Project Description

1. Research Activities.

We propose to build a 1–5 μm silicon immersion grating high-spectral resolution spectrograph for the NASA Infrared Telescope Facility (IRTF) that would be available to the entire astronomical community. We refer to this instrument as the *i*mmersion grating e*chelle* spectrograph (iSHELL).

The IRTF is a 3.0-m infrared telescope located at an altitude of approximately 13,600 feet near the summit of Mauna Kea on the island of Hawaii. The IRTF was established in 1979 to obtain infrared observations of interest to NASA. Designed for maximum performance in the infrared portion of the spectrum, it takes advantage of the high transmission, excellent seeing, minimal water vapor, and low thermal background that characterize the atmosphere above Mauna Kea. Facility instruments are provided for data acquisition, and these instruments are developed and maintained by the IRTF staff. The UH has 25% of the telescope time (10% for engineering work and 15% for scientific programs). The remainder of the time is open to the astronomical community. Approximately 50% of the available time is assigned to mission support and planetary observations, and the flexibility of telescope scheduling at the IRTF allows for daytime observing of solar system bodies (e.g., planets or comets) having limited solar elongation. The IRTF presently has about 200 unique US-based investigators applying for telescope time as a PI or Co-I, and about 17% are graduate students.

There is a great need for a high resolution ($\lambda/\Delta\lambda$ > 50,000), large format detector, cross-dispersed spectrometer for solar system and astrophysical research. Currently no such instrument is available at telescopes to which the general US astronomy community has broad access. An effort to define the needs for the astronomical community using mid-sized telescopes puts high priority on spectroscopic capability (see the ReSTAR report; available at the NOAO web site). iSHELL at the IRTF will provide vastly improved observing capabilities over any existing infrared spectrograph by offering significant advantages in sensitivity, wavelength coverage, and scheduling of observations.

We note that while the IRTF operating cost is funded by NASA, *the NSF supports instrument development on the IRTF through the peer review process by agreement between the NSF and NASA.* This agreement is attached in the supplementary document section.

1.1. Scientific Objectives

The scientific justification presented here is representative of the wide range of front-line observations that can be accomplished with iSHELL. Many active researchers contributed to the following scientific justification including C. Allende-Prieto (U. of Texas), G. Bjoraker (Goddard Space Flight Center), J. Carr (Naval Research Lab), N. Dello Russo (Johns Hopkins/APL), D. Deming (GSFC), M. DiSanti (GSFC), D. Jaffe (U. of Texas), L. Keller (Ithaca College), V. Krasnopolsky (Catholic U. of America), K. Magee-Sauer (Rowan Univ.), S. Miller (Univ. College London), M. Mumma (GSFC), J. Najita (NOAO), R. Novak (Iona College), L. Prato (Lowell Obs.), M. Simon (SUNY Stony Brook), and T. Stallard (Univ. College London). We will rely on the community to carry out the research described here.

iSHELL is optimized for the wavelength range of 2-5 μm and R=67,000 in order to maximize science return in the areas of planetary science, star formation, the interstellar medium, and galactic astronomy. A slit length of 15″ will provide the necessary spatial coverage for extended objects (e.g. planets, comets). We set the minimum slit width to 0.25″ with 3-pixel sampling to match the diffraction limit of the IRTF at 3.5 μm. iSHELL will enable ground-breaking science across a broad range of astronomical disciplines. A sample of key science areas is described in this section and demonstrates the versatility and impact of this critical new piece of the astronomical infrastructure.

1.1.1 Composition of Comets. Comets are the least altered objects from the birth of the Solar System providing the most direct means for determining the chemistry and conditions present during this formative period. Thus, the study of comets is intimately connected to research on the formation, evolution and chemical inventory of our Solar System, physical conditions and composition of circumstellar disks, and the chemistry of the interstellar medium (Mumma et al. 2003). Infrared spectroscopy provides information that is difficult or impossible to obtain from other methods, such as radio observations. This includes the direct detection of water and non-polar molecules such as CH_4, C_2H_2, and C_2H_6 (Gibb et al. 2007). There are two main regions where studies will greatly benefit from higher spectral resolving power—near 3.0 μm and between ~3.3–3.6 μm (Dello Russo et al. 2006). The higher spectral resolution of iSHELL will increase line-to-continuum contrast and thus enable the detection of known species in confused regions and also increase the potential discovery of unblended lines for important species such as HC_3N, CH_3CCH, C_4H_2, HCOOH, CH_3CN, C_3H_8, and C_2H_5OH.

1.1.2 Detection of Minor Constituents in the Atmosphere of Mars. The exploration of Mars is a major goal for the next decade within NASA's Science Mission Directorate. Spacecraft do not employ high-resolution spectrographs due to space and weight limitations. Thus ground-based observations using high-resolution spectroscopy provide unique and important data as well as a long baseline of observations not generally obtainable from space missions. iSHELL offers significant advantages that may potentially revolutionize ground-based studies of Mars. An outstanding example of this is the recent detection of CH_4 using the IRTF (Mumma et al. 2007). At present, only a single line of CH_4 can be sampled per setting using the IRTF's CSHELL spectrograph. With iSHELL, we could observe the entire CH_4 fundamental ν_3 band near 3.3 μm simultaneously. iSHELL's higher resolving power is critical since a Doppler shift is needed to resolve the Martian spectral lines from their corresponding terrestrial lines.

1.1.3 *Magnetospheres of the Outer Planets.* Over the past decade, the IRTF/CSHELL has been responsible for pioneering work in the measurement of ion winds in the upper atmospheres of the giant planets, notably Jupiter (Rego et al. 1999) and Saturn (Stallard et al. 2007a, 2007b). These winds, which occur in the auroral/polar regions of the gas giants, can be measured from the Doppler shifting of lines from the H_3^+ molecular ion. The measured velocities vary from a few hundred m s^{-1} to several km s^{-1}, requiring the high spectral resolution that iSHELL will provide. Ion winds are signatures of magnetosphere-ionosphere coupling systems, which transfer enormous quantities of energy both from the planet to the magnetosphere and vice versa. iSHELL will provide enormous advantages over current observations through lowering of the Doppler shift limit to about 50 m s^{-1}, simultaneous imaging of the slit position on the object, greater spectral coverage, and increased signal-to-noise. The capability to remotely image variations in H_3^+ ion velocities across Jupiter's disk, for example, will provide a critical measurement of the angular momentum transfer between the magnetosphere and ionosphere, a key scientific objective of the JUNO spacecraft that is scheduled to be launched in 2011.

1.1.4 Extrasolar Planets. Infrared spectroscopy has a significant role to play in the new and exciting area of physical studies of extrasolar planets. IR lines offer new possibilities for detections and can give us valuable information about the chemistry and physical conditions in extrasolar planets. The recent detection of thermal emission from several transiting exoplanets using Spitzer (Deming et al. 2005, 2006; Charbonneau et al. 2005) proves that the infrared flux from these exoplanets is significant (up to 0.005 of the stellar flux). Doppler deconvolution is a technique that can be used with iSHELL to detect the spectral signatures of these planets. The orbital radial velocity of a planet orbiting a solar-type star with a 4 day period approaches 150 sin(i) km/sec, causing a large periodic wavelength displacement of the planetary lines. Since the planetary molecular lines are numerous, narrow, and spread over large regions in wavelength, their detection by Doppler deconvolution requires a high resolution IR spectrograph with large wavelength coverage. As an example of Doppler deconvolution, a sensitive search for methane at 3.3 μm in the spectrum of the planet orbiting Tau Bootis was made using Doppler deconvolution of IRTF/CSHELL data by Wiedemann et al. (2001). For this technique, wavelength coverage is equivalent to telescope aperture, and iSHELL will improve sensitivity by a factor of 6.6, assuming optical efficiency similar to CSHELL. This is equivalent to upgrading the telescope aperture to 20 meters.

1.1.5 Extrasolar Planet Atmospheres. High resolution, high signal-to-noise, IR transmission spectra of transiting exoplanets provide constraints on cloud levels, temperature profile, winds, etc. The strongest features in models of the transmission spectrum (e.g., Brown 2001) are NaI and other alkali metals in the optical, and CO, H_2O, and CH_4 in the infrared. Absorption in the transmission spectrum of optical lines has been successfully detected from space (Charbonneau et al. 2002) and from the ground (Redfield et al. 2008). While ground-based attempts to detect CO in transmission spectra have not yet been successful, the high sensitivity, high spectral resolution, and broad spectral range of iSHELL are required to make the next advances in this field at infrared wavelengths.

1.1.6 Protostellar Evolution. Infrared spectroscopy also can play a defining role in understanding the evolution of protostars and their circumstellar disks by allowing quantitative measures of stellar properties and the properties and chemistry of the disks. Very young (< a few Myr old) protostars represent the earliest observable stages of star and planet formation (Greene & Lada 2000). Cool surface temperatures, high obscuration, and copious non-photospheric emission, however, make it difficult to study these objects at optical wavelengths (e.g., White & Hillenbrand 2004). The high resolving power of iSHELL in the infrared provides good sensitivity to absorption lines necessary for the determination of effective temperature, rotational line broadening, and continuum veiling. From such measurements we can estimate protostellar masses, rotation rates, and properties of the circumstellar environments, compare these values with those predicted from models, and clarify how the youngest stars evolve (Doppmann et al. 2005; White et al. 2007).

1.1.7 Young Star Binaries and Pre-Main Sequence Model Calibration. Because mass is the key determinant of stellar evolution, its measurement is critical to tests of main sequence evolutionary models (e.g., Hillenbrand & White 2004) and provides input for theories of binary star, brown dwarf, and extrasolar planet formation mechanisms.. Observations of young spectroscopic binaries provide measurements of dynamical mass ratios (e.g., Prato et al. 2002) and, in concert with high angular resolution observations, individual young star masses (Schaefer et al. 2008). Systems in which the stellar masses differ significantly are particularly important to test a large area of model parameter space. High resolution, near-infrared spectroscopy with iSHELL will provide a powerful tool for detecting low mass secondaries in spectroscopic binaries. Luminosity scales as a steeper function of mass in visible light compared to the infrared, thus the secondary to primary flux ratio is greater at longer wavelengths, favoring the detection of cool secondaries.

1.1.8 Magnetic Fields and Rotation—A Key to Understanding the Accretion Process. The powerful magnetic fields in YSOs play a role in the accretion process, in the evolution of protoplanetary disks, and in the transfer of angular momentum away from the star. Observations of Zeeman sensitive lines in the near-IR over the past several years with CSHELL have shown that classical T Tauri stars have organized magnetic fields of several kilogauss (Johns-Krull, Valenti, & Koresko 1999; Johns-Krull 2007). These powerful magnetic fields couple the star to its disk during the early part of the pre-main sequence period and have a significant influence on stellar rotation. High resolution observations over a broad wavelength range, coupled with disk models made from Spitzer SEDs will test accretion models. The broad coverage and high resolving power of iSHELL will allow observations of many Zeeman-sensitive lines to determine magnetic fields as well as many lines with small Lande g factors that will allow observers to measure vsini for the same stars with the same data sets.

<u>1.1.9 Preplanetary Disks—A Key to Understanding the Formation of Solar Systems.</u> The study of preplanetary disks is one of the key approaches to reconstruct the formation and early evolution of the Solar System, in addition to the origin of extrasolar planetary systems. Direct measurements of the gas in preplanetary disks are necessary to infer the conditions present in the presolar nebula, to distinguish among theories for planet formation, and to determine the likelihood of forming solar systems like our own. In particular, the high-resolution of iSHELL will provide velocity-resolved profiles of molecular transitions from which one can map the excitation temperature and abundance of molecules as a function of disk radius, thereby inferring the thermal, chemical and physical structure in the inner planet forming region (Najita et al. 2007). These spectra will also provide data to understand key physical processes that influence planet formation, including viscosity, turbulence, and mixing (e.g., Carr et al. 2004).

1.2 Results from Prior NSF Support.

1.2.1 (a) PI: Tokunaga; AST 0607574; $645,843; 2006-2010. (b) Title: NSF Visitor and Observing Support for the NASA Infrared Telescope Facility. (c) Supports non-planetary visitors to the IRTF and half of the supporting costs for vehicles, cryogens, and remote observing. (d) Publications: Many; see IRTF bibliography on it's web site.

1.2.2 (a) PI: Jaffe; NSF AST-0705064; $220,528; 2007-2008. (b) Title: Collaborative Research: Ultra-Precision Silicon Immersion Gratings for Infrared Spectroscopy. (c) This is a project being carried out with Mark Schattenburg at the MIT Kavli Institute for Astrophysics and Space Research. We are developing a new technique for the production of large, precise immersion gratings. We will combine the material processing and blazing techniques of the existing UT process with the advanced resist patterning capabilities of the MIT Nanoruler. The result will be higher precision gratings that can be fabricated on the largest available silicon substrates (up to 12 inches), suitable for instruments on 8-20 m telescopes. The funding became available in July 2007. Since then, work has gone according to plan with the UT group shepherding material through its preparatory pipeline and designing and building a new wet-etch setup while MIT modifies its Nanoruler to produce coarse patterns with a low duty cycle. The first round of test gratings will be completed during summer 2008. A high quality grating resulting from the second production round in year 2 of this grant could be shaped, AR coated, and used in iSHELL. (d) Publications will be forthcoming in Year 2 of the grant.

1.2.3 (a) PI: Tollestrup; AST 0505407; $223,564; 2005-2008. (b) Title: A Novel Technique for Corrective, Scatter Compensating Telescope Secondary Mirrors. (c) Objective is to fabricate a new secondary mirror for the IRTF that will correct for the spherical aberation of the primary mirror. Measurements made at prime focus. Data has been analysed and a request for quotation to vendors nearly done. Graduate student participated in the measurements at the telescope, lab tests, and refinement of data taking. (d) Publications: Final results to be published after completion of the secondary.

1.2.4 (a) PI: Rayner; AST 0096839; $800,394; 2000-2006. (b) Upgrade of Facility Camera (NSFCAM) for the IRTF. (c) Upgrade of the facility infrared camera with a 2048x2048 Hawaii 2RG detector. Required new optics, cryostat, electronics, and modifications to the instrument control software. Although the detector was obtained free of charge from the detector program led by D. Hall, there were noise problems with the detector array and the electronics. This delayed the use of the camera. Currently in use with background-limited performanceat 3-5 microns. Work is progressing on internal funding to reduce the readout noise. Currenlty lower priority since Tollestrup must first finish work on the new secondary mirror. (d) Publications: Beginning to appear: Sanchez-Lavega et al. 2008, Depth of a strong jovian jet from a planetary-scale disturbance driven by storms, Nature, 451, 437. Connelley et al. 2008, The Evolution of the Multiplicity of Embedded Protostars I: Sample Properties and Binary Detections, AJ, submitted.

2. Description of the Research Instrumentation.

2.1 Instrument overview. The scientific requirements for iSHELL are:

- $\lambda/\Delta\lambda$ = 67,000 at 3.5 μm, which meets the scientific requirements and is attainable with the silicon immersion grating (IG). This resolving power is chosen as a compromise between the need for high spectral resolution, sensitivity to observe interesting objects, and having sufficient slit length.
- Minimum slit width = 0.25″ and slit length = 15″. The slit width is matched to the full-width at half maximum of the Airy disk at 3.5 μm. There will be a range of selectable slit widths and slit lengths. The 15″ slit length is driven by the need to provide L-band spectra across extended objects, especially the disk of Venus, Mars, Jupiter, and Saturn as well as comets and circumstellar disks. The smallest slit width is necessary to resolve structure in these objects. For point sources the minimum slit length is 5″ to allow for sky subtraction. Larger slit widths (up to 1.0"; Table 1) will be used for absolute flux calibration observations of infrared standard stars, and for studies not requiring the highest spectral resolution capability.
- Slit sampling = 3 pixels across the slit, or 0.083″/pixel. This is needed to achieve good sampling of the point spread function.
- Use of a 2048x2048 infrared array, which allows for cross-dispersion and maximum wavelength coverage per exposure.
- Use of a slit-viewing camera to maximize observing efficiency and for accurate recording of the slit position on extended objects.
- Optimized for the K and L bands but coverage at the H and M bands is also needed, as well as part of the J band. Only part of the J band can be covered due to the absorption of Si at wavelengths less than 1.2 μm. (See Table 2 for definitions of the wavelength bands).

The IG used in iSHELL offers two significant advantages: a compact instrument and efficient use of detector space. The wavelength of light incident on the grating shrinks by a factor equal to the refractive index, n (= 3.4 for Si) when the grating is immersed in a dielectric. This means that an immersion instrument can have the same resolving power with a factor of 3.4 smaller collimated beam diameter than an instrument with the same geometry and a conventional diffraction grating in vacuum. Ruled gratings are limited to groove spacings <50 μm. The result of this limit is that orders spill off the ends of the detector in high resolution IR spectrographs, leading to fragmented wavelength coverage. The IG for iSHELL has a groove spacing of 80 μm, equivalent to 270 μm in vacuum. This coarse

Table 1. Spectrograph properties

Slit width	0.25″-- 1.0″
Slit length	≥ 5″ @ H, K; ≥ 15″ @ L, M
Resolving power	80,000 at 2.0 μm; 67,000 at 3.5 μm
Collimated beam	22 mm diameter
Collimator focal length	838 mm
Camera focal length	320 mm
Silicon immersion grating	60 mm length, 63.5 deg. blaze 12.5 grooves/mm
Detector	2048x2048 InSb, 0.083″/pixel
Optics temperature	70K
Detector temperature	~30K

spacing allows us to get continuous wavelength coverage in the L band, a critical advantage for molecular spectroscopy that is unavailable with any existing instrument.

As discussed below, a science-grade silicon immersion grating for iSHELL was fabricated by Dan Jaffe and his group at the Univ. of Texas. The maximum collimated beam it can accommodate is 22 mm, and the grating constant is 12.5 grooves/mm. David Warren (an optical consultant) has done a *rigorous* Code V optical design of the spectrograph optics. The design approach follows that of SpeX, the successful moderate resolution spectrograph at the IRTF (Rayner et al. 2003).

We have adopted a standard layout for a cross-dispersed echelle (see Fig. 1), with the exception that we are using a silicon IG for the echelle. Specifications of the spectrograph design are shown in Table 1. The collimator is designed to form an image of the pupil at the IG. Although the slit-limited resolving power is 80,000 at 3.5 μm, with a 0.25″ slit the actual resolving power will be slightly less. The theoretical resolving power for the grating is mN, where m is the order number and the N is the number of illuminated grooves. For our case N=620 and m=140 for 3.5 μm, so that the maximum theoretical resolving power is about 87,000. Note that this performance has been confirmed by measurements on the actual device we will use in iSHELL (see Section 2.7). Since we are working at the diffraction limit of the IRTF at 3.5 μm, the pupil will not be uniformly illuminated. The result will be a degradation of resolving power, and we estimate this to be a factor of about 1.2. Therefore we expect to achieve a resolving power of 80,000/1.2 ≈ 67,000.

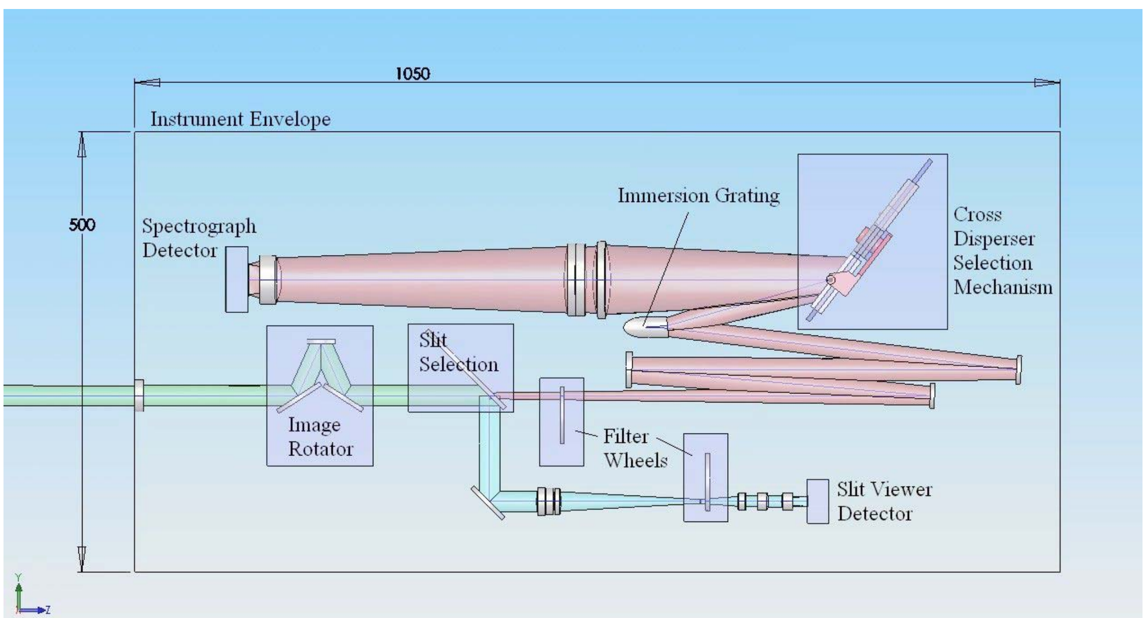


Figure 1. Layout of the spectrograph. A raytrace analysis was performed using CODE V to be certain that the design is feasible and that it has sufficient image quality. A conceptual opto-mechanical layout shows that it is possible to fit this instrument in an envelope of 1050 mm X 500 mm X 400 mm.

Priority is given to L-band observations. Placing 3.5 μm in echelle order 140 gives the required resolving power, while preserving continuous spectral coverage on the array at the longest L-band wavelength (order 120). The L-band is covered in orders 120-175 (55 orders). Table 2 shows the orders for H, K, L, and M. There are coverage gaps in M that would necessitate moving the echelle.

Table 2. Orders to be covered.

Band	Orders	Wavelength range
J	392-399	1.25-1.28 μm
H	270–339	1.46–1.84 μm
K	196–247	1.99–2.52 μm
L	120–175	2.80–4.10 μm
M	92–109	4.48–5.34 μm

The combination of high spectral resolution and long slit length make the cross-dispersion the most challenging aspect of the design. The need to separate the echelle orders by at least a slit image length requires large cross dispersion at the shortest wavelength orders of the L-band. But if this large cross dispersion is maintained across the L-band (i.e. a single cross-disperser), then it is excessive at the long wavelength end of the L-band, and results in very few orders on the array and requiring a large number of exposures to fully cover the L-band.

The trade is further complicated by the anamorphic magnification resulting from using the cross-dispersers off the Littrow condition. A minimum of 15° is required to separate the beam from the echelle and the cross-dispersed beam heading for the camera. A larger separation is desirable, but this increases the anamorphic effects introduced when the cross-disperser is used off-Littrow. We adopted an approach with the incidence angle (α) greater than the diffracted angle (β), so that the anamorphic effect works to decrease the angular field. For all exposures, β and α are negative and on the same side of the grating normal and $|\beta - \alpha|$ is fixed at 15˚.

A number of configurations and cross-dispersion options were investigated with the aim of finding a minimum set of cross-dispersers that are required to achieve the needed spectral coverage. We found that a set of two cross-dispersers can cover the L-band in 8 exposures, and that a third cross-disperser is sufficient to cover the M, K, H, and J bands in the first, second, third, and fourth orders respectively. To minimize the number of cross-dispersers, we plan to provide a minimum slit length of 5″ for K, H, and J. Thus a total of 3 cross-dispersers are required (see Table 3); each one requires multiple positions to cover all of the orders. The top priority for the J band is observations at 1.27 μm for studies of Mars. We have specifically provided for this.

In order to clear the beam entering the IG from the collimator and the dispersed beam heading from the IG to the cross-disperser, the IG is canted by 6 degrees with respect to the beam from the collimator. The plane of the cant is perpendicular to the plane of the IG dispersion. To avoid a ghost reflection from the front surface of the IG, the front and rear faces of the IG are wedged with respect to each other by a small angle. In addition, the sides of the IG are tilted to avoid unwanted internal reflections at the detector, and the front surface is anti-reflection coated.

A complete end-to-end optical design was carried out, and the opto-mechanical layout shown in Fig. 1 is based on this. Fig. 2 shows how orders 167-175 are distributed on the array for L-Band Exposure 1. This is the most difficult case for maintaining the required order separation. Typical geometric spot diagrams for L-Band exposure 1 ("L1" in Table 3), echelle orders 175,171,and 167, which cover the full array, are shown in Figure 3. Although the images are diffraction limited, the residual coma at the ends of the echelle orders could be improved by optimizing the spectrograph camera further. All exposures in M, L, K, and H bands have roughly equal image quality. In the final design, should this proposal be funded, we would perform a thorough scattered light analysis to ensure that we have suitable baffling in place.

Table 3. Summary of Cross-dispersers and Exposures Required.

Exposure name	Orders covered	Number of orders	Grating grooves/mm	X-disp. Order	Center Wavelength (nm)	Blaze Wavelength (nm)	Max. Slit length (arcsec)
J1	399-392	8	233	4	1270	1175	6.0
H1	339-311	29	233	3	1535	1633	5.5
H2	310-288	23	233	3	1663	"	6.9
H3	287-270	18	233	3	1782	"	8.5
K1	247-225	23	233	2	2097	2450	6.7
K2	224-206	19	233	2	2296	"	8.5
K3	205-196	10	233	2	2457	"	10.5
L1	175-167	9	490	1	2876	3000	18.2
L2	166-159	8	490	1	3024	"	21.4
L3	158-153	6	490	1	3158	"	25.4
L4	152-144	9	394	1	3319	3600	18.0
L5	143-136	8	394	1	3519	"	21.6
L6	135-130	6	394	1	3703	"	25.9
L7	129-124	6	394	1	3878	"	30.6
L8	123-120	4	394	1	4035	"	>35
M1	109-101	9	233	1	4672	4900	19.1
M2	100 - 94	7	233	1	5054	"	22.7
M3	93-92	2	233	1	5293	"	>25

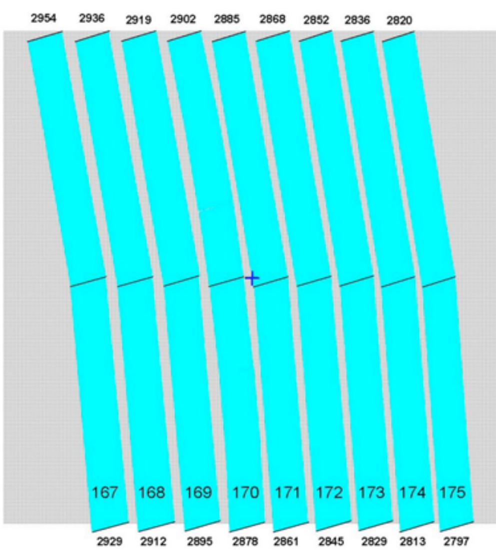


Figure 2. Order layout for L-band exposure 1 ("L1"), showing echelle orders 167-175. Slit length is 15.3″ and wavelengths in nm.

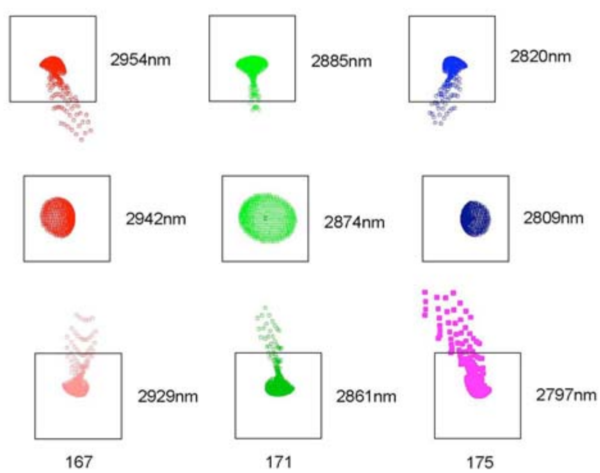


Figure 3. Geometric spot diagrams for L-band exposure 1 ("L1"). The squares represent 18 μm pixels of the array and show the 4 corners of the array. Diffraction-limited FWHMs are 40-50 μm.

2.2 Cryostat and mechanism design. Much of the design can be adapted from the successful SpeX instrument, and the overall size of iSHELL will be similar to that of SpeX. A preliminary layout of the instrument shows that we can keep within a volume of 1.1mx0.55mx0.4m. We will use existing design concepts for the mechanisms, vacuum jacket, radiation shield, thermal design, and calibration unit. Since observations of extended objects or with the slit along the parallactic angle are important we also will have a "K-mirror" to allow field rotation. The most challenging part of the design is the cross-dispersion changer, since not only is it necessary to select the cross-disperser but it must also tilt to cover all the orders. A concept of how this might be done in a straightforward manner is shown in Fig. 1. One axis allows full rotation of a grating wheel containing three cross-dispersers. This axis is mounted to a plate that can be tilted along the front surface of the cross-disperser, thus allowing the motions required with a minimum of flexure in the cables for the stepper motors and position sensors.

2.3 Slit viewer and array. iSHELL will have a 512x512 pixel slit viewer similar to the SpeX instrument. The InSb array to be used was produced in a detector foundry run organized by Michael Mumma at the Goddard Space Flight Center (GSFC) and will be provided at no cost by Mumma. It will allow automatic guiding using the light that does not enter the slit, a method that is been very successful with SpeX and will operate independently of the spectrograph array, thus allowing for great flexibility in adjusting the readout rate and guiding parameters for the slit viewing array. We need to sample the seeing-limited image FWHM that is estimated to be typically 0.5″ at 2.2 μm. With a pixel scale of 0.10″/pixel we will have an unvignetted field-of-view of 30″x30″ from 1-5.5 μm.

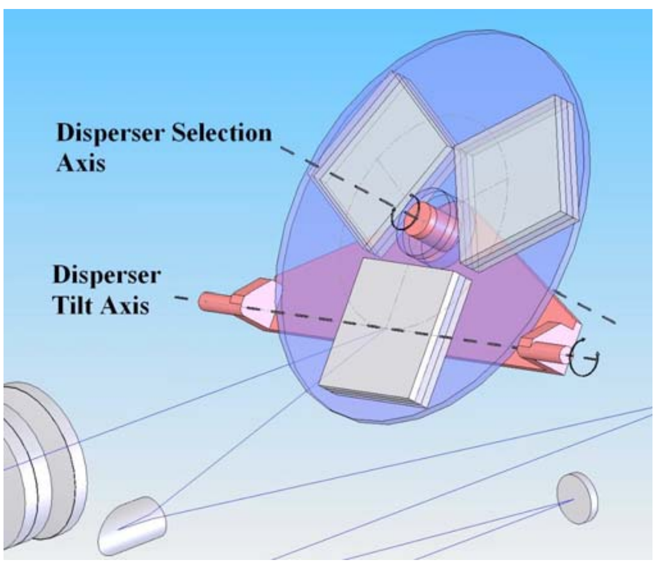


Figure 4. Concept for a cross-disperser changing and tilt mechanism. The tilt axis is along the front surface of the grating. Cryogenic stepper motors, not shown, will be used.

2.4 Electronics and data system. The array control and array electronics will be an improved version of the SpeX electronics (Onaka et al. 2003). We will use an array controller developed for the PAN-STARRS program at the IFA. This array controller will be "mass-produced" for PAN-STARRS, so there will be a high degree of reliability and expertise to support it. The group developing this controller is headed by Peter Onaka, and he will be in charge of this as well as providing supervision in the development of the instrument control electronics. Much of the instrument control hardware and software can be adapted from the IRTF SpeX and NSFCAM instruments.

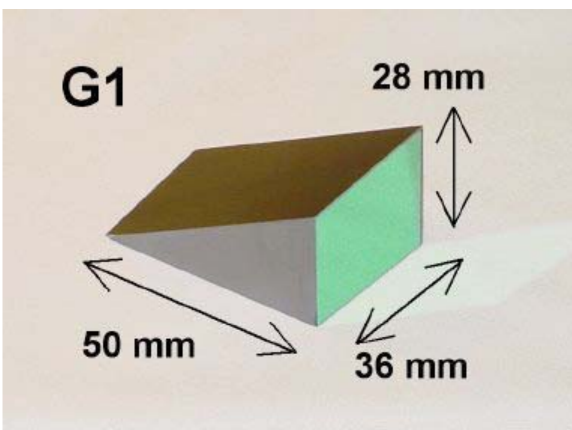
2.5 Calibration box. The calibration box is mounted on the side of the cryostat and will feed the spectrograph by means of a sliding mirror. The calibration box will provide a continuum source and three gas discharge lamps to the spectrograph with an integrating sphere. The output of the integrating sphere will have the same f/number as the telescope beam.

2.6 Software. We will adopt the software approach used in SpeX. Much of the instrument control software developed for SpeX can be utilized by iSHELL, and the software engineer who developed the SpeX software is still with the IRTF. This user interface will be similar—

consisting of spectrograph control section and a slit viewing control section. Furthermore, since remote observing with IRTF instruments is very common, we will offer flexible remote observing with iSHELL as well. Thus observing programs that require partial nights can be accommodated. The SpeX user interface and instrument control are well liked by IRTF users and remote observing is used for about 60-70% of the observing runs.

2.7 IG status. The University of Texas (UT) IR group has spent the past decade developing techniques to produce silicon IGs (Moore et al. 1992, Graf et al. 1994). Their approach has been to fabricate, test, model, and understand the gratings step by step and to publish detailed results (Jaffe et al. 1998, Ershov et al. 2001, Keller et al. 2002, Marsh et al. 2003). With support from the David and Lucile Packard Foundation, NASA, and UT, they have produced several generations of silicon micro-machined diffraction gratings leading up to the *finished* science-grade grating they have produced for the IRTF spectrograph proposed here (Marsh et al. 2006, 2007). This grating is referred to as "G1".

Specifically, they have successfully etched the silicon material, cut and polished it, applied an antireflection coating, and tested its throughput and spectral purity. They have also carried out efficiency tests by placing the IG in collimated laser light and comparing the intensity in the diffracted spectrum to the intensity of a reference mirror. Figures 5 and 6 show the measured spectrum for G1 *in immersion* at 1523 nm. The measured end-to-end throughput of G1, in immersion and on the blaze at 1.52 μm, is 59%. This wavelength happens to lie at a dip in the AR coating transmission. Efficiencies at other wavelengths will be 5-8% higher. Thus the overall efficiency of the IG compares well to conventional front surface gratings.



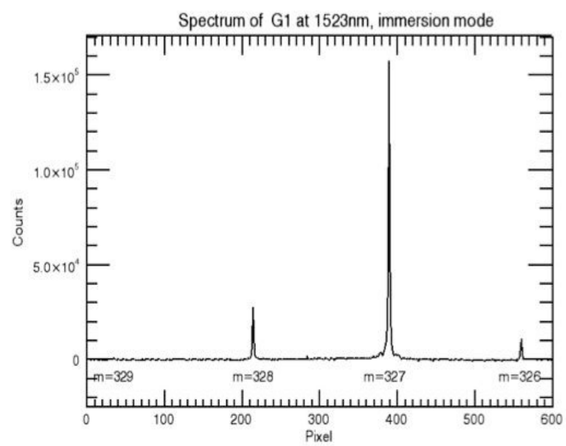


Figure 5. Left. Photograph of G1. The entrance face has been AR coated. The hypotenuse has been aluminized to improve its internal reflectivity. Right. Spectrum of grating G1 obtained with a HeNe laser line at 1.523 μm measured with a 15 mm collimated beam *in immersion*. The peak is at order 327. The efficiency on the blaze measured against a reference mirror is 64%. Note the lack of any ghost lines.

The presence of ghosts and scattered light is a major concern. Spectra, taken with G1 at 543 nm and displayed with a logarithmic intensity scale show that there are no sharp features between orders or in the cross-dispersion direction to a level of $<6\times10^{-3}$ of the peak. There are no broad features, in particular no power in the blaze, with a peak intensity greater than 3×10^{-3}. Under a currently funded NASA APRA grant, UT is working on improvements to its grating production process. Several blanks for iSHELL R2 gratings remain and UT will provide any gratings better than G1 for use in the proposed instrument. UT has recently begun work, using funding from the NST ATI program, on a promising new method for patterning immersion

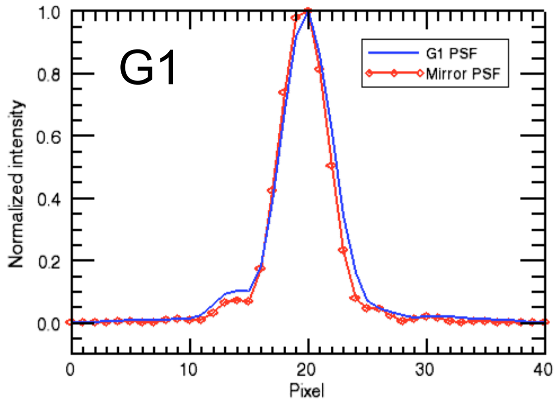


Figure 6. Spectral profile of G1, taken in the 327th order, in immersion at 1.52 μm. The FWHM corresponds to a resolving power of 75,000, limited by the collimated beamsize in the test equipment. The red line shows the diffraction-limited PSF of a flat mirror for comparison.

gratings. Jaffe's group is also willing to provide a grating from this new series should they prove significantly better than the existing parts.

2.8 Spectrograph infrared array selection. Teledyne Imaging Sensors offers a 1–5 μm HgCdTe 2048x2048 format array. For the low background we have at 1-2.5 μm, the dark current must be low as possible and is 0.01 elec./sec/pixel at 30 K. We need to have an engineering array for testing of the electronics. For Teledyne, the engineering multiplexer (MUX) cost is $25K and it is critical for testing the array electronics. An engineering array is extremely useful to have as the testing of the array electronics can be done without thermally cycling the science grade array. The cost of the engineering grade array is $50K. Thus the total cost (science grade array, engineering MUX, and engineering grade array) is $425K. The Teledyne array has been selected for JWST, and it is commercially available.

2.9 Expected sensitivity. We estimated the sensitivity using the following assumptions: signal-to-noise = 10, readnoise = 5 elec. (with multiple sampling), dark current = 0.1 elec./sec/pixel, throughput (including detector quantum efficiency)= 0.1, pixel scale = 0.083″/pixel, on chip exposure time = 300 sec for $\lambda < 2.5$ μm and 120 sec for $\lambda > 2.5$ μm, 30% observing overhead, and 50% light loss at the slit. The estimated limiting magnitudes in one hour of on-source observing (i.e. clock time) are:

J (1.25 μm)	H (1.64 μm)	K (2.20 μm)	L´ (3.8 μm)	M´ (4.68 μm)
13.1 mag	12.6 mag	12.1 mag	10.4 mag	8.5 mag

This sensitivity is about one mag fainter than IRTF/CSHELL at 2.2 μm because of the lower readnoise and dark current of the Hawaii 2RG array, while the resolving power and wavelength coverage are greatly improved.

3. Impact on the Research Infrastructure.

As mentioned previously in Section 1, the iSHELL will be a facility instrument at the NASA IRTF. Other facility instruments at the IRTF include: SpeX (a 1-5 μm low-moderate spectral resolution spectrograph), CSHELL (a 1-5 μm high spectral resolution spectrograph), NSFCAM2 (a 1-5 μm camera), MIRSI (an 8-20 μm camera), and APOGEE (a visible CCD camera). SpeX is used about 50-60%, and with CSHELL, NSFCAM2, and MIRSI at about 10%. Visitor instruments account for the remaining time.

CSHELL provides a spectral resolution of up to 40,000, but only in a single order. With a 0.5 arcsec slit, 3 pixels across the slit, and a 256x256 InSb array, it has only about 80 spectral resolution elements per grating setting. The read noise is about 40 elec. Thus the CSHELL, which was commissioned in 1993, is well beyond the normal operating life for an astronomical instrument. The primary reason we continue to offer it is that there is no other instrument in the

Northern Hemisphere that provides this high resolving power and there is demand for it. Other instruments, such as NIRSPEC on the Keck and IRCS on the Subaru Telescope provide powerful cross-dispersed spectroscopy at 1-5 μm, but with a maximum resolving power of about 20,000 and very limited access to these instruments by the US astronomical community.

To emphasize the need for iSHELL, we note that NSF recently funded a study to identify the instrumentation and observing facility needs of the US astronomical community. The Committee for Renewing Small Telescopes for Astronomical Research (ReSTAR) recently released their report (downloadable at the NOAO website). It is stated on p. 63 that "We emphasize that spectroscopy should receive the highest priority for new instrumentation, since instrumentation for imaging is in somewhat better state ... Finding: Specific instrumental capabilities on small and mid-size telescopes stand out as being essential to the progress of a wide range of research topics: optical spectroscopy at both high and low spectral resolution, and near-infrared spectroscopy at both high and low spectral resolution, optical imaging, and near-infrared imaging. The need for significant amounts of observing time with these capabilities dictates that such instrumentation should be available on national facilities. Moreover, the instrumentation available on small and mid-size telescopes at national facilities should be competitive with the best instruments available elsewhere. State-of-the-art instruments are important at all apertures."

We emphasize that the proposed instrument is being built as a facility instrument and will be full supported by the IRTF staff. We have a track record at the IRTF for both building and supporting instruments. Care will be taken to ensure reliability, good user interfaces, maintainability (spare parts), and adequate documentation. As noted in the ReSTAR report, iSHELL should be built to the same standard as facility instruments on larger telescopes. We have endeavored to do so while keeping the cost to a minimum. Thus iSHELL, if built, would be an integral part of the astronomical research infrastructure as envisioned by the ReSTAR committee and it would help to fulfill a high priority recommendation.

Since iSHELL would be the first facility instrument to utilize an immersion grating, it would would help to soundly establish this technology for use in larger telescopes (8-10 m and larger). The impact on the instrumentation budget for large telescopes would be significant since the immersion grating allows a much smaller instrument to be built for high spectral resolution. Although we are planning to use a silicon immersion grating and wavelengths shortward of 1.2 mm are not accessible, other types of materials such as ZnSe could be used in the future that would eliminate this restriction. Thus the development of iSHELL would likely have an impact on future near-infrared spectrographs on large telescopes. Silicon immersion grating technology is already being employed elsewhere (Ge et al. 2006). The design and use of the instrument will be published as reports on our web site, conferences, and refereed journals. We therefore expect that other instrument groups will be able to benefit from our experience.

The science team has identified key science to be done with iSHELL in Section 1.1. Advances in planetary science, star formation, circumstellar chemistry, and exoplanet atmospheres are expected to be achieved. Further science cases are described in the ReSTAR report. Planetary science is an important component of research on the IRTF. Because of this, daytime observing is allowed for observations of comets and planets near the Sun, and this is a unique capability of IRTF.

We expect students to benefit since classical observing at the summit is allowed and in fact encouraged. This provides valuable observing experience. The IRTF also provides remote observing capabilities with very flexible scheduling. Observing blocks as short as one hour can be accommodated. Remote observing allows more students to participate in the observing as travel costs are eliminated. In a typical remote observing session at the home institution of the PI, the instrument and telescope computer interfaces are the same as an observer would have at the facility. The IRTF currently has about 200 unique US-based PI and Co-Is on observing proposals each year and about 17% of them are students. We would expect iSHELL to be scheduled about 30% of the time on the IRTF, so that it would have a long-term impact on the field of 1-5 μm high spectral resolution spectroscopy and the cost of the instrument would be spread over a very broad range of science projects carried out by a large and diverse segment of the astronomical community.

IRTF has one graduate student position and we would place priority on having a graduate student participate in the instrument or software development. The iSHELL would be built at the Institute for Astronomy, Univ. of Hawaii, where there is a pool of about 25-30 graduate students. The use of a graduate student for software development was very successful with the fabrication of the SpeX instrument.

4. Project Management.

Overall leadership and responsibility for the project will be provided by the PI (Tokunaga), who is also the Director of the IRTF. A number of IRTF and Institute for Astronomy staff members will be helping to fabricate the instrument, including senior mechanical, electrical, and software engineers as well as technicians. They have experience in designing and building previous facility instruments and they would also maintain the proposed instrument when it is completed.

4.1 Project Manager. We have identified the IRTF Senior Mechanical Engineer, Tim Bond, as the Project Manager. His responsibilities will include management of the project work breakdown structure, schedule, and budget. The project manager will conduct weekly progress meetings, help set priorities, and expedite work required to meet established milestones. He will hold appropriate design reviews (conceptual, preliminary, and critical). Tokunaga will schedule the necessary human resources to complete the project, and Bond will provide the day-to-day oversight of the technical staff.

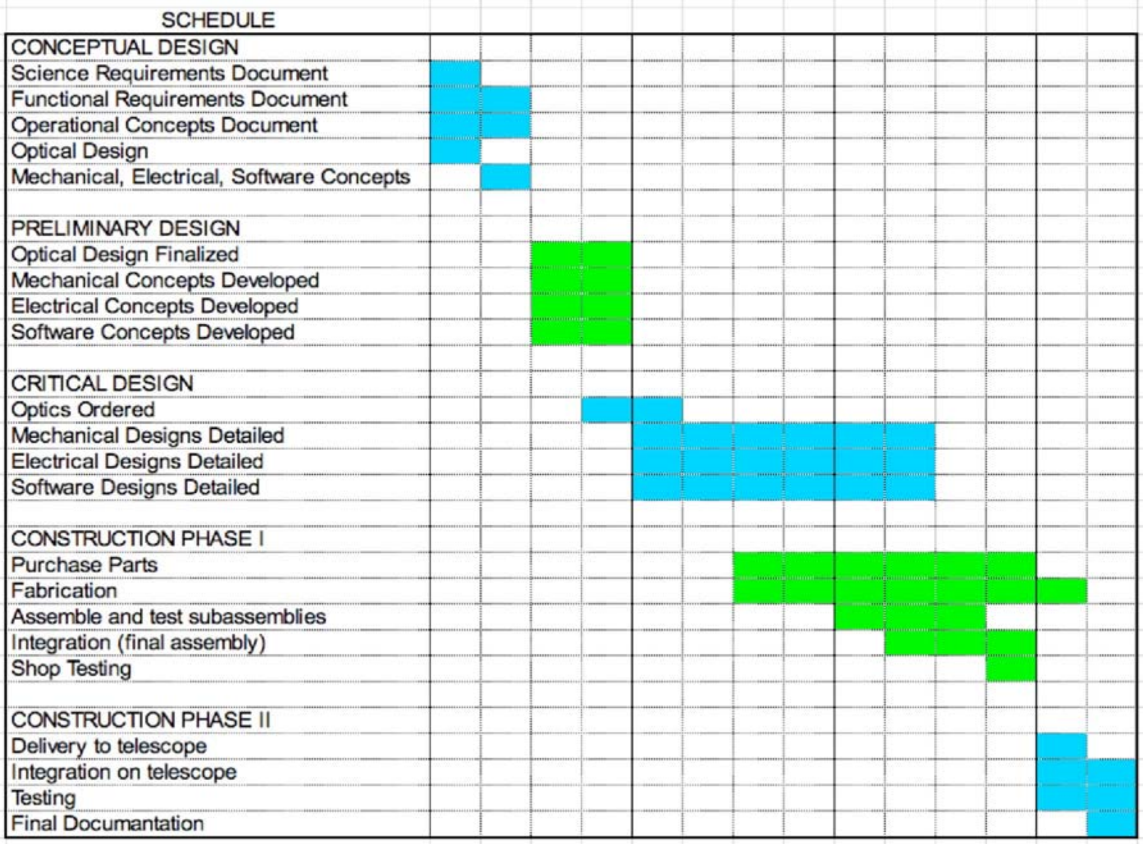
4.2 Systems Engineer. Tim Bond will also be the Systems Engineer. We will follow standard systems engineering practices throughout the duration of the project. Standard tools of the Systems Engineer will be utilized, and the entire project staff will focus on meeting the requirements that are derived through a formal process. He will derive the required error budgets, and conduct any required performance modeling studies. He will also provide on-line documentation control. The Systems Engineer will be heavily involved in the system integration, and acceptance testing. It will be the responsibility of the Systems Engineer to study methods for managing and tracking risk. Possible simple tools that may be implemented are “risk registers” and various methods of risk mitigation – such as prototyping, or early fabrication of high risk components or options for de-scoping.

4.3 Project Scientist. Tokunaga will act as the PI and Project Scientist initially. In the third quarter of the first year we plan to hire a full time Project Scientist who will carry the instrument through commissioning. A post-doctoral researcher will be hired for this position, and he/she will be responsible for carrying out the testing and calibration of the instrument, developing necessary software, assisting with the commissioning, and conducting research.

4.4 Schedule. The Project Manager will derive a complete detailed schedule based on the work breakdown structure and shall ensure that it is kept up to date (a minimum of monthly updates, and more frequent during critical periods). For the purposes of this proposal, a preliminary 3.5 year schedule has been provided showing the major design reviews as well as assembly and testing milestones. A rough schedule showing the major tasks and activities for each quarter of the project is shown in Table 4 below. The % full-time equivalents to carry out the work is also shown for each quarter. No contingency is shown. Should additional manpower be required, we plan to use existing IRTF engineering and technical staff. The level of effort for the PI is a minimum and is likely to be higher (but increases will not be charged to the proposal).

Table 4. Full-Time Equivalents per quarter (%) and rough milestones.

iSHELL Proposal	YEAR 1				YEAR 2				YEAR 3				YEAR 4		
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	
MANPOWER (%FTE)															Total FTE
PRINCIPAL INVESTIGATOR	15	15	15	15	5	5	5	5	5	5	5	5	5	5	0.275
PROJECT MANAGER	25	25	25	25	25	25	25	25	33	33	33	33	33	33	1.000
PROJECT SCIENTIST			100	100	100	100	100	100	100	100	100	100	100	100	3.000
SYSTEMS ENGINEER	25	25	25	25	25	25	25	25	33	33	33	33	33	33	1.000
OPTICAL ENGINEER	25	25	25	25	25	25					50	50	50	50	0.875
MECHANICAL ENGINEER I	25	25	25	25	25	25	50	50	33	33	33	33	33	33	1.125
MECHANICAL ENGINEER II		100	100	100	100	100	100	100	100	100			25	25	2.375
ELECTRICAL ENGINEER		50	50	50	25	25	25	25	25	25	25	25	25	25	1.000
SOFTWARE ENGINEER		100	50	50	25	25	25	25	25	25	25	25	100	100	1.500
ELECTRICAL TECH.							33	33	33	33	33	33	100	100	1.000
MECHANICAL TECH.							33	33	33	33	33	33	100	100	1.000



4.5 Budget. The Project Manager will also derive a complete budget based on the work breakdown structure and shall ensure that it is kept up to date. Initial cost estimates for iSHELL were based primarily on an audit of the expenditures for SpeX and several other projects. Of the \$4.06 million total cost, only \$2 million is requested under the MRI program. About \$1.8 million will be provided by NASA and IRTF operations, and \$265 K by the Univ. of Hawaii as a cost-sharing component. The staffing and equipment cost are described in detail in the budget narrative. As is evident, much leveraging of the MRI funds is being provided through contributions from NASA, IRTF, and the Univ. of Hawaii.

Although the total cost is relatively high, one should bear in mind that we are proposing to build a *facility instrument* that has inherently higher costs. In compensation, we can expect iSHELL to be on the IRTF 30% of the time, or 100 nights per year, so the scientific productivity will be high.

4.6 Experience, Resources, and Facilities. The PI, Alan Tokunaga, will have overall responsibility for the project. Tokunaga was PI on two previous IRTF facility instruments (CGAS and CSHELL) and more recently he was a PI on the Infrared Camera and Spectrograph (IRCS), a facility instrument for the 8.2-m Subaru Telescope. The Project Manager, Tim Bond, is the IRTF mechanical engineer and he has extensive experience in major instrument projects that including the Gemini Multi Object Spectrograph (GMOS), Gemini Adaptive Optics System (ALTAIR), CFHT Megacam, and the Magellan Telescope's Inamori Magellan Areal Camera (IMACS). Co-I John Rayner was the PI for the SpeX instrument. We will use his expertise to carry over mechanical and software designs to iSHELL. Co-I Eric Tollestrup has considerable experience in ground-based and space instrumentation and in infrared arrays. He has worked on infrared cameras at the Univ. of Texas, the Harvard Smithsonian Center for Astrophysics (STELIRCam), and Boston University (MIRSI, Mimir). He was also the Project Scientist on the Infrared Camera (IRAC) for the Spitzer Observatory while he worked at the CFA. Senior software engineer Tony Denault will be responsible for the instrument control software and user interface software. He has been the software engineer for nearly all of the IRTF instruments, including SpeX. Thus much of our instrument control software and user interface can be modified for iSHELL. Senior Electronics Engineer Peter Onaka will be responsible for the array electronics. He has developed a new generation of array electronics that will be used for the PAN-STARRS project as well as large format IR arrays. He has worked on all previous IRTF facility instruments, including SpeX. Some work may be delegated to other electronic engineers, but Onaka will provide the oversight

Co-I Daniel Jaffe will be providing the silicon IG for this project. He will be involved in the evaluation and testing of the IG in the laboratory. Co-I Michael Mumma will be providing the 512x512 InSb array to be used as the slit viewer through a prior agreement. Both Jaffe and Mumma will also plan to be involved in star formation and solar system studies respectively with iSHELL, and they will also be working with Tokunaga and Bond in refining the final design of the instrument.

The majority of the optical engineering will be handled by an outside consultant who will assist us with the final design and more detailed calculations to design baffle and to suppress scattered light. He will also assist in specifying the optics and locating vendors. Bond, Rayner, and Tollestrup will be able to provide supplementary in house optical engineering.

We will mostly rely on designs for cryostats and mechanisms that have proven to be successful in the past. Some of the mechanical engineers who have worked on previous IRTF instruments are still with the IFA and we can utilize their experience and knowledge. Fabrication of the instrument will be done in the IFA machine shops in Manoa and Hilo.

Integration and testing of iSHELL will be done in the IFA-Hilo instrument laboratory. During this phase of the project, day-to-day supervision of the fabrication will be the responsibility of Bond, and the integration and testing of the instrument will be the responsibility of Tollestrup and the postdoc. Supervision of personnel working on the instrument in Hilo will be the responsibility of Tollestrup since he is the IRTF Deputy Division Chief in Hilo and is the supervisor of IRTF personnel in Hilo.

References Cited

Brown, T. M., et al., 2001. Hubble Space Telescope Time-Series Photometry of the Transiting Planet of HD 209458. *ApJ* **552**, 699.

Carr, J. S., Tokunaga, A. T. & Najita, J. 2004 Hot H2O Emission and Evidence for Turbulence in the Disk of a Young Star. *ApJ* **603**, 213.

Charbonneau, D., et al., 2002. Detection of an Extrasolar Planet Atmosphere. *ApJ* **568**, 377.

Charbonneau, D., Allen, L. E., Megeath, S. T., Torres, G., Alonso, R., et al. 2005 Detection of Thermal Emission from an Extrasolar Planet. *ApJ* **626**, 523.

Dello Russo, N., Mumma, M.J., Disanti, M.A., Magee-Sauer, K., Gibb, E.L., Bonev, B.P., McLean, I.S., Xu, L.-H. 2006 A high-resolution infrared spectral survey of Comet C/1999 H1 Lee, *Icarus* ***184***, 255.

Deming, D., Seager, S., Richardson, L. J. & Harrington, J. 2005 Infrared radiation from an extrasolar planet. *Nature* **434**, 740.

Deming, Drake; Harrington, Joseph; Seager, Sara; Richardson, L. Jeremy 2006 Strong Infrared Emission from the Extrasolar Planet HD 189733b, *ApJ* ***644***, 560.

Doppmann, G. W., Greene, T. P., Covey, K. R. & Lada, C. J. 2005 The Physical Natures of Class I and Flat-Spectrum Protostellar Photospheres: A Near-Infrared Spectroscopic Study. *Astronomical Journal* **130**, 1145.

Ershov, O. A., Jaffe, D. T., Marsh, J. P. & Keller, L. D. 2001 Production of high-order micromachined silicon echelles on optically flat substrates. *Proc. SPIE* **4440***, p. 301.*

Gibb, E. L., et al., 2007. The organic composition of C/2001 A2 (LINEAR). *Icarus* **188,** 224.

Ge, J., McDavitt, D., Zhao, Bo, Mahadevan, S., DeWitt, C., Seager, S. 2006, The first high resolution silicon immersion grating spectrograph, Proc. SPIE, 6269, 45.

Graf, U. U., Jaffe, D. T., Kim, E. J., Lacy, J. H., Ling, H., et al. 1994 Fabrication and evaluation of an etched infrared diffraction grating. *Appl. Opt.* **33**, 96.

Greene, T. P. & Lada, C. J. 2000 High-Resolution Near-Infrared Spectra of Protostars. *AJ* **120**, 430.

Greene, T. P. & Lada, C. J. 2002 Spectroscopic Detection of a Stellar-like Photosphere in an Accreting Protostar. *AJ* **124**, 2185.

Hillenbrand, L. A., White, R. J., 2004. An Assessment of Dynamical Mass Constraints on Pre-Main-Sequence Evolutionary Tracks. *ApJ* **604,** 741.

Jaffe, D. T., Keller, L. D. & Ershov, O. A. 1998. Micromachined silicon diffraction gratings for infrared spectroscopy. *Proc. SPIE* **3354***, p. 201.*

Johns-Krull, C. M., et al., 1999. Measuring the Magnetic Field on the Classical T Tauri Star BP Tauri. *ApJ* **516,** 900.

Johns-Krull, C. M., 2007. The Magnetic Fields of Classical T Tauri Stars. *ApJ* **664,** 975.

Keller, L. D., Jaffe, D. T., Ershov, O. A. & Marsh, J. P. 2002 Large-area silicon immersion echelle gratings and grisms for IR spectroscopy. *Proc. SPIE* **4485***, 385.*

Marsh, J. P., Ershov, O. A. & Jaffe, D. T. 2003 Silicon grisms and immersion gratings produced by anisotropic etching: testing and analysis. *Proc. SPIE* **4850***, 797.*

Marsh, J.P., Mar, D.J., & Jaffe, D.T. 2006 Fabrication and performance of silicon immersion gratings for infrared spectroscopy, *Proc. SPIE* **6269**, 144.

Marsh, J.P., Mar, D.J., & Jaffe, D.T. 2007, Production and Evaluation of Silicon Immersion Gratings for Infrared Astronomy, *Appl. Opt.* **46**, 3400.

Moore, J., Ling, H., Graf, U.U., & Jaffe, D.T. 1992, *Microwave and Opt. Tech. Letters* **5**, 480.

Mumma, M. J., et al., 2007, Absolute Measurements of Methane on Mars: The Current Status. *AAS/Division for Planetary Sciences Mtg* **39**, #31.02.

Mumma, M. J., Disanti, M. A., dello Russo, N., Magee-Sauer, K., Gibb, E., et al. 2003 Remote infrared observations of parent volatiles in comets: A window on the early solar system. *Adv. Space Res.* **31**, 2563.

Najita, J. R., Carr, J. S., Glassgold, A. E. & Valenti, J. A. 2007 Gaseous Inner Disks, in *Protostars and Planets V*, p. 507.

Onaka, P. M., Lockhart, C., Tokunaga, A. T., Rayner, J. T., Toomey, D. W., et al. 2003. Redstar3 array controller-embedding Linux and PCs as a DSP replacement. *Proc. SPIE **4841**, 193.*

Prato, L., Simon, M., Mazeh, T., McLean, I. S., Norman, D., et al. 2002a The Smallest Mass Ratio Young Star Spectroscopic Binaries. *ApJ* **569**, 863.

Rayner, J. T., Toomey, D. W., Onaka, P. M., Denault, A. J., Stahlberger, W. E., et al. 2003 SpeX: A Medium-Resolution 0.8-5.5 Micron Spectrograph and Imager for the NASA Infrared Telescope Facility. *PASP* **115**, 362.

Redfield, S., et al., 2008. Sodium Absorption from the Exoplanetary Atmosphere of HD 189733b Detected in the Optical Transmission Spectrum. *ApJ* **673,** L87.

Rego, D., Achilleos, N. Stallard, T., Miller, S., Prange, R., et al. 1999 Supersonic winds in Jupiter's Aurorae. *Nature* **399**, 121

Schaefer, G., et al., 2007. Preliminary Orbit of the Young Binary Haro 1-14c. *AAS Mtg* **211**, #57.03; in press.

Stallard, T., et al., 2007a. Saturn's auroral/polar H_3^+ infrared emission I. General morphology and ion velocity structure. *Icarus* **189,** 1.

Stallard, T., et al., 2007b. Saturn's auroral/polar H_3^+ infrared emission II. A comparison with plasma flow models. *Icarus* **191,** 678.

White, R. J., Hillenbrand, L. A., 2004. On the Evolutionary Status of Class I Stars and Herbig-Haro Energy Sources in Taurus-Auriga. *ApJ* **616,** 998.

White, R. J., et al., 2007. Stellar Properties of Embedded Protostars. Protostars and Planets V, p. 117.

Wiedemann, G., Deming, D. & Bjoraker, G. 2001 A Sensitive Search for Methane in the Infrared Spectrum of tau Bootis. *ApJ* **546**, 1068.