1. 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 existence of Jupiter-mass planets spanning a much larger range in mass ($0.2-17 M_J$), orbital radii ($0.04\,\mathrm{AU} < a < 4\,\mathrm{AU}$) and eccentricity ($0 < e < 0.93$) than do 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?

Traditionally, theories of giant planet formation have focused on explaining the growth of planets under the protoplanetary disk conditions expected at 5 AU, the current orbital radius of Jupiter. However, the large spread in the observed orbital radii of extra-solar planets may be an indication that giant planets actually form over a range of disk radii and physical conditions. Indeed, it is probably inaccurate to assume that planets formed where they are now observed to be because dynamical effects, such as orbital migration due to tidal interactions between the disk and protoplanet and dynamical scattering between planets following disk dissipation, are likely to significantly alter planetary systems. Dynamical studies (e.g., Lin & Papaloizou 1993; Lin & Ida 1997) indicate that these processes can alter the masses (via mergers), orbital radii, and eccentricities of planets, as well as reduce the number of surviving planets (via mergers and ejection). In the light of these recent developments, planet formation now appears to be a much more complex process than was originally envisioned. It may well be that the observed diversity of planetary systems is a manifestation of the multitude of physical processes at work, and the interactions between these processes, in the formation of planetary systems.

The likely complexity of the planet formation process emphasizes the need for direct observational study of young disk systems ($\lesssim$1 Myr) in order to understand the basic physical processes that are responsible for the diversity of planetary architectures. This framework is needed to address the question of whether our solar system is a common or rare outcome of the planet formation process. 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.

High Resolution Infrared Spectroscopy. Observations in the thermal infrared (4–30 μm) are ideal for the study of planet formation environments at radial distances < 5–10 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 < 5–10 AU, molecules are expected to be abundant in the gas phase, and sufficiently excited to produce a rich ro-vibrational and rotational spectrum. With velocity resolved profiles, we can determine the region of the disk responsible for the emission. 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. Mid-infrared transitions of rarer molecules (e.g., hydrocarbons and nitrogen-bearing molecules) can be used to probe the chemistry of disks and, thereby, constrain the history of chemical processing in disks. Since measurements of disk chemistry provide an observational context in which to interpret cometary abundances, which carry the fossil record of the conditions in the solar nebula at its formation, the comparison of disk and cometary abundances may provide important clues to the origin of our solar system.

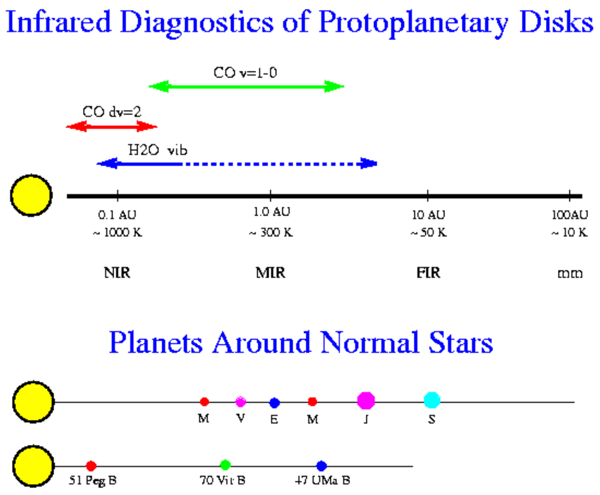

Fig. 1.— Infrared spectral line diagnostics of disks (e.g., Najita et al. 2000). These diagnostics, the CO overtone ($\Delta v = 2$, 2.3μm), CO fundamental ($v = 1-0$, 4.6μm), and the ro-vibrational water lines (K-band), probe the structure of disks at $r \lesssim 1\,\mathrm{AU}$, i.e., the terrestrial planet region of the solar system. Longer wavelength diagnostics are expected to probe disk radii $r > 1\,\mathrm{AU}$.

An Opportunity for the GSMT. 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 JWST will not 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 5–10 AU. Work to date on high-resolution IR spectroscopy of disks has focused on developing the specific gas phase diagnostics with which to probe disks over this range of radii. Thus far it has been shown that the CO overtone (2.3μm), CO fundamental (4.6μm), and H_2O (K-band) ro-vibrational lines can be used to probe the kinematics and physical structure of disks at radii $\lesssim 1\,\mathrm{AU}$ (Fig. 1; Najita et al. 2000), i.e., in what is today the terrestrial planet region of the solar system. By extending these studies to the mid-infrared (e.g., H_2 and H_2O lines) with the GSMT, it should be possible to extend these studies to the larger distances traditionally considered in planet formation theories ($\lesssim$ 5–10 AU).

When Do Giant Planets Form? Wetherill has suggested that the development of life on the Earth may be a consequence of the existence of Jupiter, because Jupiter probably cleared the inner solar system of planetesimals that would otherwise have impacted the Earth at a damagingly high rate. Thus, understanding the formation of giant planets is critical to understanding the origin of the Earth and our solar system. One of the important measurements in this regard is measuring the gas dissipation timescale of disks in order to constrain the giant planet formation timescale and, by extension, theories of giant planet formation.

The mid-infrared rotational lines of H_2O are expected to be a good probe of gas content at radii ≥ 1 AU due to their smaller critical densities and lower energy levels compared to the CO fundamental lines. H_2O is expected to be abundant in protoplanetary disks at temperatures above the ice condensation temperature ($\sim$ 150K), and has numerous mid-infrared transitions which can be used to probe disk physical conditions. As with the CO fundamental lines, telluric absorption is a significant concern. Previous work on the CO fundamental lines shows that this challenge can be overcome by using high spectral resolution to resolve the telluric line and by observing targets at appropriate times of the year when their radial velocities shift the emission from the source out of the telluric absorption line.

Even more appealing are observations of molecular hydrogen emission from disks (e.g., the 17μm S(1) line). Not only is H_2 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 as well as older debris disk systems such as β Pic (Thi et al. 1999, 2001, but see Richter et al. 2002 for a cautionary view). These observations suggest that the gaseous components of disks that are required for the formation of giant planets can survive for much longer ($\sim$ 20 Myr compared to $\lesssim$ 1 Myr) than previously deduced from infrared excesses and millimeter wavelength CO measurements. This suggests the potential for an extended period of giant planet formation that is in closer agreement with current theories of giant planet formation. 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 ($\sim 5\,\mathrm{AU}$) or at much larger distances ($> 10\,\mathrm{AU}$). 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 ($< 1M_J$).

Where Do Giant Planets Form? The diversity in the architectures of planetary systems suggests a more sinister potential impact of giant planets on the evolution of terrestrial planets. The large continuous range in the orbital radii of extra-solar planetary systems suggests that giant planets may migrate significantly inward from the distance at which they formed, potentially merging with their central stars. If they do, they are likely to sweep along any terrestrial planets that have formed at smaller radii. Do giant planets migrate significantly inward following their formation?

To address this question, one exciting possibility is the potential ability to detect the presence of young giant protoplanets through the gaps that they induce in the disks in which they form (Fig. 1). 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. By comparing measured orbital radii with the orbital radii measured for mature planetary systems, we will be able to deduce the role of orbital migration in the evolution of planetary systems.

Fig. 2.— As shown in this simulation (Geoff Bryden, personal communication), young planets are expected to carve out low column density "gaps" in their parent disks. Observations of gaps may provide an indirect means of detecting young planets and inferring their formation masses and orbital radii.

Gaps produced by Jupiter-mass companions can be detected with either imaging or spectroscopic techniques. The angular resolution required to detect disk gaps through direct imaging challenges even the capabilities of a 30-m telescope. With the angular resolution of a 30-m telescope in the mid-infrared (80 mas at 10μm), we may be able to detect via thermal emission ~ 20 AU-wide gaps formed by giant protoplanets at an orbital distance of ~ 60 AU in the nearest star-forming regions (~ 150 pc away). Using the higher angular resolution available in at shorter wavelengths (10 mas at 1.2μm), the 30-m may be able to detect via scattered light ~ 3 AU-wide gaps formed by giant protoplanets at an orbital distance of ~ 10 AU.

Protoplanet formation at smaller disk radii can be more readily probed with spectroscopic techniques. Since the gaps produced by Jupiter-mass planets at these radii are narrow (~ 0.3 AU wide at an orbital distance of 1 AU; e.g., Takeuchi et al. 1996), the resulting spectral energy distribution (SED) will be indistinguishable from a that of a disk without a gap. Even with the high photometric accuracy and continuous wavelength coverage of SIRTF (or JWST), such small gaps will be impossible to detect given the ambiguities involved in interpreting SEDs. In contrast, 8-10m telescopes equipped with high resolution spectrographs potentially have the sensitivity to detect gaps created by Jupiter-mass companions in the nearest star-forming regions. Thus, this approach can be tested out using existing facilities. The role of the GSMT will be to extend spectroscopic studies to a larger, statistically significant (and necessarily more distant) sample of young planet forming systems in order to measure the demographics of forming planetary systems.

The requirement that we probe the same range of orbital radii ($r < 5$ AU) sampled by precision radial-velocity searches for planetary companions sets the required velocity resolution. We require multiple resolution elements across the line in order to resolve the line profile (Fig. 1). Since projected disk rotational velocities at 1 AU around approximately solar-mass young stars are ∼20 km s^{-1}, we require a velocity resolution of $\sim 3\,\mathrm{km\,s^{-1}}$ or a spectral resolution R≈100,000. In order to address the evolution of planetary systems, we need to study a large sample of protoplanets whose demographics can be compared against those of known planets around main-sequence stars. If the incidence of protoplanets at orbital radii < 5 AU is the same as the detection rate of extra-solar planets from precision radial velocity searches (∼10%), we need to survey, for example, ∼1000 planet forming systems (e.g., T Tauri stars) in order to obtain a sample of ∼100 protoplanets, i.e., we need to observe to the distance of Orion (480 pc). Sampling to this distance also provides access to a variety of star-forming environments, from loose associations to dense clusters like the Trapezium.

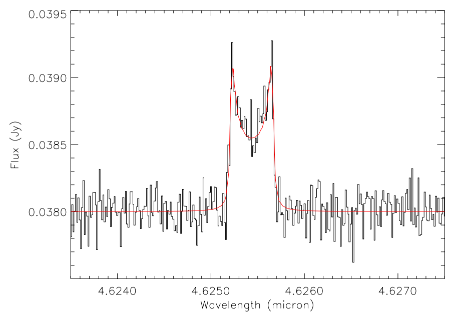

Fig. 3.— Simulated molecular line emission (R=100,000) from a disk gap created by the formation of a 1 M_J planet at an orbital radius of 1 AU from a T Tauri star at the distance of Orion, viewed at an inclination of 30 degrees. The gap is filled with residual gas with a surface density of $\lesssim 0.1$ g cm^{-2} and an excitation temperature of ~ 350 K. At this column density, the infrared dust continuum should be optically thin given the likely agglomeration of grains into larger bodies. Since the projected emitting area of the gap is small, the lines will be weak compared to the T Tauri continuum but detectable at high signal-to-noise with the GSMT.

1.1. Sensitivity Estimates

The relative gains in sensitivity for high resolution thermal infrared spectroscopy of a 30-m GSMT over 8-10m ground-based telescopes in shown in Figure 31 (Carr, personal communication). For completeness, the GSMT performance is also compared with that of a 6.5m JWST were JWST to be equipped with a similar high resolution spectrograph, although at present no such capability is planned. The comparison assumes diffraction limited images, with the slit width matched to the image width at each wavelength, and a resolution of R=100,000 (2-pixel). The detector performance is assumed to be comparable to that required by JWST (i.e., MIR: 10 e- readnoise, 1 e-/s dark; NIR: 4 e- readnoise, 0.02 e-/s dark). The throughput is assumed to be 0.35 (NIR) and 0.20 (MIR) with a slit throughput of 0.75. The telescope temperature is assumed to be 273 K (ground-based) and 60 K (JWST) with 3% emissivity in all cases. For the GSMT, the additional case of 10% emissivity is also considered.

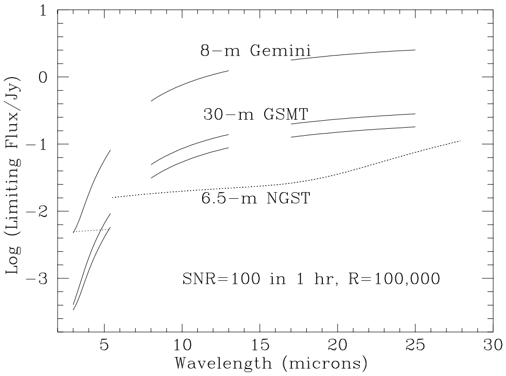

Fig. 4.— Estimated sensitivity for high resolution thermal IR spectroscopy of a 30-m GSMT compared with an 6.5-m JWST and the 8-m Gemini telescope. The comparison is made in terms of the limiting flux at which s/n = 100 (per pixel) is reached in 1 hour at R=100,000. The two GSMT curves correspond to emissivities of 3% and 10%.

Using these sensitivity estimates, we can estimate the time required to study the gas content of disks in order to address the question of when giant planets form. As a fiducial program, we might use H_2O and H_2 emission lines to measure the gas content of disks as a function of radius in sources over a range in age and environment, sampling especially the dense cluster environment in which the solar system likely formed. Since the nearest dense clusters are $\gtrsim$ 500 pc away, a reasonable target distance is 1 kpc. In order to detect moderately strong line emission superposed on the continuum of a classical T Tauri star, we require a signal-to-noise ratio of $\sim$ 25. For a GSMT with 10% emissivity and a H_2O line at 10μm, this requires an integration time of $\sim$ 5 hr. A similar signal-to-noise ratio spectrum of an H_2 line at 17μm requires an integration time of $\sim$ 7 hr. With calibration and overhead, we would require a total observing time of at least 15 hr per target. If we sample 5 clusters (to sample a range of environments), with 30 targets per cluster (to sample a range of ages), we require a total observing time of 250 nights (Table 1).

Table 1. Time Required For Fiducial Projects

	When do planets form?	Where do planets form?
Diagnostics	H_2O 10μm	CO 4.7μm
	H_2 17μm	H_2O 10μm
s/n	25	300
Time/target	15 hr	5.25 hr
No. targets	150	1000
Total time	250 nights	600 nights

These sensitivities can also be used to estimate our ability to study protoplanet formation in different star forming regions. For example, in order to study protoplanet formation using CO fundamental emission, the integration times shown in Table 2 are required. The physical situation is assumed to be that modeled in Fig. 1, but placed at the distance of the Taurus (140 pc) and Orion (480 pc) molecular clouds. The last column of the table shows the limiting distance to which T Tauri stars can be observed in 20,000s of integration. The T Tauri continuum is assumed to be 0.45 Jy at the distance of Taurus, and in all cases $s/n = 300$ on the continuum is assumed to be the requirement to detect and measure the line profile. This comparison shows that the GSMT can effectively survey star forming regions out to > 1 kpc, whereas a ground-based 8-m telescope is restricted to star forming regions < 300 pc. Given the much larger number and variety of star forming regions at 1 kpc distance compared to < 300 pc, only the GSMT will be able to carry out a statistically significant census of young protoplanets using the techniques described in this section.

As a specific program, we might use both 4.7μm CO lines and 10μm H_2O lines to search for forming protoplanets over a range of disk radii. If we restrict our targets to the distance of Orion, we could obtain a $s/n = 300$ CO spectrum on a single T Tauri star in 15 minutes assuming an emissivity of 10%. With overhead and calibration observations requiring ~ 45 minutes per target, we would be able to survey 1000 targets in 100 nights. We could also obtain a $s/n = 100$ H_2O spectrum of a T Tauri star in 4 hr, with overhead and calibration requiring a total time of at least 4.5 hr. Therefore, we could observe 1000 targets in 500 nights, for a total time of 600 nights to complete the project.

Table 2. Limiting Time or Distance

Facility	Emissivity	Taurus	Orion	20,000s
8-m Gemini	3%	450 s	12 hr	—
30-m GSMT	10%	18 s	700 s	1.0 kpc
30-m GSMT	3%	15 s	360 s	1.5 kpc

REFERENCES

Najita, J.R., S. Edwards, G. Basri, & Carr, J., in Protostars and Planets IV, ed. V. Mannings, A.P. Boss, S.S. Russell, (Tucson: U. Arizona), 457

Richter, M. J., Jaffe, D. T., Blake, G. A., & Lacy, J. H. 2002, ApJ, 572, L161

Takeuchi, T., Miyama, S.M., & Lin, D.N.C. 1996, ApJ, 460, 832