Science enabled by a 30-m telescope

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ABSTRACT

We describe some of the science programs that drive the need for the next generation ground-based OIR telescope. The programs are chosen to illustrate the power of such a telescope to enable new kinds of science via combinations of sensitivity, field-of-view, wavelength coverage, and spectral resolution.

1. INTRODUCTION

The 20th century witnessed a revolution in our knowledge of the Universe. We now know that the Sun is a star, composed primarily of hydrogen, and only one among more than 10 billion stars in our Galaxy, the Milky Way. Our Galactic home itself is but one among billions of galaxies spread out over the vast expanse of space and time in a distribution whose complexity we are only beginning to appreciate. We have also learned that these galaxies are expanding away from each other as the result of the explosive birth of the Universe more than 10 billion years ago. Closer to home, we have found compelling evidence for planets around nearby stars which raises the possibility of life and intelligence elsewhere in the Galaxy.

As a result of these discoveries, our questions about the Universe have become progressively more sophisticated. What is the origin of structure in the Universe? From the cosmic soup of the Big Bang, how did clusters, galaxies, stars, and planets arise? How did the chemical evolutionary history of the Universe result in the genesis of life on Earth? And how common is life in the Universe? The keys to answering these questions lie in deciphering the past: ancient events observable in the distant Universe, the historical record preserved in the stellar populations of the Milky Way and nearby galaxies, and present-day analogues of the birth of the sun and solar system.

While current ground-based 8-m and 10-m telescopes will greatly advance our understanding of these kinds of questions, we already know that many answers lie beyond their reach. As we describe below, answering these questions will require a novel combination of greater sensitivity, larger fields-of-view, and higher angular resolution than is currently available. Moreover, the discoveries that will be made by planned space-based or multiwavelength ground-based facilities will only be fully realized with a new large-aperture optical-infrared telescope. For example, the stars that first illuminated the Universe may be detected by NASA's Next Generation Space Telescope, but investigating their astrophysical properties (e.g., age, metallicity) is well beyond the capabilities of any current or planned astronomical instrument. Similarly, the Atacama Large Millimeter Array will probe the current birthplaces of stars in the Galaxy, but understanding the formation of planets in our solar system will be a joint effort, relying heavily on the next generation of large optical-infrared telescopes. In this chapter, we discuss some of the major astronomical questions that drive the need for a new large-aperture optical-infrared telescope.

1.1 Astronomy in 2015

Astronomy in 2015 will be powered by a diverse set of observing capabilities, covering a broad range of wavelengths, on the ground and in space. By 2015, NGST will have been launched, and perhaps already completed its (nominal 5-year) mission to explore the early universe and the creation of the first stars and galaxies. It will undoubtedly have revolutionized our view of the MIR universe. ALMA will be operational (target completion date 2011) and examining an equally broad range of astronomical problems, from the study of dusty galaxies at high redshift to the initial conditions and physical processes that produce stars and planets. The SKA will begin probing the structural evolution of primordial hydrogen gas and the formation of the first (gaseous) structures in the Universe. Chandra will have long completed its inventory of the X-ray background, and Constellation-X will be on the verge of probing the formation of galaxy clusters and the distribution of hot gas in the Universe.

By 2015, 8-10m class ground-based O/IR telescopes will have been operating for nearly 2 decades. Experience with AO will have produced huge gains in sensitivity and perhaps brought us to the point of replicating the excellent imaging quality available in space. We will by then have glimpsed the high-redshift universe, perhaps to z>8, as well as the large-scale structure of galaxies at z~4 based on studies of the brightest (>L*) galaxies. However, the nature of the first collapsed objects (z>8) and the clustering properties of sub-L* (i.e., typical) galaxies, which provide the critical test of hierarchical formation models, will lie beyond the reach of these facilities. Closer to home, we will have studied planet forming systems within ~ 200 pc using 8-10m ground-based telescopes and thereby obtained, from samples of a few tens of systems, tantalizing hints to the questions of when and how planets form. However, definitive answers to these questions and the central question of how frequently planets form, as well as an understanding of the role of dynamical evolution and its impact on the habitability of planetary systems, would await a future, more powerful facility.

In this climate of intense activity, in which numerous discoveries will be made and fundamental astrophysical problems solved, the availability of forefront ground-based optical and infrared telescopes and instrumentation will remain critical to expanding the frontiers of astrophysical knowledge. They will not only drive unique, ground-breaking science on their own, but will also remain critical to the scientific success of capabilities at other wavelengths and in space.

The reasons for this are several. Perhaps most fundamentally, most of the abundant atomic species have important transitions at UV-optical wavelengths. These include the characteristic suites of transitions that act as a “fingerprint” for the identification of individual atomic species; in particular, the strong resonance transitions, which appear in the optical in the spectra of redshifted objects; and also important forbidden line transitions. In addition, many abundant molecular species have their ro-vibrational transitions in the near- to mid-infrared. Thus, the observational diagnostics on which our understanding of stars and galaxies are based (chemical composition, gravity, stellar mass, age etc.) lie in the optical and infrared. Our depth of understanding of these diagnostics are the basis for both future progress and the interpretation of observations made at other wavelengths.

As a result, there are many opportunities for synergy between ground and space, and between multiple wavelength regions, that will lead to tremendous astrophysical progress. For example, while the SKA will probe the formation of the first gaseous structures, and NGST will determine the morphologies of the first stars and galaxies, spectroscopy with a 30-m class ground-based telescope will be needed to determine the physical properties (age, stellar content, mass, etc.) that are needed to understand the formation and evolution of these objects. A 30-m ground-based telescope is the natural spectroscopic complement to NGST in much the same way that the Keck telescopes were for the Hubble Space Telescope.

1.2 Discovery spaces for the GSMT

Although it is clear that the next generation ground-based OIR telescope will be central to our ability to expand the frontiers of astrophysical knowledge, an important unanswered question is what kind of OIR telescope would represent the optimal combination of (1) scientific productivity, (2) cost effectiveness, and (3) technological readiness for deployment by 2015? To help address this question, we have identified several potential “Discovery Spaces” for this next generation telescope, the GSMT. That is, we have identified potential opportunities for significant scientific discovery that would be accessible if the GSMT were designed to allow certain combinations of sensitivity, FOV, wavelength coverage, and spatial and spectral resolution.

Sensitivity and FOV: A large aperture, ground-based telescope can provide the critical combination of sensitivity and FOV that is needed, e.g., for definitive spectroscopic studies of the evolution of large-scale structure (see sec. 2). The same combination of sensitivity and FOV would be critical to other studies, such as stellar population studies of the Milky Way halo that would address the formation and evolution of our own Galaxy. This capability would enable the next generation telescope to fully exploit those periods (perhaps 30% of the time even at the very best sites) when atmospheric conditions (e.g., light cirrus) preclude full adaptive correction.

High Throughput, Low Resolution Spectroscopy: A high throughput, large aperture, ground-based telescope will have the sensitivity to study the detailed physical properties (e.g., star formation rates, metallicities, interstellar media, and internal dynamics) of galaxies over a range of redshifts and, potentially, of the first luminous objects in the Universe (see sec. 3).

Sensitivity and Angular Resolution: A large aperture, ground-based telescope, when equipped with an MCAO system yielding Strehls ≳ 0.5 over moderate fields-of-view (~ 1 arcminute), will have the critical combination of sensitivity and angular resolution needed to study individual stars in crowded stellar fields. With this capability, we will be able to trace the merger and star formation history of nearby galaxies (see sec. 4). The same combination of sensitivity and angular resolution can be used for other purposes, e.g., to measure the masses of galaxies from the morphological (i.e., gravitationally lensed) distortions that they induce in the appearance of background galaxies.

Sensitivity for High Resolution IR Spectroscopy: A large aperture, ground-based telescope equipped with low thermal emissivity, will have the potential for high resolution (R ~ 100,000) spectroscopy at unprecedented sensitivity at infrared wavelengths. With this capability, we will be able to carry out detailed studies of planet formation environments in samples large enough to address fundamental questions such as when, where, and how frequently planets form (see sec. 5).

High Dynamic Range Capability: A large aperture, ground-based telescope when equipped with high-Strehl adaptive optics and a coronagraph can also enable detailed studies of high contrast situations at high angular resolution. A 30-m GSMT will have the angular resolution and sensitivity needed to, e.g., directly detect the light from extra-solar planets and thereby characterize their physical characteristics (masses, radii) and atmospheres for comparison with planets in our own solar system (see sec. 6).

In the following sections, we sketch out how these discovery spaces might translate into specific science opportunities, i.e., we illustrate the kind of science that would be possible if the GSMT were designed to allow those specific combinations of sensitivity, FOV, wavelength coverage, and spatial and spectral resolution. We wish to stress at the outset that the science opportunities that are discussed are not meant to be comprehensive. Rather, our goal is to give an example of the magnitude of the scientific gain that would be possible if the GSMT were designed to enable a given discovery space.

The material in this paper was condensed from the science case described in the AURA New Initiatives Office document "Enabling a Giant Segmented Mirror Telescope for the Astronomical Community" (http://www.aura-nio.noao.edu/book). The interested reader is referred there for further details, more quantitative information, and a greater diversity of possible scientific programs for the next generation OIR telescope. Other possible programs have been described in reports for other large telescope projects such as the Canadian XLT (http://www.hia.nrc.ca/STAFF/cbt/XLT/) and the OWL (http://www.eso.org/projects/owl/).

2. SCIENCE REQUIRING SENSITIVITY AND FIELD-OF-VIEW: LARGE SCALE STRUCTURE

Recent maps of the sky have brought us two very different pictures of the Universe we live in: the remarkably smooth, nearly-featureless Cosmic Microwave Background Radiation (CMBR) that reveals the structure of the very early Universe (z ~ 1200), and the frothy distribution of hierarchically clustered luminous galaxies at the present epoch. In studies of the galaxy population, structure is found on a wide range of scales, from dynamically-organized, kpc-sized galaxies to sheets of galaxies extending over 100 Mpc or more. How did the coherent structures we see today evolve from the tiny density fluctuations in the cosmic microwave background radiation?

Current theory predicts that structure develops quite differently under different cosmological models[1]. Since these are best differentiated at high redshift, the relative merits of different models can be determined from observational studies at $z>1$. While existing (e.g., CfA) and ongoing (e.g., Sloan) galaxy surveys will map out the structure in galaxies at low redshifts ($z<0.5$), the challenge of the coming decades will be to carry out definitive tests of theories of structure formation, by comparing available theoretical predictions with future observations of the CMBR fluctuation spectrum and observations of structure evolution in the redshift range $1<z<3.5$. The redshift range $1<z<3.5$ encompasses roughly half the star formation history of the Universe and, in this redshift range, structures seen at $z<1$ will be in their initial stages of assembly. Indeed, current work over small angular fields already indicates the existence of significant structure at z>3 [2]. While space missions such as MAP will measure the CMBR fluctuation spectrum, extensive future ground-based programs will be needed to measure the evolution of structure, as traced by the galaxy and intergalactic gas distributions.

Although galaxies are the traditional tracers of large scale structure, additional emphasis has recently been given to the intergalactic gas distribution, as typically observed in absorption, because the gas that gives rise to the Lyα forest is expected to be a nearly direct (i.e., nearly unbiased) tracer of the total matter distribution. Moreover, the bulk of the baryonic matter may be in a hot phase (10^5–10^7 K)[3] and difficult to detect except in absorption against background sources. Measuring the structure traced by both galaxies and intergalactic gas would be very useful, since it would allow us to construct a high dynamic range, three-dimensional tomographic map of the universe that can be used to test theories of structure formation.

With this same set of observations, we will also be able to test fundamental assumptions about how the underlying mass distribution can be measured. For example, we will be able to test the current belief that the Lyα forest traces mass fluctuations; we will also be able to measure the degree to which galaxies are biased tracers of the underlying mass distribution. Beyond these fundamental tests, the same data can also be used to measure the detailed spatial distribution of metals in the IGM compared to galaxies to help understand the history of IGM enrichment. We can explore, for example, whether known populations of galaxies can account for the measured enrichment of the IGM, or whether new sources of enrichment are required.

In order to measure the structure traced by galaxies and intergalactic gas, we will need to study volumes large enough to measure accurate clustering statistics and to characterize the largest structures. These large volumes (~ 100 Mpc on a side; or 5 × 5 degrees for Ω_M=0.3 and Λ=0.7) are needed even to measure the clustering of galaxies on fairly small scales with the accuracy required for precision cosmology. We will also need to go faint in order to study structure at high-z and to sample densely.

More specifically, in order to probe the galaxy distribution from z=0.5 to the epoch of formation ($z \gtrsim 10$?) over angular scales $\geq$ 100 Mpc, we will need to obtain spectra of hundreds of thousands of faint (R ~ 26.5) galaxies spread over a range of mass and over large areas (> 5° × 5°). Spectroscopy at R=1000–5000 is required in order to measure redshifts and to characterize the tracer population. Faint galaxies must be studied in order to probe both the high redshift population and to obtain the dense sampling and the consequent high dynamic range that will reveal the complex structures that are predicted.

To probe the 3-dimensional structure of the intergalactic gas distribution, we will require dense sampling of the gas distribution on fine (100 Mpc) angular scales and over a large, well-sampled redshift range (i.e., >50,000 absorbers over a 5° × 5° field per Δz=1). Due to the high object density required, we need to use faint, distant objects (~ 25 AB mag) as background beacons. The high sensitivity of the GSMT is also needed to enable spectroscopy at high enough resolution (R ≅ 10,000) to probe Mpc scales along the line of sight.

Since these measurements require spectroscopy of large samples of faint objects, completing the measurements in a reasonable amount of time requires a high throughput GSMT that has a wide field of view (20'), a large telescope aperture (30-m), and the capability for highly multiplexed spectroscopy (~ 1000 objects or more at a time), primarily at optical wavelengths. Given a GSMT with these capabilities, we will be able to probe, at high redshift, the equivalent of L^* densities in the present-day Universe, probing down to Mpc scales in three dimensions, and covering volumes large enough to provide an accurate measure of clustering statistics and to characterize the largest structures (several million Mpc^3). The total on-sky observing time required for such an endeavor is quite feasible, ~ 1 yr.

3. SCIENCE REQUIRING HIGH THROUGHPUT: THE FIRST LUMINOUS OBJECTS

A high throughput GSMT, with diffraction limited capability and possibly instruments that employ OH suppression, has the potential to study very faint, new galaxy populations such as the first objects to illuminate the Universe. A variety of observational evidence suggests the existence of a significant population of luminous objects at very high redshift ($z \gg 3$). One line of evidence comes from the metallicity and ionization properties of the IGM. For example, the Lyα forest at $z \gtrsim 3$ is found to be metal enriched at a level ~ 0.01 of solar over a wide range of column densities, from the high column densities of damped Lyα systems, which are believed to be the (post-collapse) progenitors of present-day disk galaxies, to the much lower column densities ($N_{HI}=10^{15}–10^{16}$ cm^{-2}) that characterize the IGM overdensities from which galaxies eventually form[4]. The similarity in the level of enrichment for such a wide range in column density is interpreted as evidence for an early phase of metal enrichment at high redshift. In addition, the absence of Gunn-Peterson troughs in high redshift quasar spectra indicates that the IGM was reionized at $z \gtrsim 5$. The increasing rarity of QSOs at z>3 may indicate the need for a distinct high redshift population of objects capable of producing the requisite ionization.

Additional evidence comes from the properties of of high-*z* galaxies. The z~3 star forming (Lyman break) galaxies are known to be enriched in metals[5], implying significant metal enrichment at z>3. Moreover, the tight photometric sequences of galaxies in low- to intermediate-*z* clusters suggest that the elliptical galaxy population forms at high redshift[6]. Finally, some z~1.5 ellipticals are found to have old stellar populations (e.g. ≥ 3.5 Gyr[7]) which also suggests a formation redshift z>5. To this, we can also add the empirical evidence of the known existence of z> 5–6 QSOs[8] and galaxies[9]. In particular, the curious fact that 2 of the 6 galaxies known at *z*>5 were discovered serendipitously is highly suggestive of a significant population of galaxies at *z*>5.

Techniques for the detection of high-*z* objects attempt to detect the light from a young stellar population, either via the bright UV continuum which bears the characteristic imprint of HI absorption by the IGM, or via strong emission lines such as Lyα and Hα that are produced in HII regions. These techniques have led to the identification a small sample of z>5 galaxies and QSOs. Observations of known z~5 objects provide a useful guide, both to how we might expect to detect reionization sources and what we might be able to deduce about them. For example, in the case of the serendipitous *R*-band "dropout" 0140+326 RD1, the first spectroscopically confirmed galaxy at z>5, Dey et al.[10] were able to deduce from the rest-frame UV spectrum the redshift of the system (z=5.34), that the object is a star forming galaxy rather than an AGN, as well as provide constraints on the star formation rate and galaxy mass.

Estimates by Haiman & Loeb[11] indicate that it may be possible to directly observe the high-*z* population that is responsible for the reionization and metal enrichment of the IGM if an early generation of star clusters is the source of reionization. Haiman & Loeb[12] have also explored the possibility that high redshift QSOs contribute to the reionization of the IGM. Based on their estimates, a GSMT optimized for high throughput spectroscopy would be able to obtain low resolution (R=500), modest signal-to-noise (s/n=3–10 per resolution element) spectra of objects at the 1–10 nJy flux level in long integrations (≳ 8 hr). This would enable the detection of a significant population of z>10 star clusters and quasars, > 100 and > 1 per sq. arcmin per logarithmic flux interval, respectively.

4. SCIENCE REQUIRING SENSITIVITY AND ANGULAR RESOLUTION: RESOLVED STELLAR POPULATIONS

The GSMT, with the leap in angular resolution and light gathering power that it offers, is expected to make great advances in studies of resolved stellar populations in galaxies beyond the Milky Way. These studies will provide critical complementary evidence with which to reconstruct the formation and evolutionary history of galaxies: by analyzing the ensemble properties of resolved stars, we may hope to recover the historical record of individual galaxies. Given stellar kinematics, ages, and metallicities measured for individual stars, correlations between these quantities and the existence of clustered subpopulations will reveal the star formation, mass assembly, and chemical enrichment history of the galaxy.

For example, in the case of the Milky Way, recent studies have uncovered the existence of a dwarf galaxy that is currently merging with our Galaxy (the Sagittarius Dwarf[13]), thereby providing definitive evidence that mergers have contributed to the formation of the Milky Way. The possible existence of moving groups in the Galactic halo[14] indicates that multiple mergers may have contributed to the formation of the Galaxy. Correlations between stellar abundance ratios, such as alpha/Fe vs. Fe/H, are being used to understand the interplay between star formation and Galactic gas dynamics (infall, ejection, and mixing) that has driven the chemical enrichment history of the Galaxy.

While, in the coming decade, we expect to use these techniques on existing telescopes to obtain a more complete understanding of the formation history of the Milky Way, the challenge of future decades will be to understand whether the formation history of the Milky Way thus obtained is representative of the histories of other galaxies, i.e., of galaxies spanning a range of masses and morphologies. We already have tantalizing hints of diversity in galaxy formation histories that suggest the need for studies of galaxies beyond the Milky Way. For example, the metal-rich M31 halo[15] suggests a different evolutionary history for M31, a galaxy that appears otherwise quite similar to our own.

The GSMT will provide the powerful combination of unprecedented collecting area and unprecedented angular resolution that is needed to carry out these studies. By equipping the GSMT with innovations in instrumentation, specifically multi-conjugate adaptive optics (MCAO) coupled with large-format infrared arrays and advanced integral field units (IFUs), we will be able to carry out diffraction-limited imaging and spectroscopy over fields of ~ 1′. With these advances, we will be able to probe the star formation, merging, and chemical enrichment histories of galaxies in dense environments (e.g., the Galactic Center and the inner regions of Local Group galaxies), where confusion restricts current studies to only the most luminous stars. In less crowded regions (e.g., outskirts of galaxies, intracluster regions), similar observations can be carried out at the distance of the Virgo cluster and beyond.

The depth to which the frontier of stellar populations studies can be pushed is generally limited by confusion, in the case of imaging, and photon flux, in the case of spectroscopy. The tremendous impact that a diffraction-limited GSMT will have on stellar populations research is, therefore, a consequence of both its resolution and its light-gathering power, each of which gain as D^2, where D is the telescope diameter. In particular, the GSMT will be able to image and take spectra of stars 4.5 magnitudes fainter than is possible with Gemini N + Hokupa'a. In order to illustrate the scientific impact of this capability, we can look at the ability of the GSMT to study resolved stars at the distance of M32 and beyond.

As the closest example of an elliptical galaxy, M32 is a benchmark for population synthesis studies of more distant elliptical galaxies. In work done to date, no existing telescope has had the angular resolution to resolve stars in M32 fainter than the red horizontal branch, even in the lowest surface brightness regions of the galaxy. Deeper CMDs are needed in both the outer and inner regions, to confirm the mean age and metallicity, and the radial gradients thereof, that are predicted by population synthesis models. For example, population synthesis analyses find that the inner regions of M32 are dominated by a population of ~ 5 Gyr old stars of solar metallicity, with outwardly increasing gradients in age and metallicity[16]. High-resolution spectroscopy of M32 giants is also needed to test the predicted pattern of abundance enhancements.

Blum, Olsen, & Rigaut (2002, in preparation) have used simulated images in order to explore the ability of the GSMT and its MCAO system to resolve stars in dense environments such as M32. In the resulting J-K vs. K color magnitude diagram of the inner region of M32 (μ_K=10.1 mag/sq.arcsec), the photometric errors are dominated by confusion even at the resolution of the GSMT. However, the main features—the horizontal branch, the red giant branch, and the asymptotic giant branch—are sharply defined. Indeed, the color of these features is more accurately known than are their single-band magnitudes, a paradox explained by the correlation of the brightness of the background fluctuations through the different infrared bands. In comparison with Davidge et al[17], who were able to measure reliable photometry only for AGB stars ($M_K < -5$) in the outer annuli, the GSMT is able to reach stars as faint as $M_K \sim +1.5$, close to the turnoff of the 1 Gyr old population. Moreover, horizontal branch, red giant, and AGB stars are detected all the way into the nucleus of M32 with GSMT.

In this region, stars are recovered with 10% photometric accuracy to K~ 20 (K=18 in the center and K=22 at the edge of the field). To this depth, the density of recovered stars is, on average, ~ 20 stars per sq. arcsec. If the photometric errors due to crowding are correlated between J and K, as they are in the simulation, the limit for 10% J-K photometry is 2 magnitudes deeper (K=22), where there are on average 80 stars recovered per sq. arcsec. Due to the severe crowding in the inner field, only a tiny fraction (1%) of the total number of stars is recovered, although this represents an appreciable fraction (64%) of the total light. In a less crowded field 90″ from the center of M32, a region similar to that studied by Grillmair et al[18], the GSMT will be able to detect the main sequence turnoff for ages as old as 5 Gyr. Thus, with the GSMT, M32 may be the first elliptical galaxy to have an age directly measured from its turnoff.

Using these results as a guide, we can estimate the ability of the GSMT to produce CMDs and take spectra of stars in more distant galaxies. At the following distances, the GSMT could reach the following imaging depths set by confusion:

- Sculptor group (DM=26.5): $M_K \sim -0.5$ at the half-light radii of bulges, corresponding to stars just below the level of the horizontal branch.
- M81 group (DM=27.8): $M_K \sim -2.0$ at the half-light radii of bulges, corresponding to stars just above the level of the horizontal branch.
- Cen A (DM=28.5): $M_K \sim -1.5$ at the effective radius.
- Virgo cluster (DM=30.9): $M_K \sim -6.0$ at the effective radii of ellipticals, producing CMDs similar to that obtained by Davidge et al.[17] near the center of M32.

5. SCIENCE REQUIRING HIGH RESOLUTION THERMAL IR SPECTROSCOPY: PLANET FORMATION ENVIRONMENTS

The study of planet formation environments is a central part of our search for an understanding of the origin of the Earth and solar system. Indeed, our motivation to study planet formation environments is all the more intense today given the discovery of planets outside the solar system. One of the most intriguing results of searches for extra-solar planets is the discovery that the planet formation process gives rise to considerable diversity. Precision radial-velocity studies have uncovered the unexpected existence of Jupiter-mass planets that span a much larger range in mass (0.2 - 17 M_J), orbital radii (0.04 AU < a < 4 AU) and eccentricity (0 < e < 0.93) than is covered by the planets in our solar system (e.g., http://exoplanets.org). The unexpected diversity in the properties of extra-solar planets challenges traditional theories of planet formation and highlights familiar questions: What are the protoplanetary disk conditions that lead to the formation of planetary systems? How common is the formation of solar systems like our own?

The likely complexity of the planet formation process emphasizes the need for the direct observational study of young disk systems ($\lesssim$ 1 Myr) in order to guide the development of a predictive theory of planet formation. The needed measurements are measurements of the environmental (e.g., density, temperature, column density) conditions under which planets form, observational constraints on the efficiency of a variety physical processes (e.g., grain growth, orbital migration), and a census of young (1 − 10 Myr) planetary systems. Ideally, we would hope to measure masses, orbital radii, and eccentricites of planetary companions, for comparison with the properties of older (several Gyr old) systems, in order to begin to chart out the evolution of planetary systems.

For the latter set of measurements, it may be difficult to detect young planets directly during the epoch of their formation (i.e., when a substantial circumstellar disk is still present). For example, the much larger emitting area of the disk compared to the planet may make it difficult to detect the planet in the glare of the disk. Thus, we may have to rely on a more indirect, dynamical signature of the presence of planetary companions. One such signature is dynamical impact of the forming planet on its parent disk. Dynamical theory predicts that as a giant planet forms, tidal interactions between the planet and disk clear a region in the disk, a “gap”, within which the planet orbits (Lin & Papaloizou 1993; Takeuchi et al. 1996). Since the width of the gap depends on planetary mass, measurements of the location and width of gaps in protoplanetary disks can ultimately provide us with a method of inferring both the masses and orbital radii of planets at their epoch of formation.

Observations in the thermal infrared (4–30 μm) are ideal for both the spectroscopic detection of disk gaps and the study of planet formation environments at radial distances < 5 AU, since the Planck function for disk material at these radii peaks in the mid-infrared. At the warm temperatures (100–2000 K) and high densities of disks at < 5 AU, molecules are expected to be abundant in the gas phase, and sufficiently excited to produce a rich ro-vibrational and rotational spectrum. A high resolution spectroscopic approach offers several advantages: for example, the ability to provide the kinematic information by which the emitting region can be located in the disk. From the measurement of multiple resolved line profiles, physical properties such as temperatures, densities, and column densities can be determined as a function of disk radius. Abundant molecules such as CO, H_2O, and H_2 have transitions in the mid-infrared, and can be used to trace the structure and dynamics of disks.

Despite the tremendous potential of thermal infrared spectroscopy to probe planet formation environments, this spectral region has remained largely unexplored due to the severe sensitivity limitations imposed by large thermal backgrounds and strong telluric absorption. Since NGST is not expected to have high spectral resolution capability in the mid-infrared, the GSMT with its high sensitivity has the opportunity to make the first detailed studies of the dynamics, chemistry, and physical structure of planet formation environments within 5 AU. Simulations[19] show that a GSMT equipped with high spectral resolution capability (R=100,000) in the MIR, will be able to detect the spectroscopic signature (e.g., in the 4.7 μm CO fundamental lines) of gaps produced by forming Jupiter mass protoplanets in samples large enough to place statistically significant constraints on the demographics of planet forming systems.

We may also be able to constrain the gas dissipation timescale of disks in order to constrain the giant planet formation timescale and, by extension, theories of giant planet formation. Molecular hydrogen observations of disks (e.g., the 17 μm S(1) line) is one of the best diagnostics for this purpose. Not only it is the dominant mass constituent of disks, but also depletion onto grains is expected to be insignificant, and the rotational transitions remain optically thin over large column densities. The pure rotational lines have been detected by ISO in young (T Tauri) stars (e.g., GG Tau[20]) and perhaps also in older transitional objects (e.g., β Pic[21]). These observations appear to indicate that the gaseous components of disks that are required for the formation of giant planets can survive for much longer (~ 20 Myr compared to $\lesssim$ 1 Myr) than had been indicated, indirectly, on the basis of infrared excesses and millimeter wavelength CO measurements. SIRTF will extend these studies by measuring spectrally unresolved H_2 emission line strengths for a larger number of systems.

What will remain unclear even after the SIRTF measurements are made is where in the disk the gas resides, and whether it resides in the region in which planets are believed to form (~ 5 AU) or at much larger distances (> 10 AU). Thus, the role of the GSMT would be to measure the orbital radii from which the H_2 emission originates using high resolution spectroscopy. The use of high resolution spectroscopy will also allow the detection of much weaker line emission and the measurement of lower gas masses ($< 1\ M_J$).

6. SCIENCE REQUIRING HIGH DYNAMIC RANGE: EXTRA-SOLAR PLANETS

The GSMT, although not necessarily optimized for high dynamic range science, nevertheness has the potential to make remarkable contributions to the study of extra-solar planets by virtue of its large aperture and high performance AO system. As described above, precision radial velocity studies have revealed the existence of planets outside the solar system and have given us an inkling of the diversity in the properties of extra-solar planetary systems based on their rough demographics (i.e., their a, e, and $M \sin i$ distributions). Even so, we still know relatively little about the fundamental properties (such as mass, radius, and composition) of any individual planet.

One exception is the transiting planet HD209458b, which illustrates the next level of detail with which we might hope to characterize extra-solar planets. In the case of HD209458b (a=0.05), the detailed information revealed by the transit constrains not only some fundamental planetary properties (Charbonneau et al[22]; Brown et al[23]), but also the evolutionary history of the planet. For example, the transit establishes the inclination of the system (86.7 degrees), and therefore the mass of the planet (~ 0.69 M_J), as well as the planetary radius (1.32 R_J). The large radius establishes that the planet is a gas giant rather than a rocky or icy planet, i.e., planets composed of pure olivine or water ice with a mass of 0.69 M_J would have radii of 0.31 R_J or 0.45 R_J[24].

As described by Burrows et al[24], the radius of HD209458b does not simply reflect the expansion of the planet's atmosphere due to recent stellar irradiation, but more significantly, requires the planet to have experienced prolonged stellar irradiation that has retarded the (evolutionary) contraction of the planet. Thus, the large size of HD209458b at the present epoch is a tight constraint on the amount of time ($<10^7$ yr) it could have spent far (> 0.5 AU) from its primary. HD209458b either formed close to its present orbital distance, or it migrated in to its present distance within 10^7 yr of its formation.

Although transits are expected to be relatively rare (Burrows et al[24] estimate that planetary transits may be observed in perhaps 1/10 of extra-solar planets with $a < 0.1$ AU), the possibility of *directly imaging* extra-solar planets opens up the possibility of obtaining similarly detailed information for a much larger number of planets, including those with orbital distances more comparable to the giant planets in our solar system. For example, measuring the system inclination from the visual binary orbit will establish the mass of the planet. Additional multiwavelength imaging or spectroscopy of the planet will reveal detailed information about the planetary atmosphere (cloud composition and planetary albedo, etc.). Given a measured albedo, the planetary radius can be deduced from the luminosity of the planet. With synoptic monitoring, we may even be able to chart the weather on planets outside the solar system. With this level of detail, we will be able to expand planetary science to encompass planets outside the solar system. We will, therefore, be able to examine in greater detail the degree to which extra-solar planets are similar to or different from the planets in our solar system.

The emergent spectrum from the planet is a combination of light reflected from the central star (primarily at $\lambda < 2.5\mu$m) and thermal emission from the planet (primarily at $\lambda > 2\mu$m). Although planets with low albedos (i.e., no clouds) are expected to be dark in reflected light at >0.6μm, when planetary atmospheres are cool enough to permit the condensation of clouds, planets can be significantly brighter at near-infrared wavelengths due to the bright reflecting cloud layer[25]. Not only will clouds increase planetary albedos, but they will also partially fill in absorption features. Therefore, the depth and shape of absorption bands in the near-IR is a powerful diagnostic of the cloud properties of planetary atmospheres.

For the range of orbital separations accessible to the GSMT ($\gtrsim 0.1''$; or 1 AU at 10 pc), we are likely to detect planets with H_2O and possibly NH_3 clouds and, consequently, high albedos (0.4–0.6) at $\lambda < 1.5\mu$m, dropping off quickly beyond ~ 2μm[26]. Given a plausible AO system (1000 actuator deformable mirror plus coronagraph), the GSMT will be able to detect and characterize (via low resolution spectroscopy) Jupiter-like planets located within 10 pc orbiting ~ 1 AU from their central (solar type) stars.

Synoptic photometric studies of extra-solar planets may hope to detect the effects of planetary weather, e.g., the coming and going of clouds, as modulated by the rotation of the planet. In this case, we would expect to see a time variability signature on two timescales: the timescale for large-scale changes in planetary weather, and the planetary rotation timescale. By monitoring the flux in and out of spectral regions of high albedo, it may be possible to map out the surface filling factor of clouds as a function of rotational phase. Such weather-related modulations have been tentatively reported in recent studies of the higher mass L dwarfs[27].

In addition to the possibility of detecting planets in reflected light, we may also be able to detect thermal emission from planets at longer wavelengths. Due to strong line blanketing by molecular bands and collisionally broadened lines, strong thermal emission is expected in spectral regions of low atmospheric opacity. These atmospheric opacity holes are (conveniently) typically the same as the ground-based observing bands, due to the common opacity sources in the atmospheres of the Earth and other planets. Since the excess (line blanketed) flux emerges through the opacity holes, planets can be significantly brighter in these spectral regions. For example, for a planetary atmosphere at 200 K, the excess emerging in the 5μm region is $\sim 10^5$ above blackbody for a cloudless atmosphere[24].

At ages of 0.1, 1.0, and 5 Gyr, and at a distance of 10 pc, a Jupiter-mass planet viewed at 5μm will be 200, 5000, and 3×10^6 fainter, respectively, than the (solar-type) central star. Given the same plausible AO system described above, the GSMT should be able to readily detect Jovian mass planets with ages less than 1−2 Gyr, provided they are located 0.4″ (4 AU) or more from their central stars. Follow-up moderate resolution spectroscopy will provide a detailed characterization of their atmospheric composition, along with an estimate of surface gravities. The extraordinary sensitivity of the GSMT will also enable the detection of thermal emission from similar-temperature Uranus- and Neptune-like planets.

7. CONCLUSION

The science described here is merely illustrative of the frontiers that may be opened by a ground-based 30-m telescope that offers diffraction-limited capability over fields up to ~ 1′; a wide-field (~ 20′) seeing-limited capability; a spectroscopic system optimized for high throughput; thermal infrared capability; and a high dynamic range AO system. The AURA New Initiatives Office continues to work with the community both to extend and refine our understanding of the potential of the GSMT and to develop a sharper understanding of the value attached to each of the demanding telescope performance requirements – a critical next step in defining the “right” GSMT for the next decade.

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