of physics; one that promises to probe regions of parameter space beyond the reach of any conceivable laboratory equipment or particle accelerator.

As we begin the 21st century we are on the threshold of a new era of astrophysics. The cosmological world model is determined with great accuracy. We are tantalizingly close to seeing the era of first-light and reionization. A new generation of facilities on the ground and in orbit will complete the exploration of the electromagnetic spectrum with unprecedented sensitivity.

The scientific motivations for the GMT encompass forefront problems in astrophysics ranging from exoplanets to the early Universe. The National Academy of Science and the National Research Council reported the results of the Astronomy and Astrophysics Survey Committees' Decadal Survey in *Astronomy and Astrophysics in the New Millennium.* This high level study of astronomy in the coming decade identified a set of scientific issues that are both of fundamental importance and are poised for progress.

The five areas identified in the study are:

1) Determining the large-scale properties of the Universe and the distribution and nature of its matter and energy.

2) Understanding the dawn of the modern Universe and the first stars and galaxies.

3) Understanding the formation and evolution of black holes.

4) Studying the formation of stars and planets.

5) Understanding the impact of the astronomical environment on the Earth.

An inter-disciplinary effort between the Department of Energy, the National Science Foundation and NASA examined the interface between fundamental physics and astrophysics and identified eleven key science questions for the new century. These are detailed in the report, "Connecting Quarks with the Cosmos". The first three key questions are: What is dark matter, what is the nature of dark energy and how did the Universe begin? These issues are best addressed by astrophysical observations and experiments over a broad range of the electromagnetic spectrum.

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The GMT can address a broad cross-section of the key questions identified in the "Astronomy and Astrophysics in the New Millennium" and "Quarks to the Cosmos" reports. The key attributes of the GMT – its large collecting area, high angular resolution and pupil geometry – allow it to make unique contributions to many of these problems. By working in tandem with other facilities the GMT can address, to varying degree, all of the key astrophysical issues identified in both reports. We layout the key GMT science goals in the following areas:

- Star and planet formation
- Stellar populations and chemical evolution
- The nature of dark matter and dark energy
- The evolution of galaxies and intergalactic matter
- Black hole growth
- The first stars and galaxies

In each of these areas the GMT can make critical contributions, often in synergy with facilities working at other wavelengths or in survey domains. Using its adaptive secondary the GMT will image massive exoplanets around nearby stars with separations between 0.5 and 5AU. Extreme Adaptive Optics techniques in the 1-2.5μm windows will allow exoplanet imaging via reflected light. Contrast levels in the 10^7 – 10^8 range should be obtainable on angular scales from 60 to 500mas. Nulling interferometry and coronagraphy will allow thermal IR imaging of young planets in star forming regions in Taurus, Orion and other young stellar populations in the southern hemisphere. Additional techniques for exoplanet studies include transit-spectroscopy, reflected light spectroscopy, proper motion studies and radial velocity reflex-motion probes of low-mass stars and brown dwarfs.

Diffraction-limited imaging in the near- and mid-IR will allow the GMT to determine the initial mass function in crowded regions and to probe star formation over a wide range of physical conditions. The near-IR high-resolution spectrometer will allow detailed studies of the chemistry of protostars and young T-Tauri stars.

The enormous collecting area of the GMT will open a new window on stellar astrophysics and chemical evolution within galaxies spanning a broad range of Hubble types and evolutionary histories. The increased sensitivity compared to current 8m class systems will allow determinations of abundance patterns in RGB stars in local group galaxies and extreme metal-poor stars in local group dwarfs, gravities and abundances in giants beyond the local group and a wide range of other studies in fundamental stellar astrophysics. Diffraction-limited imaging and multi-object spectroscopy via IFUs will improve our understanding of star formation histories and dynamical evolution in dense star clusters and other confusion-limited environments.

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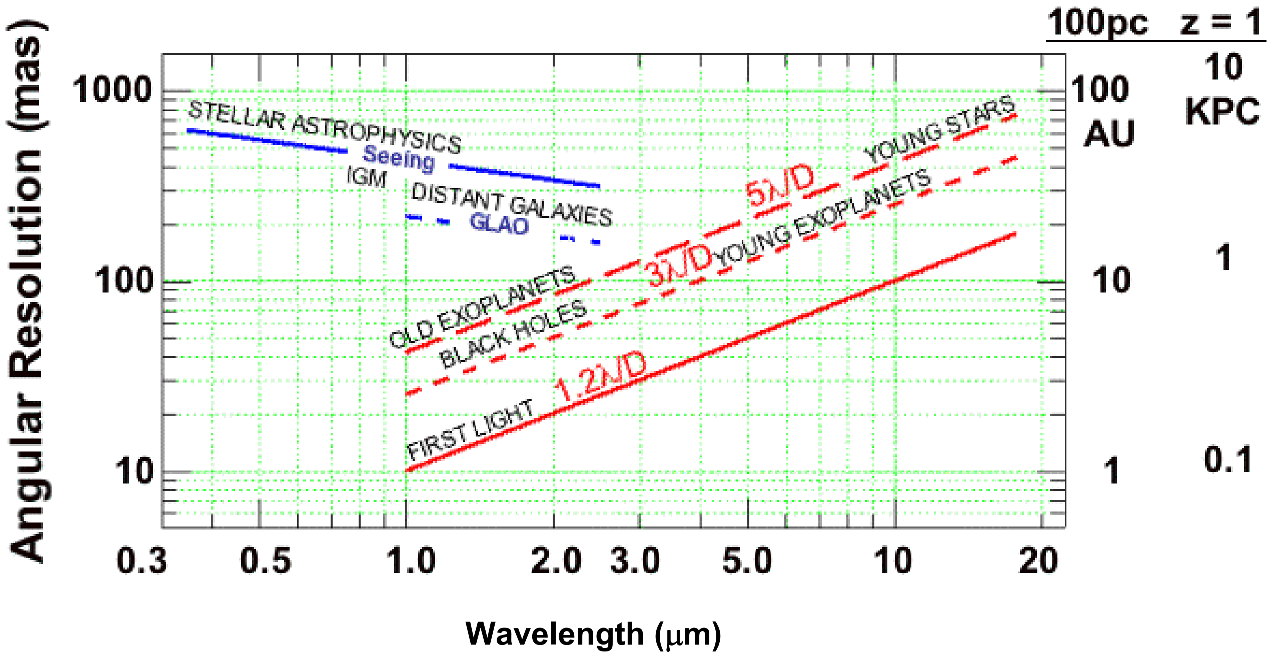

Figure 1. Angular and linear resolution discovery space for the GMT. The solid blue line corresponds to seeing-limited observations, the dashed blue line represents our best estimates for GLAO. The red lines represent diffraction-limited performance at the Raleigh limit (solid red) and at inner working distances of 3 and 5λ/D. The linear scale for galactic sources at 100 pc and cosmological sources at z = 1 are show on the right

The GMT wide-field optical spectrograph will allow tomographic studies of the IGM and reveal the interplay between galaxy evolution, star formation and the heating and enrichment of intergalactic matter. The great sensitivity of the GMT will allow us to use faint AGN and compact galaxies as background sources, achieving much denser sampling of the IGM than is possible with current QSO-based studies. Spectroscopy with the near-IR MOS will allow dynamical and chemical evolution studies of galaxies at $1 < z < 5$ with statistically valid samples, while diffraction-limited IFU spectroscopy will allow detailed dissection of individual systems. Similar techniques will allow extensions of black hole bulge mass studies to intermediate and high redshifts, probing the era of quasar growth. The GMT high-resolution spectrographs will probe the reionization epoch using $z > 6$ AGN discovered in large area near-IR imaging surveys. Lastly, by working at intermediate resolution in the near-IR, the GMT will complement JWST studies of first light.

The GMT science case is defined by the intersection of our community's scientific aspirations and the unique capabilities of the telescope and its instruments. Some of these capabilities draw largely on the dramatic gains in angular resolution promised by adaptive optics, while others rely entirely on the enormous light grasp offered the collecting area of the seven primary mirror segments and the wide field of view of the GMT survey instruments. In this sense the GMT strikes a finely tuned balance between the promise of developing technology and the well demonstrated power of telescopes with large collecting areas.

The discovery potential of the GMT can be gauged in a number of ways. The large gain in angular resolution opens discovery space in the search for exoplanets, the study of black holes, dense star clusters, distant galaxies and a host of other interesting areas. In Figure 1 we show the angular resolution of the GMT and the corresponding linear scales at distances appropriate for planetary and star formation studies (100pc) and at cosmological distances (z = 1). At near-IR wavelengths diffraction-limited GMT images will resolve structures as small as ~1AU, while in the mid-IR we can probe the terrestrial (< 3AU) regions of solar system analogs. At cosmological distances the GMT near-IR AO imager will explore galaxies and black holes on the 100-300pc scale, allowing us to study young galaxies on the same scales that we observe their local descendants. Ground-layer adaptive optics (GLAO) should allow us to image distant galaxies with ~1kpc resolution over very large fields of view, as the dashed blue line in Figure 1 illustrates.

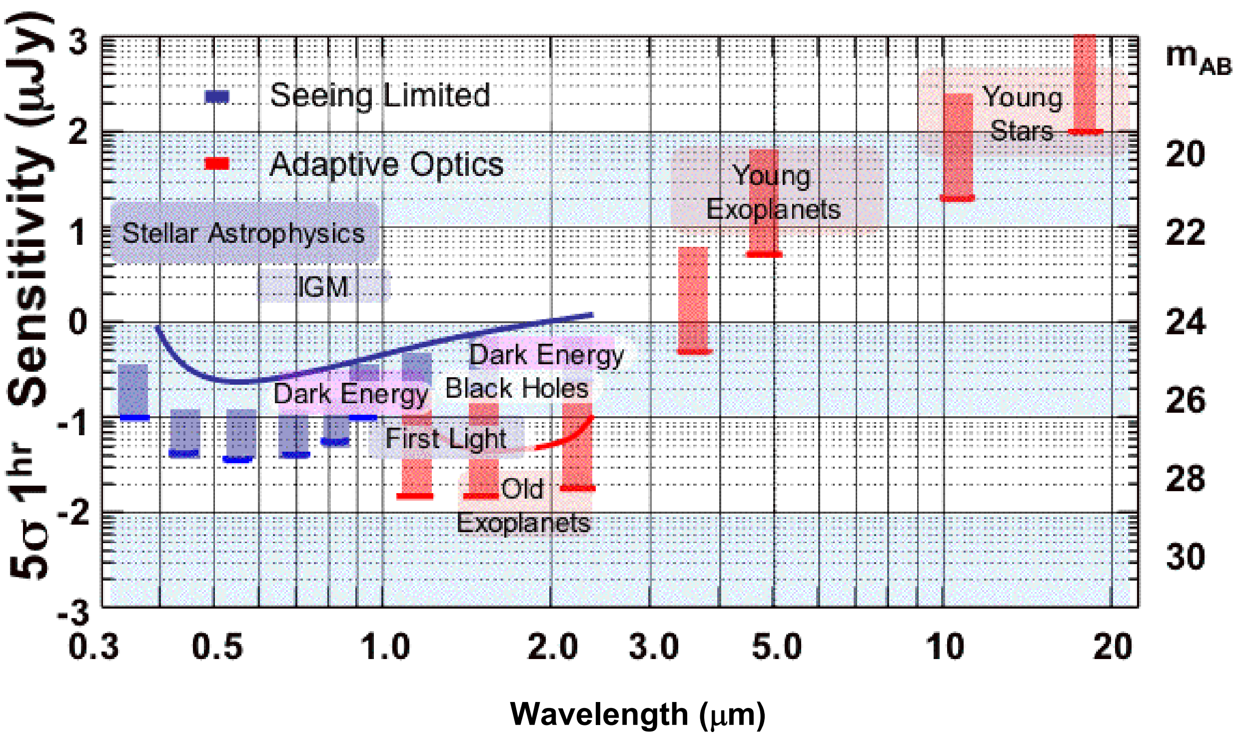

Figure 2. Sensitivity discovery space opened by GMT and its instruments. The vertical bars show the gains in sensitivity compared to an 8m aperture using similar instruments and technique. The blue bars correspond to seeing-limited applications while the red bars represent diffraction-limited performance. The blue curve represents the sensitivity of low resolution spectroscopy.

The power of the GMT lies not only in its angular resolution; its great sensitivity also opens up new discovery space. In Figure 2 we show the 5σ limiting depths for one-hour exposures with GMT instruments operating from the UV atmospheric cutoff to the mid-IR. The vertical bars show the gain in sensitivity compared to an 8m aperture using the same techniques. In the seeing limited case (blue bars) the gain in sensitivity goes like D, while the gain in speed goes like D^2. In the diffraction-limited case the gain in sensitivity is an order of magnitude (D^2), while *the gain in speed is two orders of magnitude* (~D^4). As Figure 2 shows, the GMT will open substantial new discovery space at all wavelengths and particularly in the short-wave IR.

1 Planets and their Formation

For centuries, people have dreamed of discovering habitable worlds. With the recent discoveries of planetary systems completely unlike our own, we are now also confronted with a need to understand the diversity of solar systems and ask how often planets develop the conditions needed to support life. With its superior angular resolution, dynamic range, and sensitivity, the GMT can bring these dreams within reach.

1.1 Direct Imaging of Exosolar Planets

Planets result from a long sequence of physical processes, starting with the formation of a parent star surrounded by a circumstellar disk and culminating in a dynamically stable planetary system. The discovery of giant planets like Jupiter orbiting sun-like stars was a triumph of 20th century astronomy. A primary goal of 21st century astronomy is to detect terrestrial planets and to place the Solar System in context with other planetary systems. Direct imaging of these solar systems and the exoplanets within them opens the door to physical studies of the nature of the planets and the architectures of planetary systems. The challenge for exoplanet imaging and spectroscopy lies in detecting very faint planets very close to their central stars. A Jupiter twin reflects only 10^{-9} its star's visual light, L_0; an Earth twin reflects only 10^{-10} L_0. Detecting planets directly therefore requires large aperture and high spatial resolution.

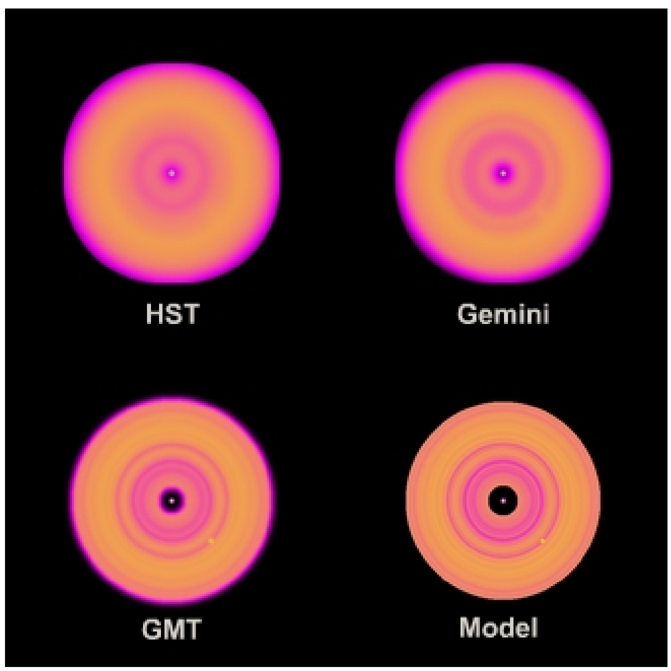

Figure 3. A model calculation of an evolving protoplanetary disk with an age of 30 million years as imaged with a perfect telescope (lower right), the Hubble Space Telescope, the Gemini 8m and the GMT, the latter two operating with extreme AO at 1.65µm. The GMT image reveals gaps and other structure in the disk, as well as the terrestrial mass protoplanet.

1.1.1 Young Planets

Because planets are brightest when they are youngest, it is easier to detect young planets. A newly formed terrestrial planet at 1 AU is molten, with a surface temperature of 1500 K and a luminosity of 10^{-}

^{7} to 10^{-6} $L_\odot$. As the planet cools over a period of 100 Myr, its thermal emission falls below its reflected luminosity of 10^{-10} $L_\odot$. Thus, mid-IR images can reveal thermal emission from young terrestrial planets with ages of 10-100 Myr, as is illustrated in Figure 5.

Radiation from gas giants like Jupiter also fades with time. The thermal luminosity is expected to drop below the reflected luminosity of 10^{-9} L_0 at 2-3 Gyr. Close-in giant planets are heated to high temperatures by their parent stars and have luminosities 10-100 times larger than more distant gas giants. Observations at 3-5 micron wavelengths provide the largest contrast between the planet and star. Thus, high spatial resolution IR imaging and high spectral resolution IR spectroscopy enable the highest quality probes of the physical properties of gas giant planets.

Nearby field stars, stellar associations, and star-forming regions provide good targets for direct detection of terrestrial and gas giant planets. At distances of 50-100 pc, the TW Hya (10 Myr), η Cha (10 Myr) and Tuc-Hor (30 Myr) associations contain bright stars with a wide range of stellar spectral types. The closest star-forming regions provide a good contrast between the low density (Chamaeleon and Lupus at 140-150 pc) and high density (Ophiuchus at 150-160 pc) modes of star formation. At 500-1000 pc, the dense Carina and Orion clouds are among the most active star-forming regions in the nearby Galaxy.

The unique GMT design will enable extremely low thermal background. Thus, the main technical challenge to direct exoplanet imaging involves correcting the low- and medium-order atmospheric errors and diffraction effects that scatter light very close to the star. Scientists in the GMT consortium are exploring several powerful techniques to provide the high level of atmospheric correction needed (e.g. Codona 2004). Current estimates of the sensitivity suggest that the GMT can acquire signal-to-noise > 10 detections of molten Earths, young Jupiters, and debris disks in 30-120 min of on-source integration time in the (1.6μm) H-band.

Because the individual off-axis mirror elements can be individually apodized, GMT coronagraphic imaging using an optimized mask controls diffraction and enables detection of planets with contrast ratios of 10^{-7} L_0 at separations of roughly 0".1. A deformable secondary can correct for pupil diffraction and atmospheric errors, without a need for an apodization mask. At 1.6 μm, differential imaging methods with this technique should enable detections of planets with reflected luminosities of 2 x 10^{-8} L_0. Finally, 2-aperture Bracewell nulling – currently in use at the MMT and Magellan – will allow searches for giant planets and debris disks to levels comparable to that observed from the local Zodiacal light. The large distinct segments of the GMT will allow multi-aperture Bracewell nulling with 21 simultaneous non-redundant baselines, providing an enormous gain in speed compared to the Large Binocular Telescope.

1.1.2 Imaging of Exoplanets from Reflex Motion Surveys

Radial velocity surveys have resulted in the detection approximately 150 planets in orbit around nearby stars. Many of these planets are quite massive (> $3M_J$) and have small orbital semimajor axes. While most of these planets are probably beyond the reach of imaging with the GMT, a number of the closer systems with large orbital diameters can be detected directly. We have estimated the reflected fraction for the full sample of known exoplanets using the database at www.exoplanets.org. These estimates are based on a Jupiter-like albedos and a nearly flat mass-radius relation.

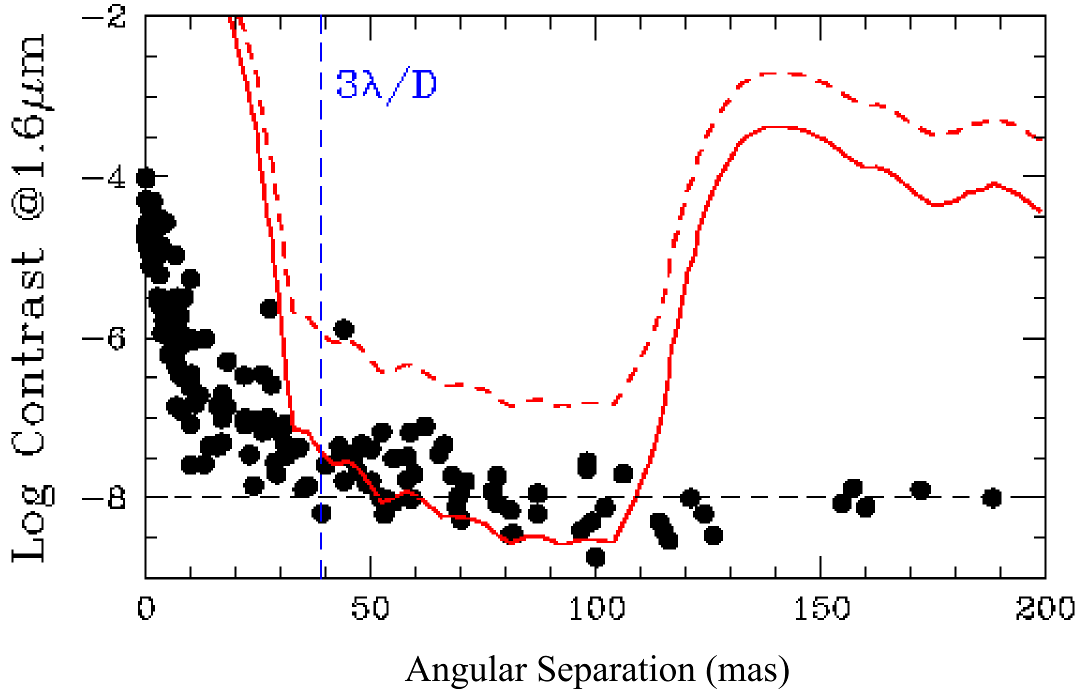

Figure 4. Reflection contrast at 1.6μm and angular separations for known exoplanets. All of the exoplanets in the Marcy & Butler data base were used to compute contrast assuming an albedo of 0.4 and a nearly flat mass-radius relation. The dashed and solid curves show the GMT PSF with adaptive phase modulation for short (1 sec) and long (> 1hr) exposures, respectively. The limit for this type of imaging is expected to be ~ 1 x 10^{-8} (5σ) at 3λ/D. Approximately 20 known exoplanets are detectable with the GMT HRCAM.

In Figure 4 we plot the expected contrast and angular separation for these known planets along with expected PSFs for the GMT ExAO imager (HRCAM) using phase modulation with the adaptive secondary. We should be able to detect ~20 known exoplanets with declinations less than $+20^0$. These span a range of masses from $1M_J$ to nearly $20M_J$. Direct imaging of these systems will allow us to explore the physical properties of exoplanets over a wide range of masses and ages.

It is also of interest to ask how many planets of various masses and ages can be detected via thermal emission. Direct measurement of the thermal emission from planets of known mass will constrain models of giant planet formation and evolution. Unlike the reflected light case, the challenge in the mid-IR is more a matter of sensitivity than suppression of the light from the central star. We expect that simple PSF subtraction will remove much of the signature of the central star and that we will be sky limited in as close as 3λ/D. High dynamic range can be achieved using the same adaptive phase techniques that are illustrated in Figure 4 for the near-IR.

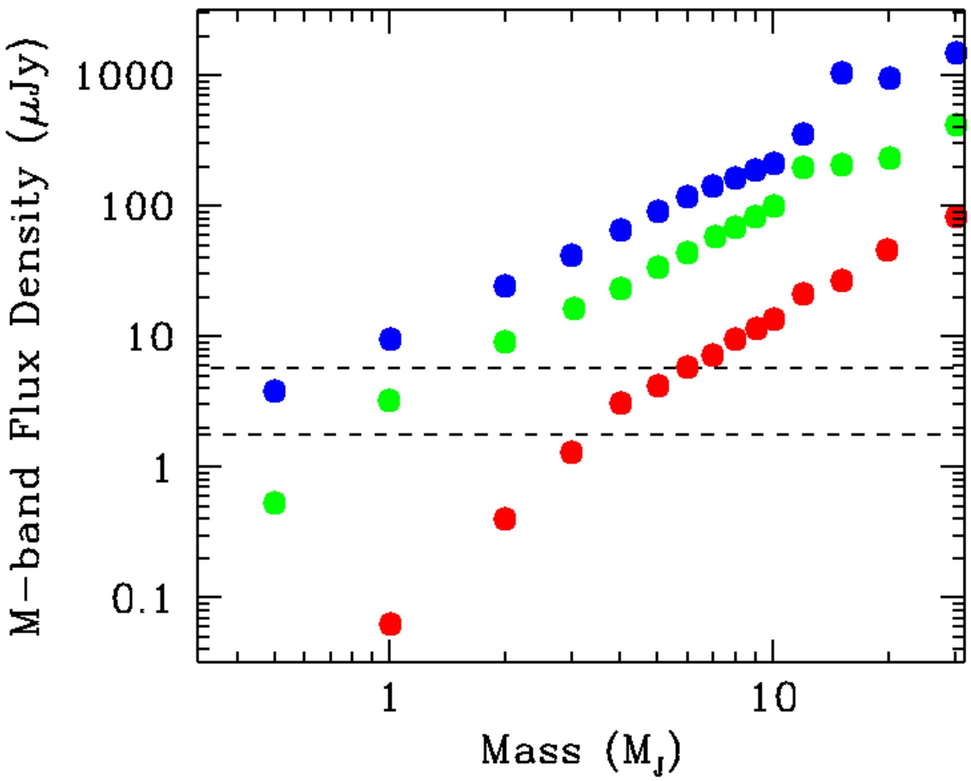

Figure 5. Thermal emission from young exoplanets. The 4.8μm (M-band) flux density is plotted against mass for exoplanets at a distance of 50pm. Models from Burrows et al. (20003) with ages of 1Gyr (red), 100Myr (green) and 30Myr (blue) are shown. The dashed lines show the 1-hour and 10-hour sensitivity limits expected for the mid-IR AO imager. The GMT will detect young (< 1Gyr) exoplanets in the nearest star forming regions to masses below $1M_J$ and young Jupitors in more distant star forming complexes. In the Appendix we tabulate a number of star forming regions within reach of the GMT, their ages and the expected number of young stars around which we will search for young planets.

We have used the model atmospheres from Burrows et al. (2003, 2004) to estimate the flux density in the M-band (4.8μm) for the sample of known exoplanets. We adopt a uniform age of 5Gyr, appropriate for a volume-limited sample of solar neighborhood stars. The results are fairly discouraging, as only a handful of the ~150 known exoplanets are bright enough to be detected at 5μm, primarily because of their large ages. The mid-IR is, however, fertile territory for planet searches and it opens a range of parameter space that is not covered by the radial velocity surveys. We illustrate this in Figure 5 where we show the expected 4.8μm flux density for planets spanning a range of ages and masses at a distance of 50pc. As Figure 5 shows the GMT is capable of detecting young planets with masses in the sub-Jupiter and larger range with ages and distances appropriate for star forming complexes in the southern Milky Way.

1.1.3 Mid-IR Imaging of Intermediate Age Planets

A survey of 100 intermediate age (~1 Gyr) stars within 10pc is likely to yield dozens of massive planets at larger radii than those probed by the radial velocity surveys. The Webb telescope will also be a powerful tool for addressing this issue, but the superior resolving power of the GMT will allow it to probe to larger distances and smaller orbital diameters.

At larger distances, on the order of 100pc, several active star-forming regions are well placed for observation from Chile. While the angular scale is less favorable, these planets, by virtue of their youth, are quite luminous and can be detected by the GMT to masses below $1M_J$. The Ophiuchus dark cloud should be a particularly productive location to search for planets with ages of only a few million years. In the Appendix, we list some of the parameters of a young planet survey program and the most promising targets.

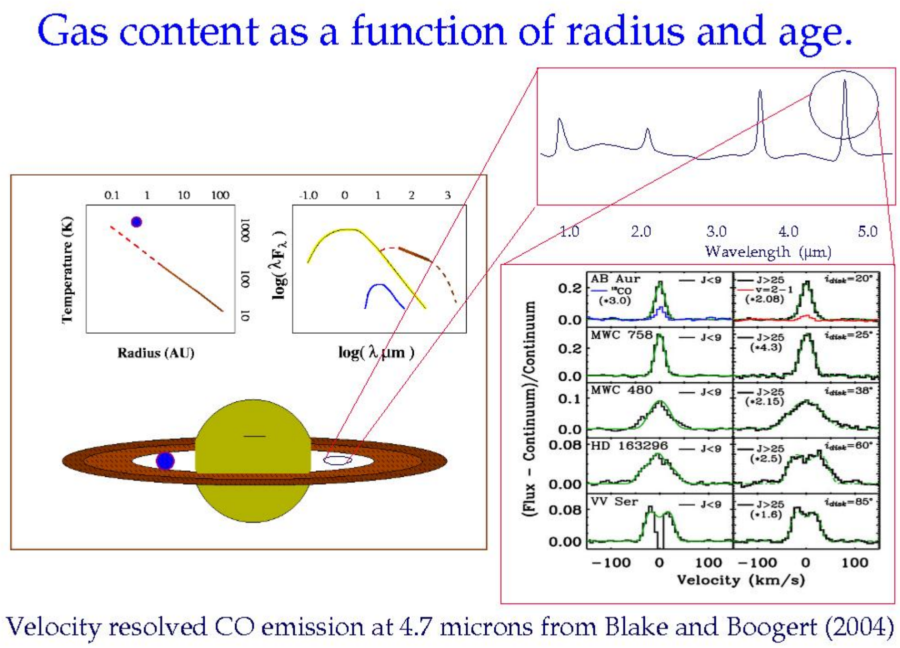

Figure 6. Near-IR spectra of a protoplanetary disk. The GMT near-IR Echelle will allow one to probe kinematics, densities and chemical properties of unresolved disks. Line profiles can reveal velocity structures indicative of gaps in the disk even if they are spatially unresolved. From Blake and Boogert (2004).

1.2 Radial Velocity Planet Detection

The GMT will also yield large samples of extrasolar planets from standard optical Doppler techniques using an iodine absorption cell or other techniques. Most extrasolar planets have been detected around nearby stars with F, G, and K spectral types. Compared to today's Keck telescope, GMT spectroscopic surveys of more distant FGK-type stars can sample ten times the volume, potentially yielding more than one thousand close-in gas giant planets. This sample could provide critical tests of migration, the slow inward motion of a gas giant planet interacting with a gaseous disk. Because these surveys will also increase the sample of M-type stars by a factor of ten, the high resolution (~ 80,000) near-IR Echelle spectrograph on the GMT can provide the first statistically significant sample of extrasolar planets orbiting M-type stars and brown dwarfs.

The small masses of M-type stars and brown dwarfs greatly increase the probability of detecting terrestrial planets with Doppler techniques. With an Echelle spectrograph, the GMT can detect an Earth-mass planet in the habitable zone of a late M-type star. Because the radius of a rocky planet is 5%-10% of the stellar radius, subsequent data could yield observable transits of the planet across the stellar disk.

1.3 From Disks to Planets

High spatial and spectral resolution observations with GMT will directly probe the physical processes that transform a circumstellar disk into a planetary system. These probes will yield more robust links between the physical structure of circumstellar disks, the census of planetary systems, and the properties of individual planets. By tracking the evolution of disks, the GMT will reveal the dynamical and chemical history of circumstellar disks and discover whether planets are an inevitable outcome of star formation.

In our current picture of disk evolution, several processes dominate changes in the structure of the disk. Coagulation produces large grains which rain out into a dense midplane and grow into planetesimals, km-sized objects that are the building blocks of planets. Although continued growth of planetesimals leads to terrestrial planets, the origin of gas giant planets is unclear. Coagulation may form giant Earths that can accrete gas directly from the disk (Kenyon & Bromley 2004). In contrast, a gravitational instability in a massive disk may produce self-gravitating clumps that collapse directly into a gas giant. Along either path, collisions between leftover solid material produce widespread debris, as in the famous disks around β Pic and Vega, which is much easier to detect than planets.

Studying this evolution requires the high spatial and spectral resolution of the GMT. High sensitivity AO images with 3 AU resolution will enable the first direct views of the terrestrial and gas giant formation zones in disks around the youngest nearby stars. If planets form on 1-10 Myr timescales, these images will enable searches for the bright rings and clumps, dark bands and shadows, and warps that provide indirect evidence for planets. At later times, GMT images will provide direct comparisons between detected planets and the morphology of the gas (e.g., long slit spectra of H_2, CO, and H_2O) and dust (e.g., HKL, 2-10 μm ice bands, and silicate features) within the disk. In both cases, images from ALMA will yield information on the temperature and composition of grains in the disk, yielding complementary tests of planet formation models.

By measuring temperatures and line widths, high resolution IR spectroscopy also probes the structure of gas and dust within the disk. The sensitivity of current 8-10 m telescopes has been sufficient only to probe disks around bright, high mass stars and those least embedded in their parent molecular clouds. A much wider range of stellar properties and evolutionary states come into reach with the GMT. At early times, spectra of H_2, CO, H_2O, and other transitions at 1-5 μm and silicate grains at 10-20 μm probe the structure of the disk at 0.1-10 AU, enabling studies of mass flow through the disk, the growth of grains, and the formation of organic molecules within the disk, as is illustrated in Figure 6. At later times, IR spectra will enable the first measures of the relative abundances of gas and dust in the terrestrial and gas giant zones.

Current models suggest that massive gas giants (such as Jupiter) form beyond the “snow line,” the boundary beyond which ices condense out of gas in the disk. At disk radii of 3-10 AU around solar-type stars and at 30-100 AU around massive stars, high spatial resolution near-IR measurements with modest spectral resolution at 2-5 μm will detect absorption lines from ices on grains and will yield vital new constraints on the chemistry and physical conditions within the disk. High quality radial profiles will reveal the range of disk radii where ices have condensed out of the gas. The GMT can detect long carbon chain molecules that form the basis for complex, organic molecules. Mid-IR spectra from ISO first showed the similarity between the icy material in star-forming regions and comets in the Solar System. High quality GMT spectra will enable the first detailed comparisons of the composition, density, and temperature of comets and planet-forming disks.

1.4 The Solar System

The Solar System is our best opportunity to study the dynamical history of a planetary system and its impact on the initial composition and architecture of planetesimals and larger objects. By enabling deeper imaging surveys for faint objects and more sensitive spectroscopy of brighter objects, the GMT will make the first comprehensive probes of the evolution of primordial materials in the Solar System.

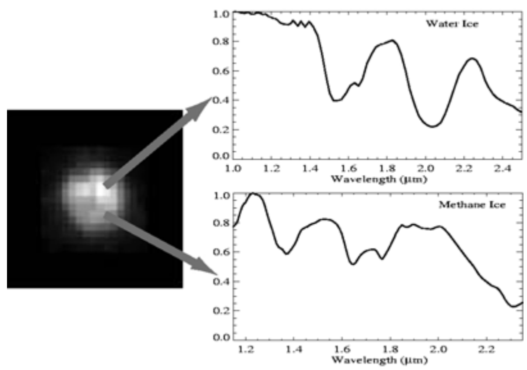

Figure 7. Near-IR spectra of Pluto, the nearest large KBO. Resolved near-IR spectra reveal spatial variations in the ices and other surface features. The GMT will have the spatial resolution and collecting area to determine the surface properties Sedna, Xena, and other small bodies in the solar system that probe the early evolution of the solar nebula.

Understanding the structure of the outer Solar System from the Kuiper belt to the Oort comet cloud is one of the greatest challenges in planet formation. Beyond the orbit of Neptune, there are three classes of icy Kuiper belt objects (KBOs) with radii of 500-1000 km and smaller: (i) classical KBOs with circular orbits at 42-48 AU, (ii) resonant KBOs in 2:1 (47 AU) or 3:2 (39 AU) orbital resonance with Neptune, and (iii) scattered disk KBOs with perihelion distances of ~ 40 AU and orbital eccentricities e exceeding 0.5.

The recent discovery of the reddest object in the Solar System, Sedna, at 90 AU (Brown et al. 2004) suggests at least one more class of objects with $e > 0.5$ and perihelion distances of 60-80 AU. The outer part of Sedna's orbit reaches roughly the inner edge of the Oort cloud at ~ 1000-2000 AU, providing a transition between the scattered disk and the roughly spherical Oort cloud that extends to 1-2 x 10^4 AU.

KBOs exhibit great diversity in their broadband colors, probably a result of variations in the albedo and other surface properties. By resolving KBOs with diameters of 150 km and larger, GMT near-IR AO imaging will provide the first direct measurements of albedo for hundreds of KBOs. With current 8-10 m class telescopes, low resolution (~100), near-infrared surface spectroscopy of the brightest KBOs is limited to about one object per night. GMT spectra will measure other differences in surface properties and provide detailed tests of models for KBO surface chemistry as a function of dynamical population. This is illustrated in Figure 7 for the case of Pluto where spectra at different locations reveal either water or methane ice.

GMT observations will test models for the formation of KBOs. Recent HST observations indicate a break in the size distribution (the number of KBOs as a function of size) at 10-20 km. This break is close to the break expected from theoretical calculations of KBO formation. Combined with measurements of albedos, deep AO imaging of selected fields along the ecliptic will enable tests of the theoretical prediction that the number of KBOs as a function of radius is flat from 1 km to 10-20 km. Because small KBOs have been more collisionally eroded than large KBOs, GMT spectroscopy will provide the first tests of predicted composition differences between the smallest and largest objects.

Finally, because Sedna's perihelion lies outside Neptune's gravitational influence, its orbit shows that a (probably young) star passed within 150-1000 AU of the Solar System when the Sun was less than roughly 100 Myr old. In this encounter, the Sun may have captured Sedna and other icy planets. Spectra of Sedna-like objects can probe the conditions of the outermost part of the Sun's planetesimal disk or that of the passing star's.

GMT can provide unique tests of this and other scenarios for the formation and evolution of the outer Solar System. Deep searches for fainter Sednas well above the ecliptic plane will yield the statistics needed to test the capture hypothesis. AO imaging and spectroscopy will enable comparisons of the albedo and other surface properties between KBOs, "Sednas," and distant comets. Whether these observations confirm or deny the notion that our Solar System contains the nearest extrasolar planet, (captured from the passing star), they will provide unique tests of planet formation theories. In Figure 7 we show an AO image of Pluto and spatially resolved spectra to illustrate what the GMT will be able to detect on small bodies, such as Sedna and Xena, in the outer solar system.

1.5 Star Formation and the IMF

Stellar evolution is one of the most successful theories of twentieth century astrophysics. From the faintest brown dwarfs to the most luminous blue supergiants, this theory explains the basic observable properties of stars. The theory also accounts for changes in the physical properties of stars as they age, exhaust their nuclear fuel, and become red giant stars or supernovae.

Despite these accomplishments, stellar evolution theory is incomplete. We do not have a clear understanding of how stars form, how they influence their environments, and how they die. In the last twenty years, GMT consortium scientists have played a leading role in constructing a broad picture of star formation and evolution in our galaxy. We now seek to resolve the main uncertainties in this picture and to understand the complex processes that lead from clouds of gas and dust to stars, and from there to planets and the emergence of life.

1.6 The Initial Mass Function

Figure 8. The GMT will enable us to image unique southern hemisphere clusters in the Milky Way and local group with resolution 10 times that of the Hubble Space Telescope at wavelengths that penetrate regions of high extinction. The image of the Trapezium shown on the left, obtained with NICMOS and WFP2 on HST, reveals a dense region of star formation at a distance of 150pc. On the right we show a simulated GMT H-band image of the Trapezium at a distance of 100kpc. We will be able to resolve the initial mass function below the hydrogen burning limit in clusters of similarly high densities in the LMC and SMC, as well as probe the ratio of high to low mass stars throughout the local group.

The origin of the initial mass function (IMF) of stars and sub-stellar objects remains one of the most important unsolved problems in galactic astronomy (e.g. Chabrier 2003). Many stars are in binary or multiple systems. Thus, measuring and understanding the origin of the companion mass ratio distribution (CMRD) is closely linked to the IMF. In addition to providing fundamental constraints on theories of star formation, measuring the shape of the IMF and the CMRD as a function of chemical composition, star formation rate, and galactic environment is vital to improving our understanding of the formation and evolution of galaxies. The high resolution and sensitivity of the GMT will enable a wide range of studies targeted at understanding the origin of the IMF and the CMRD as function of the "initial conditions" of star formation.

Together with measurements of planetary masses, the IMF and the CMRD of unique southern hemisphere targets provide the relative frequency of stars, brown dwarfs, and planets as a function of environment and time. A GMT database of these measurements will enable robust studies of the physics of star and planet formation. Among other issues, we envision that this GMT database will yield robust measures of the efficiency and outcome of star and planet formation as a function of metallicity, magnetic field strength, and other intrinsic properties of the interstellar medium (including those that mimic conditions in distant galaxies and the clouds where the first stars form) and environment, and a better understanding of how high mass star formation differs from low mass star formation and how brown dwarf formation differs from planet formation.

Recent observations show that some clouds produce dense clusters of hundreds of stars, while others form loose associations of 10-20 or fewer stars. Within this diversity of clusters, the IMF for roughly 0.2-30 M_0 stars is apparently universal, with little variation from cloud to cloud in the Galaxy. However, there is considerable variation at lower and higher masses. Per unit mass, clouds with dense star clusters appear to form more brown dwarfs and perhaps more massive stars than low density clouds with loose stellar associations. Furthermore, in contrast to the companion mass ratio distribution in the stellar mass range, there appears to be a deficit of brown dwarfs companions within 3AU, inconsistent with these substellar companions having been drawn from the field IMF. Moreover, there is some evidence for variations in the IMF among nearby galaxies, where the high mass end of the IMF often appears top-heavy compared to the "standard" IMF. In both local clouds and nearby galaxies, it is still not clear whether variations in the high mass end of the IMF are real or due to sampling errors. At the low mass end, searches for brown dwarfs have been limited.

If the differences in the high mass and low mass IMFs are real, the IMF becomes a unique probe of the physics of star formation within molecular clouds and places limits on the mass-to-light ratio we can expect in galaxies. These data then test efficiency of star formation as a function of the initial conditions (e.g. temperature and density) and a measure of dynamical encounters within the evolving cluster. Establishing the importance of initial conditions and dynamical interactions will require the large complete samples of clusters and star-forming regions in the Milky Way and other nearby galaxies that are accessible with the GMT.

The advanced AO capabilities of the GMT will enable tremendous advances in our understanding of the IMF. In the Galaxy and the Local Group, sensitive, high spatial resolutions observations will reveal complete samples of brown dwarfs in more distant star-forming regions (e.g., M17) and older open clusters (e.g., NGC 1805 and NGC 1818), where we currently observe only massive stars. These data will enable detailed comparisons with local dense clusters (Orion) and looser associations (Chamaeleon and Lupus). For example, a GMT with AO images at HKL can detect all objects with mass less than 2 Jupiter masses (M_J) and ages < 3 Myr through as much as 55 magnitudes of visual extinction in roughly three hours of on-source integration over a 30″-40″ field of view. In one hour, low resolution multiobject near-IR spectra (R < 300) would then yield estimates of temperature and surface gravity to distinguish background field stars from cluster members and to provide a complete IMF.

To illustrate the GMT impact on the CMRD, near-IR, high contrast AO images would provide a complete sample of low mass companions at separations > 10 AU to distances of 500 pc. The distribution of binary separations of sun-like stars in the solar neighborhood peaks at 30 AU; thus observations of this type would yield the vast majority of binaries down to mass ratios > 50 for low mass stars. At orbital separations of 100 AU or more, the GMT can resolve planets > 2 M_J around sun-like stars at the distance of Orion. At the distance of nearby star-forming regions like Chamaeleon (150 pc), this combination corresponds to Jupiter mass objects at separations of 30 AU or more. High spatial resolution and high-contrast multiobject spectroscopy would yield temperatures and surface gravities crucial for accurate estimates of the mass and age of substellar/planetary companions, as well as provide empirical points of comparison for evolutionary models used in determining the shape of the IMF and star forming history of these regions. In Figure 8 we show one of the prototypical dense clusters in the Milky Way, the Trapezium in Orion. The GMT will be able to resolve star clusters with similar densities throughout the galaxy and in the Magellenic Clouds.

1.7 Collapse of Molecular Clouds to Stars and Disks

Star formation begins with molecular clouds, where discrete clumps of gas and dust undergo gravitational collapse to form protostars. Radio and sub mm observations that penetrate the large optical extinction of dark clouds reveal the early stages of this process, but we have yet to learn what initiates the collapse or how the collapse evolves with time. We do not know how and when protostars first form or why a cloud collapses into a single star, a multiple star, or a star cluster. Although we detect circumstellar disks around protostars, our understanding of disk formation and early evolution is sketchy. Observations show clear evidence for the formation of complex molecules within the collapsing clumps and the circumstellar disk. We have made some progress in understanding the chemistry of this material, but we are a long way from learning which processes lead to the complex organic molecules that form the basis of life.

When a molecular cloud collapses, conservation of angular momentum produces a protostar surrounded by a disk. Interactions between the star and the disk drive a high speed jet and a bipolar molecular outflow. Although the extinction through the collapsing cloud is too large for optical observations, IR images and spectra with the GMT will yield the first spatially resolved probes of the protostar, the newly-formed disk, and the bipolar jet. Low resolution multiobject spectroscopy and high resolution (~ 80,000) near-IR line profiles will yield stellar temperatures and luminosities, rotation rates, magnetic field strengths from Zeeman sensitive lines, and surface gravities, leading to more robust tests of theories for protostellar evolution.

Studies of the evolution of the gas will benefit from synergy between ALMA and the GMT. From the GMT side, AO imaging and spatially resolved spectra of H I, H_2, and other species will probe the geometry and ionization state on unprecedented (~ 3 AU) scales, providing robust measurements of the mass infall, accretion, and outflow rates as a function of time and stellar mass, the radial density and temperature structure of the disk, and the velocity dispersions, masses, and lifetimes of embedded clusters. In the nearest star forming regions, AO imaging will probe the geometry, density, and temperature of gas in the region where a disk/stellar wind is focused into a well-collimated jet, ~ a few to tens of AU from the central star. ALMA should provide information on similar scales, leading to detailed tests of MHD models for jet formation. In the mid-IR, a single object cross-dispersed Echelle operating from 8-24 μm at R > 50,000 would provide crucial data on the evolution of icy and silicate grains throughout the collapse and detections of new molecules and ices, including those with water and organic materials. These data will enable a thorough census of the complex chemistry in clouds and disks that ultimately lead to the conditions favorable to life.

2 Stellar Populations and Chemical Evolution

Baade's recognition of distinct stellar populations provided an enduring framework for studies of galaxy formation and evolution, stellar chemistry, and stellar dynamics. Today any viable model for the formation of the Milky Way must address the origin of thin disk, thick disk, bulge and halo populations and the diversity of their dynamical, chronometric and chemical properties. Our understanding of stellar populations in external galaxies is quite limited and is based largely on integrated-light spectra. The GMT will open a number of avenues for detailed studies of stellar populations in the local group and beyond. The two principal techniques that the GMT will bring to the study of stellar populations are diffraction-limited photometry of resolved stars, and high-sensitivity high-resolution spectroscopy of individual stars and unresolved stellar populations. The case for diffraction-limited imaging with extremely large telescopes has been clearly articulated by the GSMT SWG and we only briefly summarize it here. The case for high-resolution stellar spectroscopy has received less attention and we expand on it in more detail below.

2.1 Diffraction-limited imaging of resolved stellar populations

By operating at the diffraction-limit the GMT will realize its maximal sensitivity to point sources, achieving the full D^4 gain compared to the present generation of 8m class telescopes. The high angular resolution offered by the GMT in the near-IR will allow it to address critical issues relating to the formation and evolution of dense stellar systems. Two critical areas relate to understanding the origin of the initial mass function (IMF) and the ubiquity of multiply episodic star formation.

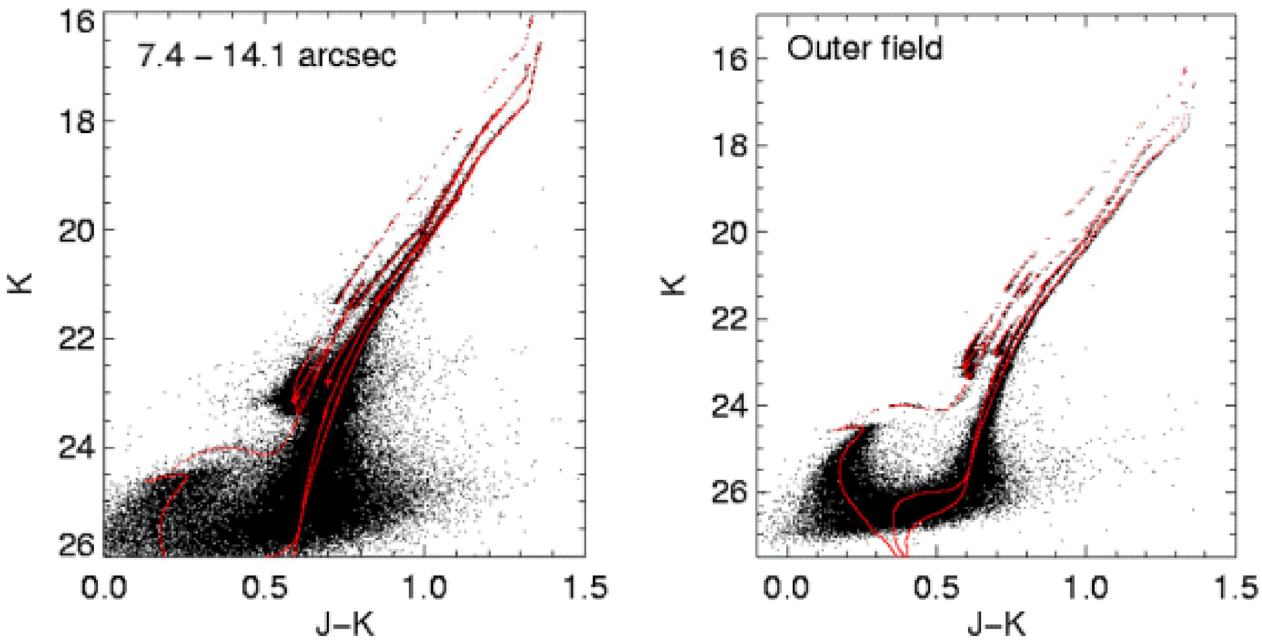

Figure 9. Simulated near-IR color-magnitude diagrams for M32 as observed with a diffraction-limited 30m telescope. The central region remains confusion limited for K > 25, while in the outer regions reliable photometry is possible to K ~ 26. The GMT will not reach as faint as a filled-aperture 30m, but in confusion-limited fields the GMT will have 80% of the resolution of a 30m and will thus probe nearly as deeply. From the GSMT SWG report "Enabling Science with a Giant Segmented Telescope".

Current studies of the IMF are limited in the range of environments that can be explored. The GMT will allow detailed studies of the IMF in more extreme environments, particularly those with high stellar densities, unusual chemical abundances, or exotic physical conditions. There are suggestions from studies of starburst galaxies (e.g. M82, Arp220) that the IMF in dense regions is top-heavy. A solid demonstration, or contradiction, of this in local group star forming regions would have important implications for our understanding of star formation in young galaxies and luminous starburst systems, models of the chemical evolution of galaxies, the star formation history of galaxies, and, potentially, the evolution of the global star formation rate over cosmic time. Thus there is a strong science driver for accurate determinations of the IMF in regions of extreme star formation as a function of chemical composition, stellar density, and galactic environment.

Most of the dense star formation regions in the galaxy are barely resolved with current instruments. Present observations of 30 Dor in the LMC are confusion, rather than sensitivity, limited at $1M_{sun}$. The GMT, with its exquisite spatial resolution and smooth, stable PSF, will allow us to extend current studies a factor of 3-4 in resolution yielding an order of magnitude in increased sensitivity for a fixed amount of telescope time. This would enable crucial studies of the IMF in the LMC down to 20 M_j with broadband JHK imaging and to the Hydrogen burning limit with R=100 narrow-band imaging.

Furthermore, the spatial resolution of the GMT with Laser Tomography Adaptive Optics (LTAO) will permit us to resolve the bulk of the stars in a Trapezium-like cluster at the distance of the LMC.

The southern hemisphere location of the GMT makes it ideally suited to studies of the nearest ultra-dense stellar clusters and the nearest supermassive black hole: the galactic center. The high angular resolution of the GMT will allow us to push studies of the dynamics of the black hole sphere of influence to new levels and may also allow us to identify a near-IR counterpart to the central radio source, SgrA*. Current limits on the near-infrared source put it below the crowding limit (K ~ 17), but theoretical models allow a huge range of near-infrared emission from the accretion flow. A clear detection of a near-IR counterpart, or a restrictive upper-limit, will constrain models of accretion onto the black hole at the center of the Milky Way.

The GSMT SWG has simulated diffraction-limited photometry of dense stellar populations in the nearby galaxy M32. While observations of M32 are not practical from Chile with the GMT, the GSMT simulations provide a very useful baseline for gauging the performance of a 24-30m telescope in the study of crowded fields. To date, no one has resolved stars in M32 fainter than the red horizontal branch. Deeper color magnitude diagrams (CMDs) are needed in both the outer and inner regions to confirm the mean age and metallicity and the radial gradients that are predicted by population synthesis models. The GSMT group has used simulated images in order to explore the ability of a 30m-class ELT and MCAO system to resolve stars in dense environments such as M32. Their M32 simulation assumed a mix of 1 Gyr ([Fe/H] = 0), 5 Gyr ([Fe/H] = 0), and 10 Gyr ([Fe/H] = -0.3) old populations, each drawn from a Salpeter IMF and extending to masses well below the crowding limit. The 1, 5, and 10 Gyr old populations were assumed to comprise 10%, 45%, and 45% of the total, by mass, respectively.

In the GSMT committee's near-IR color magnitude diagram of the inner region of M32 (Figure 9) the photometric errors are dominated by confusion, even at the resolution of a 30m aperture. The main features of the CMD are well defined and one can distinguish CMD morphologies arising from distinct star formation histories and abundances. Current state of the art AO CMDs on 8m telescopes provide reliable photometry only for luminous AGB stars (MK < -5) in the outer annuli; a 30m-class ELT will probe 6-7 magnitudes deeper, reaching stars close to the turnoff for a 1 Gyr old population.

In the right panel of Figure 9 we show the GSMT group's CMDs for the outer annulus (7.4-14.1") of the inner field. The basic features of the CMD are well defined and there is a clear color separation between the old and intermediate age populations. While M32 is not easily observed from GMT sites currently under consideration, the GSMT committee's work demonstrates the great potential for photometric studies of star formation histories in crowded regions with diffraction-limited ELTs. There are, however, serious challenges related to our ability to carry out robust photometry with the AO point spread function. Variations in the PSF with spatial position, time and wavelength will pose challenges and may ultimately limit the utility of this technique. Recent modeling suggests that photometric precision of ~ 2% should be possible with an MCAO imager. Fortunately, there are ambitious MCAO programs underway on the current generation of telescopes that will go a long way towards clarifying these issues as the GMT development proceeds.

2.2 High Resolution Stellar Spectroscopy

Stellar atmospheres contain a fossil record of the material from which they formed as well as the products of internal nucleosynthesis that may have been brought to the surface. High spectral resolution abundance studies of stars of differing populations (e.g. AGB stars, metal-poor giants, supergiants) provide insight into the chemical evolution of galaxies and their interstellar matter. Chemical composition depends upon environment; distinct components of the Galaxy have taken a chemical enrichment path dependent on local physical conditions. Studies of a handful of the brightest stars in the closest dwarf spheroidal galaxies have revealed a great variety in their chemical composition, suggesting that in even the smallest galaxies, chemical evolution is a local process. The GMT will have a dramatic impact in the study of nucleosynthesis as it will open up hitherto unreachable classes of stars for study.

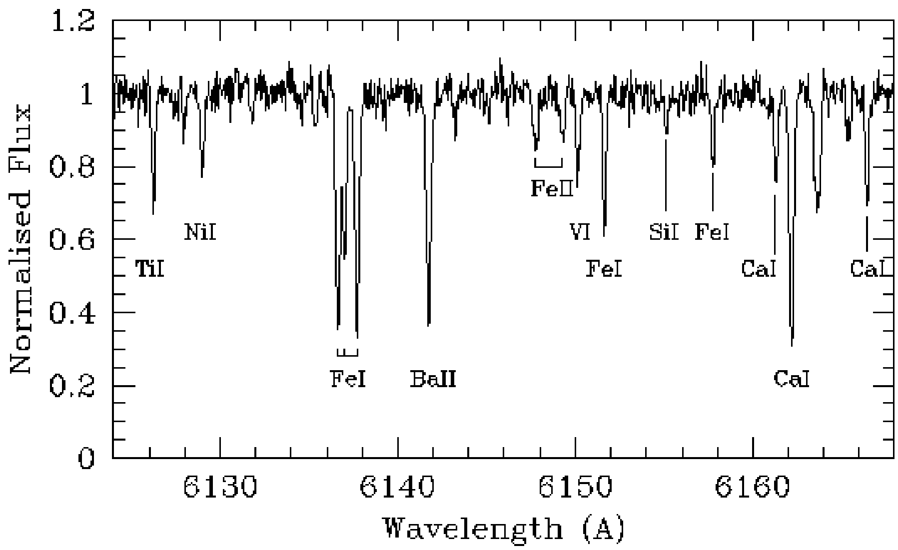

Figure 10. Simulated GMT typical high resolution spectrum anticipated for individual RGB stars in the halos of Local Group galaxies (S/N~30, R~25,000). For M33 halo RGB stars this would require approximately 35 one-hour exposures. The same quality spectrum could be obtained for RGB stars in galaxies at 2Mpc by combining 40 multi-object spectra, each comprised of 24 one-hour exposures. From A. McWilliam, private communication.

2.2.1 Abundances in Local Group Giants

Red giant stars are particularly useful for measuring the history of chemical evolution of nearby galaxies. Their high luminosity makes them accessible at great distances, their low temperatures result in the presence of lines from many elements and molecules, and their progenitors have ages up to ~13 billion years. Indeed, the chemical composition of red giant stars provides a fossil record of the history of galaxy evolution.

The GMT will allow abundances to be routinely measured for RGB stars in members of Local Group galaxies visible from the Southern hemisphere. This includes nearby galaxies such as the irregular galaxies LMC and SMC, a host of dwarf spheroidal galaxies (e.g. Sculptor, Carina, Fornax, Leo I), and objects like Leo II (dSph-E0p). High resolution spectra of RGB stars in more distant Local Group galaxies, such as NGC 6822 (IBm IV-V) at 495 Kpc, IC~1613 (IBm/Irr V) at 725 Kpc, Tucana (dSph-dE5) at 890Kpc and M33 (Sc,cd II-III) at 795Kpc would require considerable effort: up to 35 one-hour exposures for S/N ~ 30. But this would be worthwhile if the spectrograph is equipped with a multi-object capability; one might obtain S/N ~ 30 spectra for several hundred RGB stars in one of these galaxies with a modest investment of observing time. An example of what one such spectrum would reveal is shown in Figure 10.

2.2.2 Detailed Chemical Composition History for Galaxies beyond the Local Group

A natural step in understanding the evolution of galaxies, using the chemical composition of red giant stars as fossil record, will be to study and inter-compare results from all galaxy morphological types. Unfortunately, the Local Group of galaxies contains a very limited census of galaxy morphologies, so it will be necessary to make detailed chemical abundance studies of RGB stars for galaxies beyond the Local Group.

The GMT will allow us to measure the history of chemical enrichment for galaxies outside the Local Group, including several spirals and dwarf elliptical galaxies, for the first time. This feat will be accomplished by combining low S/N, multi-object, spectra of carefully selected RGB stars.

Even with the GMT it will not be possible to acquire a high resolution spectrum of single RGB stars outside the Local Group with sufficient flux for detailed chemical abundance analysis. Co-adding spectra of many stars, however, will allow us to reach stars beyond the reach of individual study. The GMT high-resolution spectrograph, possibly fed by a multi-fibre system, will allow one to obtain high S/N high resolution spectra by combining large numbers of the individual low S/N spectra. Program stars will be selected from photometric studies that indicate similar stellar parameters and metallicities; velocities from the low S/N spectra will permit appropriate shifting of the spectra before combining.

2.2.3 Super-High S/N Spectra of Extreme Metal-Poor Stars

Extreme metal-poor stars ([Fe/H] < -2.5) are thought to precede the main halo population, possibly from a pre-Galactic era; some stars are so metal-poor, and have such unusual compositions that they are thought to contain the composition of individual supernova events. These objects are profoundly important for understanding the first step in chemical enrichment, and provide important constraints on the yields of type II supernovae. However, because they are so metal-poor, (the most metal-poor with [Fe/H] ~ -5) lines from interesting elements are too weak to measure in normal high dispersion spectra with S/N ~ 100. With the GMT it will be possible to obtain spectra with S/N ~ 1000 in a few hours; this would enable the detection of very weak lines (~0.1mA) from various elements. The resulting abundance patterns would be critical for identifying nuclear reaction processes and understanding the earliest phase of chemical evolution.

Figure 11. Large spiral disks have been present since $z \sim 2$, yet their disruption via mergers may play a key role in the formation of elliptical galaxies. By probing the mass, dynamical and chemical abundance evolution of disk and spheroidal galaxies in the critical $1 < z < 5$ epoch, GMT will improve our understanding of the origin of the Hubble sequence.

3 The Assembly of Galaxies

3.1 From Seed Fluctuations to the Hubble Sequence

The ability to directly observe the development of galaxies from nascent 'proto-systems' in the early universe through to the mature, well-structured systems (Figure 11) we see today remains a fundamental ambition of observational cosmology and is a major science driver for ELTs. GMT can play a significant role in taking some large steps forward towards this goal, through focusing on two key areas: 1) tracking galaxy development in the key growth epoch and 2) following the evolution of *all* forms of mass - baryonic mass in both diffuse and condensed forms, and the ubiquitous dark matter.

For the first task we need to track galaxy development over the critical redshift range $1 < z < 6$. Current observations indicate that this is the interval over which ~80% of the total star formation and heavy element production within the Universe took place, and hence is the major epoch of galaxy formation and assembly.

An important contextual framework is provided for these goals from the general concordance that has emerged in recent years on a ΛCDM cosmology, together with results from state-of-the-art numerical simulations (Springel et al. 2005). These suggest a scenario where tiny seed fluctuations in the primordial dark matter, relics of the inflation era, grow through gravitational instability into the progenitors of present day galaxies. The infall of gas and smaller stellar systems into the deepest of these dark matter potential wells eventually results in the build-up of baryonic mass in galaxies. The continual merger of dark matter haloes and infall of matter leads to a progressive increase in the mass and size of galaxies with cosmic time.

While this hierarchical galaxy formation paradigm has many successes, it has serious shortcomings on small scales, particularly those appropriate for individual galaxies. Irrespective of ΛCDM, our understanding of galaxy formation and evolution has substantial gaps. For example, the relative importance of gravitational as opposed to gas dynamic processes is poorly understood at this time. Feedback from stellar winds and supernovae can dramatically influence the star formation efficiency in galaxies, particularly in low mass systems, but the impact of this effect has yet to be quantified. The detailed distribution and structure of the intergalactic medium, which is the main reservoir of gas available for galaxy and star formation, remains poorly determined. Additionally, the numerical simulations do not yet have the resolution or the necessary physics to provide reliable information on the internal 'astrophysics' of galaxies as they proceed through their build-up phase.

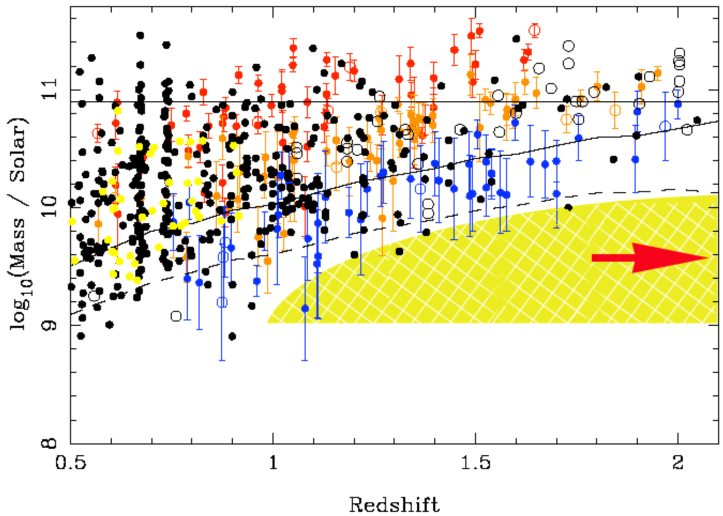

Figure 12. Evolution of stellar mass in galaxies from z = 2 to the present. The horizontal line shows the present value of M^*. We know very little about sub-M^*galaxies at redshifts above 1.5, the peak epoch of galaxy building. The GMT will allow us to explore the evolution of sub-M^* galaxies at z < 2 and beyond. The yellow hatched region shows the parameter space that will be explored by the GMT, the red arrow indicates that GMT will also explore mass evolution to higher redshifts than has been possible to date. Adapted from Glazebrook et al. (2004).

To significantly advance our understanding beyond this point requires an empirical attack on each of these issues. GMT will be extremely well placed to do this, particularly when working in concert with ALMA and the JWST. GMT's wide-field ground-layer AO optimized visible and near-IR multi-object spectrographs will allow us to directly measure the buildup of mass, both dark and light, over much of cosmic time. GMT will have a strong synergy with JWST in this area. In addition, GMT will have the sensitivity to measure star formation rates and chemical abundances for thousands of galaxies with great confidence at high redshift, and therefore determine the evolution of these quantities as a function of environment and time. It will also have the capacity to probe the intergalactic medium tomographically at high redshift via the absorption features it imprints on the spectra of background sources, thereby providing a complete census of the cosmic baryons and insights into this component's role in fueling galaxy and star formation. These exciting possibilities are further elaborated in the subsequent sections.

3.2 The Evolving Galaxian Stellar Mass Function

One of the clear predictions of the hierarchical model of galaxy formation is that there should be a dramatic evolution in the distribution of galactic masses as a function of cosmic time. At early times there were no massive galaxies, but there was an abundance of low mass systems, the building blocks of today's spiral and elliptical galaxies. As these small systems merge to form larger galaxies, the mass function will evolve towards more massive systems. Since a redshift of one, and perhaps earlier, the galactic mass density has been dominated by L* and more massive systems. At some high redshift all of the stellar mass that is presently in these galaxies must have been in smaller units and in the form of gas. A clear test of the hierarchical model, and a requisite part of any empirical understanding of galaxy evolution, is the evolving galaxian stellar mass function.

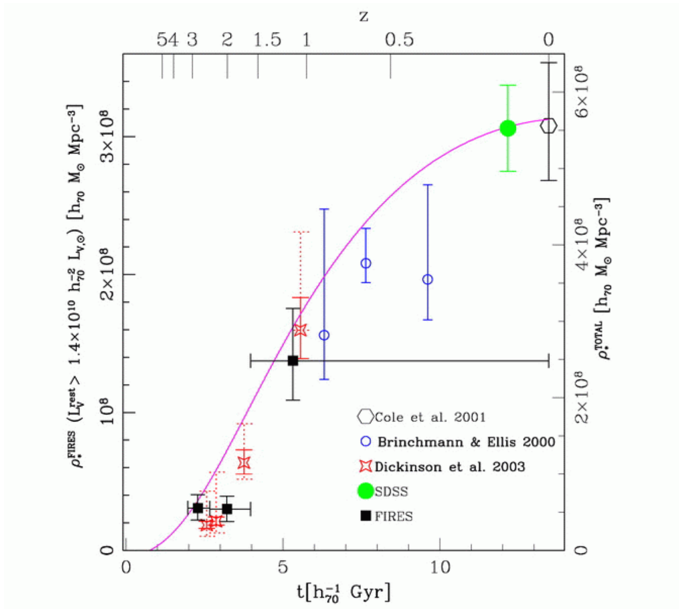

Figure 13. The evolving stellar mass density from high redshift to the present. The mass density at high redshifts is quite uncertain as it is based on photometric redshfit surveys of small areas. The GMT will enable spectroscopy of mass-complete samples that reach well below M^* over representative volumes. From Rudnick et al. (2004).

Recent work with 8-m class telescopes has probed the mass evolution of M^* galaxies to z ~ 2 (Glazebrook et al. 2004; Dickinson et al. 2003). The space density of massive galaxies evolves slowly, but there is general agreement that the total stellar mass density has grown by roughly a factor of two since z ~ 1.5. As Figure 12 and Figure 13 show, high mass galaxies were in existence as early as z ~ 2, even though the total stellar mass density was only 20-30% of its present-day value. At redshifts beyond 1.5 or so, contemporary surveys are unable to obtain redshifts and spectral diagnostics for galaxies with $M < M^*$ in samples that are mass complete. Thus it is not possible to track the evolution of low mass systems into larger systems via dry mergers, if indeed this is a significant process. Mass complete samples at these redshifts are beyond the reach of spectroscopy with current telescopes, but the GMT will improve this situation, allowing spectroscopy well into the 0.1 to 1 M^* regime without bias against high M/L objects.

The shortcomings of the current generation of telescopes for this type of work become more acute at higher redshifts. There are strong indications that a significant fraction, from 30 to 60%, of the total stellar mass at z ~ 3 is in objects with colors redder than the nominal Lyman break samples (e.g. Labbe et al. 2005). These distant red galaxies are likely an important piece of the puzzle linking the full range of present day Hubble types with their progenitors at high redshift. Spectroscopy of these distant red galaxies is confined to objects with masses greater than $10^{11}M_{sun}$ and significant on-going star formation. Passive systems and sub-M^* objects are beyond the reach of current telescopes. The GMT visible and near-IR spectrographs will open up this critical galaxy population to spectroscopic analysis. The GMT will have substantial synergy with JWST in this area and with the legacy data products from the Spitzer IR space telescope. Working in deep HST and JWST survey fields the GMT will be able to track the evolution of mass in spheroids, disks and dwarf galaxies to further our understanding of the origin of the Hubble sequence.

Stellar masses are determined from spectroscopic redshifts and multi-color photometry, particularly in the near-IR. Both JWST and Spitzer will provide rest-frame 1 micron luminosities for large samples of candidate objects at z > 3. The GMT, with its sensitive spectrographs and wide field, will allow redshift determinations for large numbers of these objects, down to depths that will include many sub-L* objects at redshifts of 2 and beyond. Deep surveys being carried out now with the Hubble and Spitzer space telescopes far outstrip the spectroscopic capabilities of any telescope in existence. The GMT will help these space telescopes achieve their full scientific potential by building on the legacy of their data archives. A complete accounting of the conversion of gas to stars over the full span of time will be within the reach of the GMT and the next generation of space telescopes.

3.3 Mapping the underlying dark matter

By its very nature, dark matter can only be traced indirectly through observation of its gravitational influence on objects in the visible universe. For such visible 'tracers' to be useful in the context of understanding galaxy assembly and large-scale structure formation, they must sensitively probe this influence in a quantitative way that allows the dark matter distribution to be accurately charted over scales ranging from those as small as individual galaxies (~10 kpc) to the megaparsec scales of clusters and large-scale galaxy structure. Here the extra light grasp and high spatial resolution of GMT will enable significant advances in exploiting three such tracers for this purpose: (1) quasars and remote galaxies that are gravitationally lensed by foreground dark matter concentrations associated with individual galaxies and clusters of galaxies, (2) giant cD galaxies which pinpoint the centers of the dark matter potential within clusters and whose large extended envelopes allow its influence to be traced out to several hundred kiloparsecs, and (3) intracluster planetary nebulae which provide a rich supply of test particles for tracing the dynamical influence of dark matter over cluster scales.

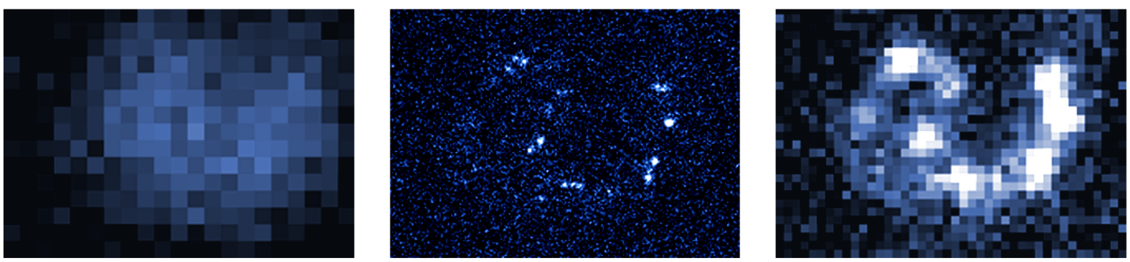

Figure 14. Simulated images of the interacting galaxy, the antennae, as seen in [OII]3727 emission at z = 3.3. The left panel shows the image in natural seeing with FWHM = 0.5″. The center panel is for a 20m with MCAO, the right panel shows the same field with a GLAO PSF with FWHM = 0.15″. Each panel is 2″ x 1.5″.

Gravitational lensing provides one of the best probes of dark matter on galaxy and galaxy-cluster scales at epochs most relevant to galaxy assembly. Strongly-lensed objects (e.g. quasars and cluster arcs) are particularly useful in that they provide information regarding the spatial distribution of localized dark matter concentrations. Lensed quasars typically probe haloes of individual galaxies. In contrast, strong lensing by galaxy clusters provides unique insight into their core mass distribution, in addition to it having the action of a 'cosmic telescope' in bringing very distant and otherwise inaccessible objects into view (c.f. cB58). For mass modeling the lenses, the most important piece of information is redshifts for the arcs and, secondarily, redshifts for the individual galaxies along the cluster core line-of-sight. The best approach to studying the mass distribution is to globally compare large lensing simulations to the global statistics of a large sample of lensing clusters. Such samples will be forthcoming in the near future; an effective comparison to detailed models requires the ability to gather redshifts for a large set of objects which are densely distributed on the sky, and which often have extremely distorted morphologies. This requires medium to low resolution optical and near-infrared spectroscopy, and would be most effectively done using a large format (1 x 1 arcminute), fully-filled IFU operating in either a natural seeing or GLAO mode.

The outer regions of cD galaxies provide useful dynamical probes of the dark matter distribution in clusters. Typical surface brightness limits at which useful velocity information can be recovered are about 26.2 magnitudes per square arcsecond in the V-band. This projects to a 50kpc radius for the systems studied to date. Long-slit observations are non-optimal in part because of the limited spatial sampling, and because uniform sky subtraction is very challenging across a very long slit. A better approach would be to use a large IFU in conjunction with the GMT multi-object spectrograph on somewhat more distant targets. Such a system could readily address cD dynamics with adequate S/N for a large set of cluster cD galaxies.

Given a sufficient number of discrete test particles (typically 1000 or more), one can in principle recover details of the dark matter density distribution. The Virgo cluster contains approximately 200 intracluster PNe per square degree, providing a powerful set of dynamical tracers. Exploring the Coma cluster, our closest example of a truly massive rich cluster, requires significantly greater (about 4 magnitudes) sensitivity than available on current 8m class telescopes. Large samples of PNe can be identified at the distance of Coma with a wide-field imager. A wide-field multi-object spectrometer, using either multi-slits or fibers, is needed to measure the velocity field. PNe-based dynamical studies, be they based on narrow-bandpass imaging or spectroscopy, are photon starved observations and so they benefit dramatically with the large collecting area of the GMT.

3.4 Star Formation and the Origin of the Hubble Sequence

Present-day galaxies have a generally well-ordered set of morphologies, with most luminous galaxies being classified as either disk or spheroid systems or some combination of these two types. Hubble ordered the range of morphologies in a sequence ranging from pure disk at one extreme to pure spheroid at another, with no physical basis for this order. We now understand the Hubble sequence to reflect a transition from rotationally supported dynamically cold stellar systems (disks) to those supported by random motions (spheroids). Explaining the origin of the Hubble sequence remains one of the forefront challenges of stellar dynamics and galaxy evolution. It is likely intimately related to star formation, gas cooling and galaxy mergers.

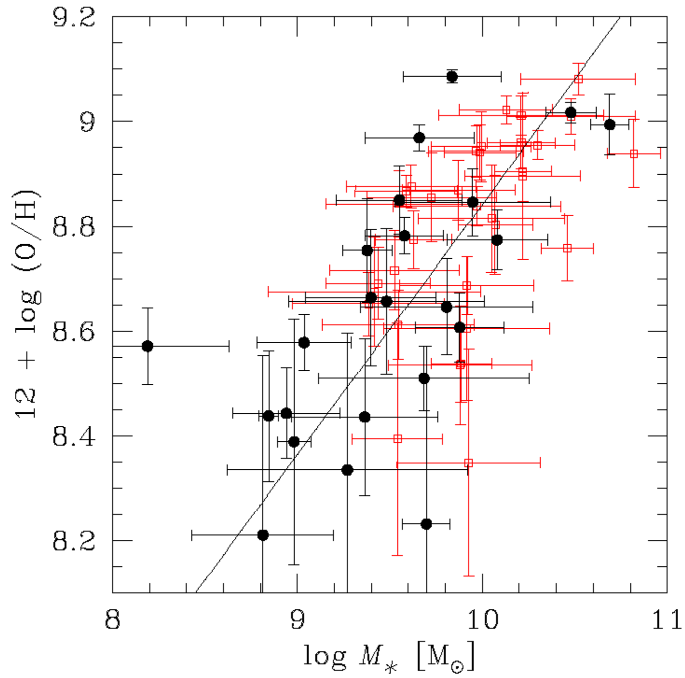

Figure 15. The mass-metallicity relation at z ~ 0.7 from the CFRS and GDDS samples. Stellar masses provide a means of linking high and low redshift galaxies together when tracing their chemical evolution. The GMT, working in concert with JWST, will allow this powerful tool to be brought to bear over the full redshift range of galaxy formation and assembly. From Savaglio et al (2005).

Deep HST observations show that the basic Hubble types have been in place since z ~ 1 (e.g. Abraham et al. 1999). Galaxies at z > 3, however, do not appear to show the standard spiral or elliptical morphologies. The impact of the changing band-pass, called the "morphological K-correction" is disputed. Observations at a fixed rest-frame wavelength are clearly needed and this requires high spatial resolution and high sensitivity imaging at near-IR wavelengths for samples at z > 1. The GMT, operating in either the GLAO or LTAO mode, will have both the resolution and sensitivity to address the origin of the Hubble sequence. In Figure 14 we show images of the merger candidate, the Antennae, in simulated GMT images with native seeing, GLAO and MCAO. The ground-layer corrected image reveals most of the basic structure of the system. The large fields, and thus large sample sizes, available to GLAO make it ideally suited to statistical studies that require both high resolution and high sensitivity. The LTAO images, while confined to modest fields of view, will allow detailed dissection of individual objects into their structural and star-forming parts, and enable spectroscopic measurement of such quantities as the star formation rate and the stellar and gas dynamics, that delineate the different Hubble types. The LTAO and MCAO modes will be most powerful when used in conjunction with multiple integral field units feeding intermediate resolution (R~5000) NIR spectrographs, while the GLAO mode will enhance the power of the multi-object spectrographs.

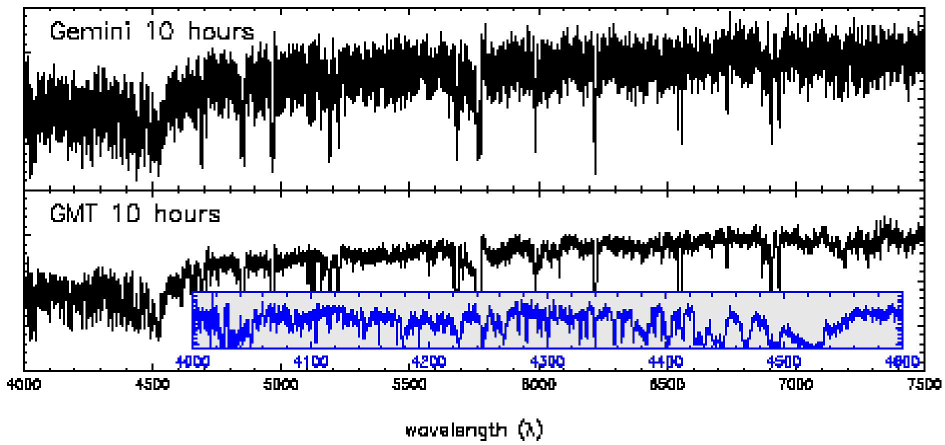

Figure 16. High-resolution (R~10,000) spectra of a z = 2.7 Lyman Break Galaxy with an apparent magnitude of r = 24 as observed with an 8m (top) and the GMT for 10 hours. The simulated GMT spectrum has SNR = 20. The insert shows the rich structure in the Lyα forest region of cB58, which will be used to study the three-dimensional structure of the IGM and its relation to galaxy evolution. At longer wavelengths, these spectra also a rich spectrum of stellar and ISM absorption features internal to the galaxy. The cB58 spectrum was kindly provided by A. Shapley.

3.5 The Chemical Evolution of Galaxies

The chemical elements heavier than Lithium are created in nuclear reactions in stellar cores or in the violent explosions of supernovae. The evolution of the Universe from its primordial Hydrogen and Helium composition into the rich chemical diversity we see today was an essential process in the creation of terrestrial planets and carbon-based life. Just as cosmic star formation leads to a build up of stellar mass in galaxies, the total mass and relative abundances of heavy elements will grow with time. While the total number of heavy nuclei provides a measure of past star formation, the distribution of abundances by element provides diagnostics of physical processes in stellar evolution and in the physics of SNe.

Our best approach to an empirical measure of the chemical evolution of the Universe comes through studies of the gas phase abundances, both in galaxies and in the intergalactic medium. Present work is significantly constrained by our inability to compare the same ionization states and transitions within a particular element at both high and low redshifts. The GMT will enable large gains in sensitivity for near-IR spectroscopy. This will allow us to apply standard abundance determination techniques to the integrated light of star forming galaxies to very large redshifts. The critical lines of [OIII] can be observed in the K-band to z ~ 3.5, allowing a single abundance determination technique to be employed over 90% of the available look-back time.

Critical issues in this field center around the validity of closed-box models, feedback, and the impact of environment on chemical evolution. Matching galaxy samples at high and low redshift poses a significant challenge in testing chemical evolution models. The mass-metalicity relation offers a clear path to matching galaxy samples over a wide range of cosmic time and significant progress is currently being made in this area, as shown in Figure 15.

One class of model produces the low abundances seen in dwarf galaxies and the enrichment of the IGM via outflows driven by stellar winds and SNe associated with massive starbursts at high redshift. These models predict that chemical enrichment within low mass galaxies is an episodic process, while in massive galaxies heavy element abundances increase more smoothly and monotonically over time. There clearly is vigorous star formation going on at intermediate and high redshifts (e.g. $2 < z < 4$) but it is unclear to what degree this period represents the first, or even the dominant, star formation episode in these systems. Abundance determinations can go a long way to resolve this uncertainty. Early indications of abundances not far from the solar level are suggestive of earlier star formation, but these measurements are confined to a small number of high luminosity objects.

Near-IR spectroscopy of large mass-defined samples is the key to the abundance problem at high redshift. Present investigations are limited by the small detector formats and the difficulty in overcoming the detector noise-floor. The GMT, with its large collecting area and field of view, coupled with expected improvements in detector technology, will break open this field. The GMT near-IR imaging spectrograph will allow spectra of tens to hundreds of objects to be observed simultaneously with sufficient resolution to resolve out the atmospheric OH emission. The large collecting area of the GMT will allow us to overcome the detector read noise, particularly if, as anticipated, it can be driven below $4e^-$. There is a great deal of synergy with JWST in this area. JWST will excel at low-resolution spectroscopy; the GMT will out perform it in the high-resolution modes. Working together, the two facilities can carry out powerful surveys of the chemical evolution of the Universe.

3.6 Tomography of the IGM: probing the gas reservoir for galaxy formation

The intergalactic medium (IGM) contains most of the baryons in the Universe, and is the birth-place of galaxies at high-redshift. Understanding the evolution of the thermal and ionization state of the IGM and its chemical enrichment history has been a central part of cosmology since the very first high-redshift quasar was discovered in 1960s. Currently, IGM evolution is studied in the framework of so-called fluctuating Gunn-Peterson effect, in which IGM absorption arises from and traces the baryonic density distribution (e.g. Hernquist et al. 1996). It has also become clear in the last decade that the strong interplay between galaxies and their surrounding intergalactic and intracluster media, through galactic winds, the radiation field and AGN feedback, might hold the key to understanding both the evolution of the IGM and the formation and growth of galaxies and AGNs. Such studies, however, are extremely demanding for the current generation of telescopes, because luminous background sources suitable for IGM studies are rare, and objects with the high sky density required to map out the large scale structure of galaxies and the IGM distribution at high redshift are very faint. Major investments of time on 8-10 meter class telescopes (e.g. Adelberger et al. 2005) have begun to show promising results, including suggestions that star-forming galaxies at $z \sim 2$-3 can affect large volumes of the IGM through galactic feedback, up to a distance of 1Mpc. These observations are at the limit of current 8-10 meter telescopes and wide-field spectrographs, and are affected by the small survey volumes, small number statistics and low S/N.

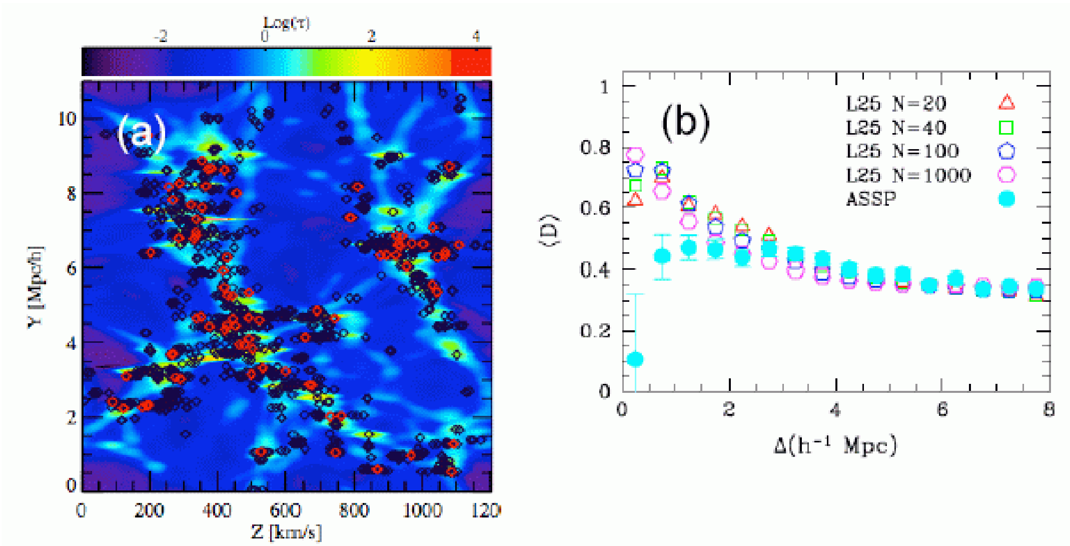

Figure 17. Panel (a) shows the distribution of optical depth of the Lyα absorption in the IGM in the simulations of Kollmeier et al. (2005). It also shows the location of star forming galaxies in the simulation box. The IGM tomography survey with the GMT will be able to resolve both the IGM structure and galaxy distribution down to < 1 Mpc scales. Panel (b) shows the relationship between average HI absorption (<D>) in the IGM and distance to the nearest LBG in both the simulations and the observations of Adelberger et al. (2003). The observations suggest that galactic feedback could impact the IGM at Mpc scales. The IGM tomography survey with the GMT will be used to study the feedback process as a function of galaxy and IGM properties.

A redshift survey with dense sampling of background sources and with detailed information on field galaxies is needed to probe the three-dimensional structure, or tomography, of the IGM and the galaxy/IGM connection. The GMT, with its wide-field, highly multiplexed spectrographs, will revolutionize this field. We estimate that with night-long (~10 hour) exposures, the GMT will achieve a S/N of 20 in the Ly alpha forest region of a $z \sim 3$ object as faint as $r \sim 24$ with a spectral resolution of R ~ 10,000. This is sufficient to detect and resolve individual Lyα forest lines down to a column density of ~ 10^{13} cm^{-2}, yielding ~ 200 lines along the observable line of sight that probe the low-density phase of the IGM. In addition, it will also enable detection of a handful of metal absorption systems per line of sight (e.g. CIV at $N_{CIV} > 2 \times 10^{13}$ cm^{-2}), which trace high-density, metal-enriched regions in the IGM, likely associated with galactic halo and wind/outflows. While quasars/AGNs are relatively rare at this magnitude (60 deg^{-2} at $r \sim 24$ in the range $z = 2 - 4$), the surface density of Lyman Break Galaxies (LBGs) is two orders of magnitude higher (~ 4000 deg^{-2}), fully capable of providing the dense grid required to map the IGM structure. In Figure 16 we show the spectrum of the highly lensed galaxy cB-58, scaled to have a continuum S/N ~ 20 at R ~ 10,000, achievable in a night-long exposure of a $r \sim 24$ LBG using the GMT. Note the presence of the Lyα forest signature at $\lambda < 4600$Å which can be used to map the IGM density at $1.6 < z < 2.7$ in this object.

To probe the high-redshift IGM structure and its connection to galaxy formation, we envision a survey of bright background sources (AGNs and bright LBGs) and faint field galaxies over a few square degrees at z = 2–4 using GMT. It consists of two components:

(1) An IGM tomography survey with night-long exposures to provide a dense grid of background AGN/LBGs down to $r \sim 24$. At spectral resolution R ~ 10,000 and source density of 4000 deg^{-2}, we will be able to map the three-dimensional IGM tomography down to 30 km/s, or ~ 300 h^{-1} kpc in the velocity direction, and on average ~ 700 h^{-1} kpc in the transverse direction.

(2) A galaxy redshift survey with an exposure time of ~ 3 hours, which enables redshift determination of field galaxies to $r \sim 26.3$, thereby probing to a fraction of L^* at $z = 2$-3.5. The surface density of such galaxies is ~30,000 deg^{-2}. Assuming a multi-object spectrograph with a field of view of 16′ x 16′ (comparable to the current design for GMACS), this portion of the program would require ~20 nights to map one square degree. This redshift survey will be comparable to the current DEEP2 survey at $z \sim 3$, both in volume and the total number of objects it contains. The redshift range probed corresponds to the peak of star formation, galaxy merger and AGN activity in the Universe. It is also the 'sweet spot' for using optical spectrographs to study Lyα and CIV/SiIV absorption lines. GMT will be able to push such studies to $z \sim 3$-5, probing volumes and source densities comparable to the current work at $z = 2$-3 with 8 and 10 meter telescopes.

In Figure 17 we show the IGM density, optical depth and galaxy distributions in a state-of-the-art hydro-dynamical simulation of the IGM at $z \sim 3$ that includes feedback from galactic winds (Kollmeier et al. 2005). The GMT IGM tomography survey will directly map the relation between galaxies and the IGM, and will be used to address fundamental questions concerning galaxy and IGM evolution at the peak of the galaxy formation era. The redshift structure of the IGM and galaxy distribution will reveal the three-dimensional topology of the IGM and its relation to dark and luminous matter on scales from individual holes to large-scale filaments, walls, and voids. Lyman α line widths and weak metal lines will probe the enrichment and heating of the IGM and the role of stellar winds, SNe and AGN in the evolution of both intergalactic gas and the interstellar medium in galaxies.

In addition, such a survey will generate a superb set of spectra of moderate to high resolution and S/N for galaxies and AGNs at high-redshift, allowing a wide array of galaxy/AGN science to be addressed, such as the stellar populations in distant galaxies, and the evolution of large scale structure. One particularly promising aspect would be to use SNAP/JDEM or JWST to obtain weak-lensing maps of parts of the survey area to determine the underlying dark matter distribution, thereby directly probing the relationship between galaxy/IGM evolution and that of dark matter.

4 Black Holes in the Universe

The existence of black holes in the Universe was once thought of as a consequence of galaxy formation that had little to do with the galaxy as a whole. It has now become clear that in order to understand how a galaxy forms and evolves, one has to include the influence of a supermassive black hole. Even though we have now found black holes in essentially every galaxy where we have looked, we still do not understand why the mass of the black hole is tightly related to global properties of the host galaxy. While it is clear that the black hole plays a substantial role in shaping the galaxy, we have little understanding of the details. The GMT will play an important role in illuminating why black holes are essential components for galaxies. The GMT will open up new avenues for black hole research that are presently unavailable given the current suite of telescopes. Some of the keys to understanding the role of black holes are exploring the largest black holes in the Universe, exploring the smallest black holes, studying the detailed of the physics around the black hole and how they are fed. The GMT will have significant impact in each of these areas.

4.1 The Largest Black Holes

The power of the spatial resolution offered by HST has produced a remarkable correlation between black hole mass and various galaxy properties (e.g., velocity dispersion, total galaxy mass, total light; (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000). Figure 18 shows the correlation between black hole mass and host velocity dispersion. Given this current set of data on black hole masses, it is very difficult to discriminate between the large number of theoretical models that attempt to explain the correlations. As is often the case in science, the extremes of a distribution have the most leverage on the physical interpretation. The upper and lower mass range of black holes has enormous potential to discriminate among the various models. But those extreme masses are the most difficult to observe presently, and are excellent targets for GMT.

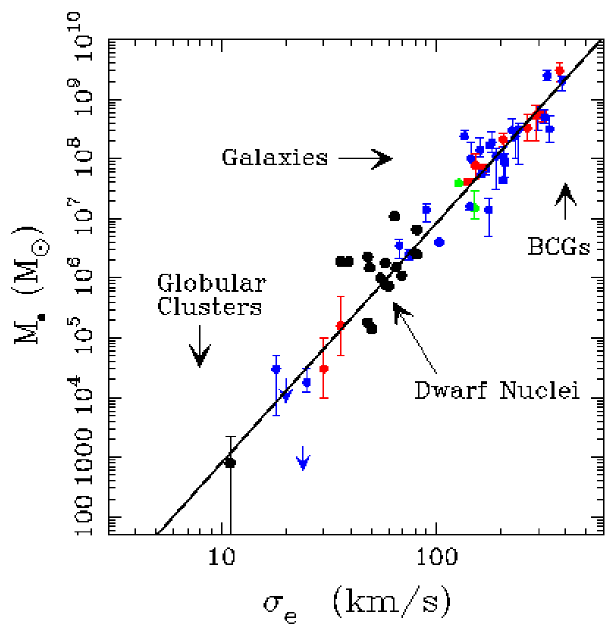

Figure 18. The correlation between black hole mass and bulge velocity distribution for stellar systems ranging from globular clusters to massive galaxies. The GMT will probe the extreme ends of the distribution; black holes with $M > 5 \times 10^9 M_{sun}$ in the most massive galaxies and low mass systems in dwarf galaxies and galaxy clusters.

The largest black holes are particularly important. The brightest quasars have black hole masses estimated to be around 5×10^9 M_{sun}. There is large uncertainty in this number, but it is clear that we expect a significant number of very massive black holes in the Universe. The largest measured black hole is the one in M87 at 3×10^9 M_{sun}. At this point, there is no direct evidence for the existence of these very massive black holes. If we do not find them we have a serious crisis in understanding quasars. By using the number density of the most massive black holes, we do expect to have some in the Sloan Survey, and the question now becomes which ones to search. Ideal targets are brightest cluster galaxies (BCGs). However, since the most massive galaxies are rare (and assuming the most massive black holes are in the most massive galaxies), one has to probe a volume larger than that available to HST. Unfortunately, even with the adaptive optics on the 10-meter telescopes, we can only probe dynamical measurements out to about a redshift of 0.1 (due to a combination of spatial resolution and sensitivity limitations). The volume to $z \sim 0.1$ is not large enough to contain a substantial number of very massive black holes. With LTAO on the GMT, any black holes with masses greater than 10^9 M_{sun} can be measured out to $z \sim 0.5$ and holes with $M > 10^{10} M_{sun}$ can be seen to $z \sim 1$ and higher, as is shown in Figure 19. The GMT has the ability to push black hole studies into a portion of parameter space beyond the reach of current instruments, either on the ground or above the atmosphere.

The ideal instrument for this work is an IFU working at the K-band diffraction limit, with a resolving power of $R \sim 3000$. A long-slit spectrograph would work as well, but would require longer total integrations in order to build up adequate two-dimensional coverage (at least 3 position angles are required to overcome degeneracies in the dynamical models). In order to measure a 5 x 10^9 M_{sun} black hole at z=0.3 with an IFU on the GMT requires approximately 5 hours of integration. The increased spatial resolution from the larger aperture and the increased sensitivity are both essential for this science.

4.2 The Smallest Black Holes

The smallest black holes have nearly as much importance for theoretical models as the most massive black hole. Essentially every theoretical model requires the existence of a seed black hole, but no model suggests what these seeds are. Thus, finding the smallest black holes in the centers of stellar systems will naturally constrain the seed mass. Furthermore, just as the massive holes determine the correlations with host mass, the low mass end is as important for discrimination. As we push the black hole measurements to smaller and smaller systems, we also push the theory for the formation of galaxies themselves. If we find that stellar systems from vastly different mass scales have the same black hole scaling laws (e.g., comparing globular clusters to massive galaxies), then there is likely a fundamental underlying process that governs both; this would be a significant challenge to our current understanding of how both small and large stellar systems form.

Looking for the smallest black holes requires the same advantage as looking for the largest: spatial resolution. While there are plenty of small stellar systems nearby, their expected black hole masses are also small. Thus their kinematic signature is limited to a small sphere of influence. Thus we must be able to probe to very small scales to see the effects of these black holes. Current telescopes will be able to place significant constraints on black holes in globular clusters over the next 10 years. However, there is significant controversy over whether black holes even exist in clusters (Baumgardt et al. 2003; Gebhardt, Rich, & Ho 2005). More likely candidates that harbor small black holes include nuclei of dwarf galaxies. Nearly all of the dwarf nuclei will only be accessible by ELTs, given their distances and expected black hole sphere of influence. For globular cluster black holes, the GMT will easily provide interesting limits for the masses in nearly all clusters in the Milky Way. The same instrument as for the largest black holes is required (an AO-fed near-IR spectrograph). In fact, it is now clear that dwarf nuclei contain black holes (Barth, Greene, & Ho 2005), but it is essentially impossible to make a direct measure of the black hole mass due to their distance and small sphere of influence.

Low-mass X-ray binaries (LMXBs) have been hotly debated for many years as to what powers the x-ray source, with the two main theories being fortuitous disk geometry or accretion onto an intermediate mass black hole. As of this writing, there is no obvious choice. If LMXBs are powered by intermediate mass black holes, they provide evidence for a substantial population of stellar mass black holes. The implied high space density will then have a direct and significant role in understanding how supermassive black holes are grown, understanding evolution of dense stellar systems (including globular clusters), and predicting the frequency of events for future gravitational wave experiments. The GMT will be able to study spatially-resolved kinematics around LMXBs, thereby illuminating the underlying source.

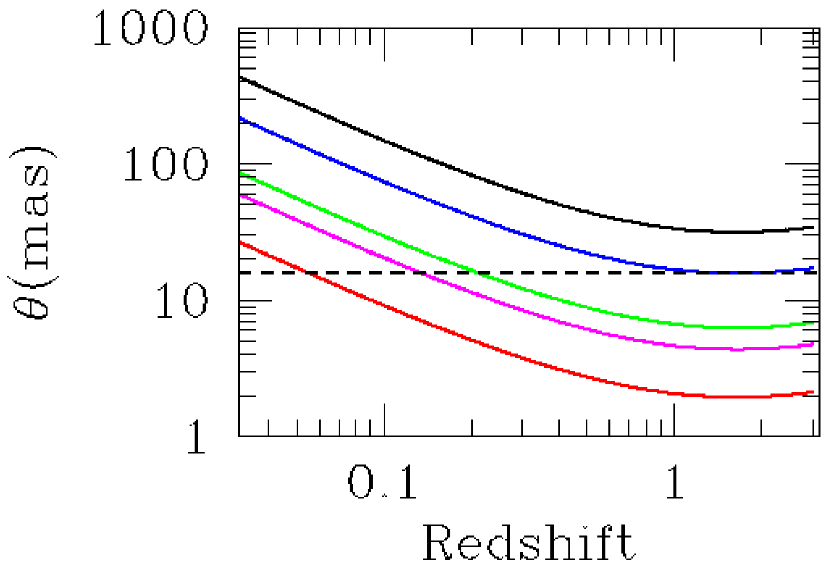

Figure 19. The angular size of the black hole sphere of influence as a function of redshift for black hole masses of 2 x 10^8, 10^9, 2 x 10^9, 5 x 10^9, and $10^{10}M_{sun.}$ The resolving power of the GMT LTAO imaging spectrograph operating in the H-band is shown as the dashed line. The GMT will be able to probe black holes with masses larger than 5 x 10^9 M_{sun} at any redshift.

At present we have a wide range of theoretical models that connect galaxy and black hole formation and no clear way to discriminate between them. One clear path forward is to probe the extreme ends of the mass distribution. It appears unlikely that the 10-meter class telescopes will overcome their fundamental limitations in this area. This leaves a clear role for the GMT in the study of black holes in the coming decade.

5 The Accelerating Universe

Dark energy is one of the greatest mysteries facing science in the 21^{st} century. The vacuum energy accounts for more than 70% of the total cosmic mass-energy density, yet presently we have no physical understanding of its nature. The key to understanding the nature of the dark energy is to study its evolutionary history over the full span of cosmic time. There are numerous efforts currently underway, or in the planning stages, that address the evolution of dark energy. These programs, however, concentrate on constraining dark energy at redshifts below one. Even though some of the programs address the behavior of dark energy at higher redshifts (up to 3.5), the influence of dark energy is only seen through the integral from the present to the observed redshift, leading to strong constraints only at redshifts lower than those observed. Unfortunately, there are many theoretical models that only show an evolution of dark energy at higher redshifts. Thus, even the constraints expected from the currently planned surveys will not distinguish early time evolution. At the time of GMT commissioning, our understanding of dark energy is likely to be in one of two states: either the best fit model will be a static dark energy model which then would call for constraints at earlier times, or we will have detected evolution which again would call for early time observations for confirmation. In any case, there will be a strong need to push the redshift envelope in order to constrain dark energy models. The GMT will be in the unique position to measure evolution of dark energy at early times due to its enormous collecting area and large field of view.

There are three observational approaches that GMT can take in the study of dark energy. These are baryonic oscillations, supernovae, and follow-up to LISA sources. All three play to GMT's strengths.

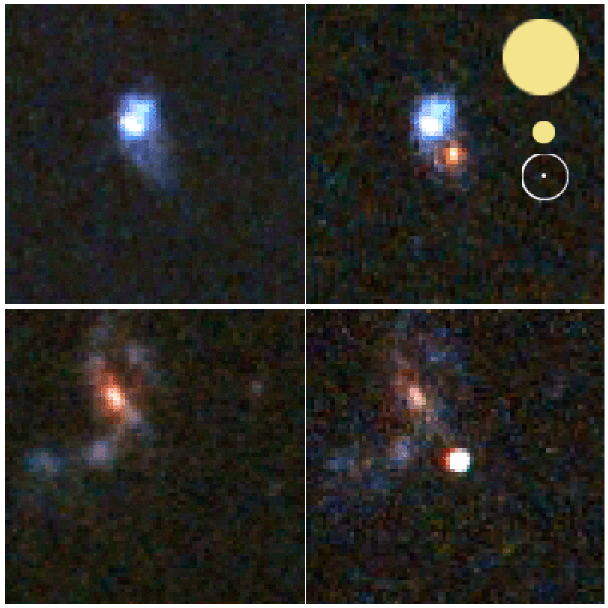

Figure 20. HST/ACS images of distant type 1a SNe. Confusion with the host galaxy is limiting factor in seeing-limited imaging of distant SNe. The yellow circles show the size of the H-band PSF from the ground (0.5″), HST (0.15″) and the GMT (0.02″). The GMT PSF is circled for clarity. The GMT, operating in the LTAO mode coupled with an IFU near-IR spectrometer, will obtain rest-frame visible spectroscopy, and photometry, of distant faint SNe without contamination from host galaxies.

5.1 Baryonic Oscillations

One of the new techniques to measure the expansion history of the Universe is to the use the standard ruler imprinted during the very early universe on large-scale structure of galaxies (Eisenstein & Hu 1998; Eisenstein et al. 2005). These baryonic oscillations come from very well understood physics, and the cosmic microwave background results show that we should find extra power on a scale of around 147 Mpc. By tracking this standard ruler over time, one then determines the expansion history of the Universe, and hence the influence of dark energy. Thus, the idea is simple: measure many galaxies over a large area and determine the scale for this extra power. The number of galaxies and total volume required are well determined from statistics (and also compared to cosmological simulations). There are many surveys targeting similar observations at redshifts below 4, but none beyond 4. The GMT will be sensitive to redshifts out to 7 (and possibly larger). A potential program would entail spectroscopy of a 3-5 x 10^5 objects in the range $5.5 < z < 6.5$ over 50 square degrees. These observations will constrain the galaxy power spectrum to ~1%, which is the lower limit for constraints on dark energy due to uncertainties from theoretical interpretation (thus, there is little motivation to improve the accuracy beyond this level). A target surface density of ~ 3 galaxies per square arcminute would enable an efficient survey. For Lyα emitters, this density corresponds to a line flux of 2 x 10^{-18} erg s^{-1} cm^{-2}. For a 12 x 12 arcminute field and 30-minute exposures, GMT will reach these numbers in about 50 clear nights of observations. These observations will produce a strong, independent constraint on dark energy and at the highest redshifts.

5.2 Supernovae at High Redshift

Supernovae are the closest thing that astronomers have to standard, or calibratable, candles with sufficient luminosities to be seen at cosmological distances. Evidence for an acceleration in the expansion of the Universe was provided by the type Ia SNe Hubble diagram. While most of the impact of dark energy on the Hubble diagram is at modest redshifts, distant SNe studies are essential for disentangling cosmological effects from SNe evolution and observational selection effects. Distant SNe also provide a probe of the expansion history at early times. Late time light curves require accurate host-galaxy correction and currently are best be done from space. LTAO imagers have the potential to resolve the host galaxies and improve the galaxy-SNe contrast dramatically. Currently distant SNe searches are most effectively carried out with HST, a vanishing resource. This is illustrated in **Figure 20** where we compare the size of the PSF for ground-based seeing, HST F160W and the GMT operating at the diffraction limit with the size of two $z > 1$ SNe host galaxies before and after a type Ia explosion.

The GMT equipped with a modest field GLAO imaging capability may be able to reach into the $z > 1.2$ territory from the ground. At redshifts of 1 and higher the LTAO-fed near-IR imaging spectrograph will sample the rest-frame visible spectra.

One of the potential sources of systematic uncertainty in the SNe Hubble diagram relates to asymmetry in the expanding blast wave. This will introduce an aspect angle dependence to the light curve and could produce environmentally driven sample biases. Spectropolarimetry is the most sensitive tool for probing asymmetry in unresolved sources, and extremely large telescopes are well suited for this photon-starved problem. The GMT with its straight Gregorian focus is ideally suited to polarimetary as there are only two reflections to the focal plane, and no 45 degree reflections, thus producing a minimal, and stable, instrumentation polarization signal.

Discovery, and accurate follow-up, of SNe Ia at high redshift is constrained by the maximum fluence associated with the explosion event. SNe at $z > 1.5$ are faint and quite difficult to observe. Gamma ray bursts, however, produce much higher fluence and, if caught early, can be seen to very high redshifts with high signal-to-noise ratios. There have been suggestions recently that GRB light curves can be calibrated to a uniform isotropic luminosity with a scatter of only ~ 0.1 magnitudes. (Ghirlanda et al. 2004). The GMT will be able to follow GRB light curves well past the break associated with the jet, allowing determination of the opening angle and hence the isotropic luminosity.

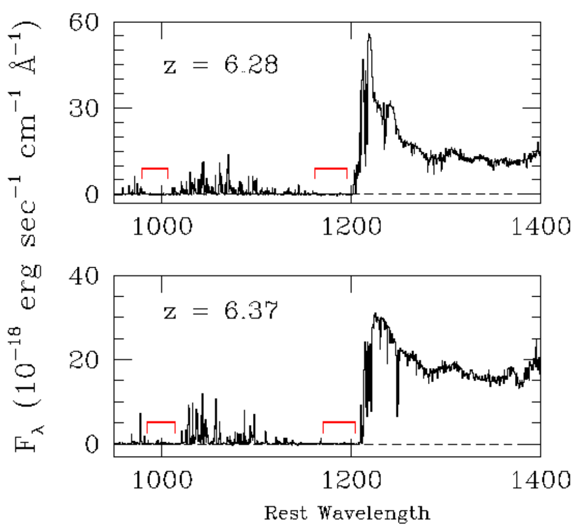

Figure 21. High dispersion spectra of two $z > 6$ quasars that show the signature of reionization via deep Gunn-Peterson troughs in their spectra. Redshift intervals in which the Lyα forest is completely opaque are shown by the red bars. These spectra, 8-hour integrations with a high-throughput spectrograph (ESI) on the Keck telescope, reveal the limits of what can be achieved with the current generation of telescopes. From White et al. 2003.

5.3 LISA follow-up

One of the more exciting prospects for astronomy is the detection of gravitational waves, with either the NASA LISA satellite or the ground-based LIGO experiment. Detection of gravitational waves will open up whole new avenues for the study of strong gravitational fields. There is a potentially huge benefit for dark energy observations. By determining the positions and redshifts of LISA sources, we will have one of the most accurate direct distance determinations in the history of astronomy. The GMT will be one of the few telescopes able to utilize this technique in conjunction with the LISA satellite. If we can directly measure the physical distance to a LISA source with high precision and obtain a redshift with the GMT, we will have the most accurate direct distance determinations at high redshift ever. LISA will detect strong signals from merging supermassive black holes. The gravitational radiation signal provides a physical distance to the source. However, we only have limited information on where that source is on the sky, and we have even less information on the redshift. For these two, we are dependent on optical follow-up of the merging system. If an optical/IR counterpart is clearly identified, we can obtain a precise direction to the gravitational source. Since the distance uncertainty is tightly coupled to the uncertainty in the source direction for modeling gravity waves from binary black holes, using external position accuracies removes this degeneracy and dramatically reduces the uncertainty in the physical distance (see Dalal et al. 2006). Second, if we determine a redshift, we can then obtain a direct distance measurement to better than 1% accuracy. Thus, with just one source we can determine the cosmological parameters, and, hence, the influence of dark energy. The expected event rate from LISA ranges from tens to hundreds of events per year. Each has a positional error ellipse a few arcminutes in diameter. The optical transients may occur simultaneously with the gravitation signal, or may appear a few years following the merger event. The expected LISA detection threshold corresponds to a black hole mass of $\sim 10^5$ - $10^7 M_{sun}$. The expectation is that the merging event will produce an accretion flare that will be luminous enough, in either emission-lines or in the continuum, to stand out from the host galaxy luminosity. The luminosity expected in the flare is highly uncertain. The sky density of galaxies hosting likely typical LISA sources, is roughly 10 per square arcminute, or approximately 100 potential targets within a LISA error circle. LISA will provide a 1 to 2 day advance warning of a merger event, and GMT can periodically monitor about 100 sources over a few arcminute field of view for several days. This project calls for a large telescope (since we do not know the optical brightness) with a moderate field (due to the LISA error circle). There are numerous problems that would benefit from optical detection of merging black holes and their gravitational wave signature, but cosmology, and dark energy in particular, are among the most fundamental. If the event rate is as expected and even a modest fraction of the LISA sources can be identified, high precision determinations of the expansion history of the Universe can be obtained in only a few years time. This will improve our constraints on dark energy models by more than a factor of ten.

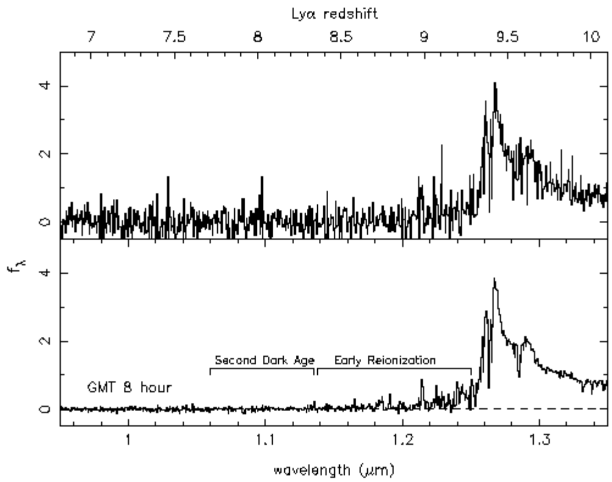

Figure 22. Simulated spectra of a z=9.4 QSO observed with an 8m (top) and the GMT (bottom). The signature of double reionization can be seen in regions of IGM transparency at z ~ 9. GMT spectroscopy of ultra-high redshift quasars, which may be discovered in wide-area IR surveys could probe the early evolution of the IGM and the first galaxies. Simulation by X. Fan.

6 First Light and the Reionization of the Universe

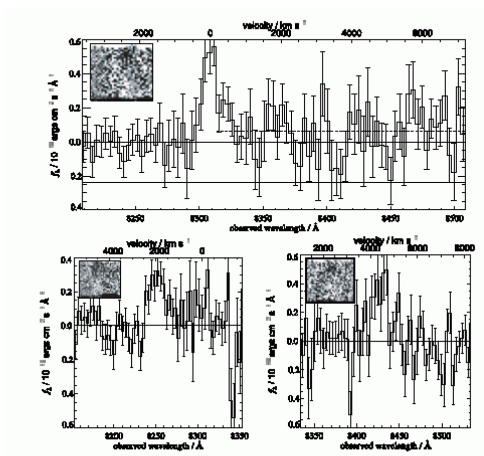

Figure 23. Ly alpha emission from galaxies at z ~ 6 taken with the Gemini telescope. The GMT will allow detailed studies of these and fainter young galaxies. From Stanway et al.

6.1 Reionization of the IGM

Some 300,000 years after the Big Bang the matter in the Universe combined to form neutral H and He. Today, and to very high redshifts, the intergalactic medium is highly ionized. Thus at some high redshift the intergalactic medium was reionized. Recent observations of distant quasars reveal that the epoch of reionization appears to have ended near z ~ 6 (Becker et al. 2001; Fan et al. 2006), as illustrated in Figure 21. The detection of polarization in the CMB reveals a significant optical depth to Thompson scattering and suggests that reionization began at a very high redshift, ~ 15 (Kogut et al. 2003), although the uncertainty is fairly large. There may have been two, or more, reionization epochs, with a partial recombination between (e.g. Cen et al. 2003).

High dispersion spectroscopy of quasars provides a powerful probe of the reionization epoch. The SDSS has produced a sample of z ~ 6 quasars suitable for this purpose. Higher redshift quasars are likely rare, but they may still lurk in the Sloan data set. Large area near-IR survey cameras (e.g. VISTA, UKIDSS, 4STAR on Magellan) offer a means to identify quasars at redshifts well above 6. These will enable the GMT to probe the history of reionization, as shown graphically in Figure 22.

The topology of the IGM at the end of the reionization era is expected to be complex; ionization fronts surrounding luminous sources will produce bubbles of ionized material that expand and eventually overlap. Spectroscopy of individual bright quasars can probe line-of-sight structure in the early IGM. The SDSS quasars are near the limit of high dispersion spectroscopy with 8 to 10m class telescopes. The surveys that will find z > 6 quasars in large numbers must probe to fainter magnitudes. A large aperture telescope like the GMT will be required to study the line-of-sight IGM topology and reionization history in these distant targets. The near-IR Echelle on the GMT will have an intermediate resolution mode (R ~ 10,000) that can be used for spectroscopy of faint z > 7 quasars, should they be found. Higher density UV sources can, in principle, allow one to map structure in the partially ionized IGM in the plane of the sky. At present the number of galaxies known at z > 5 is quite small and the objects are faint. Ultra-deep spectroscopic observations, with a large IFU or dense multislit could probe the structure of the IGM and the sources of ionizing radiation at z >5. It may be that one will have to co-add spectra of many z > 7 galaxies to obtain a reliable determination of the IGM optical depth at these redshifts. JWST will very likely provide the target list and the GMT optical and near-IR multi-object spectrographs could use multi-night integrations to obtain their spectra for studies of both the galaxies themselves and the IGM.

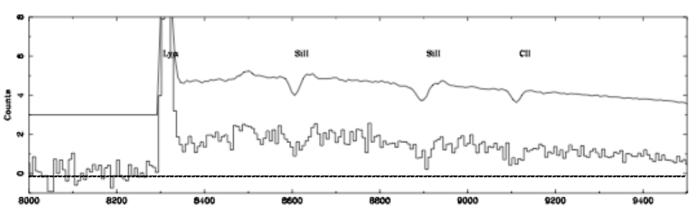

Figure 24. Simulated GMT spectrum of the brightest of the three Ly alpha galaxies shown in Figure 23. The simulation is for a 15 hour exposure using the GMT in natural seeing.

The energetics and chemistry of the IGM at the highest redshifts are poorly understood. Recent observations and models suggest that the chemical abundances in the IGM depend strongly on local density in addition to redshift, and that high density regions were enriched very early, at z > 5. High dispersion near-IR spectroscopy of quasars and GRBs will allow direct comparison of columns in CIV and MgII, high and low ionization species, respectively, over the full redshift range from 0 < z < 10 if sufficiently bright sources can be found. Presently there are suggestions of a change in the CIV columns at the highest redshifts, but the evidence is highly uncertain. The deployment of instruments on the GMT was designed with the rapid response to GRBs, and other transient targets, in mind. Thus we will be able to obtain spectra of very high redshift GRBs on 10 minute time scales. To date, GRBs have been identified to z = 6.3 (Kawai et al. 2006). GRBs at similar, and higher, redshifts will provide unique probes of the history of reionization (Barkana & Loeb 2004).

6.2 First Light

Reionization is the signature of a major energetic event in cosmic history. The source of the ionizing photons is uncertain, but the leading candidate is the first generation of stars and galaxies. Numerical simulations now suggest that the first objects to form are super-massive stars in small halos. Single stars with masses well in excess of $100M_{sun}$ form in mini-haloes of dark matter and quickly destroy themselves via stellar winds and supernovae. This process imparts a significant amount of energy to the IGM. These first generation massive stars are, in all likelihood, too faint for detection with currently envisioned ground-based telescopes and are probably beyond the reach of the JWST.

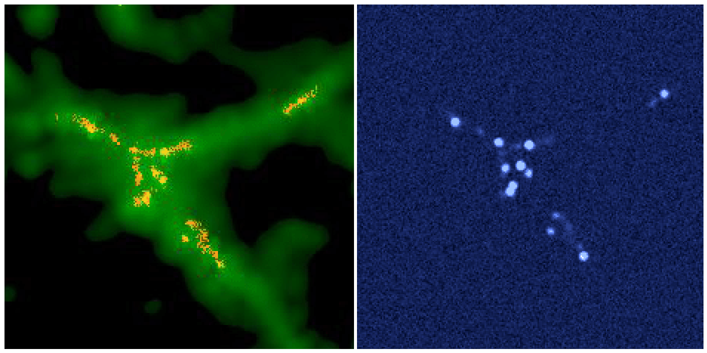

Figure 25. A simulated GMT 10-hour narrow-band (R=3000) image of star forming regions at z=10 based on a cosmological hydro calculation by Davé et al. This image is in the light of HeII 1640 and assumes a top-heavy IMF appropriate for primordial population III stars. From Barton et al.

The formation of the first condensed objects, be they galaxies or massive black holes, is likely to be accompanied by a second generation of star formation. These young galaxies may be quickly enshrouded in dust of their own making, but some of them may have clear escape paths for the UV photons. The far red and near-IR is the appropriate window for observation of these young galaxies. Ly alpha emission is the strongest and most direct spectral signature, but Ly alpha may escape in only a small fraction of $z > 5$ objects. HeII 1640 emission may be a better tracer of primordial populations. Strong HeII emission is an indicator of high mass Population III stars. Deep narrow-band images with the GMT can reveal early star formation sites and the intersections of filaments in the early density distribution, as shown in Figure 25.

Lyman continuum breaks provide a more universal, but difficult to detect, signature of very high redshifts. Several $z \sim 6$ galaxies have been detected in the Hubble Ultra-Deep Field with magnitudes of $z' \sim$25-27. Spectroscopic confirmation of these objects required very long (~25-hour) integrations with an 8m telescope (Figure 23); the full depth of the UDF cannot be plumbed even with 100-hour exposures with 8-10m telescopes. The GMT, operating in the diffraction limit AO-mode, can exceed the depth of the UDF in imaging modes and, more importantly, will allow spectroscopy of $z > 6$ objects in reasonable exposure times. The GMT can play a key role in exploring the dark ages, both via spectroscopy and wide-field studies of clustering and luminosity distributions. The GMT will also excel at high resolution and narrow-band applications in the near-IR. The synergy between the GMT and the James Webb telescope provides a uniquely powerful set of tools for studies of the early universe and first light. The Webb telescope will excel at identifying $z > 6$ galaxies from their broad-band colors. The GMT will be able to perform follow-up spectroscopic and narrow-band imaging observations with greater sensitivity and angular resolution. An example of what a GMT spectrum of a $z \sim 6$ galaxy might yield is shown in Figure 24. This is in marked contrast to the best that can be achieved with 8m telescopes, as shown in Figure 23.

The theoretical models suggest that star formation at high redshifts occurs in small sub-galactic scale units. This is in large part what makes them so challenging to detect as even vigorous star formation in objects with $M \sim 10^6 M_{sun}$ is quite faint at $z > 6$. There are reasons to be optimistic that nature may know how to make massive galaxies and immense star bursts at very large redshifts. First, the existence of luminous quasars implies massive ($\sigma \sim 200$ km s^{-1}) black holes if the M_{BH} - σ relation (Figure 18) is in place at early times. If the quasar phase of black hole growth has a low duty cycle, as it must to meet the current space density of supermassive black holes, then massive galaxies may be orders of magnitude more abundant than quasars at high redshift. Secondly, the $10^{11} M_{sun}$ passively evolving galaxies at $z \sim 2$ imply early star formation for the bulk of their stellar mass. It is possible that these galaxies were assembled from smaller units in the ~ 2Gyr between $z > 5$ and $z = 2$, but a substantial fraction of the stellar mass may have been assembled at early epochs.

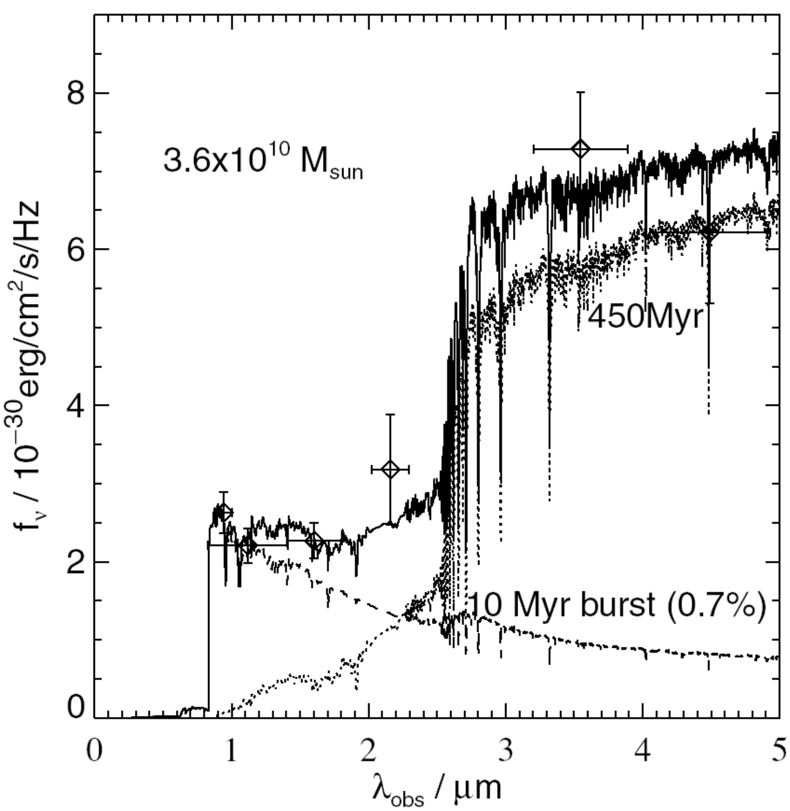

Figure 26. Spectral energy distributions of SBM03#1, one of two $z \sim 6$ galaxies detected with the Spitzer space telescope in the Hubble Ultra Deep Field. The best fitting models have ages of a few x 10^8 years and stellar masses on the order of 3 x $10^{10} M_{sun}$. These objects reveal significant star formation at $z >> 6$ and may probe the epoch of first star formation. From Eyles et al. (2005).

Recent observations with the Hubble and Spitzer space telescopes suggest that there was significant star formation in massive galaxies at $z \sim 10$. Rest-frame visible photometry of $z \sim 6$ galaxies with Spitzer has revealed large stellar masses (10^{10} - $10^{11} M_{sun}$) and intermediate (3 x 10^8 yrs) in a number of systems. Taken at face value, the ages and masses of these systems imply a period of intense star formation at $z >> 6$. Even for constant star formation between $z = 100$ and $z = 6$, the implied star formation rates are in excess of 10 M_{sun} per year; more realistic models with star formation time scales comparable to the dynamical time for a 10^{10} - $10^{11} M_{sun}$ system imply star formation rates in excess of 100 M_{sun} per year.

Star formation rates of this order are well within the reach of JWST and GMT operating in the near-IR. Thus there are reasons to be optimistic that in the next decade we will directly observe the first major event in the formation of today's massive galaxies.

7 Closing Thoughts

The GMT science goals span a broad range of astrophysics. Working alone, or in concert with facilities operating in other domains, the GMT can address the key questions in astrophysics today. Investigations with the GMT will also impact broad areas of thought in other branches of science and in public awareness of the Universe around us. In this document we have highlighted a subset of the scientific applications of the GMT and its instrument suite. These selected science questions address the priorities identified by blue-ribbon panels drawn from the international community as part of the decadal survey and other planning exercises and thus address the aspirations of the astronomical community at large.

Developing the science case for the GMT not only clarifies the motivations for building the telescope, the process is also critical to numerous decisions regarding the architecture of the telescope and its subsystems. While this is a necessary exercise we should not lose sight of the discovery nature of astronomy. We expect that the most exciting contributions that will be made by the GMT are as yet unanticipated. This has been the case for nearly all telescopes (HST, Keck, etc). Maximizing our potential for new discovery should remain a guiding principle as we develop the GMT and its instruments.

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GMT Science Case

Appendix – Example GMT Science Programs

1 Exoplanet Imaging

Direct imaging of Exoplanets is one of the key GMT science goals. In this section we expand on three programs in this area: imaging of planets discovered in radial velocity surveys via reflected light and thermal emission, and mid-IR searches for large separation young planets in star forming regions.

1.1 Imaging of Known Giant Planets

Table 1.1 Exoplanet targets for H-band ExAO imaging**.**

Planet	Mass	a(AU)	θ(mas)	Contrast(10^{-9})	H(mag)	Dec
HD196050b	3.0	2.5	53	10.0	26.1	-60
HD114729b	0.8	2.1	59	9.8	25.3	-31
HD10647b	0.9	2.1	121	10.0	24.4	-53
HD106252b	6.8	2.6	70	10.9	25.9	+10
HD168443c	17.1	2.9	87	11.3	20.5	-09
HD10697b	6.1	2.1	71	15.9	24.2	+20
HD213240b	4.5	2.0	50	16.2	25.0	-49
HD114386b	1.0	1.6	58	17.0	25.9	-35
HD111232b	6.8	2.0	68	19.1	25.3	-68
HD81040B	6.9	1.9	60	20.0	25.5	+20
HD128311c	3.2	1.8	106	20.0	24.6	+09
HD160691b	1.7	1.5	98	23.2	27.2	-51
HD147513b	1.0	1.3	98	28.2	22.9	-39
HD114783b	1.0	1.2	55	31.0	24.4	-02
HD19994b	2.0	1.3	58	32.3	22.5	-01
HD27442b	1.3	1.2	65	35.1	20.5	-59
HD210277b	1.2	1.1	50	40.3	23.4	-07
HD128311b	2.2	1.1	66	46.2	24.6	+09
HR810b	1.9	0.9	59	65.5	22.3	-50

The massive planets discovered in radial velocity surveys have rather small semimajor axes compared those of the gas giants in the solar systems. Most of the 140 or so known exoplanets thus have angular separations well below 50 mas and they are likely beyond the reach of the GMT. We have estimated the H-band reflected fractions, and magnitudes, of all of the exoplanets in the www.exoplanet.org database. The contrast is computed using a peak H-band geometric albedo of 0.4. This is not the albedo averaged over the full H-band, but rather the highest albedo in a 0.1micron band pass.

The planetary radii are computed using a mass-radius relation that goes as $M^{1/8}$ for masses below 1 M_J and fixed at $R = R_J$ for $M > M_J$. The limiting contrast for the GMT ExAO imager (HRCAM) is expected to be approximately 5×10^{-9} (5σ) in a few hours. Longer integration times are not likely to produce higher contrast, as systematic noise associated with uncorrected speckles is likely to dominate the noise at this level. We restrict our search to targets with Dec < $+20^0$ and the vast majority of the targets are at negative declinations.

Restricting the sample to objects with separations larger than 50mas gives 19 systems potentially within reach of the GMT ExAO system. These are listed in Table 1.1. Each object will be observed in two closely spaced wavebands (one in and one out of a deep absorption band) to allow spectral differencing. Thus the total exposure time for each target is one the order of 6-8 hours, or the equivalent of one full night. Surveying these 19 targets will require on the order of 20-30 nights depending on the operating efficiency of the AO system.

A few of the wider separation systems are more easily detected at 5 microns where the contrast against the central star is more favorable. Imaging of these systems in the thermal IR provides additional physical information not available from the reflected light studies. The ages and atmospheric properties of these objects may by inferred from their mid-IR colors and luminosities, given the dynamical masses determined from the radial velocity studies (modulo sin(i)).

Table 1.2 Star forming regions for M-band searches for young planets.

Association	Number of Stars	Age (Myr)	D (pc)
Ophiuchus Lupus I-III Chameleon I-III	Hundreds	1-3	150
Upper Sco	50-100	3-10	100
η Chameleon	20-30	10-30	100
TW Hydra	20-30	10-30	50
β Pictoris	20-30	10-30	30
Tuc-Hor	30-50	30	50
IC 2391/2602	50-100	55	150
Blanco I	50-100	100	150
Field Stars	Hundreds	300-1Gyr	50
Field Stars	Hundreds	1-3 Gyr	20

1.2 Giant Planets around Young Stars

Our highest priority programs include a comprehensive search for giant planets around nearby young stars as well as a complete census for circumstellar debris intimately connected to the origin of the terrestrial planets and possibly life on Earth. Unique samples of sun-like stars (masses between 0.75-1.5 M_{sun}) within 200 parsecs with ages from 1 Myr to 1 Gyr year are found in the southern hemisphere as indicated in Table 1.2.

We plan a multi-wavelength survey using the unprecedented sensitivity of AO on the GMT to search for: 1) warm planets with masses down to 0.1M from 0.3 - 30 AU surrounding the nearest young stars; and 2) signatures of dust debris down to levels comparable to that expected from solar system analogues at ages less than 1Gyr. Our initial survey would consist of 200 young stars with ages 1 - 100 Myr (50 in each of 1 - 3, 3 -10, 10 - 30, and 30 - 100 Myr) in the H- and L-band to search for planets through high contrast imaging. We expect such a survey would take of order 75 nights (3 per night in each of two wavelengths). The next phase of the survey would be multi-color imaging and/or spectroscopy of potential planetary mass candidates (one per night ~ 25 nights). We would also conduct an N-band survey for this sample to search for warm debris in ~ 30 nights (6 stars per night).

Additional programs would include ~ 30 nights for high resolution imaging of key debris disk targets, 30 nights for key Kuiper Belt studies, and ~ 30 nights for key jet/outflow targets.

We would also plan a major survey of 75 nights (3 targets per night at two settings) for high resolution spectroscopic survey of 200 protostellar and T Tauri objects in the 2-5μm windows to trace the evolution of molecular gas from the diffuse ISM through the collapse phase, and to protoplanetary disks surrounding sun-like stars, as well as a major 75 night survey of IMF in galactic clusters (10-20 Milky Way clusters as a function of galactocentric distance including unique targets in the galactic center only accessible from the southern hemisphere [varying metallicity, pressure in the interstellar medium, and magnetic flux to mass ratio] as well as 10-20 targets including the LMC/SMC, local group galaxies, and the nearest starbursts, and low/high metallicity galaxies). Each cluster would require 1 night for multi-color imaging (J/H/K) as well as 2 nights follow-up narrow-band imaging spectroscopy in these barely resolved stellar populations.

2 Black Holes at the Extreme Ends of the Mass Function

In section 4, we reviewed our understanding of the demographics of black holes and noted the importance to exploring the extreme ends of the mass function. In this section we briefly elaborate on how we might explore both the high mass end ($M > 5 \times 10^8 M_{sun}$) of the spectrum as well as probe for very low masses.

2.1 The Most Massive Black Holes

The black hole-bulge mass correlation suggests that the best place to look for massive inactive black holes is in the center of massive early type galaxies, or bulge dominated spirals. Hierarchical models also show that the most massive holes should be found in regions of high density, the rare peaks that collapsed early and are presently regions of high overdensity. The cores of rich massive galaxy clusters at modest redshift are likely to be productive territory. We will select a sample of ~ 50 massive clusters, either from the Lauer and Postman sample, or from the other surveys presently under development (e.g. Dark Energy Survey, S-Z survey). These surveys will provide large samples of mass selected clusters over a wide range of redshifts and follow up surveys that will measure the redshifts, either spectroscopicaly or photometricaly, are currently in the development stages. We will restrict our sample to clusters with $0.3 < z < 0.6$, at least in the first stage. We will obtain quick spectra of the central cluster galaxy for each cluster in the parent sample as needed. This will allow us to reject objects with active nuclei, recent star formation, double nuclei and other sources of confusion for dynamical studies.

The velocity fields will be determined from diffraction-limited spectroscopy in the near-IR. We will likely use the CaIII triplet in the J-band, if sufficiently high Strehl ratios can be achieved. If this is not feasible we will work in the H-band where high Strehl ratios are possible. The brightest cluster galaxies will be observed with an IFU as part of the HRCAM instrument. LTAO will be used to provide the necessary adaptive correction and we will use the nucleus of the BCG in the K-band to correct for tip-tilt. If this is not possible, we will select clusters at intermediate galactic latitude to ensure sufficient numbers of natural guide stars for tip-tilt correction. Intermediate resolution spectra (R~3000) will be used to derive the full two-dimensional velocity field from the IFU data. These will be modeled to derive the mass as a function of radius and the mass of any central compact objects.

Much of the preparatory work for this program can be carried out using 8m class telescopes. The GMT will be needed for the diffraction-limited, and photon-starved, spectroscopy of the central regions of the final list of candidates. We expect that roughly five hours of integration will be needed for each target. Calibration observations and set up of the AO system are likely to add significant overhead. Even with 100% overhead, a sample of 25 objects can be observed in roughly 25 nights.

2.2 The Smallest Mass Black Holes

The logic that dictates that searches for the most massive black holes should be confined to massive galaxies suggests that dwarf galaxies and globular clusters are the appropriate place to search for low mass black holes. The same techniques will be used as in the case of the massive black holes. Spectroscopy in the near-IR with an AO fed IFU sampled at the diffraction limit. For the local star clusters and nearby dwarfs we will use the strong CO features in the H and K-band spectra to derive velocity profiles. For the clusters we will have an abundance of stars suitable for tip-tilt correction for the LTAO system. For dwarf galaxies we may have to prescreen for suitable systems. Integrations times will be short for these objects as we will be working with resolved stellar systems. Resolution is the key parameter as the black-hole sphere of influence is small for these objects. It may be advantageous to work in the J-band to gain resolution at the expense of Strehl ratio. This will need to be modeled in detail as the properties of the AO system are better understood.

3 Tomography of the Intergalactic Medium

As discussed in section 3.6, one of the key challenges in understanding the physics of the IGM is finding the link between galaxies and intergalactic gas. The GMT multi-object spectrographs can make unique contributions in this area by virtue of their high sensitivity and large fields of view. Below we describe what an IGM tomography program would entail and how it might be carried out.

3.1 IGM Probes

The structure of the IGM is revealed through absorption lines, primarily Lyα, seen against the spectra of background objects. Quasars, the current standard source for Lyα forest studies, are too scarce to reveal the structure of the IGM on intermediate and large scales. We will use fainter AGN and high surface brightness galaxies to probe the Lyα forest. An appropriate survey field needs to be on the order of 1 square degree in extent. We will work in fields that have been surveyed by HST, allowing us to sample compact high-surface brightness galaxies. The Cosmos field is the best candidate field as its large (2 square degree) extent; deep HST I-band images and equatorial location are not matched by any other survey. We will select galaxies with $1.8 < z < 5$ and $R < 24$, either on the basis of photometric redshifts, or using redshifts from the current generation of spectroscopic surveys of this field. The surface density of these objects is ~ 1 per square arcminute, so there will be high density of targets.

Spectroscopy of these targets will be carried out using the GMACS spectrograph using its highest resolution (R ~ 10,000) mode on the blue channels. Exposure times will be on the order of 8-10 hours to yield continuum signal-to-noise ratios of ~ 20 per resolution element. On the order of 100 targets can be observed at any time in this mode. A complete survey of the suitable background galaxies within a one square degree area will thus require approximately 10-15 clear nights, depending on overheads. This will yield Lyα forest spectra along ~ 1000 lines of sight with a typical co-moving spacing of ~ 500 kpc at z = 3. The Lyα forest spectra seen in each background object can be correlated with each other to reveal structures within the IGM on a variety of scales. In addition, the brightest quasars within this volume (there will only be a few) will be observed with the visible Echelle to provide very high-resolution spectra that will provide information on the dynamical state and chemistry of the IGM along a small number of sight lines.

3.2 The Galaxy Distribution

The primary goal of this program is to explore the link between galaxies and the IGM. This requires a deep galaxy redshift survey within the volume probed by the Lyα forest survey. For this we will use GMACS in its lower resolution survey mode. Galaxies will be targeted on the basis of photometric redshifts, allowing us to filter out objects with redshifts outside the range of interest. We expect to reach to R ~ 26-26.5, in exposure times of a few hours. The spectra should be of high enough quality for both accurate redshifts and crude measures of gas-phase abundances and line widths. The total number of potential targets in the appropriate redshift range is on the order of 30,000 in a one square degree survey area. In the survey mode GMACS should be able to obtain spectra of ~ 500 objects at one time. If we sample every other galaxy, then the total time needed for this portion of the program is around 20 dark nights.

Not all of the galaxies in the survey volume will yield redshifts from the GMACS spectra. The red galaxy population, both evolved and obscured systems, may be better probed using the NIRMOS spectrograph. The smaller field of view for this spectrograph yields a lower survey speed, but only a minority fraction of the galaxies need be observed spectroscopically in the near-IR. A similar investment of time (~ 20 nights) would allow us to observe 10% of the GMACS sample. This is likely to be sufficient to complete the redshift survey.

Structure in the galaxy distribution and Lyα forest can then be directly correlated using the two data sets. This will allow one to examine the role of outflows from star forming galaxies in heating and enriching the gas, to compare the relative bias between the galaxy and Lyα forest distributions, and to determine the relationship between density and chemical abundance in both the IGM and in galaxies. Crucial additional information relating to the masses and morphologies of the gas can be derived from the HST imaging and mid-IR photometry from Spitzer or JWST. If JWST imaging is not available at the time GMT goes into operation, NIRMOS can be used to obtain deep J,H, and K imaging to complement the 3-8 micron photometry from Spitzer. This will allow accurate stellar masses to be determined for all of the galaxies in the survey.

This program will likely form one of the key extragalactic science legacies of the GMT. It will use three of the GMT first generation instruments and will require on the order of 50 nights of observing time.