

APPENDIX 2.D

STAR AND PLANET FORMATION WITH A GSMT

Report of the Star and Planet Formation Panel, September 2000.

Star and Planet Formation with a GSMT

1. Introduction

The members of the star and planet formation panel were Frank Shu (chair; UC Berkeley), Geoff Blake (Caltech), Jonathan I. Lunine (LPL), Joan Najita (NOAO), Anand Sivaramakrishnan (STScI), Alan Tokunaga (IfA), and David Wilner (CfA). We discussed three general topics: the formation and evolution of planets, the formation of stars, and the specialized instrumentation that would be needed to achieve our science goals. The frontiers of planetary formation and evolution that would be crossed with the GSMT include: the study of planet formation environments (section 2.1), the study of the atmospheres of extrasolar giant planets (section 2.2), the study of the Kuiper Belt of our own Solar System (section 2.3), and the detection of Earth-like planets using high precision astrometry (section 2.4). The GSMT will advance our understanding of star formation both through the study of the individual physical mechanisms that govern star formation (e.g., the origin of stellar jets; section 3.1), as well as by relating the end products of star formation to their initial conditions in order to bring us closer to a predictive theory of star formation (section 3.2). Many of these observational programs will require high dynamic range imaging and high resolution spectroscopy in the thermal infrared. Considerations regarding the implementation of these capabilities are discussed in sections 4 and 5.

2. Formation and Evolution of Planetary Systems

2.1. Structure and Evolution of Disks around Young Stellar Objects

Surveys of young stars at infrared and millimeter wavelengths show that most exhibit emission from small particles thought to be distributed in disks with properties similar to those of the young Solar System. Models of spectral energy distributions indicate disk sizes of tens to hundreds of AU, consistent with an origin in the gravitational collapse of slowly rotating dense molecular cloud cores. These disks are believed to be conduits for the buildup of stellar masses, as well as reservoirs of mass for the formation of planetary systems. Although there is now abundant evidence for the existence of circumstellar disks around young low-mass stars, our understanding of the detailed properties of disks, in particular at planet formation distances (< 30 AU), is still in its early stages. The angular resolution and sensitivity of a 30-m diameter GSMT will far exceed that of existing optical and infrared facilities, and will thereby enable direct imaging and spectroscopy of the planet forming regions of nearby disks. These capabilities will complement those available at other wavelengths (e.g., ALMA).

GSMT observations of the gas and dust constituents of disks, carried out primarily at infrared wavelengths, will address fundamental questions such as: How long does it take to form giant

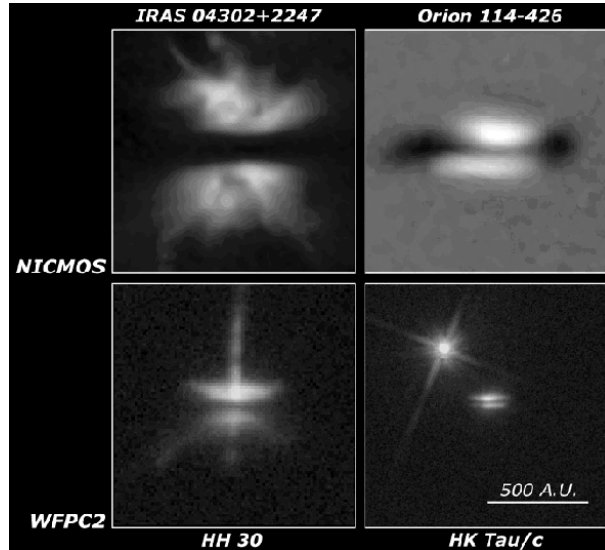


Fig. 1.— Hubble Space Telescope images of circumstellar disks in nearby dark clouds revealed in scattered optical and infrared light (from Meyer & Beckwith 2000). A diffraction limited 30-m GSMT will improve the angular resolution by two orders of magnitude in solid angle and reveal a wealth of structural detail.

planets? What determines the masses of planets? Did the solar system form under ‘typical’ conditions?

Imaging Disk Structure The benefits of high angular resolution are readily apparent in images of disks made with the Hubble Space Telescope. Figure 1 shows several systems, viewed close to edge-on, where opposing disk surfaces are visible in scattered light from the central star. The analysis of the scattered light images constrains the radial and vertical structure of the disk, which bears on theories of energy transport, and also constrains dust grain properties. The scattered light images are sensitive to very small quantities of dust, less than the mass of the moon. When equipped with adaptive optics, the GSMT will enable qualitatively new structural investigations by providing diffraction limited imaging approaching $0''.010$ resolution in the near-infrared, corresponding to < 2 AU, with the excellent surface brightness sensitivity afforded by a filled aperture.

For example, detailed modeling of isophotes may allow us to infer the existence of young planetary bodies, as revealed by their dynamical influence on their parent disks. Broadband spectral energy distributions sometimes show deficits in continuum emission over a range of wavelengths, interpreted as reduced continuum opacity for a range of disk radii, i.e. gaps. While this interpretation is not unique, millimeter interferometry and infrared imaging have already directly imaged huge inner holes in the disks that surround some young stellar systems, for example the 200 AU radius cavity in the circumbinary disk of GG Tau shown in Figure 2. While only the largest proto-planets may form gaps of sufficient width to be imaged directly, smaller bodies likely will produce

detectable inner holes once the bulk of disk material interior to their orbits has been accreted. More detailed, interferometric, images may uncover small scale departures from axial symmetry, such as spiral modes induced by companion bodies (see below).

Spectroscopy: Physical Conditions, Composition, Kinematics The infrared region of the spectrum is rich in the vibrational-rotational transitions of molecules sensitive to the physical and chemical conditions of warm, dense, disk material, including the innermost regions where giant and terrestrial planets form. The large aperture of the GSMT will enable moderate to high resolution emission and absorption line spectroscopic study of these regions.

If the GSMT is equipped with high resolution thermal IR spectroscopic capability, we will be able to address questions such as “How long does it take to form giant planets?” That is, the timescale for giant planet formation can be constrained directly by measuring the gas content of protoplanetary disks as a function of age. One of the most important diagnostics for this measurement is H₂, which is highly favored for this measurement because it is the dominant mass constituent of disks; it is expected to remain in the gas phase rather than depleting onto grains; and the H₂ transitions remain optically thin over large column densities. The H₂ content of disks can be measured with a series of lines, in particular the J=3→1 S(1) line at 17.0 μm. The first observations of this low lying pure rotational line from a disk system were recently reported for the GG Tau binary, but with neither the spatial nor spectral resolution to locate the origin of the emission (Thi et al. 1999). Theory suggests that the typical H₂ line flux from a single face-on surface layer in a flared disk atmosphere will be $\sim 10^{-15}$ erg s⁻¹ cm⁻² (Thi et al. 1999), which the GSMT should easily detect and resolve into many elements. Thus, for the study of the giant planet formation region, which can be spatially resolved, integral field spectroscopy will be ideal for many of the compact, bright, target sources.

In comparison, the terrestrial planet formation region is too small to be spatially resolved even with the GSMT (1 AU \simeq 6 mas at the distance of the nearest star forming regions). Consequently, high resolution spectroscopy will be the only way to probe the physical structure of these regions. That is, the kinematic information provided by high resolution spectroscopy can be used to locate the region of the disk that is responsible for the emission, and observations of multiple transitions will probe the physical conditions (e.g., temperature and density) of the emitting region. High resolution spectroscopy ($R > 100,000$) with the GSMT will enable kinematic studies with resolution < 3 km s⁻¹, commensurate with orbital motions of disk material out to Kuiper Belt distances. The physical and chemical structure of disks can be studied using a variety of trace gas phase diagnostics, e.g., CO, H₂O, C₂H₂, HCN, and CH₄.

High spectral resolution observations of the CO fundamental and overtone lines at 4.6 μm and 2.3 μm with 3-m class telescopes show great promise, already revealing the bulk rotation of inner disk material and probing possible gaps in close binary systems (Najita et al. 2000; Carr et al. 2000). These studies show that only very tiny amounts of residual gas in gaps are needed to produce bright, detectable emission. Thus, high resolution spectroscopy of trace species can be

used to search for protoplanets at small orbital radii. Since the mean radius and width of gaps are related to, respectively, the orbital radius and mass of the planet, the measurement of these properties of gaps may allow us to determine when and where planets form, as a function of planet mass. Situations with special geometries will be ideal for exploiting high resolution spectroscopic capabilities, for example in the T Tau binary, where the outer disk of the northern star extends in front of the southern infrared bright companion, which can be used as a background lamp to study the outer disk in detail.

With high resolution spectroscopic studies, we will also be able to measure the relative molecular abundances of disks as a function of disk radius. We will thereby obtain an observational context in which to interpret cometary abundances. Since cometary abundances carry the fossil record of the conditions under which the solar system formed, the comparison of disk and cometary abundances may lend us insight into whether the solar system formed under “typical” conditions.

At lower spectral resolution ($R \lesssim 2000$), we will also be able to study the “mineralogy” of disk solids through the silicate bands and PAH features. One interesting issue is the origin of the crystalline silicate features found by ISO in solar system comets as well as in disks around young intermediate mass stars. Crystalline features indicate “annealing”, i.e. exposure to ~ 1000 K temperatures for moderate periods of time, conditions which are highly contradictory to the simultaneous presence of icy material in comets. This indicates that material from warm inner disks is recycled, perhaps by aerodynamic launching in winds (e.g., Shu et al. 1994), into cold outer disks where icy mantles can be accreted. If this scenario is true, then the composition of comets records the *dynamical* as well as physical conditions present at the formation of the solar system! We can test this hypothesis by looking for an increasing fraction of crystalline material as a function of age in nearby star forming systems.

Interferometric Imaging of Wakes of Giant Planets in Protoplanetary Disks Considerably more detailed questions can be investigated if the GSMT is equipped with mid-infrared imaging capabilities at milliarcsecond resolution. For example, imagine a proto-Jupiter which has formed at a radius $\varpi = 5$ AU in the nebular disk surrounding a young star. The proto-Jupiter is expected on the basis of current theory to open up a gap in the disk of perhaps $\Delta\varpi = 0.5$ AU width on either side of the planet. A width of 0.5 AU at the distance, ~ 150 pc, of the nearest active regions of star formation in the Taurus and Ophiuchus molecular clouds corresponds to an angular separation of 3 mas. The gravitational potential energy associated with gas at a distance of 0.5 AU from a Jupiter is about 10^{-2} that associated with the same gas at a distance of 5 AU from the sunlike central star (assuming a mass ratio of planet to star of 10^{-3}). Thus, the velocity perturbation Δv produced in the nearby nebular gas by the planet will be $\sim 10^{-1}$ the circular velocity of that gas about the central star, i.e., $\Delta v \sim 2$ km s $^{-1}$. Such a perturbation is supersonic if we make the standard assumption that the proto-Jupiter has formed beyond the “snowline” in the nebular disk, i.e., at a radius where the local gas (mostly H $_2$) has a temperature below ~ 150 K. Thus, shockwaves will form in the wakes of the perturbed flow of nebular gas at the edges of the gap on either side of the proto-Jupiter (see Figure). These shocks can be expected to raise

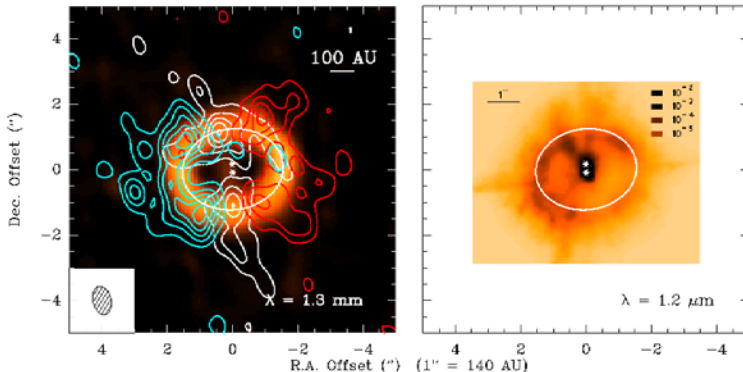


Fig. 2.— Images from of the circumbinary disk in the GG Tau system (from Guilloteau et al. 1999): (a) ^{12}CO J=2-1 line emission at 5.55 km s^{-1} (blue), 6.30 km s^{-1} (white) and 7.05 km s^{-1} (red) overlaid on 1.4 millimeter dust continuum emission, and (b) $1.6 \mu\text{m}$ light resolved by adaptive optics on the Canada-France-Hawaii-Telescope. The 200 AU radius hole in the GG Tau circumbinary disk is analogous to much smaller scale features expected to be cleared in circumstellar disks by planets in formation.

the postshock gas temperature in excess of 200 K, which is sufficient to excite the $17 \mu\text{m}$ (pure-rotational transition) line of H_2 and cause it to go into emission relative to the radiation from the surrounding unshocked gas. In other words, there will be two local “hot spots” if the disk can be imaged with sufficient sensitivity in the $17 \mu\text{m}$ line of H_2 .

One can expect that the shocks will excite a mass of H_2 that is some appreciable fraction of the mass associated with the local surface density Σ_g of the gas in the disk times the area of the annular gap $(2\pi\varpi)(2\Delta\varpi)$. For a disk equal to a minimum solar nebula, the latter mass $4\pi\varpi\Delta\varpi\Sigma_g \sim 10^{30}$ g, which is comparable to the mass of warm H_2 that has already been spectroscopically detected by ISO in some young stellar objects (but not with resolved line-profiles, nor do the large-beam measurements of ISO reveal where in the system the excited H_2 is arising). With the greater sensitivity and velocity resolution of GSMT, the radial location of the hot spots can be inferred even without the interferometric ability to spatially image the disk on a scale of a few mas. Line-imaging capability at this level would, however, allow astronomers to pinpoint both the radial and the angular positions of a forming giant planet even though the (unresolved) proto-Jupiter may not be sufficiently bright in the mid-infrared continuum to allow its direct imaging against the confusion of the light from the much larger disk.

Synergy with ALMA On the same timescale as GSMT, the Atacama Large Millimeter Array (ALMA), an international telescope project planned for the high desert of Chile, will begin to provide complementary views of the disks around young stars at wavelengths where dust continuum emission has low opacity and trace molecular species have very low excitation rotational transitions. ALMA will be two orders of magnitude more sensitive than existing millimeter instruments and,

arguably, represents a much greater leap forward in capabilities at these wavelengths than the progression from 10-m optical/infrared telescopes to a 30-m GSMT. The long baselines of ALMA will provide angular resolution reaching $0''.010$, and heterodyne detection techniques will naturally provide velocity resolution better than 1 km s^{-1} . Together, ALMA and GSMT will provide imaging spectroscopy at comparable resolutions of the entire spectrum of disk emission accessible from the ground. ALMA observations of millimeter and submillimeter emission will largely probe the cooler, outer disk zones and deep interiors, while GSMT will detect optical and infrared light emerging from the inner disk and extended atmosphere. Observations of both regimes are critical for developing a full understanding of disk structure and energy balance. The capabilities of the GSMT for resolved observations of H_2 emission will be essential to help sort out the physical and chemical gradients observed in trace molecular species in light of the complexities of gas phase chemistry and grain evaporation processes in the protoplanetary environment.

2.2. Giant Planets

Giant planets are the alpha and the omega of solar system formation. They must form before the gaseous disk is dissipated, and as they grow they perturb the orbits of the remaining rocky and icy debris left over from their formation. The resulting dynamical excitation results in the reshaping of orbits and differing fates for icy outer solar system planetesimals.

We know a great deal about the giant planets of our own solar system, and in particular evolutionary models of Jupiter and Saturn have been precisely tuned to their known properties and our current understanding of the equation of state of dense hydrogen and helium. For this reason it is possible to take relatively simple data on extra-solar planets, for example the mass, radius and orbital semi-major axis of HD209458 b (the “transit planet”) and constrain both the composition of this body and its migration history (Burrows et al. 2000). (Indeed, it has even been possible to successfully challenge one low signal-to-noise observation of an extrasolar planet on the basis of theoretical modeling of radius-mass relationships;(Burrows et al. 2000). However, the ability to study directly the atmospheres of extrasolar giant planets would open up entire new avenues of research in comparative planetology and the cosmogony of extra-solar planets.

We currently possess modest (10^3) spectral resolution optical and near-infrared spectra of a handful of so-called T-dwarfs, objects that are cool enough that methane rather than carbon monoxide dominates as the carbon-bearing species in the visible atmosphere. (Resolution of 10^4 has been accomplished with Keck over limited wavelength regions as well; see Burgasser et al. 2000). All but one of these objects are free-floaters (the exception being Gliese 229 b; (Oppenheimer et al. 1998), and the masses of all of these bodies derived from evolutionary models exceed 10–20 Jupiter masses. Arguably none of these objects formed through an accumulation process, but instead formed through primary or binary collapse in the manner that stars form. We have yet to study the spectra of true extra-solar giant planets.

To bring the compositional study of extra-solar planets into the quantitative realm of direct spectroscopy will require large apertures and effective coronagraphic or nulling-interferometric capabilities. Reflectance spectra will be possible of objects at moderate separations (close enough to the parent to be bright in reflection but distant enough to allow coronagraphic separation. Thermal emission spectra of giant planets in distant orbits may be possible by selection of appropriate wavelength regimes in which the object will be overluminous relative to blackbody fluxes. An example is the 5 micron region of the spectrum where Jupiter is known to be bright (Sromovsky et al. 1996) and where extrasolar planets over a variety of effective temperatures are predicted to be overluminous (Burrows et al. 1997). We argue for coronagraphic capabilities for GSMT elsewhere in this report, and such would enable study of extrasolar giant planets at moderate separations (i.e., exceeding 1 AU) from their parent stars for stars within the 10 parsec solar neighborhood.

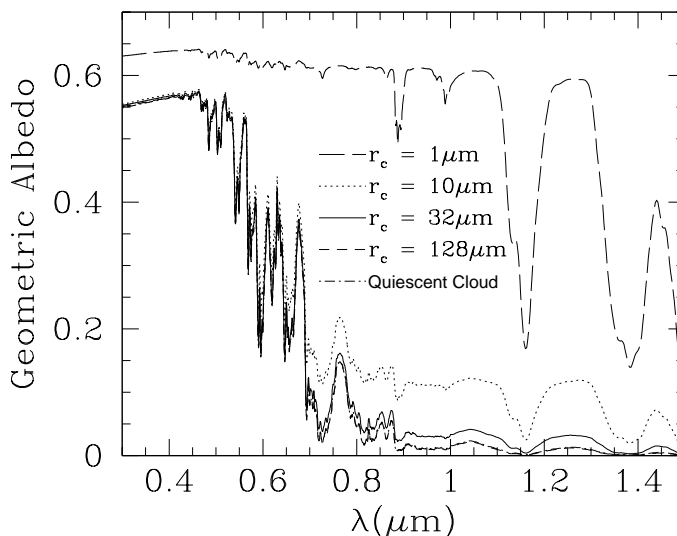


Fig. 3.— Appearance of the model reflectance spectrum of an object with a gravity of 22 m s^{-2} and effective temperature of 300 K, for water clouds with particle sizes labeled. For this exercise cloud particles are assumed to have a single particle size, rather than a distribution characterized by a modal size. From Marley et al. 1999.

Reflectance spectra of extrasolar giant planets at high ($R \simeq 10^4$) spectral resolution would allow the compositions of major molecular species to be determined, such as methane, as well as infer the occurrence and locations of clouds through the relative band depths of molecular features of varying strength, as shown in figure 3 (Marley et al. 1999). Detection of secondary molecular species of major elements in warm giant planets in spectra, for example ammonia features at $\sim 7 - 8 \mu\text{m}$, or carbon monoxide features in the methane dominated atmosphere, provide powerful tools for gauging the extent of vertical mixing in atmosphere as well as the atmospheric temperature profile. (The physics behind this lies in the steep temperature dependence of both the minor species abundance and of the rates of the reactions which interconvert the primary and secondary species

of a given major element; Saumon et al. 2000). Keck observations represent the state of the art, yet again these observations are limited to self-luminous bodies with masses of tens of Jupiter masses. To bring such compositional and dynamical investigations down to the Jovian mass realm will require much larger apertures than Keck, and coronagraphic or interferometric capability.

A potential threshold indicator of mass with high sensitivity is the presence or absence of deuterium in an extrasolar planet. Deuterium fusion does not occur in hydrogen-helium objects with masses below $13M_J$ (Saumon et al. 1996). Indeed, deuterium and ^3He are found in relative abundances—and individual abundances normalized to hydrogen—in excellent agreement with the hypothesis that no deuterium fusion has occurred in Jupiter in the 4.5 billion years over which the Sun has undergone hydrogen fusion (Mahaffy et al. 1998). Our confidence in the structural and evolutionary models of brown dwarfs is such that the presence or absence of deuterium in an extra-solar planetary atmosphere is a powerful discriminator of whether the mass of the object is above or below $13M_J$. It is independent of the mass determination derived from the luminosity and system age coupled to evolutionary models. (Extra-solar planets with masses below $13M_J$ that are extremely close to their parent star, and that achieved that distance immediately after formation, might remain hot enough for deuterium fusion to occur. However, such extreme “roasters” (Sudarsky, Burrows, & Pinto 2000) would not be observable with the coronagraphic capabilities of GSMT.)

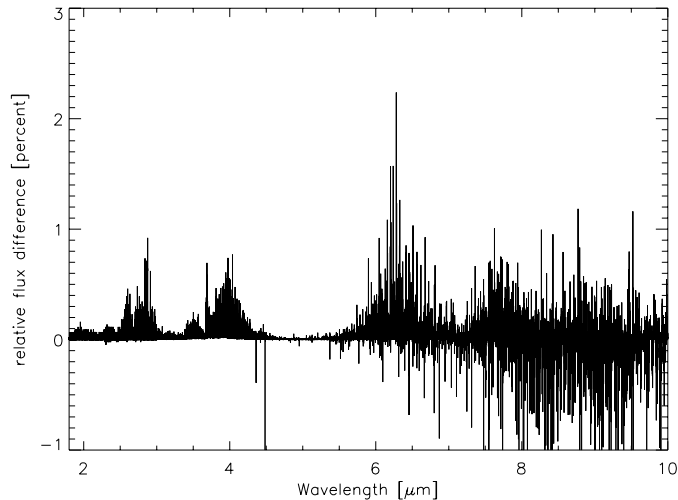


Fig. 4.— Relative difference between model thermal spectra for a planet with and without the cosmic abundance of deuterium, for a spectral resolution of 30,000. The object has effective temperature of 2500 K and gravity of 22 m s^{-2} . From Chabrier et al. (2000).

Figure 4 shows the difference between theoretical spectra of a hot (2500 K) object with and without deuterium (Chabrier et al. 2000). The spectral difference is due to the corresponding presence or absence of HD in the atmosphere, and requires very high ($R \geq 30,000$) spectral resolution

for detection. In cooler objects a better strategy might be the presence or absence of CH_3D absorption features to assess depletion of deuterium (Chabrier et al. 2000), but such an effort would require very high spectral resolution as well. Thus, the identification of cosmic-abundance deuterium in an extrasolar planet provides a firm upper limit on the mass of the planet. It also opens the door to comsogenic investigations regarding formation processes; for example to ultimately test the hypothesis that stellar-like collapse processes to form brown dwarfs requires deuterium burning (Shu, Adams, & Lizano 1987).

2.3. Kuiper Belt

The dynamical excitation by giant planets results in the reshaping of orbits and one of four fates for icy outer solar system planetesimals:

- Inward evolution and eventual collision with the Sun or terrestrial planets.
- Outward ejection into interstellar space, the Oort Cloud or the scattered component of the Kuiper Belt.
- Agglomeration into the giant planets, or into the embryos which eventually form the terrestrial planets.
- Mutual collisions and grinding down into dust, which is removed from the system by Poynting-Robertson drag.

These processes sculpt not only the outer solar system but also play a role in the volatile budget of the inner solar system—hence affecting the inventory of water and organic molecules that the Earth and other terrestrial planets acquired. Over time spans of billions of years they have cleared out the “classical” Kuiper Belt, resulting in a very sparse population of remnant planetesimals strongly structured by orbital resonances. Beyond the classical Kuiper Belt there should be a “scattered disk”, consisting of material whose orbits were enlarged by early interactions with the giant planets, shaped perhaps by mutual collisions but not by subsequent dynamical interactions with the giant planets. We know of only a handful of Kuiper Belt objects whose orbits label them as from the scattered disk, in contrast to the numerous known members of the classical Belt.

A raft of questions about the Kuiper Belt remain unanswered with existing ground-based facilities (For a much more detailed review of our present knowledge of the Kuiper Belt, refer to the several chapters on the topic in *Protostars and Planets IV*; Mannings et al. 2000). The original mass of the Kuiper Belt is a key question which is driven by the inference of much more massive debris disks around a number of nearby stars younger than (and of earlier spectral type than) the Sun. It will largely have to be addressed by deeper surveys into the scattered disk and by in situ missions to do crater counting on the surfaces of Pluto and other Kuiper Belt objects. Telescopic

facilities other than GSMT are likely to be more efficient at conducting such searches. However, GSMT deep pencil beam surveys provide opportunities to (a) probe outward toward the 100 AU semi-major axis realm, (b) sample Kuiper Belt members down to cometary size, (c) to discover Pluto-sized or larger objects hundreds of AU from the Sun.

The special role of GSMT will be the collection of high signal-to-noise spectra of Kuiper Belt objects. With its large aperture, GSMT could allow near-infrared reflectance spectra of objects in the classical disk with spectral resolutions comparable to those now available for Pluto, i.e., $R = 10^3$ – 10^4 , and allow for spectral resolution on Pluto itself of $R = 10^4$ – 10^5 . Spectra of Kuiper Belt objects other than Pluto are today difficult to obtain even with Keck, and the results among different groups seemingly contradictory and hence controversial (cf. chapters in Mannings et al. 2000). The expected increase in the information content that will be achieved with the GSMT is likely to be comparable to that available in spectra of Pluto from the 1970s ($R = 20$; Soifer et al. 1980) compared to that available today ($R = 350$; Owen et al. 1993). An increase in spectral resolution of one order of magnitude leads to the identification of several major ices, determination of the physical state of the ices (pure, solid solutions or physical mixes), and even the temperature of the ice through the narrow 2.16 micron N_2 feature. With GSMT, similar or better quality spectra of Kuiper Belt objects 1/10 the diameter of Pluto can be obtained. Exposures of ices will indicate collisional processes that expose fresh ice to the space environment, and the relative abundances of N_2 , CH_4 , CO , CO_2 and others can be compared to Pluto and to comets. We seek to understand the differences in major molecular species abundance differences among Kuiper Belt objects, and between Kuiper Belt objects and comets. Long-period comets provide a record of the Oort Cloud, and hence Saturn-Uranus zone, volatile inventory, while comparison with short-period comets (whose inventory will be obtained in detail by Rosetta) will test the hypothesis that the Kuiper Belt is the source of such bodies.

Very high resolution spectra of Pluto may allow the measurement of the deuterium-to-hydrogen ratio in water ice on Pluto’s surface. This isotopic measurement is known for water in long-period, Oort-cloud comets and for various molecular cloud species, and provides a key point of comparison for the origin and processing of ices from the molecular cloud through the proto-planetary disk. Since we also know D/H for terrestrial ocean water to be lower than that for Oort Cloud comets, getting a Kuiper Belt value will be of high interest for understanding the role, if any, of Kuiper Belt material in seeding the terrestrial planets with volatiles.

In summary, the capability to do high-resolution spectroscopy ($R = 10^4 - 10^5$) with GSMT opens the door to compositional and evolutionary studies of both Kuiper Belt objects in our own solar system and giant planets around other stars. Given the cosmogonic ties between giant planets and debris disks of remnant planetesimals, such studies promise to revolutionize our understanding of the formation and evolution of systems with giant planets, and to provide an important perspective on the commonality or specialness of our own planetary configuration.

2.4. Astrometric Detection of Earth-like Planets

The Decade Survey Report in Astronomy and Astrophysics has identified the detection of earthlike planets around other stars and the characterization of their atmospheres as a high-priority goal of American science in the beginning decades of the twenty-first century. However, the report goes on to say that any NASA commitment to build a Terrestrial Planet Finder (TPF) should be contingent on the prior demonstration of the existence of terrestrial planets outside the solar system. Our panel believes that the superb light-gathering power of the GSMT, coupled with the ability for precision relative astrometry may be able to provide this proof for the most important potential targets, namely the same sunlike stars within 10 (or 13) pc of the solar system that would be on any list for TPF investigation.

To detect the wobble of a central star associated with the reflex motion of an earth circling at 1 AU in a system which is located at a distance of 10 pc requires an astrometric precision of $0.3 \mu\text{as}$ in the stellar position relative to a background of reference objects. There are therefore two problems which requires further immediate study: (a) How many useful background stars bright enough to be used a reference source are there in a nominal FOV of say, $2' \times 2'$? (b) Can the PSF stability of the telescope be maintained long enough to obtain an astrometric accuracy of $0.3 \mu\text{as}$ for this reference star? (The nearby target star is so bright that defining its center of light very accurately is not a problem.)

A preliminary investigation by our panel suggested that the answers to questions (a) and (b) may both be negative; namely, (a) except for special fields, there appear to be generally insufficient numbers of background sources to serve as possible points of reference, and (b) the PSF in light scattered outside of the central core may be too complex and too unstable to achieve the desired accuracy in relative astrometry with respect to the expected faint reference stars.

Thus, to succeed in this challenging and important problem probably requires the kind of dual-star interferometry techniques that has been developed and successfully applied for the Palomar Testbed Interferometer. Studies are needed to examine the feasibility of building *two or more* GSMTs separated by distances of hundreds of meters and operating them in a dual-star inteferometry mode in the near infrared. The panel recognizes that this is a highly challenging project and cannot be realistically pushed as a first-stage priority. However, we would urge NOAO not to make design-study decisions that would eliminate the possibility of going down this path on a timescale compatible with NASA's plans with respect to the Terrestrial Planet Finder.

3. The Formation of Stars

3.1. Mechanics of the Central Machine of Young Stellar Objects

Jets and collimated outflows occur in a wide variety of astrophysical objects. However, only in young stars are the objects close enough to allow us to think realistically about spatially resolving

the central machine within the timescale of the next generation of ambitious astronomical projects. It is a double bonus that YSO jets can be imaged in spectral lines, and not only in the continuum, which adds indispensable kinematic information to the images as diagnostics of what is happening physically.

There are two main competing theoretical models for the central machines of YSOs. In both pictures, the activity arises as a natural consequence of the coupling of rapid rotation and strong magnetic fields. In both pictures, the source of the rapid rotation is a Keplerian disk that surrounds a young star which is forming from mass accretion from that disk. In the disk wind model, the strong magnetic fields intrinsically reside in the disk itself, having been dragged in from the surrounding interstellar medium by the prior gravitational collapse of the system. In the x-wind model, the strong fields are rooted in the central star, having been generated by dynamo action inside the star, with a possible contribution from the interaction of the stellar magnetosphere and the inner edge of the accretion disk. In the x-wind model (Figure 5), the latter interaction creates both an outflow that eventually collimates into a YSO jet, and an inflow that funnels the complementary fraction of the disk accretion that is not channeled into the x-wind onto the central star. In the disk wind model, any magnetized funnel flow onto the central star is unrelated to the outflow from the disk wind, which occurs over a much larger range of radii than the innermost radii of the disk that characterizes the x-wind model.

In addition to all of the above advantages, the hydrogen line profiles associated with T Tauri stars are known to be highly time variable, changing on a timescale of hours to days. In the x-wind model the emission from the funnel flow should be correlated with the emission from the outflow. In the disk wind model, there should be no such correlations since the two flows involve distinctly different sources of the attached magnetic fields. Although temporal correlations between inflow and outflow signatures have been detected in a few sources, and are interpreted as supporting the x-wind type of picture, the phenomenon is not universal. To provide definitive discriminants, one must be able to correct for the temporal decorrelations that occur because the emission is coming from spatially extended regions that have considerable structural complexity. Spatially resolved images of hydrogen emission lines that are also spectrally resolved would provide such conclusive tests.

The inner edge of the disk is expected on the basis of the theoretical models to be located at a radius of about 0.06 AU. At the distance of the closest T association, ~ 40 pc, the radius 0.06 AU will subtend an angle of ~ 1.5 mas. The best line-diagnostics for both the funnel flow and the x-wind are probably the permitted H lines in the near-infrared (Paschen or Brackett series). The angular resolution requirements, being in the near-infrared rather than the mid-infrared, therefore are somewhat less severe than the previous project, but interferometry rather than adaptive optics would still be required. (Adaptive optics is, of course, a prerequisite to infrared interferometry. In this context, we should remember that the study of structures surrounding nearby young stars always has a bright infrared source in the FOV for wavefront corrections, namely the central star itself.) The line luminosities are in the range $10^{29} - 10^{30}$ erg s $^{-1}$, and are mostly concentrated to

an angular scale within the central few mas. Thus, the surface brightness of the lines should not pose a sensitivity problem for the imaging.

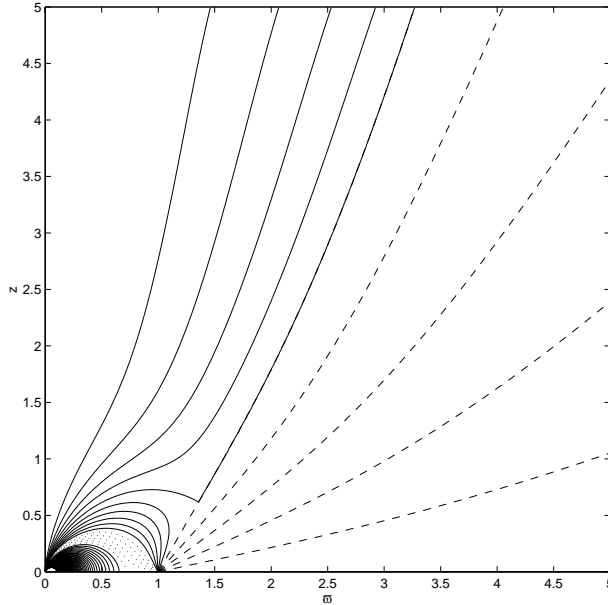


Fig. 5.— The poloidal magnetic field configuration resulting from the interaction of a magnetized star and a surrounding accretion disk. The inner edge of the disk with radius R_x is the point of convergence where the stellar field lines try to push into the disk and abut against their counterparts swept in by the accretion flow inside the disk. The funnel flow onto the surface of a star of radius R_* (not depicted because R_* is arbitrary as long as it is smaller than R_x) is denoted by dotted lines. The funnel flow is in pressure equilibrium with a dead zone of closed field lines (solid curves) that thread through the disk too vertically to induce any magnetocentrifugal dynamics. Also denoted by solid curves are stellar field lines opened by the X-wind that connect at infinity to the dashed lines in the X-wind. The calculation assumes that all field lines that rooted in the star would be dipole field lines if there were no interaction with the disk.

3.2. Toward a Predictive Theory of Star Formation

Stars illuminate the Universe and produce the heavy elements that we are made of. What determines their most fundamental property, i.e., their masses? Answering this question likely requires a combination of observations and theory. From the observational side, we hope to measure the initial conditions that give rise to star formation, e.g., the density, temperature, ionization and magnetic field structure of molecular clouds. We also hope to study the detailed physical processes that govern star formation, e.g., the launching of protostellar winds, the evolution of stellar angular momentum, and the physics of disk accretion. Finally, we hope to measure the outcome of the star

formation process, e.g., the IMFs and star formation efficiencies as a function of metallicity and environment. By relating the outcomes to their initial conditions, and guided by our understanding of the physical processes involved, we hope to come up with a predictive theory of star formation.

The GSMT has an important role to play in each of the measurements described above. In terms of measuring initial conditions, the GSMT will be able to carry out detailed studies of molecular cloud conditions using high resolution ($R = 100,000$) absorption line spectroscopy, primarily in the infrared ($\sim 2 - 20\mu\text{m}$). These measurements will complement the emission line measurements to be made with ALMA. To date, absorption line studies are limited by the sensitivity of current telescopes and have been restricted to the use of bright infrared sources *embedded in* molecular clouds as background beacons. These embedded sources may themselves influence the structure and properties of molecular clouds. In contrast, the more sensitive studies that can be carried out with the GSMT can make use of fainter beacons located outside of molecular clouds. These are likely to produce more reliable, unbiased results.

The detailed study of the physical processes that govern star formation ($R = 10,000$ spectroscopy at $0.5 - 5\mu\text{m}$) has focused, again due to sensitivity limitations, on young stars within ~ 150 pc and yielded considerable insight into the formation of approximately solar mass stars under solar metallicity and in primarily low density environments. With the greater sensitivity of the GSMT, we will be able to extend existing studies to a wider range of stellar masses, to regions of higher and lower metallicity (the Galactic center, the outer Galaxy and LMC), and richer star forming environments.

Similarly, measurements of IMFs covering a wide range of stellar masses have, thus far, probed somewhat more distant regions ~ 1 kpc, using broad band imaging and moderate resolution spectroscopy ($R = 2,000, 0.4 - 2.5\mu\text{m}$). With the greater sensitivity of the GSMT, we would be able to study the outcomes of star formation under a wider range of environmental conditions. Given the need to sample typically hundreds to thousands of sources in regions of modest angular size ($\sim 1'$), multi-object spectroscopic capability would be highly advantageous.

4. High Dynamic Range Considerations for a GSMT

As adaptive optics (AO) techniques mature, diffraction-limited imaging with a telescope such as a GSMT enters into the realm of the possible. We present some general systems analysis that is implicit in defining science capabilities of the GSMT, and indicate areas that could profit from further investigation in order to understand how such a telescope could be developed to provide interesting planet and star formation science by operating at its diffraction limit. We avoid discussing many of the detailed technical AO problems that must be addressed in order to perform high dynamic range science with the GSMT.

We note that high dynamic range imaging from the ground is somewhat orthogonal to wide-field multi-conjugate AO (MCAO). Since natural guide star (NGS) AO and MCAO systems might

share one or a few AO sub-systems, the areas of overlap (e.g. laser beacon AO around a single bright natural AO target) should be developed in tandem because of this commonality. Here we concentrate on NGS AO, since we have some hard data to use as a basis for extrapolation. As MCAO techniques develop it will become clear how traditional AO and MCAO will benefit each other.

4.1. Assumptions

4.1.1. Deformable Mirrors and Wavefront Sensing

Current technology produces deformable mirrors (DMs) with 1000 actuators. We assume the existence of 3000-actuators “traditional” DMs or deformable secondaries at the time GSMT comes into operation. The step beyond that, DMs with tens of thousands of densely packed actuators, is foreseeable in ten years. Cryogenic dense DMs are also likely to be in existence on that timescale (eg. Dyson et al. 2000). Low noise wavefront sensors are also assumed in this study: current CCD-based wavefront sensors operate at about 4 electrons read noise. Noiseless, small APDs (???) also exist. It is likely that many thousand channels of wavefront sensing will be routine in ten years. Therefore Strehl estimates for GSMT should typically include scenarios based on essentially photon-counting wavefront sensing.

4.1.2. Fundamental Considerations

In the standard (Kolmogorov turbulence) model of atmospheric wavefront aberration, the expected phase variance (in square radians) between two points separated by a distance r is $6.88(r/r_o)^{5/3}$, where r_o is the Fried length. In this model, r_o varies as $\lambda^{6/5}$, an almost linear dependence. At Strehl ratios S above ~ 0.2 , $S = e^{-\sigma_\phi^2}$.

Sivaramakrishnan et al. (2000) present some estimates of AO performance which can be used to predict how well AO might work on GSMT. Their AO modeling is taken from monolithic aperture telescope models where the AO is simulated with a high-pass spatial frequency filter derived from Palomar AO data taken by Oppenheimer et al. (2000). They predict that when $D/r_o = 10$, a 200-channel AO system produces a Strehl ratio of $\sim 80\%$. When $D/r_o = 30$, a 2000-channel system is required for the same Strehl ratio. Table 1 contains rough estimates of various parameters pertaining to AO on GSMT. It is based on the cited work, and fundamental principles of optics, but it does not include effects of a segmented primary.

Table 1. Approximate AO parameters for GSMT

$\lambda/\text{microns}$	1.0	2.0	5.0	10.0	20.0
r_o/m	0.4	1.0	3.0	7	16
D/r_o	69	30	10	4	2
λ/D (")	0.007	0.014	0.034	0.069	0.138
# channels for $S = 95\%$	25000	6400	1000	250	64
# a/cm for $S = 95\%$	16	32	82	164	325

S is the Strehl ratio, and a is the spacing of wavefront sensor channels. The latter determines the limiting magnitude of natural AO guide stars.

4.1.3. Integrating Science and Engineering

Chanan & Troy (1999) have shown that for more than a few segments, the Strehl penalty of an rms $\lambda/60$ inter-segment piston error is about 5%. This means that early, high-quality imaging will only be possible at longer wavelengths. A deformable secondary mirror will enable immediate low-order AO to deliver moderate-Strehl diffraction-limited images at ~ 5 microns, and high Strehl images at longer wavelengths with minimal extra thermal background. Studies of the types of science feasible with GSMT as the segment phasing and AO correction improve will pay off in early science results from GSMT. Routes with one or a few DMs (and even a segmented DM to ease phasing problems) should be considered.

4.2. High Dynamic Range Imaging

As Racine et al. (1999) pointed out, the limits of high dynamic range imaging with AO is set by the correlated nature of residual wavefront error, *viz.* speckle noise. Instrument simulations and trade studies for GSMT should take this into account. If emission lines are strong components of the objects of interest, such speckle noise can be reduced by *e.g.* simultaneous in-band/out-of-band imaging. Approaches to reducing the effect of speckle noise would be extremely useful to high dynamic range imaging, and should be encouraged.

4.2.1. Stellar Lyot Coronagraphy

Extrapolating from existing coronagraphic data taken at a Strehl ratio of $\sim 70\%$, greatly increased dynamic range is expected when Strehls are above 80%. This improvement occurs in an annulus around an occulting field stop with an angular diameter greater than about $\sim 4\lambda/D$ (which blocks the central natural AO target star), and persists out to the edge of the AO-improved image of the AO guide star, at a separation of $\lambda/2a$ from the AO target (Sivaramakrishnan et al.

2000). Here a is the spacing of wavefront sensor channels on the primary.

In order to take advantage of this improved dynamic range, low-scatter, cold coronagraphic optics and AO correction should be investigated. Current high order AO systems (e.g., a 1000-channel system on the 3.67m AEOS telescope on Haleakala, or an upgraded Palomar AO system with ~ 500 AO channels) are potential test-beds for such instrumentation.

Simulations of direct imaging on a 4m telescope in the H -band with 1000-channel AO system, a 15 magnitude dynamic range (with a $5\text{-}\sigma$ detection) is predicted at a separation of 0.16 arcseconds from a bright central object in a 10000s exposure image (Oppenheimer & Sivaramakrishnan 2000). This is a monolithic aperture result, with residual speckle noise after wavefront correction by the AO system. A Lyot coronagraph on a segmented telescope suffers from scatter due to inter-segment gaps. By considering the Fourier optics of a coronagraph, it can be shown that the interaction between the number of segments and gap sizes, and the occulting spot size defines the amount of scattered light from inter-segment gaps. If high dynamic range imaging and spectroscopy is to be a science driver for GSMT, this scatter needs to be quantified in order to understand the impact GSMT primary segmentation has on the dynamic range of coronagraphic imaging.

4.2.2. *Stellar Interfero-Coronagraphy*

Recent work has demonstrated K -band interferometric nulling methods on an astronomical telescope (Baudoz et al. 2000). Such instruments null out the central bright source within its first Airy ring, and are therefore useful for investigations closer to central sources than Lyot coronagraphy permits. At the moment these methods are in their infancy, but they may well become mainstream on a ten year timescale. They complement traditional Lyot coronagraphs by opening up a smaller search area within the first few Airy rings of AO target stars.

5. Instrumentation Considerations

General considerations for instrumentation that is required to support the key areas of the star and planet formation field are discussed here. We assume that the GSMT will be used at the diffraction-limit through the use of adaptive optics and that the field-of-view will be approximately 1 arcminute or less. We also assume that the GSMT must do unique observations that would be unmatched by any ground-based or space-based facility. In particular the GSMT must be able to complement NGST. Given these assumptions, GSMT has the potential to achieve higher angular resolution than any other filled aperture telescope within the next 2 decades, and it will have unmatched sensitivity for high resolution spectroscopy. These key advantages are discussed below in the context of star and planet formation and evolution.

5.1. High Angular Resolution, High Dynamic Range, and Low Emissivity

We envision deep exposures in the search for massive planets around nearby stars as well as spectroscopy of such objects when they are found. A mature AO system providing a high Strehl ratio and a stable point spread function (PSF) is therefore critical for these studies. While much of the discussion has been focussed on the problems of building an AO system for GSMT, it is equally important for studies of planets that the PSF be stable and to have as little scattered light as possible. In the case of a design where many small segments are employed (such as that suggested by the CELT project), the magnitude of the scattered light to the PSF should be given careful consideration. Not only is the amount of scattered light important, but the stability over a long exposure is critical. Careful attention to this problem will help to ensure that reasonable high dynamic range is preserved.

An unobscured aperture has many advantages to reducing scattered light as discussed by Kuhn and Hawley (1999). The scattered light from the spiders and the central hole in the primary are eliminated and the rotating spider pattern in an alt-az mount design is eliminated as well. *Given these advantages for greatly reducing scattered light, it would be important to consider the technical and cost tradeoffs in building an unobscured aperture telescope compared to a standard Cassegrain design.*

The GSMT cannot effectively compete with an 8-m NGST at thermal wavelengths ($\lambda > 2.5 \mu\text{m}$). See for example, Gillett & Mountain (1998) for a discussion of the comparison of a ground-based telescope to NGST. However, the GSMT has a niche in providing high resolution spectroscopy ($R=10^4 - 10^5$) at 10 and 20 μm since it is unlikely that NGST will provide this capability. Minimizing the emissivity of the telescope will improve the signal-to-noise in proportion $1/\sqrt{\epsilon}$, where ϵ is the emissivity of the telescope. *Therefore technology development for adaptive secondaries merit consideration.* This will eliminate the thermal emission from the mirrors of an AO system as well as improve throughput. However the large secondaries that would be required (3 m diameter at f/15 for a 30 m primary) suggests that adaptive secondaries will be practical only for f/no greater than f/45. With these slow beams, the field of view will be small, perhaps not larger than 20" in diameter.

5.2. High Resolution Spectroscopy

The large aperture of the GSMT and the small pixel scales ($\lambda/D = 9 \text{ mas}$, 11 mas , and 15 mas at J , H , and K respectively) allow GSMT to be more sensitive than NGST for spectroscopy at J and H assuming the use of an OH suppression spectrograph as described by Maihara et al. (1993). At longer wavelengths the thermal background becomes a limitation for GSMT relative to NGST. If we assume a detector dark current of 0.02 elec./sec, then we can compute at what resolving power the thermal background on the array is less than or equal to the dark current of the detector. We find that the resolving power must be greater than 500 at $2.0 \mu\text{m}$, 5×10^3 at 2.2

μm , and 5×10^4 at $2.4 \mu\text{m}$, assuming each pixel has a linear width of $\lambda/2D$. Thus moderately high resolving power allows the GSMT to compete effectively with NGST. A detailed discussion of these issues can be found in Gillett and Mountain (1998).

At wavelengths longer than $2.5 \mu\text{m}$ GSMT will have a competitive advantage over NGST at resolving powers greater than 10^4 since we do not expect NGST to include instruments with such high resolving power. For star and planet formation studies the greatest gains will come from high resolving power observations ($R \geq 10^5$), and this will be an area where GSMT will have unsurpassed sensitivity.

5.3. Spectrograph Considerations

It is required to have high spectral resolution spectrographs on GSMT. Practical spectrographs for high spectral resolution will have slits matched to the diffraction limit of the telescope and employ techniques for reducing the size of the instrument. *One such technical advance that is essential is the development of immersion gratings.* These gratings diffract light within a high index of refraction substrate, such as silicon. The dispersion achieved is increased by the index of refraction of the substrate. The collimator size may then be reduced by the same amount, effectively reducing the instrument linear size by a factor 3.4 in the case of a silicon substrate. See for example Jaffe et al. (1998) for a discussion of these points.

The instrumental requirements will flow from the scientific requirements. We anticipate the following cases: (1) Spectroscopy of massive planets near a bright star. The bright star is important to allow the wavefront error to be measured. The planet will be close to the bright star, so the reduction of scattered light is essential as mentioned above. It would be ideal if an integral field spectrograph were used for this experiment to eliminate the need of centering the planet onto a slit. (2) Measurement of the $17 \mu\text{m}$ H_2 line. In many cases one is looking at the emission from a disk or surrounding circumstellar material. A cryogenic imaging Fabry-Perot system would likely be best for these observations. The pros and cons of one or the other approach is left to future tradeoff studies. (3) Spectroscopy of emission lines and bands at $1\text{--}5 \mu\text{m}$. The critical point is to observe the collimated gas very close to the central star so as to discriminate between various bipolar outflow mechanisms. Various approaches may be considered, including (1) An integral field spectrograph using fibers at $1\text{--}1.8 \mu\text{m}$; (2) A cryogenic integral field spectrograph employing an image slicer at $\lambda > 2 \mu\text{m}$; and (3) A cryogenic imaging Fourier Transform Spectrometer for larger field of view.

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