The NASA Infrared Telescope Facility (IRTF)
Report to the Independent Review Panel

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List of Acronyms

AAA	Airborne Astronomy Ambassadors (STEM teachers)
ADS	Astrophysics Data System
ADAP	Astrophysics Data Analysis Program
A&G	Acquisition & Guiding
ASAS-SN	All-Sky Automated Survey for Supernovae
ASM	Adaptive Secondary Mirror
ATLAS	Asteroid Terrestrial-impact Last Alert System
CCD	Charged Coupled Device
CDR	Critical Design Review
CFC	Chlorofluorocarbon
CFHT	Canada France Hawaii Telescope
ClO	Chlorine Monoxide
CSO	Caltech Submillimeter Observatory
CTIO	Cerro Tololo Inter-American Observatory
DDT	Director Discretionary Time
DECam	Dark Energy Camera
DENIS	Deep Near Infrared Survey of the Southern Sky
DESI	Dark Energy Spectroscopic Instrument
FEMA	Federal Emergency Management Agency
FOV	Field of View
FTE	Full Time Equivalent employee
GSA	Government Services Administration
GSFC	Goddard Spaceflight Center
GUI	Graphical User Interface
H2RG	Hawaii 2RG Array
HIPWAC	Heterodyne Instrument for Planetary Wind and Composition
HR	Human Resources
HVAC	Heating Ventilation and Air Conditioning
IAWN	International Asteroid Warning Network
IDIQ	Indefinite Delivery, Indefinite Quantity contracts
IfA	Institute for Astronomy
IFS	Integral Field Spectrograph
IFU	Integral Field Unit
IPAC	Infrared Processing and Analysis Center
IRSA	Infrared Science Archive at IPAC
IRTF	Infrared Telescope Facility
ITAR	International Traffic in Arms Regulations
KOE	Kama’ãina Observatory Experience
LBT	Large Binocular Telescope
LCROSS	Lunar Crater Observation and Sensing Satellite
MIM	Multiple Instrument Mount
MIRSI	Mid-Infrared Spectrograph and Imager
MKSS	Maunakea Support Services
MMT	Monolithic Mirror Telescope
MOA	Memorandum of Agreement
MOC	MIRSI Optical Camera
MOU	Memorandum of Understanding
MORIS	MIT Rapid Imaging System
MSIP	Mid-Scale Innovations Program
MUX	Multiplexer
NASEM	National Academy of Sciences, Engineering, and Medicine
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NEOO	Near Earth Object Observations Office

NIHTS	Near-Infrared High Throughput Spectrograph
NIKUG	NASA IRTF-Keck Users Group
NIR	Near infrared
NOAA	National Oceanic and Atmospheric Administration
NOIRLab	National Optical-Infrared Astronomy Research Lab
NSF	National Science Foundation
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PDCO	Planetary Defense Coordination Office
PDR	Preliminary Design Review
PI	Principal Investigator
ppbv	parts per billion per volume
PSD	Planetary Science Division
PSF	Point Spread Function
R	Resolving Power $\equiv \lambda/\Delta\lambda$
R&A	Research and Analysis
R&D	Research and Development
RV	Radial velocity
SAO	Smithsonian Astrophysical Observatory
SDSS	Sloan Digital Sky Survey
SED	Spectral Energy Distribution
SETI	Search for Extraterrestrial Intelligence
S/N	Signal-to-Noise Ratio
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOW	Statement of work
SPECTRE	Spectrograph Express
SPHEREx	Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer
STEM	Science Technology Engineering and Math
STScI	Space Telescope Science Institute
TAC	Telescope Allocation Committee
TCS	Telescope control system
TNO	The Netherlands Organization for the ASM project
TNO	Trans-Neptunian Object
T-ReCS	Thermal-Region Camera Spectrograph
2MASS	Two Micron All Sky Survey
UKIDSS	UKIRT Infrared Deep Sky Survey
UKIRT	United Kingdom Infrared Telescope
UH	University of Hawaii
VLT	Very Large Telescope
VNC	Virtual Network Computing
WISE	Wide-field Infrared Survey Explorer

EXECUTIVE SUMMARY

The NASA Infrared Telescope Facility (IRTF) is a 3.2-m diameter infrared telescope located at an altitude of approximately 4,200-m near the summit of Maunakea on the island of Hawaii. The University of Hawaii (UH) runs IRTF under contract to NASA. Funding for IRTF currently comes from the Planetary Defense Coordination Office (PDCO) of the Science Mission Directorate. The current operating contract runs from 2019 to 2024. A Statement of Work from PDCO outlines the contract requirements. The current sublease for the telescope site is between NASA and UH and ends in 2033. Renegotiation of the lease is uncertain since the authority for the master lease is being transferred from UH to a just created 'Mauna Kea Stewardship and Oversight Authority'.

Available observing time on the telescope is open to the entire astronomical community, with 50% of the time reserved for observations of the solar system and NASA space mission support, and with the balance for observations outside the solar system ('astrophysics'). Observing time on the telescope is allocated through peer review of proposals by an independent Telescope Allocation Committee. Nearly all observing is now conducted remotely. The PDCO requires IRTF to physically characterize NEOs to assess potential impact damage. PDCO does not call out specific goals for IRTF but leaves it to the NEO and small body community of observers through the peer review of observing proposals to do so. About 20% of observing time currently goes to studies of NEOs and main belt asteroids with the remainder for general solar system science and astrophysics.

IRTF operates with three major facility instruments covering the 0.5-20 μm wavelength range with imaging and spectroscopy (R=5-10^5). Thousands of NEOs and main belt asteroid have been characterized by measuring sold-state features at $R\approx100$ across the range 0.7-2.5 μm. This observing mode has also been highly productive for measuring the spectral energy distributions of cool stars and brown dwarfs. The most highly cited IRTF work is the $R\approx1000$ 0.8-5 μm stellar spectral library, which has proved a valuable community resource. The very high resolving power R=50,000-90,000 3-5 μm observing modes are optimum for studying comets, planetary atmospheres and planet-forming disks. IRTF is unique for an optical-infrared telescope by having regular daytime observing, allowing observations of planets almost year-round. The recent commissioning of a wide-angle visible finder scope and of simultaneous visible/mid-infrared imaging adds capability to acquire NEOs and measure their sizes. Visitor instruments add capability for R=10^5-10^7 7-25 μm spectroscopy primarily for planetary atmospheres. IRTF is a unique NASA asset for planetary defense, planetary science and space mission support.

Independent assessment of metrics for research productivity indicates that IRTF is as productive as most other 4-8-m class telescopes for overall science despite 50% of observing time being allocated to the significantly smaller community of ground-based solar system astronomers. Metrics also indicate that IRTF is the premier ground-based observing facility for solar system science. IRTF has a long history of educating and training undergraduate and graduate students. Through the Maunakea Scholars program local high school students get observing time on the telescope. IRTF staff participate in many outreach programs. These include local community tours of the telescope; STEM teacher immersion visits to the telescope; 'astrodays' in Honolulu, Hilo and Kona; and staff attendance at career fairs.

For research productivity it is important for us to continually upgrade the telescope and instrumentation. The IRTF community workshop in 2018 strongly endorsed our plans for a 0.4-4.2 μm R=150 integral field spectrograph, primarily for NEO and small body characterization (planetary defense), and infrared transient follow up. In addition, we are planning for active control of the telescope optics to improve overall telescope sensitivity and efficiency. IRTF has averaged a downtime of only 2.5% of scheduled observing time due to technical faults over the past five years.

NASA Infrared Telescope Facility (IRTF)
Report to the Senior Review Panel

1 INTRODUCTION

The NASA Infrared Telescope Facility (IRTF) is a 3.2-m diameter infrared telescope located at an altitude of approximately 4,200-m near the summit of Maunakea on the island of Hawaii. The University of Hawaii (UH) runs IRTF under contract to NASA. The astronomical observing time on the IRTF is allocated as follows: 75% of the total observing time is defined as available observing time; 15% of the total observing time is allocated to UH as a condition of the site lease agreement; and 10% of the total observing time is allocated to IRTF scientific staff as engineering time to ensure high quality performance of the telescope and auxiliary instrumentation. The available observing time is open to the entire astronomical community, with 50% of that time reserved for observations of the solar system and NASA space mission support, and the balance for observations outside the solar system ('astrophysics'). NASA's strategy in operating a dedicated, ground-based observatory continues to be the support of NASA's missions and science goals.

1.1 Brief History

In 1972 a National Academy of Sciences committee gave high priority to the construction of a 3-m class infrared telescope. NASA was willing to fund the telescope because of its importance to planetary astronomy and in February 1974 NASA awarded the contract to manage and operate IRTF to the University of Hawaii (Waldrop 1981). Funding for IRTF originally came from the *Voyager Project* and the first light observations of Jupiter in July 1979 were done in support of the *Voyager 2* flyby of Jupiter (see Figure 1).

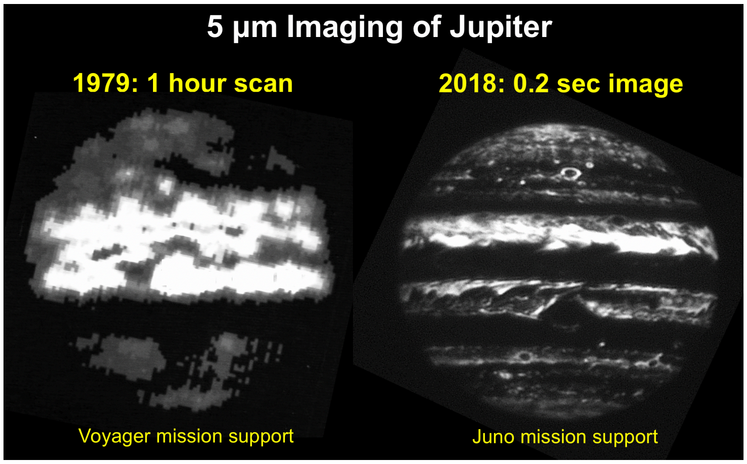

Figure 1. (*Left*). First light image constructed by raster scanning a single-element infrared photometer (RC1). (*Right*) Image taken with the SpeX 512x512 pixel infrared guider in 2018. Through technical improvements the imaging efficiency increased by a factor of ~100,000 over the 40 years between these two images.

Funding for telescope operations then moved into the Research and Analysis (R&A) program managed by the Planetary Science Division (PSD). In 1983 a Memorandum of Agreement (MOA) on the operational support of IRTF was signed by NASA and NSF[1]. It was agreed that i) approximately one-half of the available observing time on IRTF will continue to be used for NASA-required observations, with the remainder of the time being made available to the astronomical community to undertake observations of general scientific interest, ii) NASA will provide long-term operational support for IRTF, iii) NSF will endeavor to provide support for the development of instrumentation, and iv) NASA will reexamine the role of IRTF in its programs periodically, at intervals of approximately five years.

Since that time the UH has operated IRTF under a consecutive series of five-year grants, co-operative agreements or contracts with NASA, each with a negotiated and agreed Statement of Work (SOW – see Appendix 1). The current agreement is a contract worth about $30M covering the period 2019-2024. In

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[1] http://irtfweb.ifa.hawaii.edu/meetings/senior_review_2022/NASA-NSF_agreeement_1983.pdf

addition, NSF funded non-NASA time Visitor Support costs (Hale Pohaku stays, consumables, and a share of remote observing costs) through ad hoc proposals to NSF at the level of $150k per year (2018 dollars) until 2020. Although this funding has now ended, the originally agreed allocation of observing time has not changed.

In 2014 funding for IRTF was switched from PSD R&A to PSD Near-Earth Object Observations (NEOO) Program Office. NEOO was incorporated into the PDCO when it was created in 2016. Despite the change of funding source from PSD R&A to NEOO, the PDCO remain satisfied with the amount of observing allocated to NEOs through the peer review of observing proposals and the 1983 MOA, and their authority to trigger IRTF observing time of NEOs at of short notice when needed. The PDCO requires IRTF to physically characterize NEOs to assess potential impact damage. PDCO does not call out specific goals for IRTF but leaves it to the NEO and small body community of observers through the peer review of observing proposals to do so.

Most of the original suite of facility instruments, comprising several single-element photometers covering the wavelength range 1-30 µm, were built with NASA support as part of the original complement of facility equipment. Since the 1983 MOA between NASA and NSF, major facility instruments have been largely funded by NSF with some support from NASA and UH. Continually upgraded state-of-the-art instrumentation has been key to maintaining the high scientific productivity of IRTF (see section 9), all of which have been designed and built by IRTF staff. IRTF has also been able to capitalize on the engineering expertise at UH, in particular the expertise of the infrared detector group lead by the late Don Hall. The current suite of facility instruments was funded before IRTF became part of PDCO. PDCO requirements will be an important part of future instrument plans (see section 3). PI-class visitor instruments are also available to observers (see section 1.2)

In addition to the instrumentation development program, the telescope facility itself has undergone several major upgrades since first light in 1979. These include major upgrades to the HVAC system and dome interior thermal control, resurfacing of the dome exterior with reflective aluminum tape for improved thermal control, replacement of the telescope shutter drive, and replacement and upgrade of the telescope control system (TCS), all funded from telescope operations and NASA task orders. NASA also funded a fast tip-tilt system for the telescope. Although the system did not have the bandwidth to significantly improve the near-infrared seeing as planned, a hexapod secondary mirror mount developed for the project and subsequent upgrade is now being used for active control of the telescope image quality. NSF also funded a project to build and refigure of the f/38 telescope secondary mirrors to remove spherical aberration from the telescope optics.

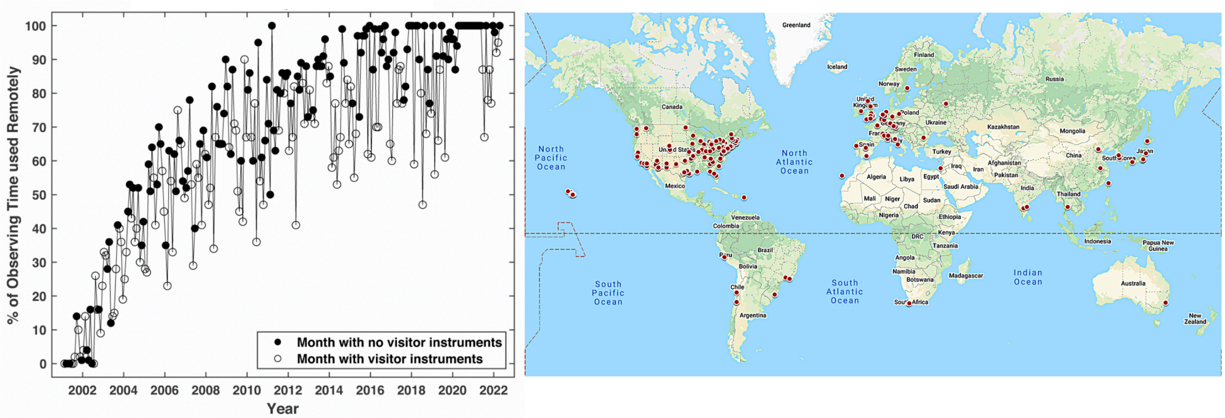

Figure 2. (*Left*). The amount of remote observing has steadily increased since its inception in 2002. (*Right*) The current map of world-wide remote observing sites. These include institutions and homes; all that is required is a suitable internet connection.

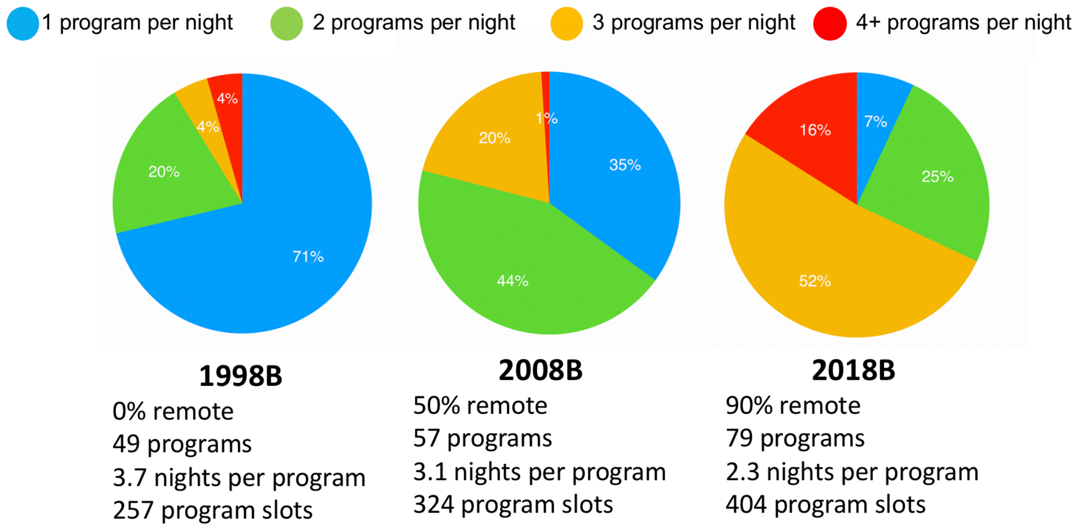

Figure 3. The number of observing programs that can be carried out each night has significantly increased through the combined effects of making all four MIM-mounted instruments available and the ability of observers to observe remotely. Interchanging instruments during observing takes about 30 minutes. Observing programs can use more than one instrument.

Another important development includes the deployment of the Multiple Instrument Mount (MIM) in time for the comet Shoemaker-Levy 9 (S-L 9) collision with Jupiter in July 1994. The MIM allows up to four instruments to be stowed on the telescope and one then placed at the Cassegrian focus within about 30 minutes. This significantly enhanced IRTF's science return during the S-L 9 event (Orton *et al.* 1995). Of equal importance was the start of regular remote observing in 2002. Currently, over 90% of observing is conducted remotely from sites all over the world (see Figure 2) via VNC, and user-friendly GUIs, also built by IRTF staff. By increasing the number of observing programs that can be carried out each night (see Figure 3) these two innovations have significantly increased the scientific productivity of IRTF (see section 9).

The Telescope Allocation Committee (the TAC) reviews proposals for observing time. The IRTF Director selects the reviewers, four solar system experts and four non-solar system experts, who serve two-year terms (four observing semesters). The solar system and non-solar system TACs meet separately. The TAC is independent of IRTF staff except for input on the technical feasibility of proposals. As requested by NASA HQ we introduced formal dual-anonymous proposal review (DAPR) starting in observing semester (2022A). This required significant changes in proposal writing and internal proposal management.

The breadth of the science addressed by IRTF is vividly illustrated by the list of observing proposals awarded telescope time in 2022 – see Appendix 2 and 3.

1.2 Current Capabilities

IRTF currently has three facility instruments available every night (see Figure 4). SpeX is a R=50-2500 0.7-5.4 μm spectrograph and imager (Rayner et al. 2003). SpeX was commissioned in 2000 and upgraded with a new H2RG array and electronics in 2014. It is the IRTF's workhorse general science instrument and is currently averaging about 60% of all awarded observing time. The observing modes include one shot 0.7-2.5 μm and 1.9-5.3 μm cross-dispersed R~2000 spectroscopy, one-shot 0.7-2.5 μm R~100 prism spectroscopy, and a multi-filter 1-5 μm slit-viewer and infrared guider with a 60″ x 60″ field of view (FOV). The prism mode in SpeX has been hugely productive for the characterization of NEOs and asteroids (see section 3 and 5). A dichroic-fed CCD camera (MORIS) attached to the side of SpeX can be used to acquire simultaneous visible imaging and infrared spectroscopy or infrared imaging.

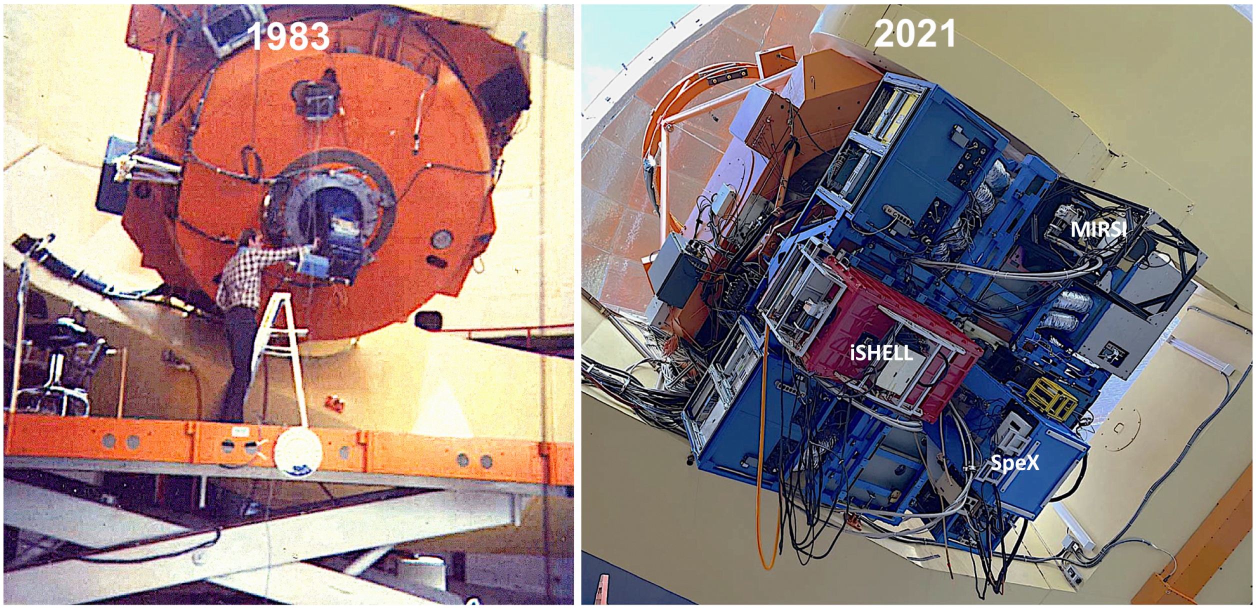

Figure 4. (*Left*). The Cassegrain focus of the telescope in 1983 with one single-element photometer (with a dichroic-fed A&G TV camera) mounted. (*Right*) The Cassegrain focus of the telescope in 2021 showing the three major facility instruments: SpeX (in the on-axis position), iSHELL (in the north stow position), and MIRSI (in the west stow position); the south stow position, to which visiting instrument are mounted, is unoccupied. The blue boxes above the instruments house cooled electronics.

MORIS is optimized for rapid imaging during occultations (≥ 0.05s for spatial resolutions of ≥1 km depending on the event) of stars by solar system objects. Due to its remote location in the middle of the Pacific Ocean, Hawaii is an ideal location for shadow paths that cannot be reached from other ground-based sites, particularly since the demise of the SOFIA airborne facility. With MORIS and SpeX, the IRTF is one of the very few observatories offering simultaneous optical and infrared observations optimized for the fast readouts required for high spatial resolution (i.e., shadow transits) during solar system occultations. MORIS has also significantly improved guiding capabilities for SpeX observations of (visible wavelength) solar system targets.

iSHELL is a R=20,000-90,000 1.06-5.3 μm spectrograph and infrared imager (Rayner et al. 2022). iSHELL incorporates a silicon immersion grating that greatly simplifies getting wide-band high-resolution infrared spectroscopy on IRTF. The silicon immersion grating is an R&D project done in collaboration with Dan Jaffe's group at the University of Texas at Austin. It is a capability not available with *JWST*. iSHELL was commissioned in 2016. Compared to SpeX it is a more specialized instrument because of its very high resolving power. iSHELL is optimum for 3-5 μm high-resolution spectroscopy of planetary atmospheres, comets, and planet-forming disks, for example (see sections 6 and 7).

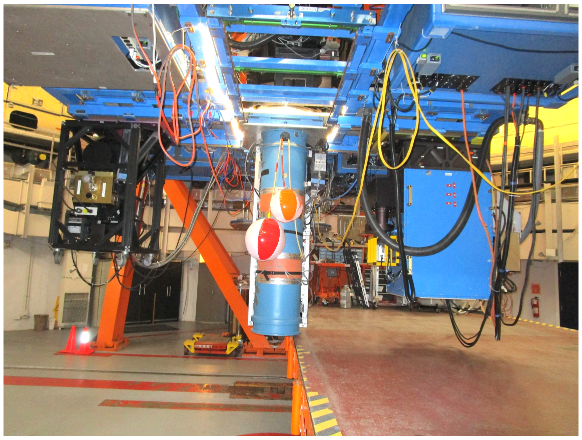

Figure 5. TEXES in the on-axis observing location. MIRSI (left) and SpeX (right) are in their west and east stow positions respectively.

MIRSI is a 5-20 μm spectrograph and imager (Kassis et al. 2008). It was used as a visitor instrument on IRTF from 2002 until 2010. MIRSI has since been upgraded with a closed-cycle cooler replacing the liquid nitrogen and liquid helium cryostat, and new array control electronics. A dichroic-fed CCD camera has also been added (MOC). MIRSI was recommissioned as an IRTF facility instrument during 2021. Its main scientific use is for simultaneous visible and mid-infrared photometry of NEOs to measure albedos and estimate diameters (see section 3) for IRTF's planetary defense role. MIRSI is currently the only regularly available MIR camera in the northern hemisphere. Our near-term plans are to replace the current engineering grade array with a science grade array and add a chopping mode to the hexapod secondary to improve sensitivity.

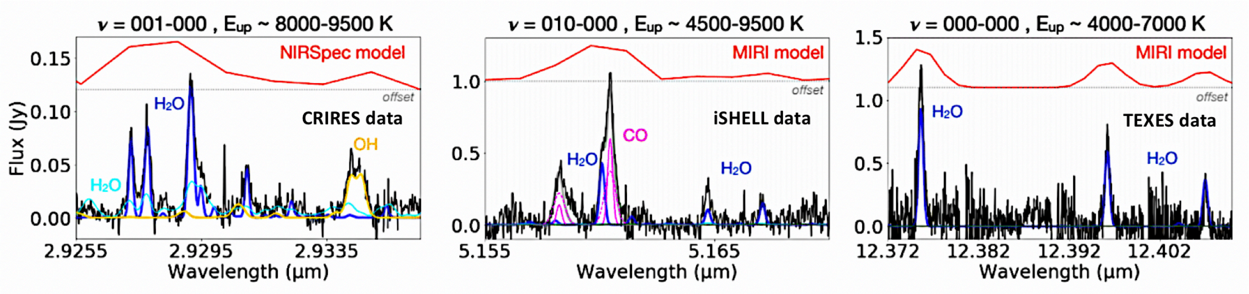

Figure 6. For planet-forming disks *JWST* provides very large spectral coverage but loses entirely any kinematic information on the observed emission, and blends together lines from multiple emission and absorption features. iSHELL and TEXES data complements *JWST* data by providing high resolving power kinematically-resolved data but only in limited high telluric transmission regions visible from Maunakea, the best ground-based site for mid-infrared astronomy in the northern hemisphere (see Figure 43). The data are for DR Tau (black). The plots are from Banzatti et al. (2022b).

The south stow position on the MIM is currently made available to visitor instruments. These are typically PI-class instruments that are operated by the PI's team at the telescope with support from IRTF staff. Since 1990 about 20 different visitor instruments were awarded observing time on the telescope. Over the past decade however, requests for visitor instrument runs have virtually disappeared, possibly due to a dearth in the funding of PI-class instruments. The two exceptions are TEXES and occasionally HIPWAC. TEXES is a R=5000-100,000 8-26 μm spectrograph built by the University of Texas at Austin (Lacy et al. 2002, see Figure 5). HIPWAC is a 7.5-8.5 μm $R \sim 10^7$ heterodyne spectrograph for the measurement of line profiles in planetary atmospheres (Glenar et al. 1982). TEXES typically gets about one month of observing per year. Observers requesting time with TEXES are required to collaborate with the TEXES team and submit joint proposals. IRTF is now the only telescope on Maunakea (and possibly the northern hemisphere) offering regular mid-infrared observing. As with iSHELL, TEXES is an infrared capability not available with *JWST* (see Figure 6).

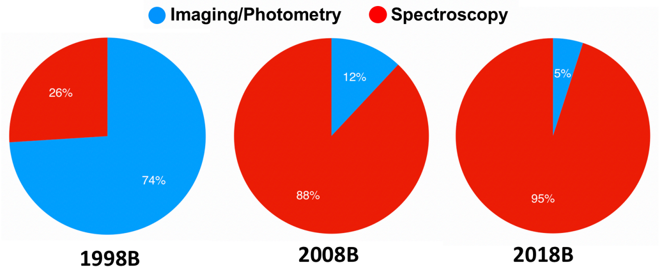

Figure 7. The change in observing from mostly photometry and imaging to nearly all spectroscopy over the past two decades.

It is interesting to note how the nature of observing on IRTF has evolved over the past couple of decades. In observing semester 1998B 74% of observing programs were for imaging and photometry compared to 26% for spectroscopy. This compares with only 5% for imaging and 95% for spectroscopy in 2018B (see Figure 7). The reasons for this are twofold: the relatively small FOV available at the Cassegrain focus (< 3′, limited by the off-axis A&G camera patrol field) and the increasing size of focal plane infrared arrays. Other 4-m class optical-infrared telescopes have exploited the increasing size of focal plane infrared arrays by deploying wide-angle imagers either at Cassegrain or prime focus. As a planetary telescope IRTF only needs a FOV of ~1′ to image planetary disks. IRTF has exploited the larger format of infrared arrays by increasing one-shot spectral coverage by building the cross-dispersed spectrographs SpeX and iSHELL. The infrared slit viewers and guiders in these instruments were designed to have ~1′ FOVs and multiple filters for planetary imaging.

‘Opihi is a commercially procured 0.43-m diameter corrected Dall-Kirkham telescope with CCD camera attached to the side of the telescope (Lee et al. 2022, see Figure 8). Its main purpose is to provide a large 32′ FOV for the recovery of NEOs with positional uncertainties larger than can be feasibly found with the < 3′ FOV for IRTF at the Cassegrain focus. The efficiently recovered NEOs can then be characterized with the low-resolution prism mode of SpeX. ‘Opihi was funded from telescope operations at the request of IRTF NEO observers in support of NASA planetary defense efforts. It was installed in early 2022 as part of two graduate student projects and is currently being commissioned. In addition, ‘Opihi can be used by observers as an extinction monitor, to bootstrap absolute photometry to SpeX observations, and as a general visible wavelength context camera (SDSS g′, r′, i′, z′ and *open* filters).

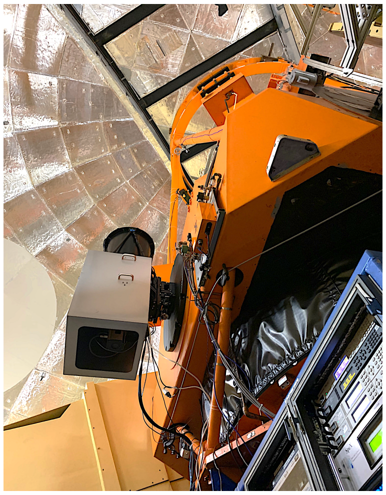

Figure 8. The ‘Opihi finder scope attached to the side of the telescope.

IRTF was one of the first ground-based telescopes to provide a data reduction pipeline with instrument delivery. Spextool (Cushing et al. 2004 and Vacca et al. 2003) is an IDL-based package for the reduction of spectral data obtained with SpeX and which is driven by a set of GUIs. The package has since been modified to also reduce iSHELL data. Spextool is also used to automatically extract spectra during observing sessions for ‘quicklook’ purposes. SpeX and iSHELL observers are thus able to nearly instantaneously inspect the signal-to-noise values of their spectra, and the presence of any spectral features of interest, and adjust their observing plans accordingly, greatly enhancing the efficiency of observing runs. Modified versions of Spextool are also used at several other facilities (SOFIA, NIHTS at the Lowell Discovery Telescope, ARCoIRIS/Triplespec at CTIO and FIRE at Magellan). Burgasser, Cushing et al. have received NASA Astrophysics Data Analysis Program (ADAP) funding to convert Spextool from IDL to Python (pySpextool) and to run Spextool in batch mode, and to re-reduce 50,000 sources (30 Tb of data) from the IRTF Legacy Archive (raw SpeX data covering the period 2001-2016). The spectra will be archived at the Infrared Science Archive (IRSA) at IPAC. The IRTF started archiving raw data from SpeX and iSHELL in 2017 at IRSA, which, as of 2019 includes figures and signal-to-noise values of extracted, but not flux calibrated spectra. The goal is to archive fully reduced data once the Spextool conversion is completed and data can be reduced in batch mode. Further upgrades include the use of telluric models to reduce the time spent on standard stars. Several iSHELL users have already benefitted from the beta version of the atmospheric modeling program that is currently offered.

IRTF is unique amongst major ground-based optical-infrared telescopes in having regular daytime observing. For planetary science and mission support this gives access to planets and comets most of the year round except close to conjunction. It is standard practice on IRTF to observe as close as 20 degrees from the sun and with special precautions even closer (see section 5). Over the past several years IRTF has averaged about 200 hours of daytime observing per semester, which is about 10% of the available night-time hours (see Figure 9). Major daytime observing programs during this period were mission support and science for the *Akatsuki* Venus Climate Orbiter, the *Juno* orbiter at Jupiter, and perihelion observations of comets.

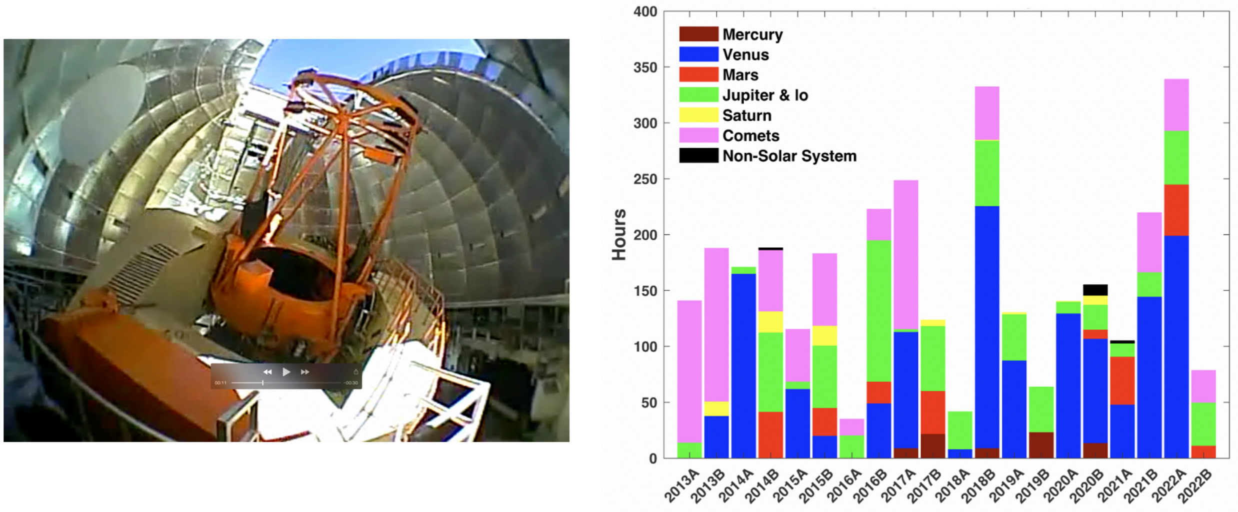

Figure 9. (*Left*) Daytime observing on IRTF. (*Right*) The average daytime observing run is about six hours. With an average of about 200 hours per observing semester over the past several years, IRTF averages about 30 daytime observing sessions per semester (176 days), nearly all for planets and comets.

Recently the Chlorine Monoxide (ClO) monitor (Nedoluha et al. 2020) that was originally housed at CSO has been moved to the IRTF bunker (see Figure 10) since CSO is being decommissioned. There were no other easily accessible sites for the monitor at the summit. The IRTF bunker is a small building at the perimeter of the IRTF site. It was originally built to exhaust warm dome air but that is no longer needed. ClO is a proxy to estimate the destruction of ozone in the stratosphere. It is important that the monitor be sited at 4,200-m on Maunakea rather than lower at the NOAA atmospheric observatory on Mauna Loa. Manmade CFCs are photo-dissociated in the stratosphere to form Chlorine radicals that then react with ozone forming ClO, depleting ozone, and increasing harmful UV exposure. These measurements are valuable to check compliance with the 1987 Montreal CFC protocols that regulate the production of ozone depleting substances. The ClO monitor is owned and operated by NOAA staff with a small amount of support from IRTF staff.

Figure 10. The ClO monitor is housed in the IRTF bunker at the perimeter of the IRTF site (diameter about 100-m centered on the telescope).

1.3 Ongoing Projects

Aside from general facility maintenance and upgrades IRTF has several ongoing projects that we consider important to maintain the scientific productivity of IRTF.

Image quality at IRTF is dominated by atmospheric seeing but second order effects due to focus drift and astigmatism are an issue (see the May 2022 IRTF staff presentation to the NIKUG for the image quality budget[2]). FELIX is a project to replace the visible wavelength off-axis acquisition and guide (A&G) camera with an upgraded CCD camera incorporating a 2x2 Shack-Hartmann wavefront sensor. The camera plus pick-off mirror rides on an x-y stage that patrols the unvignetted ~25 sq. arcminute FOV surrounding the science field. In wavefront sensing mode off-axis guide stars as faint as *V*=18 are used to

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[2] http://irtfweb.ifa.hawaii.edu/meetings/senior_review_2022/Presentations_to_NIKUG/NIKUG_IRTF_24may2022.pdf (page 60)

measure the focus. In the initial implementation focus will be tracked and corrected approximately once per minute.

In addition to focus, the FELIX Shack-Hartmann sensor provides information on astigmatism, which can be corrected by an adaptive secondary mirror (ASM). Mark Chun (PI, IfA Hilo) has NSF funding to develop and deploy an ASM on the UH 2.2-m telescope on Maunakea (Chun et. al. 2020, Kuiper et al. 2020). The ASM uses the hybrid variable reluctance actuators being developed by the Dutch company TNO. This technology has several advantages over the voice-coil actuators used at other telescopes (e.g., LBT, MMT and VLT): much higher force output and electrical efficiency enabling a thicker and more robust mirror shell, actuators are connected to the mirror shell providing better stiffness, low heat dissipation, and a less complex opto-mechanical system.

In collaboration with Mark Chun, we are in the initial stages of planning to build and deploy an ASM first on IRTF for R&D. The UH 2.2-m secondary mirror has a diameter of 0.6-m, significantly bigger than the 0.24-m f/37 secondary on IRTF. By building a smaller ASM with fewer actuators and testing it first on IRTF, this incremental approach will speed development and reduce risk. It is also the best and soonest approach to providing IRTF with low-order active (slow) wavefront control together with FELIX. Progress on the ASM is also of great interest to the Keck Observatory who are seriously considering the TNO approach for their proposed adaptive secondary. Engineering time on IRTF for this development will be made available. In the long term deploying the ASM opens the possibility of adaptive optics on IRTF.

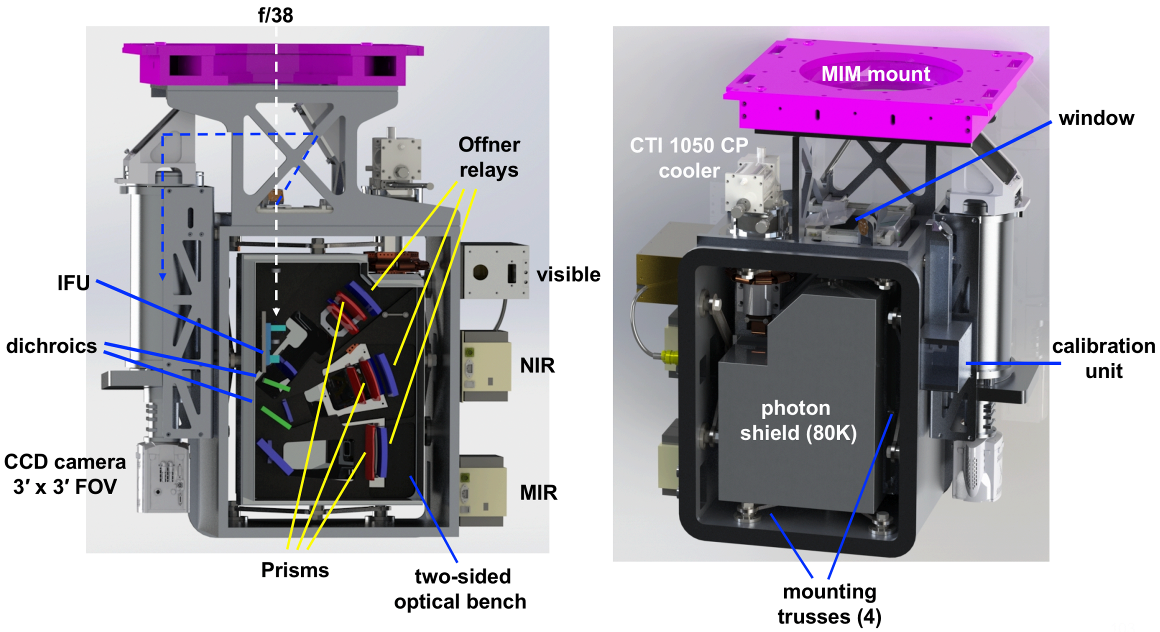

Figure 11. Preliminary cryo-optical and mechanical design layout of SPECTRE, the proposed new facility instrument. SPECTRE attaches to the MIM via the MIM-mounting truck shown at the top (purple).

Probably our most important ongoing and future project is the development of the new facility instrument, SPECTRE. SPECTRE is a 0.4-4.2 μm *R*=150 integral field spectrograph. It is being designed primarily as a capability to characterize NEOs and other small solar system bodies (see section 3 and 5), and as a capability for fast characterization of variable objects discovered by transient sky surveys such as ZTF[3], ATLAS[4], Pan-STARRS[5] and Rubin Observatory[6] (see section 7). The unique features of SPECTRE

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[3] https://www.ztf.caltech.edu/

are the one-shot wide-band 0.4-4.2 µm wavelength coverage together with a 7″ x 7″ FOV integral field unit for slit-less absolute spectrophotometry on point sources. This feature is particularly valuable for the spectral characterization of NEOs and main belt asteroids, observations of which can be compromised by stitched-together-spectra taken at different times due to rotation and phase effects. The wide-band coverage is achieved with three optical channels (visible: 0.4-0.9 µm, NIR: 0.9-2.5 µm, and MIR: 2.5-4.2 µm). SPECTRE is a single mode instrument with no moving cryogenic optics. It will include a 3′ x 3′ FOV CCD for A&G and for guiding on fast flyby NEOs (see Figure 11). The design has been brought to PDR-level through internal funding. Construction of SPECTRE requires further funding of about $3m from NSF or NASA.

In the near term other ongoing projects include the deployment of an all-sky camera on the IRTF bunker (see Figure 10) to assess sky-observing conditions for Keck Observatory. An 'all-sky' camera at the Keck site would be significantly vignetted by the Keck domes. IRTF will also make use of this camera. Also, since the TEXES team is finding it increasingly difficult to find personnel to support observing runs, we are considering taking over support duties, effectively converting TEXES into a facility instrument. Mid-infrared high-resolution spectroscopy is now an IRTF niche, particularly for planetary atmospheres.

Independent of the telescope facility, the high altitude, undisturbed air, remote location, and minimal influences of vegetation and human activity at the IRTF site are beneficial for many atmospheric measurements, including the ClO monoxide monitor discussed previously. Another example is the LIDAR experiment that GSFC is planning to bring to IRTF in spring 2023. Abshire et al. 2022[7] are planning to demonstrate a breadboard of a small atmospheric LIDAR to address the needs of a future lander on Mars to probe the planetary boundary layer (see Figure 12). The LIDAR demonstration requires a high and dry site.

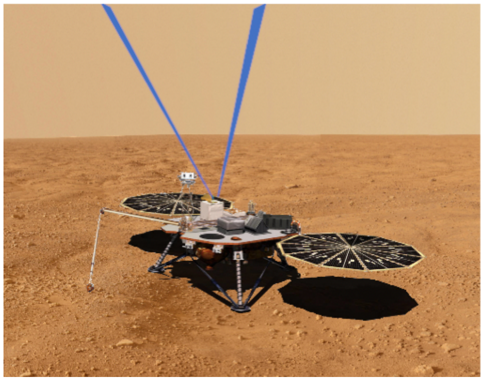

Figure 12. Concept sketch of two laser beams exiting the small LIDAR on a Mars lander to profile aerosols, water vapor and winds, simultaneously.

1.4 Maintaining Efficient Observatory Operations

The IRTF was commissioned in 1979. Since then several major IRTF telescope systems have been either replaced or undergone major upgrades. A Major Restoration and Modernization Project was overseen by the US Army Corp of Engineers in the mid-1990s, primarily to reduce dome-seeing through cooling the dome interior by replacing and enhancing the HVAC system, adding additional refrigeration plumbing, insulating the dome, and upgrading the electrical distribution system. This work included building a dome air exhaust tunnel to a new small fan building (see Figure 10). Exterior dome work included adding maintenance platforms to the top of the dome, installing an exterior sliding door and new interior vented (filter) sliding door, adding a dome shutter de-icing system (that proved ineffective), and painting the building exterior. Further interior work included installing of environmental monitoring, control and recording systems, and repainting the telescope and yoke. The original chain-driven shutter was replaced with an elevator-type shutter in 1996 and the original all-analog telescope control system was replaced with an analog-digital system (TCS3) in 2008.

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[4] https://atlas.fallingstar.com/home.php
[5] https://panstarrs.ifa.hawaii.edu/pswww/
[6] https://www.lsst.org/news
[7] http://www-mars.lmd.jussieu.fr/paris2022/abstracts/poster_Abshire_James_small_lidar.pdf

Additional measures to improve dome thermal control were resurfacing the dome with reflective aluminum tape in 1998 and 2018 (the dome was originally painted white), and adding cooled boxes (‘Coolracks’) to house electronics that need to be located close to the observing instruments to the MIM in 2002. The Coolracks prevent warm air from entering the dome near the light path (see Figure 4).

The original all-analog telescope control system was replaced with an analog-digital system (TCS3) in 2008. Maintenance and upgrades of the IRTF computer network and systems is continuous and is designed to meet NASA cyber security requirements.

Given the age of some of the telescope systems, timely preventative maintenance by the day crew is key to efficient operation of the telescope (risk assessment is discussed in section 10). Regular alignment and maintenance of the dome bogey wheels and drive motors is now performed following dome rotation stalls in 2015. The RA and Declination drives are original and following drive problems in 2019 some parts have been replaced and performance is now closely monitored (by measuring tracking stability and drive currents). Upgrades have also been made to the primary mirror axial (three hard points and 13 air bags) and radial (mercury ring) support systems, reducing stiction and improving static image quality.

To maintain high reflectivity and low emissivity, the primary mirror is CO_2 cleaned once a month, and water cleaned when CO_2 cleaning does not maintain a low emissivity (typically 0.05). The main source of contamination is wind-blown dust entering through open shutter during observing. Measurements of the emissivity of the telescope optics is done regularly with the infrared pupil viewer in SpeX (measured at 3.8 μm). On average the primary mirror needs re-aluminizing once every ten years. The last time was in 2012. The mirror is transported to CFHT for recoating in their coating chamber, requiring a downtime of about two weeks. In the long term (several years) we are monitoring erosion around the telescope building that may eventually affect transport by truck of the mirror to CFHT. However, we have a plan in place for a site survey and possible installation of retaining walls. Since the telescope secondary mirror is downward looking it is much easier to keep clean.

Two important telescope systems require vendor visits to assess their health, and provide support and advice for maintenance: the RA and Declination drives and brakes (Philadelphia Gear/Timken), and the shutter (Alimak). Recent visits by Philadelphia Gear examined the telescope RA and Dec. gearboxes and re-certified the RA and Dec. brakes. Following an enforced delay due to the pandemic, Alimak visited the telescope to examine the shutter in September 2022. Although the shutter was found to be in good condition and well maintained by the day crew, Alimak reported that the installed safety devices (inertial emergency brakes to prevent free fall of the shutter cars should the operational brakes fail) were out of warranty and recommended that telescope operations cease (from November) until they could be replaced. Due mostly to delays in the State of Hawaii Tax Department updating Alimak’s tax compliance, we expect Alimak to visit and install new safety devices by early January 2023.

Over the past five years the downtime in scheduled observing and engineering time due technical faults (telescope and facility instruments) is averaging 2.5% (excluding the recent shutter incident). By comparison the downtime due to weather closures averages about 25% of scheduled observing and engineering time.

2 ADDRESSING NASA AGENCY GOALS

Overall NASA agency goals are articulated in the latest NASA Strategic Plan 2022[8], and Science 2020-2024: A Vision for Scientific Excellence in 2021 from the Science Mission Directorate[9].

The NASA Strategic Plan 2022 identifies four major strategic goals:

1) Expand Human Knowledge Through New Scientific Discoveries
    - Understand the Earth System and its climate
    - Understand the Sun, solar system, and universe
    - Ensure NASA's science data are accessible to all and produce practical benefits to society
2) Extend Human Presence To The Moon And On Towards Mars
3) Catalyze Economic Growth And Drive Innovation To Address National Challenges
4) Enhance Capabilities And Operations to Catalyze Current And Future Mission Success
    - Attract and develop a talented and diverse workforce
    - Transform mission support capabilities for the next era of aerospace
    - Build the next generation of explorers

IRTF operations address goals 1) and 4) of the NASA Strategic Plan. 1) By conducting peer-reviewed telescope observations, many scientific and programmatic investigations of interest to NASA are addressed (see Figure 13). IRTF also has a role in measuring climate effects as explained in section 1.2. Through the IRTF data archive hosted at IRSA by IPAC, all IRTF data, including the in-house legacy archive, is open source after a proprietary period.

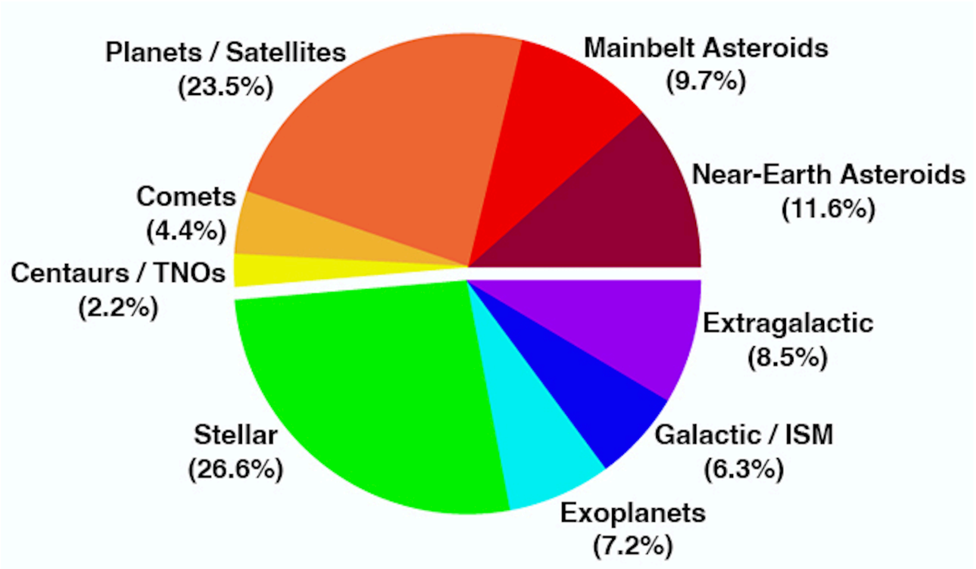

Figure 13. The average distribution of peer-reviewed observing time on IRTF for the past three years, illustrating how IRTF is addressing NASA strategic goals in science.

IRTF is making considerable efforts to address goal 4) as discussed in section 13. These efforts include offering employment opportunities to the local community, offering observing time to Hawaii high school students, funding graduate students and interns, and engaging in education and outreach. In addition, we give astronomy and planetary science graduate students the opportunity for on-site and hands-on observing, opportunities that are increasingly not offered at other facilities.

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[8] https://www.nasa.gov/sites/default/files/atoms/files/fy_22_strategic_plan.pdf

[9] https://science.nasa.gov/science-pink/s3fs-public/atoms/files/2020-2024_NASA_Science_Plan_YR_21-22_Update_FINAL.pdf

The Science 2020-2024 plan is designed to capture Science Mission Directorate (SMD) science and discovery goals, NASA core values (excellence, integrity, teamwork, safety and inclusion), and leadership. The plan emphasizes SMD support of the science priorities identified in the National Academy of Sciences, Engineering, and Medicine (NASEM) planetary[10] and astrophysics[11] decadal surveys. Implementation of the decadal recommendations is of course contingent upon NASA funding. IRTF capabilities and observations address many of the science priorities and recommendations discussed in the planetary decadal report (see Appendix 4). Prominent among these is Planetary Defense. IRTF's role is to spectrally characterize NEOs to infer material properties such as grain density and physical strength, to better assess potential impact damage. Importantly, simultaneous optical and mid-IR photometry with MIRSI/MOC measures albedo and size. It follows that from linking the SpeX and MIRSI/MOC observations, the mass can be estimated using the inferred bulk density (see section 3.2). IRTF also has a role in pre-impact characterization of recovered impactors and thereby strengthening links between NEOs, meteorites, and the main-belt asteroid and comet source populations (see section 3.3).

Congress has directed NASA to find, track, and characterize NEOs larger than 140-m in size. The PDCO requires IRTF to physically characterize NEOs. PDCO does not call out specific goals for IRTF but leaves it to the NEO and small body community of observers through the peer review of observing proposals to do so. PDCO can trigger observing when needed through IRTF Director Discretionary Time (DDT).

The astronomy and astrophysics decadal survey prioritizes The New Messengers and New Physics science theme and recommends a fleet of small to medium scale space missions to capitalize on time domain astrophysics discoveries made with major US facilities (LIGO, Rubin, Roman). The proposed IRTF facility instrument, SPECTRE, is a unique capability to follow up on time domain phenomena (see sections 1.3 and 7).

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[10] https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032

[11] https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

3 PLANETARY DEFENSE

The detection, characterization, and mitigation of potential asteroid impactors is one of the key functions of NASA, as recognized by the 2016 creation of the Planetary Defense Coordination Office within the agency. IRTF plays a key role in the characterization of NEOs and remains a vital asset in NASA's planetary defense efforts, providing capabilities that are unduplicated with other NASA assets.

3.1 Complementary Roles of *NEO Surveyor* and IRTF

The *NEO Survey*or space telescope[12] is a five-year mission designed to discover and produce accurate orbits for two-thirds of NEOs larger than 140 m. The spacecraft will operate in the mid-infrared, allowing it to measure sizes and albedos of asteroids by fitting the observed 5 and 8 μm fluxes to a blackbody. The mission description also lists the goal of determining spin rates and shapes of NEOs, though this capability will be limited by the observing cadence used for the all-sky survey. NEO Surveyor will not provide any reflectance colors or spectroscopy needed for understanding the composition and material properties of the targets it observes. By contrast, IRTF is not a survey telescope, but focuses on observations aimed at the physical characterization of individual targets, as discussed below.

3.2 NEO Characterization with IRTF

A full understanding of the impact risk posed by NEOs is predicated on knowing the physical properties of the NEO population. Important parameters include size and density (mass), composition and material properties, shape and spin state. Our understanding about the physical nature of NEOs, and asteroids in general, has grown from a wide variety of ground- and space-based observations, meteorite studies and laboratory experiments. Through studies of orbit perturbations, asteroid binaries and a handful of spacecraft encounters, the masses of several hundred asteroids have been measured with varying degrees of precision (Carry 2012). For small asteroids, there is a critical spin period of 2.2 hours, below which objects cannot remain intact under self-gravity alone (Pravec and Harris 2000, Polishook et al. 2016). NEOs with rotation periods longer than 2.2 hours are likely to be gravitationally-bound rubble piles while fast rotators must have some internal strength, and are likely solid monolithic bodies. While asteroid light curves are not a primary objective of the NEO observations made with IRTF using SpeX, images taken with MORIS, usually simultaneously with spectroscopy, have provided important light curve results. An example is the fast-rotating NEO 2018 KW1 (see Figure 15).

A major capability of IRTF in NEO studies is low-resolution near-IR spectroscopy using SpeX. Data from 0.7-2.5 μm are key for constraining composition and mineralogy of NEOs, for linking them to meteorite analogs, and for identifying plausible source regions amongst the main-belt asteroids or comet population. When an asteroid can be linked to a meteorite class with some level of confidence (e.g., Gaffey 1993, Sunshine et al. 2007), results from the laboratory studies of those meteorites place constraints on the material properties of that asteroid, such as grain density and micro-porosity, tensile strength, heat capacity and thermal conductivity (e.g., Opeil et al. 2012, Pohl and Britt 2020). If an NEO can be linked to an asteroid source region, then studies of the main-belt asteroid family members from which the NEO originated can help establish the collisional history of the object, and potentially put limits on its bulk density and mass (e.g., Masiero et al. 2015). IRTF observations with MIRSI/MOC can further refine the sizes and albedos of NEOs, and when these measurements cover a range of heliocentric distance and solar phase angles, they provide input to thermophysical models of individual NEOs (e.g., Chamberlain et al. 2011, Hinkle et al. 2022). Together, these observations help inform estimates of the

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[12] https://www.jpl.nasa.gov/missions/near-earth-object-surveyor

impact hazard posed by NEOs, as well as hazard mitigation strategies and future spacecraft mission planning.

IRTF has measured the spectral properties of thousands of main belt asteroids (e.g. Arredondo et al. 2021, Moskovitz et al. 2010). With over 1000 calibrated 0.7-2.5 µm prism spectra, the IRTF/SpeX MIT-Hawaii NEO Spectroscopic Survey (MITHNEOS, Binzel et al. 2019) is the largest publicly available database of NEO spectra. Impact hazard assessment models (e.g., Reddy et al. 2022a) estimate that for small diameter NEOs (<100 m), those with metallic composition cause the most significant damage. In contrast, for NEOs larger than 200 m diameter, hydrous C-type objects are estimated to cause the greatest damage (due to air bursts), while anhydrous S-types cause the least damage, and metallic objects cause moderate damage.

3.3 Rapid Response to Close NEO Flybys

With the advent of all-sky survey facilities such as Rubin and ATLAS, close flyby NEOs (within the orbit of the Moon) can be found hours or even days before encounter, tracked and characterized by IRTF. The IRTF is unusual in its capability to track on targets moving as fast as 60″/sec (four times the sidereal tracking rate). This allows tracking on NEOs as close as five Earth radii. Moskovitz et al. already have a well-established target-of-opportunity (ToO) observing program on IRTF for close flyby events.

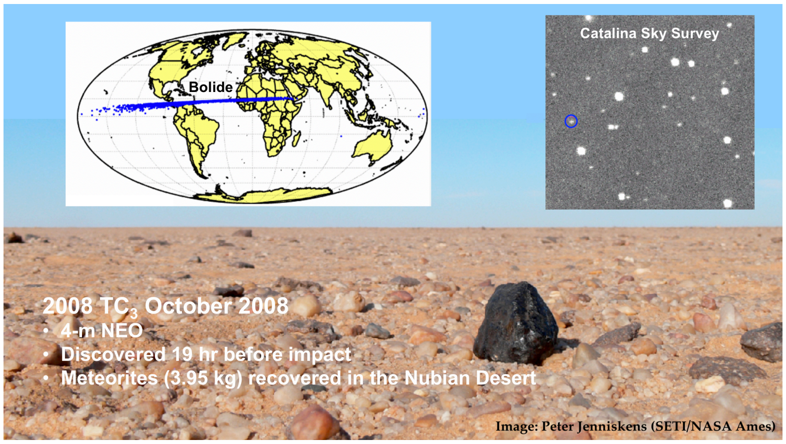

Image: Peter Jenniskens (SETI/NASA Ames)

Figure 14. 2000 TC$_3$ pre-impact NEO discovery recovered in the Nubian Desert. Jenniskens et al. 2009.

Only six impactors have so far been discovered, all within one day, before hitting Earth, but with no pre-impact multi-wavelength characterization. The most recent were discovered by the Catalina Sky Survey (2018 LA, 3 m diameter) and ATLAS (2019 MO, 3 m diameter). Two of the impactors were recovered during ground searches (2008 TC$_3$ discovered by the Catalina Sky Survey 19 hours before impact and recovered in the Nubian Desert, Jenniskens et al 2009, see Figure 14; and 2018 LA discovered by the Catalina Sky Survey 8 hours before impact and recovered in Botswana, Jenniskens et al. 2021). Correlation of astronomical measurements with meteorite ground truth (i.e., nature's version of a sample return mission) is the holy grail of asteroid exploration.

The close flyby of 2018 KW1 was observed by Moskovitz et al. as part of their ToO program (see Figure 15). Table 1 shows the timeline of the flyby from the discovery of 2018 KW, the Minor Planet Electronic Circular (MPEC) issue to the Minor Planet Center (MPC), the IRTF observations, and the results being sent to the PDCO. Once Rubin comes online we expect some very close flyby NEOs to be discovered as early as several days before encounter leading to improved ephemerides, better planning and more time for observations.

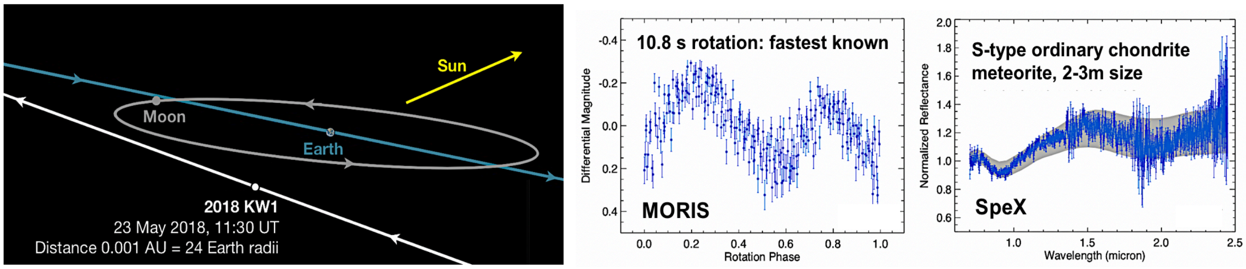

Figure 15. (*Left*) Close approach of NEO 2018 KW1 to 24 $R_{\oplus}$, IRTF observations were obtained four hours before closest approach. Observational challenges led to only 15 minutes on target. (*Middle*) MORIS photometry revealed the shortest known rotation period of any asteroid (10.8 s). (*Right*) SpeX obtained a low S/N spectrum consistent with ordinary chondrite meteorites. A rough estimate of the size is obtained through asteroid spectral class correlations with albedo (Thomas et al. 2011). The fast rotation period indicates substantial mechanical strength and that 2018 KW1 is not a rubble pile, important information for potential impact damage assessment.

Table 1. Timeline of 2018 KW1 flyby and IRTF observations

Date/time (UTC)	Event
2018-05-22 04:34	First detection by Catalina Sky Survey
2018-05-22 17:11	MPEC issued by the MPC
2018-05-22 19:47	IRTF notified of ToO request
2018-05-23 07:30	Start of SpeX + MORIS observation
2018-05-23 10:30	End of observability from IRTF
2018-05-23 11:30	Closest approach at 24 $R_{\oplus}$
2018-05-23 21:08	Results sent to NASA PDCO

The current pre-impact discovery rate of 0.25 per year is expected to increase to about 2.5 per year once Rubin is online (Moskovitz priv. comm.), significantly increasing the likelihood of pre-impact spectral characterization by IRTF, thereby testing of the link between NEOs and meteorites and improving impact hazard assessment. In addition, close flyby (< 30 $R_{\oplus}$, the threshold for seismic shaking) spectral observations can reveal the effects of tidal stresses, and landslides can reveal un-weathered sub-surface material. Some of these NEOs will be captured and become mini-moons (estimates of four per year discovered by Rubin). Low $\Delta v \leq 4$ km/s NEOs are also potential mission targets (40 per year from Rubin). Rubin will have the cadence and sensitivity to find small NEOs probably days before close flybys, allowing for better follow up with IRTF.

3.4 Planetary Defense Exercises

To test the operational readiness of the global planetary defense capabilities, IRTF has participated in three community-led global planetary defense exercises, with support from NASA's PDCO and the International Asteroid Warning Network (IAWN), involving observations, modeling, prediction, and communication. These campaigns focused on the characterization (by direct imaging, radar, and spectroscopy) of NEO 2012 TC4 (Reddy et al. 2019), NEO 1999 KW4/Moshup (Reddy et al. 2022a) and NEO Apophis (Reddy et al. 2022b). Moshup has a diameter of 1.4 km and was observed at 0.04 AU (see Figure 16). IRTF's role was to provide spectral characterization. Moshup was selected due to its binary nature since binaries make up roughly one sixth of the NEA population larger than 200 m in diameter. In addition, the campaign results were applied to ground-based characterization of binary NEA (65803) Didymos, the target of the *DART* mission.

Spectral observations of Moshup show that the best meteorite analogs are L chondrites. The meteorite analog was used to estimate the distribution of the base densities and by comparing the base and bulk densities, the porosity was calculated. Base density, bulk density and porosity are all key inputs into the impact risk model. Reddy et al. (2022a) also studied the 1.7–4.2 µm region of Moshup over one full rotation and found that the asteroid does not exhibit 3 µm absorption features suggesting that the entire surface is anhydrous. An anhydrous or hydrous nature of Moshup would be used to constrain base and bulk density and porosity if the visible and NIR spectra did not yield a meteorite analog. The 3-µm data provided a confirmation of Moshup's anhydrous nature. Impact risk of a hypothetical impactor based on Moshup's physical properties was assessed using the Probabilistic Asteroid Impact Risk model. Assessment was performed for three epochs as the state of knowledge of Moshup improved. The uncertainty in the risk estimates were substantially reduced as additional characterization information became available for civil defense planning.

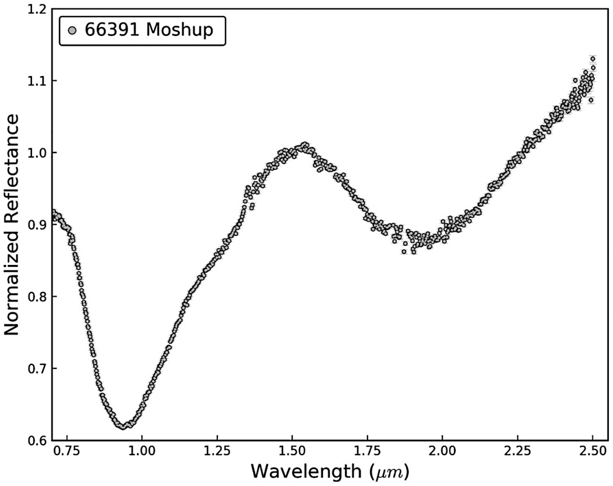

Figure 16. SpeX prism observations of NEO Moshup during the May 2019 planetary defense exercise at IRTF. The best spectral match is a Q-type asteroid and the best meteorite analogs are L chondrites.

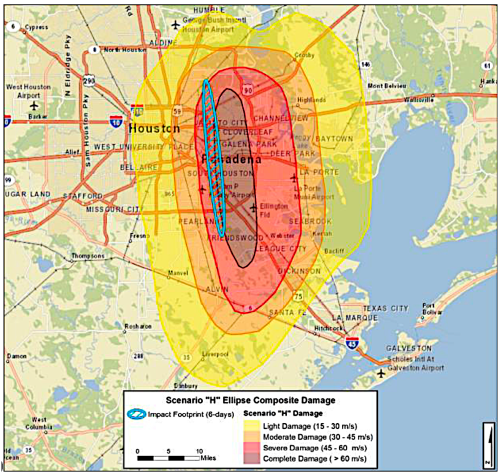

Figure 17. Damage assessment based on information from all available assets six days before impact: 12 km high 4 MT airburst of a slightly porous stony object 50 m in diameter.

These observational exercises feed into Federal Emergency Management Agency (FEMA) tabletop civil defense exercises, one of the first of which was conducted for NEOO in 2014 (Boslough et al. 2015, see Figure 17). The purpose of the exercises is to assess leadership reactions, information requirements, and emergency management responses to a hypothetical asteroid impact with Earth. The scripted exercises consist of discovery, tracking, and characterization of a hypothetical asteroid, and include details of mission planning, mitigation, response, impact to population, infrastructure and GDP, and explicit quantification of uncertainty. Participants at the meetings include representatives of NASA, Department of Defense, Department of State, Department of Homeland Security/FEMA, and the White House.

3.5 Critical Capabilities for Planetary Defense

IRTF has several critical capabilities for planetary defense. Finding recently discovered NEOs with uncertain ephemerides is aided by the recent addition the 0.5-degree FOV CCD finder to the telescope (see Figure 8) together with the integration of JPL Scout software for ephemerides of recently discovered objects into the telescope control system. For fast flyby NEOs the fast-non-sidereal tracking of the telescope is critical (e.g., see Figure 18). The combination of

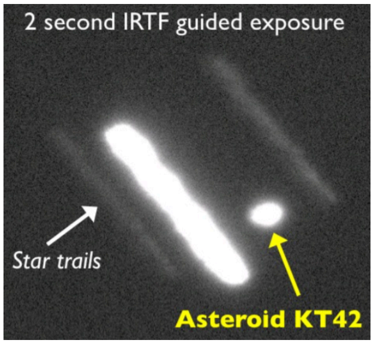

Figure 18. MORIS guiding on 2012 KT42 at a distance of only 6 $R_\oplus$.

SpeX/MORIS (spectral characterization) and MIRSI/MOC (albedo and size) provides IRTF with a unique set of instrumentation for NEO characterization. The IRTF's flexible scheduling allows for observations of targets near peak observability as well as rapid turnaround target-of-opportunity observations and DDT requests for newly-discovered close-approach NEOs.

A very recent example of IRTF capabilities is the *DART* impact with Dimorphos. The impact occurred at about noon Hawaii time on September 26, 2022 when the object was below the horizon. However, later that evening and over the following days MIRSI/MOC observed the expanding ejected dust cloud from which the ejected dust mass can be estimated using the combination of thermal and optical data (see Figure 19).

With the proposed new instrument, SPECTRE, spectral features would be recorded across the entire 0.4-4.2 μm range in a single shot, removing uncertainties resulting from assembling spectra taken with different instruments at different epochs. The 0.4-4.2 μm coverage is critical for mineralogical characterization - from weakly featured asteroids such as C types that have diagnostic absorption features in the visible (0.7 μm) and in the mid-IR (3 μm), to strongly featured spectral classes, such as S-, Q-, A- and V-types, that exhibit strong silicate absorptions at 1 and 2 μm. A unique feature of SPECTRE is the capability to very accurately measure spectral slope across the visible and NIR wavelength range since the instrument does not suffer wavelength dependent slit losses (e.g., Marsset et al. 2020). This feature is particularly useful to classify weakly featured asteroids and is also an independent confirmation for general mineralogical characterization (DeMeo et al. 2009). In addition, the simultaneous visible and infrared observations resolve ambiguities that can occur when combining visible and infrared spectral classifications schemes. A one-magnitude increase in sensitivity will allow measurements of smaller or more distant NEOs, and faster mapping of NEOs over rotational phase.

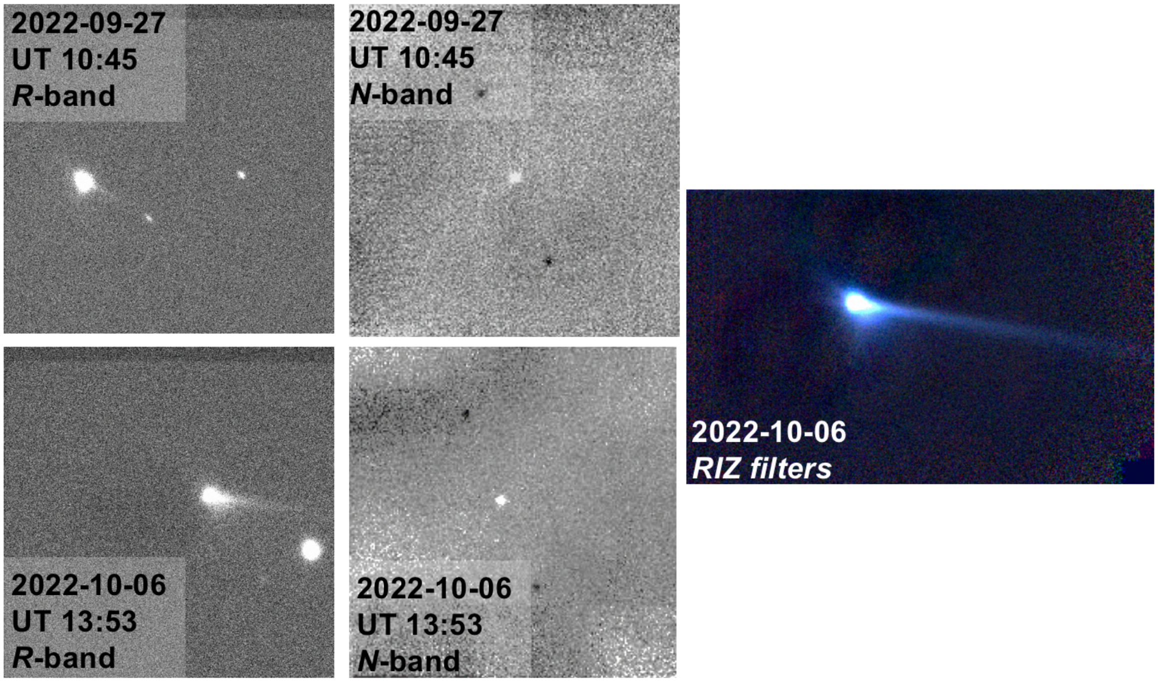

Figure 19. The Didymos system imaged in the *R* (0.66 μm) and *N* (10.6 μm) filters with MOC (*left*) and MIRSI (*right*), 11 hours (*top*) and nine days (*bottom*) after the DART impact. A dust cloud, tail and background stars are seen in the optical while the Didymos system is a point source in the MIR. The FOV is 60″ x 60″. (*Inset right*) MOC *RIZ* composite image nine days after the impact, integration time about one minute in each filter, image is median filtered to remove background stars.

3.6 Comparison of IRTF Capabilities for Planetary Defense with Other Ground-based Assets

As discussed previously, IRTF is not a survey telescope to find NEOs. Its primary role is physical characterization of NEOs and potentially hazardous objects for Planetary Defense. This is done with a suite of facility instrumentation (see section 1.2).

IRTF assets for NEO characterization

The primary capability IRTF provides for NEO characterization is the measurement of solid-state spectral absorption features using the 0.7-2.5 µm R~100 prism mode in SpeX. The prism mode is very efficient compared to grating spectrographs (about a factor of two in throughput), making IRTF competitive with grating spectrographs on larger telescopes. Solid-state absorption bands in asteroid spectra are key for constraining composition and mineralogy of NEOs, and can help place limits on bulk densities and masses of NEOs (see section 3.2). SpeX also has a 2.5-5 µm mode that is frequently used for the characterization of hydration features in NEOs and mainbelt asteroids. In addition, a dichroic-fed CCD camera attached to SpeX (MORIS) allows visible multi-filter photometry to be obtained simultaneously with infrared spectroscopy (providing information about spin and shape from light curves). Both MORIS and the infrared slit viewer/guider in SpeX allow for accurate guiding on fast moving NEOs.

SPECTRE, the proposed one-shot 0.4-4.2 µm *R*=150 capability (see section 1.3), will be a significant upgrade to IRTF's capabilities for planetary defense, in particular by removing the degeneracy in identifying asteroid spectral types that can result by obtaining visible and infrared spectroscopy at different times and at different telescopes.

The recently commissioned wide-field (0.5º FOV) CCD camera ('Opihi – see Figure 8) attached to the telescope provides the capability to image recently discovered NEOs with poorly determined orbits and ephemerides and place them in the FOV of SpeX or MIRSI, and to bootstrap absolute spectro-photometry by comparing the target fluxes to stars across the wide 'Opihi FOV.

Simultaneous photometry in the mid-infrared and visible with the MIRSI/MOC (see section 1.2) combination provides the capability of measuring albedos and sizes of NEOs. No other facility in the world has this capability. Mid-infrared photometry (needed to measure sizes) has now been largely abandoned at other ground-based facilities in the northern hemisphere.

Compared to other optical-infrared telescopes on Maunakea, IRTF is unusual in its capability to track on targets moving as fast as 60 arcsec/s (four times the sidereal tacking rate). This allows tracking on NEOs during passes as close as five Earth radii. This compares to non-sidereal tracking limits of about 60 Earth radii (the Moon's orbit) for Keck and Gemini (about 5 arcsec/s). In addition, scheduled observing can be interrupted within minutes at the discretion of the IRTF Director following NEO alerts, and through programmatic requests by the PDCO since the IRTF is owned by NASA. Programs designed for Target of Opportunity (ToO) observations are encouraged as part of the standard proposal and TAC review process (see section 3.3).

Except for the ALMA submillimeter array (5,060-m) and the proposed 6.5-m optical-infrared Tokyo Atacama Observatory (5,640-m) in the Atacama Desert of northern Chile, and sites in Antarctica with very limited accessibility, IRTF is located at the one of best sites for infrared astronomy in the world. It is also the best overall observing site in the northern hemisphere (clear, dark and dry skies, with state-of-the-art infrastructure and access). Maunakea is also positioned in the middle of the Pacific Ocean, a unique location filling a big gap in the time zone coverage needed for planetary defense.

When considered together, the specialized capabilities of the IRTF telescope and instrumentation, the high altitude and superior sky conditions of Maunakea, flexible scheduling, dedication to Solar System observations and control by NASA make IRTF a unique and valuable asset to the PDCO for NEO characterization. This ensemble of capabilities IRTF provides for NEO studies is not duplicated by any other ground-based telescope (see the following section).

Other assets for NEO characterization

Visible-wavelength photometry and colorimetry helped lay the foundation for asteroid and NEO characterization in the 1970s with accurate measurements of brightness, colors and lightcurves. The taxonomic classification of asteroids naturally grew out of the differences observed in asteroid colors, and matured with the introduction of CCD spectrographs in the 1990s. Today, small- and medium-sized telescopes around the world, both amateur and professional, are providing visible-wavelength astrometry, photometry, colors and spectroscopy that are greatly expanding our knowledge about the NEO population. While taxonomy is a useful tool for differentiating groups of asteroids, to more fully understand details about an asteroid's composition and surface properties requires observations at longer wavelengths. The IRTF is optimized for the near- and mid-IR wavelengths where these more detailed properties of asteroids (NEOs, mainbelt, and more distant objects) can be investigated.

On Maunakea, NIRES on Keck (which is like Triplespec) and GNIRS on Gemini (Elias et al. 2006) have cross-dispersed R~1000-3000 0.8-2.4 µm modes compatible with these larger-aperture telescopes, but no high-throughput R~100 one-shot 0.7-2.5 µm prism mode. (Note that prisms are typically a factor of two more efficient than gratings since prisms have no grating function and associated light losses.) The higher-resolution modes can be used for NEO spectroscopy by binning up pixels to measure very broad absorption features, but both Keck and Gemini have limited non-sidereal tracking and visible/IR guiding capabilities. GNIRS can cover the 3.0-5.1 µm wavelength range but only as three separate single-order observations. It does not have a one-shot 2-5 µm mode needed to characterize the broad 3-µm region where spectral bands associated with hydration and organics are found.

The family of Triplespec instruments (Wilson et al. 2004) on the 5-m Palomar telescope, the 3.5-m Apache Point Observatory telescope, and the 4.1-m SOAR telescope on Cerro Pachón, have a cross-dispersed R~3000 0.9-2.4-µm capability but no high throughput prism or 2-5 µm modes. Each instrument has a fixed *K*-band filter for acquisition and guiding. The lack of visible or *J*-band guiding limits non-sidereal guiding to brighter asteroids.

NIHTS (Gustafsson et al. 2021) on the Lowell Discovery Telescope (LDT) is a high-throughput R~200 0.9-2.4 µm one-shot prism spectrograph that includes a *Y*+*J*-band guider and a dichroic-fed simultaneous visible imager. In capability NIHTS on LDT is similar to the SpeX and MORIS combination on IRTF. However, parts of the 0.9-2.4 µm wavelength range suffer from significant telluric absorption compared to IRTF due to the low altitude of the LDT site (2,360 m).

The FIRE spectrograph (Simcoe et al. 2013) on the Magellan Telescope is similar to SpeX at 0.8-2.5 µm and includes a high-throughput prism mode together with fixed *J*-band filter for acquisition and guiding. X-shooter on VLT (Vernet et al. 2011) is a cross-dispersed R~10,000 0.3-2.5-µm spectrograph. Since Magellan and VLT are in the southern hemisphere their sky coverage is complementary to IRTF.

Another invaluable asset for the characterization of NEOs for PDCO is planetary radar. Until its demise in 2020, the 300-m antenna at Arecibo Observatory (NAIC) was the primary source for NEO radar observations. Data obtained at Arecibo provided ultra-precise astrometry as well as size and shape models, spin parameters and information on binarity for 100s of NEOs that made close passes (typically <

0.1 AU) to Earth. Since 2020, the gap left by the loss of Arecibo has been partially filled by the radar capabilities of the Green Bank Telescope, the Very Large Baseline Array, and the Goldstone dish of NASA’s Deep Space Network. The information obtained by radar is highly complementary to the spectroscopy and thermal imaging obtained by IRTF. Combination of the radar models and IRTF data have led to detailed (rotationally resolved) studies into the thermophysical properties of NEO surfaces, including maps of thermal inertia and surface roughness derived from IRTF observations obtained through wide ranges of insolation and viewing geometries (e.g., Shepard et al. 2006, Howell et al. 2018).

4 MISSION SUPPORT

Many IRTF observing programs provide ground-based data supporting current and future spacecraft missions to solar system bodies. IRTF accommodates requests directly from NASA and by peer review of observing proposals through the TAC. Unlike NASA observing time on Keck, for example, IRTF does not require written endorsement from the mission team. The need and justification for mission support is assessed by the TAC as part of the proposal science case. This affords more flexibility but does lead to some ambiguity on what is true mission support (e.g., is it needed for mission planning or calibration?) and what is done more for context. As a result, IRTF does more 'mission support' than would be done if formal endorsement were required. (For example, see the listing of mission support observing proposal for semesters 2022A-2020B in Appendix 5.) Part of the original science case for IRTF was to do mission support for *Voyager*. Important mission support observations were also conducted for *Galileo*, *Cassini* and *New Horizons*, and continues for *Juno* and *Akatsuki*. Critically, IRTF can provide observations to backup missed mission observations due to spacecraft problems (see the following discussion).

4.1 Small Bodies

IRTF has supported almost all previous, current and planned future small body missions to help with mission design and maximize science return, usually through TAC proposals. IRTF participated in the ground-based observing campaigns for the *Deep Impact* mission to Comet Tempel 1 2005 (brightening observed) and the *LCROSS* lunar impact event in 2009 (nothing observed). SpeX/MORIS and MIRSI/MOC observations of the Didymos-Dimorphos system before and after the *DART* kinetic impact on September 26, 2022, were conducted to search for any spectral and photometric changes in the Didymos-Dimorphos system. The *Lucy* and *Psyche* missions are being supported through TAC proposals (e.g., see Appendix 5).

4.2 Galileo

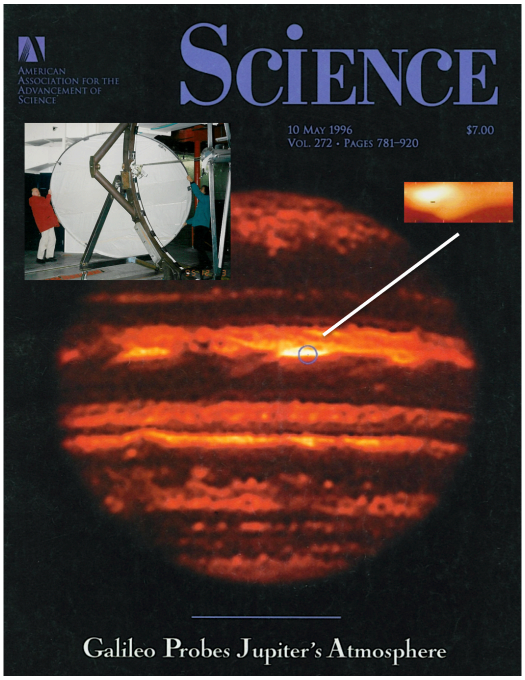

Figure 20. The *Galileo* probe entry site imaged at 5 µm with IRTF/NSFCAM (Shure et al. 1994) on November 21, and hours before entry on December 7 (*inset right*) with the 'world's largest filter' (*inset left*).

One of the most consequential mission support operations was that for the *Galileo* probe entry into Jupiter's atmosphere in 1995 (Orton et al. 1996). The *Galileo* orbiter was unable to provide images to target the probes entry site in the weeks and hours before encounter due the undeployed high gain antenna together with the need to store probe entry data on the balky data recorder. Using mostly IRTF 5 µm imaging and probe radio signals the probe is known to have entered the atmosphere at a 5 µm 'hot spot' (see Figure 20). IRTF images taken hours before the probe entry were very challenging because Jupiter was only 9 degrees from the center of the sun. A thin sheet of polypropylene was laid over the primary mirror, allowing transmission of only infrared radiation (see inset Figure 20). One of the major puzzles resulting from the probe data was the lack of oxygen (in the form of H_2O). The conclusion was that the hot spots, covering only a few percent of the planet, are unusually dry and that water was probably abundant elsewhere below the clouds. (In fact, hot spots had been targeted for the probe due to the downward winds allowing the probe to get deeper into the atmosphere.) The search for water in Jupiter and its implication for the formation of Jupiter, were a major motivation for the *Juno* mission and the planned Microwave Radiometry (MWR) experiment (see section 5.3)

4.3 Juno

Juno arrived at Jupiter in 2016 and entered a highly elliptical polar orbit with a period of 54 days. The plan was to execute a Period Reduction Maneuver to place *Juno* in a 14-day science orbit. Unfortunately leaks in helium check valves precluded further burns of the main propulsion system and so *Juno* was left in the 54-day orbit for the remainder of the mission. The unplanned orbit does not affect the science return during the peri-Jove passes but it does increase the length of the mission. It does however complicate the tracking of atmospheric features and IRTF imaging has been used to support this aspect of the mission (see Figure 21). IRTF imaging also provides valuable context to the *Juno* MWR measurements at peri-Jove.

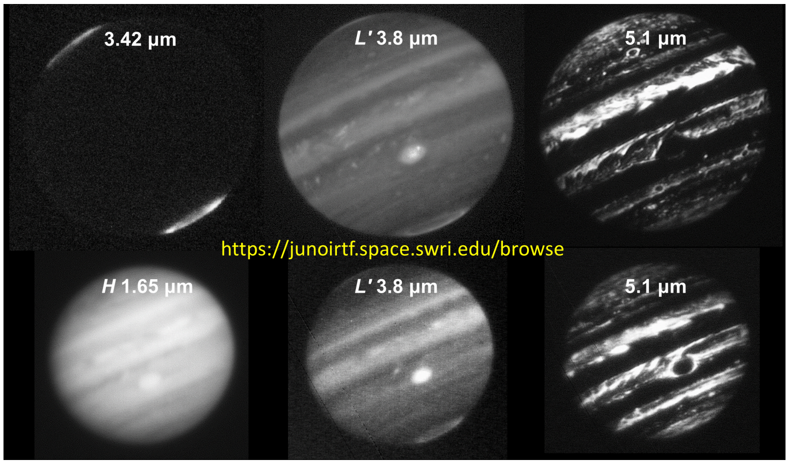

Figure 21. SpeX imaging of Jupiter in support of the *Juno* mission. IRTF can image Jupiter for most of the year: at opposition (top row) and close to superior conjunction during daytime (bottom row, with slightly degraded daytime seeing). This is a unique capability for a major ground-based optical-infrared telescope. Images courtesy of Orton et al.

4.4 Akatsuki

The JAXA *Akatsuki* mission to Venus (*Venus Climate Orbiter*) also experienced problems with the helium pressurization system of its main propulsion system. After missing its planned orbital insertion maneuver in 2010 it eventually entered orbit in 2016 but in a highly elliptical nine-day orbit instead of the planned 30-hour orbit. The unplanned orbit together with the eventual failure of the spacecraft's IR1 (1 µm) and IR2 (2 µm) cameras increased the need for ground-based mission support, particularly from IRTF, due to its infrared instrumentation and daytime observing capabilities (see Figure 22).

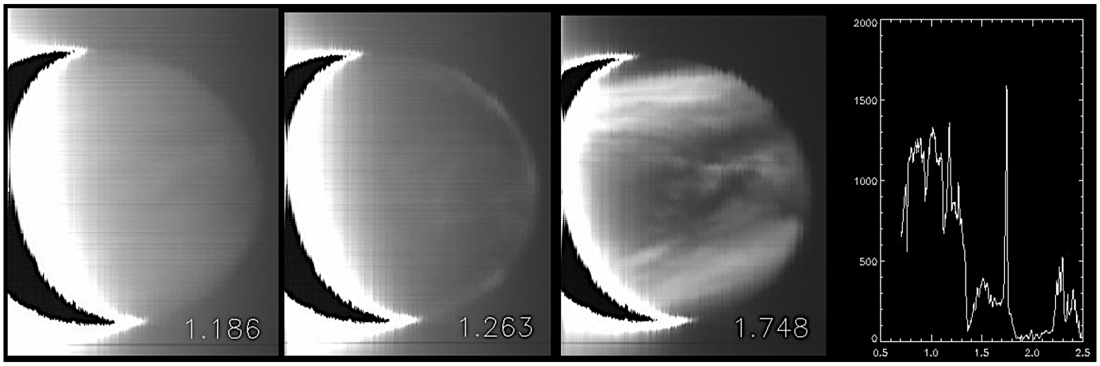

Figure 22. 3D image cube of the night side of Venus taken in the SpeX prism mode by scanning the 60″ slit across Venus in a few minutes: 1.186 µm showing thermal emission from the surface and lower atmosphere, 1.263 µm showing O_2 airglow at the limb, and 1.748 µm showing absorption in SO_2 clouds at altitudes of about 50 km. The Venus nightside global average R~100 0.7-2.5 µm spectrum is also shown (*right*). Images courtesy of Elliot Young et al.

4.5 *New Horizons*

The flyby hemisphere of Pluto by *New Horizons* was selected from *HST* imaging in 2002-2003 and decade-long near-infrared spectroscopy with SpeX on IRTF (see Figure 23). The *HST* visible imaging identified a bright albedo region at longitude 180 degrees east, now known as Sputnik Planitia. Although Pluto is effectively spatially unresolved on IRTF (about 1″), its six-day rotation period allows SpeX to spectrally map it at sub-hemispheric resolution. This spatially resolved spectroscopy identified N_2 and CO ice features coincident with the bright albedo feature and this hemisphere was selected for *New Horizon's* close flyby in 2015.

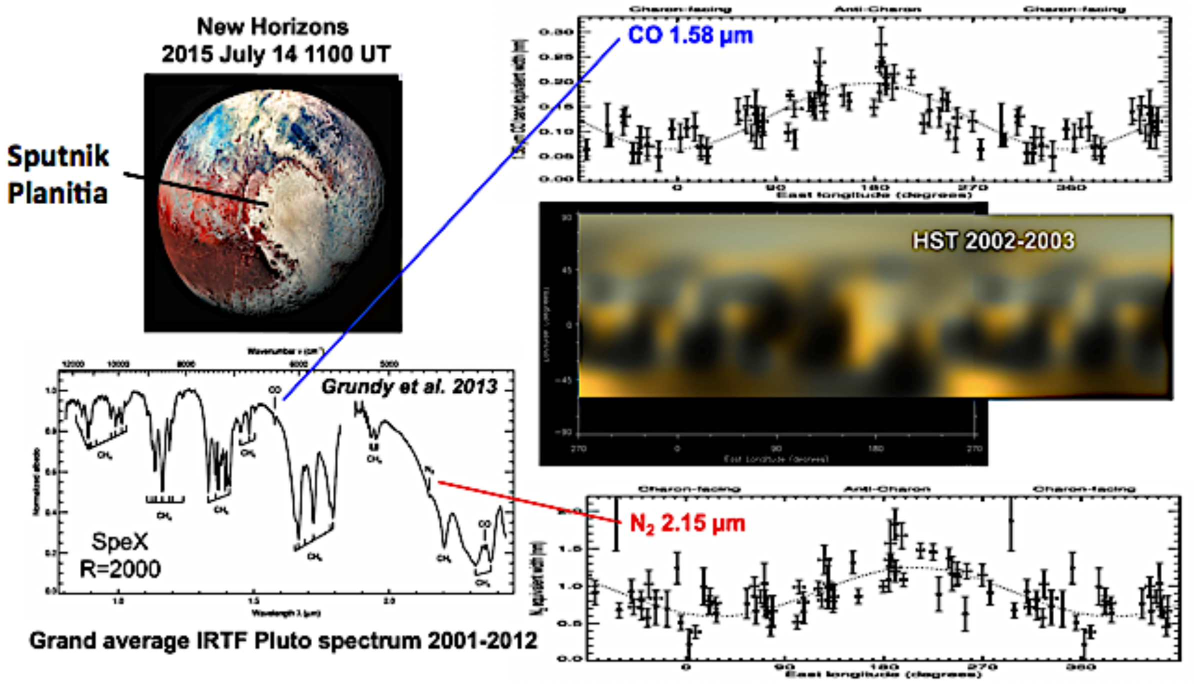

Figure 23. *HST* visible imaging in 2002-2003 together with 2001-2012 IRTF *R*=2000 0.8-2.5 μm spectroscopy of Pluto was used by the *New Horizons* mission team to select the flyby hemisphere containing the bright albedo feature at 180 degrees east associated with N_2 and CO ice (Grundy et al. 2013). This feature is now known as Sputnik Planitia.

5 PLANETARY SCIENCE

Through a mixture of facility and visitor instrumentation IRTF offers an unmatched 0.5-26 µm suite of imaging and spectroscopic (R=10-10^7) capabilities for solar system studies (see section 1.2). Ground-based telescopic observations continue to provide key support to robotic space missions by characterizing targets in advance of spacecraft encounters, and ongoing observations provide data between missions as well. Ground-based facilities have the benefit of longevity, and their capabilities can increase over time as science instruments can be upgraded, repaired, or replaced. These instruments have relaxed mass and size constraints compared to spacecraft instrumentation, delivering capabilities such as high spectral resolution, spectral multiplexing, and the strong light-gathering power of large apertures. IRTF devotes 50 percent of its time to solar system studies, but all other facilities rely on competitive proposals each semester, with limited NASA/ESA guidance on priorities for spacecraft mission science support. The following sections highlight some recent planetary science being done on IRTF and potential future projects

5.1 Primitive Bodies

Small solar system bodies – asteroids, comets, Centaurs, and trans-Neptunian objects (TNOs), are the primitive leftovers of the formation and evolution of our Solar System. By studying each of these sub-populations through spectroscopy and photometry, we gain critical information regarding the environments where they formed, and how they evolved over time. Almost 30 % of peer-competed IRTF observing time (see Figure 13) goes to small bodies (i.e., 60% of solar system time). IRTF is probably the premier facility for the spectral characterization of asteroids and NEOs. Using the R~100 prism-mode (0.7-2.5 µm) of SpeX to measure solid-state absorption features, thousands of these objects have been spectrally characterized. The MITHNEOS survey of over 1000 NEOs (Binzel et al. 2019, see Figure 24), representing more than 5% of the currently discovered population, has been a key study for advancing all aspects of NEO understanding for both science and planetary defense. The survey data presents a compilation of results including their taxonomic classification within a single internally consistent framework, and performs a preliminary analysis on the overall NEO population characteristics with a concentration toward deducing key physical processes, and identifying their main belt source regions and dynamical pathways to planet-crossing orbits. All the spectra are publicly available online[13].

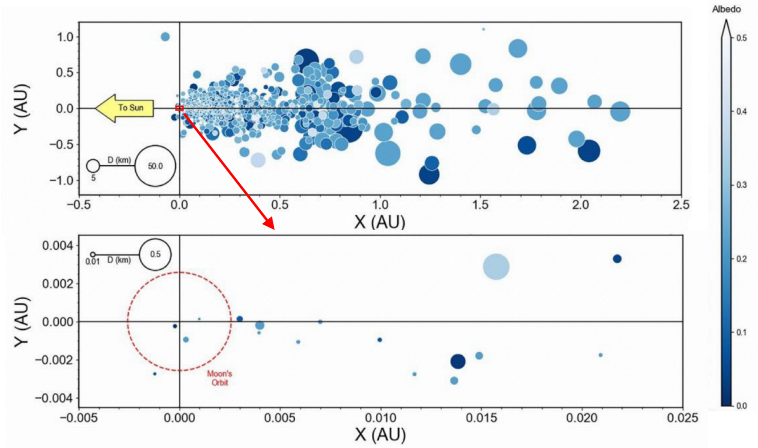

Figure 24. Inner solar system position of all MITHNEOS targets. Circle size depicts the estimated diameter of each object according to the scale at left for each panel. Shading scale indicates measured or inferred albedo according to taxonomic class. Adapted from Binzel et al. (2019).

Observations of distant Centaurs and TNOs are particularly challenging due to their intrinsic faintness. Even so, successful spectroscopic observations have been obtained with SpeX on the IRTF for some of the brightest TNOs. The increased sensitivity and spectrophotometric accuracy of SPECTRE will increase by a factor of ten the number of Centaurs and TNOs that will be observable with IRTF across the 0.4-2.4 µm wavelength range and allow for monitoring of rotational and seasonal variations of surface color and spectral absorption bands. SPECTRE will also provide a unique capability for the one-shot wide-band characterization of interstellar objects.

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[13] http://smass.mit.edu/catalog.php

Short of sending spacecraft to the small and primitive bodies in the outer solar system, stellar occultations provide the best method to accurately measure diameters, from which we can derive albedos, and to discover and characterize atmospheres or other activity. Simultaneous visible and infrared spectroscopy with SpeX and MORIS can probe atmospheres (hazes, pressure etc.) and the particle sizes of ring systems (diffraction and scattering as a function of wavelength). An example is the double occultation of Charon and Pluto in 2011 (Gulbis et al. 2015). The wavelength-resolved data of Pluto's atmosphere are best fit by a clear upper atmosphere with a lower level haze due to µm-sized tholins (see Figure 25).

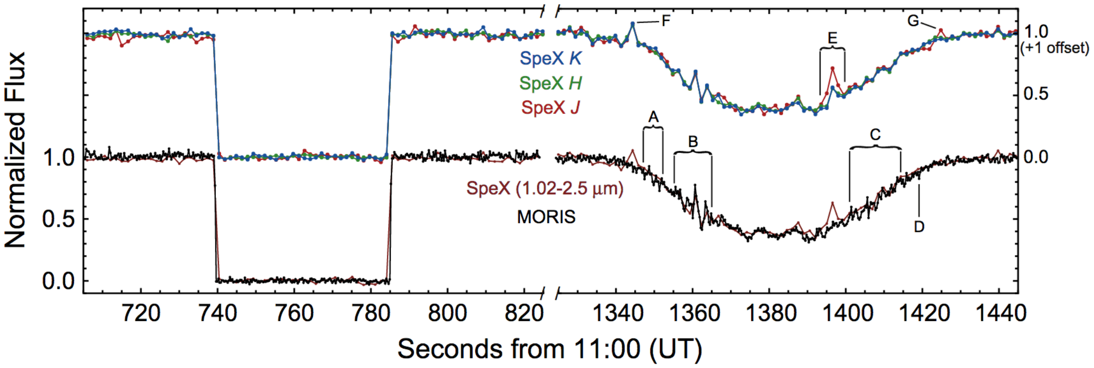

Figure 25. Occultation of Charon (left) and graze of Pluto (right). The SpeX data have been summed into standard *JHK* filter bandpasses and are best fit by a clear upper atmosphere with a lower level haze due to µm-sized tholins. Gulbis et al. 2015.

5.2 Comets

Spectroscopic studies of comets throughout their orbit give clues about their volatile and refractory inventories and help constrain models of comet formation and evolution. A key question is whether comet nuclei are primordial survivors of the solar nebula and young primordial disk, or are re-accumulated debris from the collisional breakup of once larger parent bodies among the TNO population. Gases released by cometary bodies close to perihelion are best studied at the high spectral resolutions provided by iSHELL. A plethora of molecules of interest are accessible in the 3-5 µm wavelength range. An excellent example of IRTF and iSHELL capabilities is the observations of Comet C/2020 F3 NEOWISE

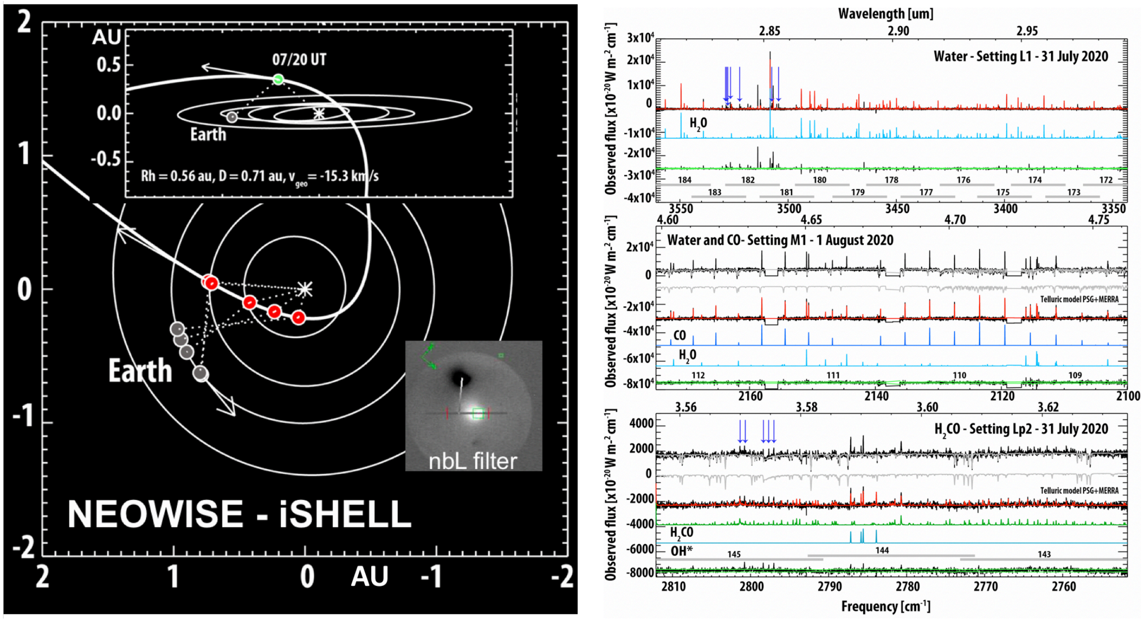

Figure 26. (*Left*) Location of Comet C/2020 F3 NEOWISE during daytime observations with IRTF/iSHELL that required guiding in a thermal filter (inset - warm dust in the coma at 3.5 µm). (*Right*) Twelve molecular species are identified: 9 primary volatiles (H_2O, HCN, NH_3, CO, C_2H_2, C_2H_6, CH_4, CH_3OH, and H_2CO) and 3 product species (CN, NH_2, OH), providing evidence for the heterogeneous chemical composition of the comet's nucleus. Faggi et al. 2021.

(Faggi et al. 2021, see Figure 26). Upon its discovery in 2020 March, Director Discretionary Time at IRTF was approved. The comet approached the Sun, down to 0.3 AU, in early 2020 July, providing a spectacular perihelion passage and revealing itself as one of the brightest comets that have appeared in the northern hemisphere in recent decades. During this interval, the comet was a daytime object with a solar elongation angle that varied from 20° to 52°. IRTF uniquely permits daytime investigations and iSHELL offers superior image guider performance, allowing the selection of different image filters - essential to properly follow a comet during daytime.

5.3 Planetary Atmospheres

Infrared imaging with the facility 1-5 µm cameras and visitor mid-IR cameras has provided a several decades-long monitoring of the dynamical processes in planetary atmospheres, supplementing the higher resolution but shorter timescale imaging provided by spaceflight missions. These capabilities are now provided by the multiple filter infrared slit viewers built into SpeX and iSHELL. SpeX, iSHELL and TEXES are slit spectrographs but they have also been successfully used to obtain three-dimensional image cubes by scanning the slit across a planetary disk (e.g., see Figures 22 and 27).

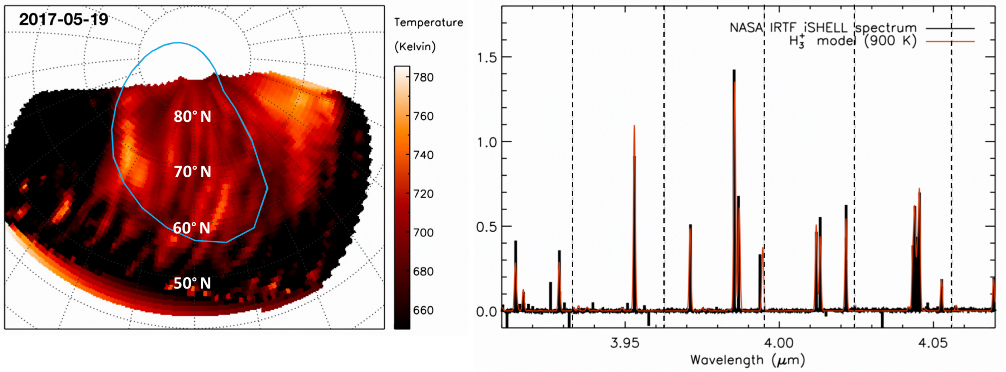

Figure 27. (*Left*) iSHELL slit scan of Jupiter forming a high-resolution H_3^+ spectral image and a temperature map. The grey line indicates the average location of the main auroral oval as observed by *HST*. (*Right*) A Jupiter auroral spectrum (R=80,000) showing strong lines H_3^+ and an H_3^+ spectral model at 900K. The observations are coordinated with Juno observations (Melin et al. in prep.).

The upper atmospheres of planets form a key interface between the planet itself and its space environment. In the case of magnetized planets, this space environment forms a magnetosphere, a region of space (partially) shielded from the solar wind, under the control of the planet's magnetic field. Earth and all the giant planets have magnetospheres. Except for the solar wind the Jovian magnetosphere is the largest structure in the Solar System. IRTF observers have been using emission from the key Jovian ionospheric component H_3^+ since this ion was first discovered in Jupiter's auroral/polar regions 25 years ago to trace energy inputs from the magnetosphere into the upper atmosphere and to measure the ion winds generated. IRTF has been studying Jupiter's magnetosphere through observations of H_3^+, first through imaging (Connerney et al. 1993, see Figure 28) and later with high-resolution infrared spectroscopy (e.g., Melin et al. in prep., see Figure 27).

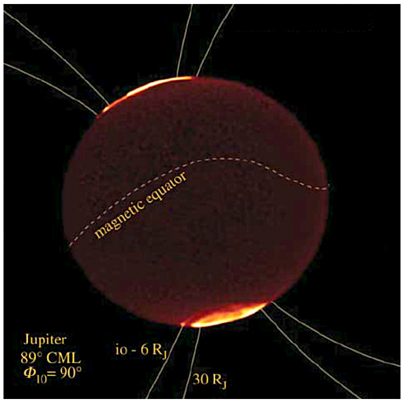

Figure 28. Mosaic of nine IRTF/ProtoCAM images of Jupiter at 3.40 µm on 12 January 1992. The bright polar features are caused by H_3^+ emission occurring well above the methane homopause (Connerney et al. 1993).

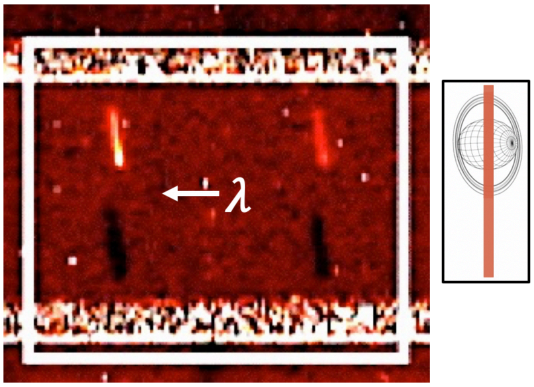

Figure 29. (*Left*) H_3^+ lines at 3.95 µm at high resolving power with iSHELL. The line tilt is due to the rotation of Uranus. H_3^+ emission is due to the impact of the solar wind. The intensity brightening at dawn (lower in the slit) is possible evidence for infrared aurora. (*Right*) Placement of the 15″ slit, long enough to nod Uranus in the slit for sky subtraction.

Most known exoplanets are "ice giants", presumably much like Uranus and Neptune. The Planetary Decadal 2023-2032 Survey selected the *Uranus Orbiter and Probe* mission as its highest priority flagship mission for launch as early as 2031. The mission would transform our knowledge of ice giants. Uranus itself is one of the most intriguing bodies in the solar system: an extreme axial tilt; low internal energy; high speed winds and active atmospheric dynamics; and complex magnetic field all present major puzzles. Uranus' aurorae were first detected in *HST* UV images in 2011. During iSHELL commissioning in 2016 the aurorae were possibly first detected in the infrared though the detection of H_3^+ lines at 3.95 µm in R=80,000 spectra (see Figure 29, Melin et al. 2019). Upcoming *JWST* Guaranteed Time Observations (GTO) campaigns will observe Uranus in the infrared, providing high spatial resolution 2D mapping of H_3^+ intensities, densities, and temperatures across Uranus. *JWST* is unable to extract ion flow velocities due to low spectral resolution (R~2,700), however, coordinated IRTF/iSHELL observations (R=80,000) can easily resolve these ion flows providing crucial context to *JWST*. Taken together the observations will provide insight into the magnetospheres of ice giant worlds and help in mission planning for the *Uranus Orbiter and Probe.*

The 5-µm region is a window to the deep atmosphere of Jupiter because of a minimum in opacity due to H_2 and CH_4. Jupiter's 5 µm spectrum is a mixture of scattered sunlight and thermal emission that varies significantly between Hot Spots and low-flux regions, such as the Great Red Spot (GRS). High resolution (R~50,000) infrared spectroscopy with iSHELL fully resolves pressure-broadened line profiles and provides a wealth of information about the gas composition and cloud structure of the troposphere. Observations by Bjoraker et al. (2018) of water cloud-top altitudes in the GRS, combined with CO measurements, have constrained Jupiter's O/H ratio to be between 2 and 9 times solar (see Figure 30). This agrees with the *Juno* Microwave Radiometer (MRW) value of 1 to 5 times solar at the equator and it is independent of the technique used by the MWR team (Li et al. 2020). Together these observations find the 'missing' water (see section 5.2). Each MWR channel sees a continuum dependent on temperature, NH_3 opacity, and H_2O as a minor component. iSHELL measurements of individual absorption lines of NH_3 and H_2O help break this degeneracy at pressures lower than 8 bar in the *Juno* MWR data, providing a more accurate O/H ratio than is possible using *Juno* data alone.

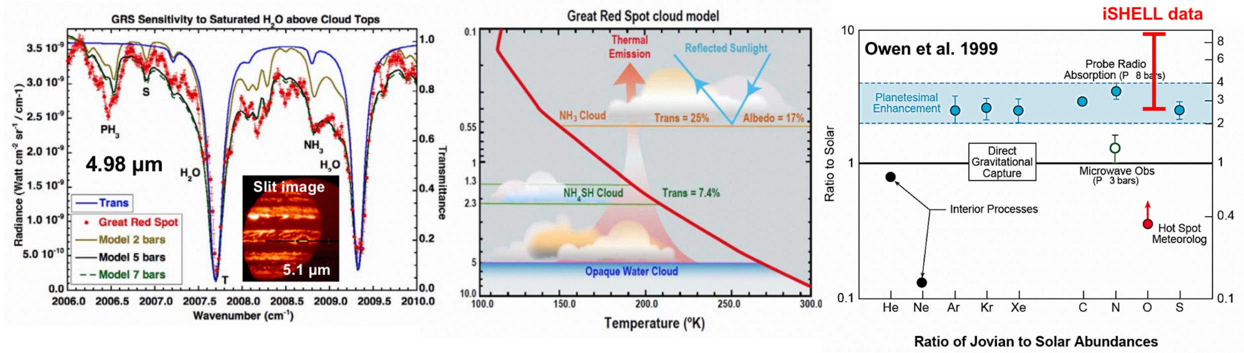

Figure 30. (*Left*) iSHELL 5 µm spectroscopy of the GRS. The inset shows the slit placement, guiding was done on a hot spot. (*Middle*) Simplified cloud model from Bjoraker et al. 2018 of the GRS plotted with the *Galileo Probe* temperature and pressure profile. (*Right*) Ratio of Jovian to solar abundances from Owen et al. (1999) showing the iSHELL oxygen (i.e., water) abundance and the *Galileo Probe* hot spot measurement.

Upcoming iSHELL observations by Bjoraker et al. will measure H_2O, NH_3, and water clouds on Jupiter near features targeted by *JWST* and along the ground track of the *Juno* MWR, and to characterize changes in volatiles and clouds in Jupiter's Northern Equatorial Belt (NEB, see Figure 31). The 13x higher spectral resolution and broader spatial coverage of iSHELL will place the high spatial resolution *JWST* (NIRSPEC and MIRI) 5 μm data into regional context. A comparison of retrievals of Jovian H_2O from *JWST* (free of telluric H_2O) and iSHELL data (where Jovian H_2O features are broader than the telluric lines) will validate ground-based techniques.

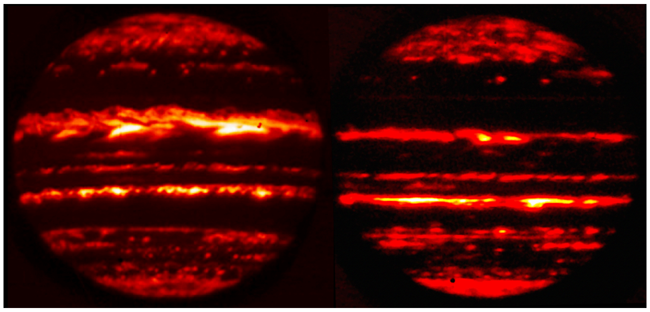

Figure 31. iSHELL 5 μm images show dramatic changes in the NEB from April 2019 (left) to November 2021 (right).

The exploration of Mars is a major goal within NASA's Science Mission Directorate. Spacecraft do not employ high-resolution spectrographs (with the possible exception of Fourier Transform 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. An outstanding example of this is the detection of CH_4 (Mumma et al. 2009; see Figure 32) by CSHELL on IRTF (the precursor to iSHELL, Tokunaga et al. 1990 and Greene et al. 1993) and NIRSPEC on Keck. Due to photochemistry the survival time of Martian CH_4 is several hundred years at most and so needs an active source. The ultimate origin of Martian CH_4 is uncertain and could be either abiotic or biotic. Some workers question the veracity of these measurements due to the potential for telluric contamination. However, in situ measurements appear to confirm episodic CH_4 detections but at lower concentrations (Webster et al. 2015 with the *Curiosity* rover in Gale crater). Recent iSHELL observations by Novak and Mumma (2021) detect CH_4 absorption with high S/N at 251° W (25 +/-2

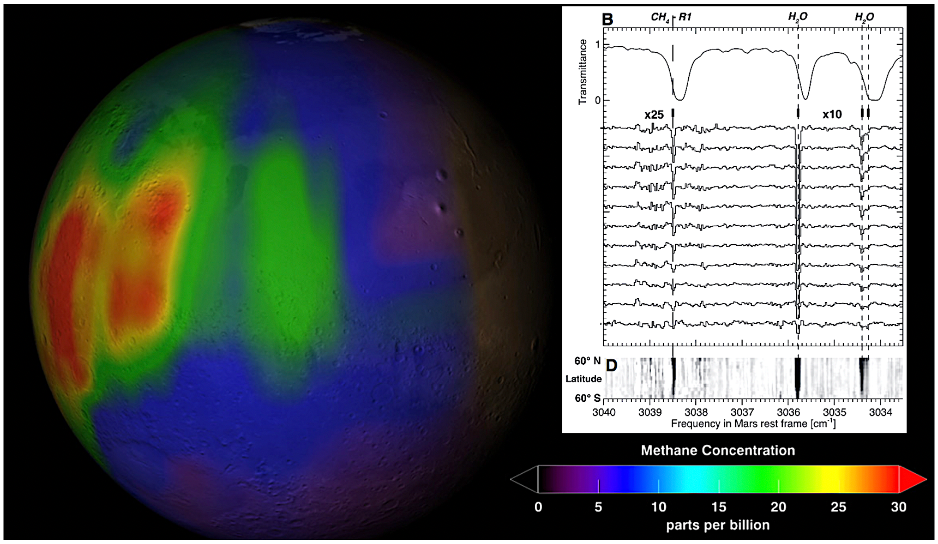

Figure 32. Detections of CH_4 and water vapor on Mars on UT 19 and 20 March 2003. (*Left*) CSHELL slit scans of Mars showing methane concentration. (*Right*) Spectra taken on 20 March were extracted at 11 equal intervals (0.6″ each) along the slit (ranging from 70°N to 70°S), after binning over longitudes 277° to 323°W. Strong lines of telluric water and CH_4 (labeled) appear in a typical spectrum, shown at the top of this panel. Narrow spectral lines of H_2O (three lines, short dashes) and CH_4 (the R1 line, long dashes) are seen at the Doppler-shifted positions expected for this date. Mumma et al. 2009.

ppbv), but within the noise limit at 203° W suggesting a local release of methane from the sub-surface near 251° W.

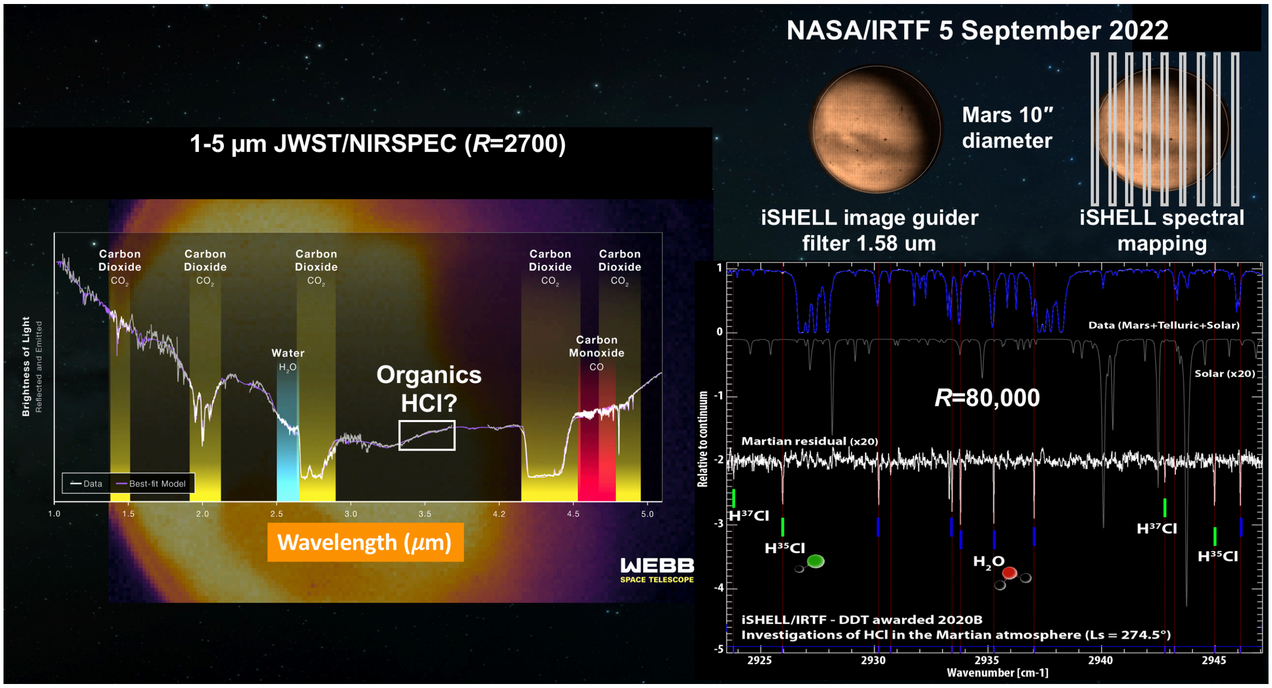

Figure 33. Mars atmospheric composition. (*Left*) Recent JWST/NIRSPEC 1-5 µm *R*=2700 spectrum showing the broad CO_2, CO and H_2O absorptions not easily observed from Earth. (*Right*) Complementary IRTF/iSHELL *R*=80,000 spectrum in the 3.4 µm region revealing isotopes of HCl. By scanning the slit across Mars using the iSHELL guider the entire disk can be mapped. Courtesy of Faggi et al., DPS 2022.

The first detection of HCl in the atmosphere of Mars was recently achieved by the infrared spectrometers (ACS and NOMAD) onboard the *ExoMars Trace Gas Orbiter* (*TGO*), revealing the presence of chlorine species in the Martian atmosphere. *TGO* occultations can provide very accurate, but only localized vertical coverage. During follow up observations on IRTF, full rapid hemispheric mapping of HCl and its isotopes were obtained using iSHELL. IRTF is the only ground-based facility able to provide daytime observations, which are essential for Mars (and Venus) observations to provide temporal cadence and extended seasonal coverage. The observing campaign focused on investigating the HCl temporal cycle, while simultaneously obtaining the first Mars/JWST NIRSpec observations targeting the entire 1- 5 µm wavelength range (see Figure 33). These simultaneous measurements fell in the high HCl season, and their complementary role is critical for fully interpreting the HCl chemistry.

In complement to in-orbit observations recorded by space missions, high-resolution spectral mapping from the ground allows us to obtain instantaneous global maps of the planets, and thus to trace transient phenomena or temporal variations of minor atmospheric species over short and long timescales. Over the past twenty years, Encrenaz (2022) and collaborators have been monitoring the behavior of minor atmospheric species on Mars and Venus, using the TEXES on IRTF: H_2O_2 and H_2O on Mars, D/H on Mars, SO_2 and HDO at the cloud top of Venus (see Figure 34). The two SO2 maps are separated by 2 hours and the SO_2 plume is shifted by 7.5°, in agreement with the 4-day rotation of the clouds. It is interesting to note that the TEXES maps of SO_2 in the infrared range are in

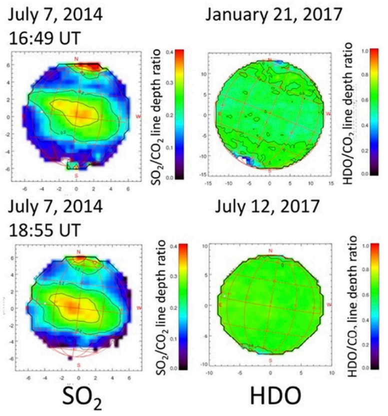

Figure 34. TEXES SO_2 and HDO maps of Venus at 7.4 µm. Encrenaz 2022.

very good agreement with the UV maps recorded by the *Akatsuki* spacecraft; this agreement illustrates that the TEXES data can be used to monitor SO2 on the night side of Venus where UV observations cannot be done. By testing global dynamical and photochemical models, such observations can be understood in the context of the past and present history of these planets.

Ultra-high resolving powers ($R \leq 10^7$) are needed to fully resolve line profiles to provide unique information on the variability of temperature and abundance, measure planetary scale wind velocities, and to separate planetary features from telluric features by Doppler shifts (e.g., as needed to measure ozone on Mars). These capabilities are provided by the visitor mid-IR heterodyne spectrometer HIPWAC. For example, HIPWAC measurements from IRTF coordinated with *Mars Express* SPICAM measurements from Mars orbit in 2008 resulted in generally consistent ozone abundance retrievals, providing mutual validation, and supporting the combined use of retrievals from these infrared and UV instruments for testing photochemical models (Fast et al. 2009, see Figure 35).

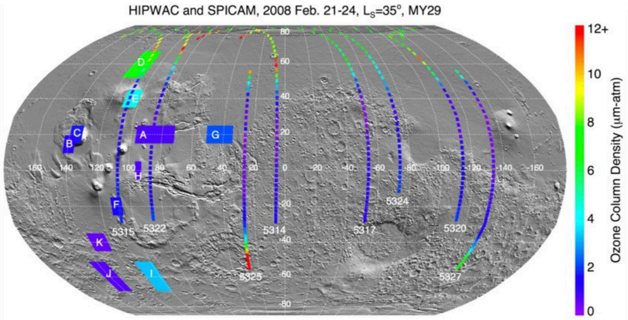

Figure 35. Comparison of HIPWAC (solid) and *Mars Express* SPICAM (tacks) observations of ozone on Mars 2006-2008.

5.4 Observing Campaigns and Long-term Monitoring Programs

Dedicated IRTF observing campaigns are highly valued by the planetary community. IRTF responds to community requests to schedule weeks-long observing campaigns, e.g., the S-L 9 Jupiter impact campaign in 1994 (Orton et al. 1995), the *Deep Impact* mission observations of Comet 9P/Tempel 1 in 2005, Comet C/2012 S1 (ISON) in 2013, and Comet 46P/Wirtanen in 2018. For observing campaigns, a set amount of observing is put aside and is competitively awarded. For example, the predicted bright apparition of Comet Wirtanen in 2018 represented an excellent opportunity to characterize a potential spacecraft target, and so 150 hours of observing time with both facility and visitor instruments were allocated to the campaign, with all data obtained made public.

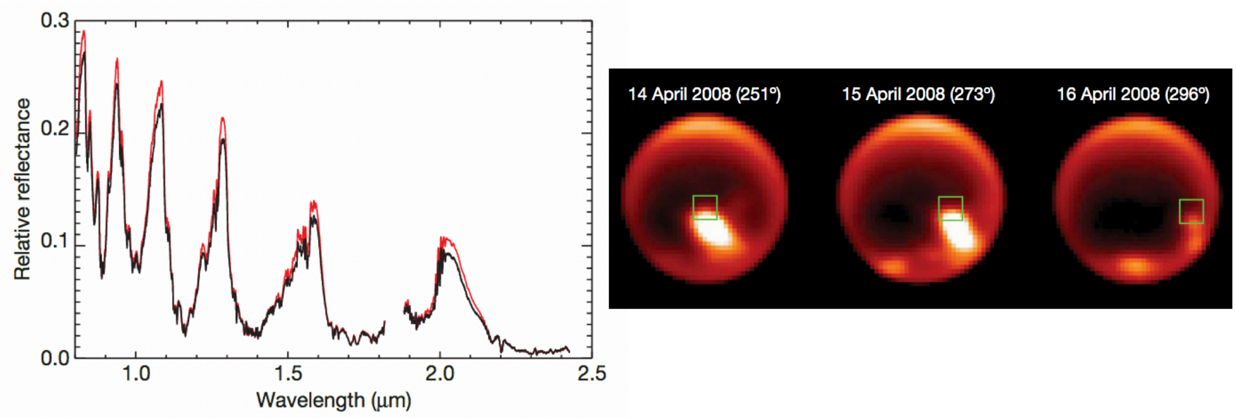

Figure 36. (*Left*) Near-infrared spectra of Titan from 28 March and 13 April 2008. The spectrum from 13 April (red) shows increased flux in the transparent regions of Titan's atmosphere (0.8, 0.95, 1.2, 1.6 and 2.0 µm) while staying the same brightness in the high-opacity regions, indicating cloud formation. (*Right*) Gemini North AO images of Titan from the following night show the presence of a large extended methane cloud taken through the 2.1 µm filter that probes to Titan's troposphere. The methane rainout from these large storms is thought to be responsible for carving Titan's streams and valley networks. From Schaller et al. 2009.

Long-term observing programs such as synoptic observations of Pluto, Triton, Titan and Io extend over decades and supplement the 'snapshot' observations of flybys and even orbital missions. Planetary seasons and dynamical processes in planetary atmospheres last decades in the outer solar system, also requiring long-term monitoring. Flexibility in scheduling has been enhanced with the introduction of remote observing, which allows for observing periods as short as 30 minutes to be scheduled. A good example is the short duration, but many night, service-observing program, executed by the Telescope Operators, to search for methane clouds on Titan. Any detections are immediately followed up with AO imaging on Gemini North (see Figure 36, see Schaller et al. 2009). (SpeX is always available but AO on Gemini North is not.) Solar system targets, such as asteroids, do not require long observing runs but do require short and irregular observing windows to match apparition and phase angle needs. IRTF regularly accommodates target of opportunity requests that are critical for observing new comets, for example.

6 ASTROPHYSICS

Fifty percent of available observing time on IRTF is allocated to non-solar system science – ‘astrophysics’. Unlike the change to dedicated sky surveys on other similarly sized telescopes (e.g., Mayall/DESI, UKIRT/UKIDSS and Blanco/DECam), IRTF continues to do classical observing through the peer review of observing proposals to the TAC, providing the opportunity for new ideas and fast follow-up to new discoveries. The following sections highlight some recent astrophysical science being done on IRTF and potential future projects. These programs directly address NASA's strategic goals of exploring the origin and evolution of stars and planets that make up our universe, and discovering and studying planets around other stars.

6.1 Stars and Brown Dwarfs

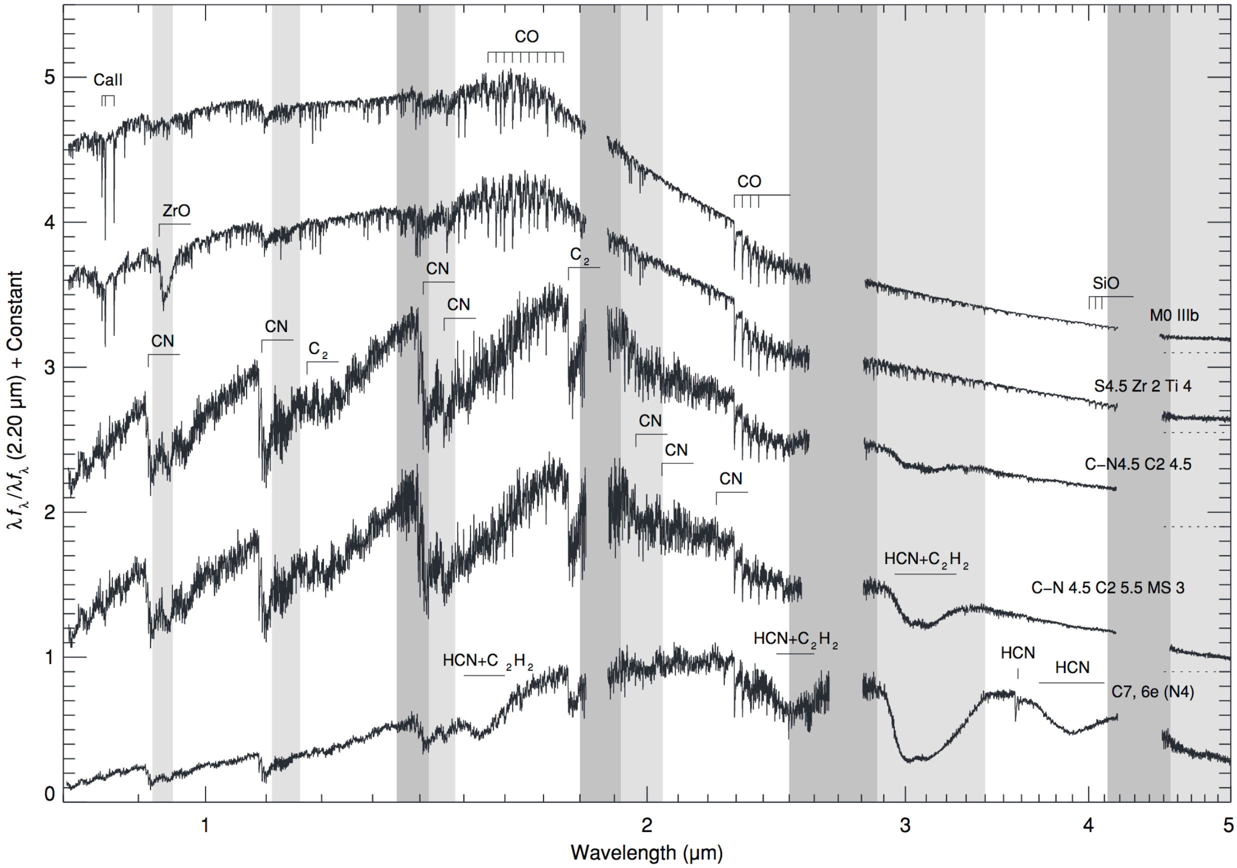

Figure 37. IRTF Spectral Library: Cool Stars. Sequence of M, S and C giant stars observed with SpeX. Rayner et al. 2009.

The 0.8-5 µm *R*=2000 IRTF Spectral Library of several hundred stars observed using SpeX (MLT dwarfs: Cushing *et al*. 2005, FGKMSC stars: Rayner *et al*. 2009) has proved a valuable community resource (e.g., see Figure 37). As of 2022, the series of IRTF Spectral Library papers have an ADS count of almost 1200 citations. Applications include: physics of cool stellar and substellar atmospheres, classification of optically embedded and cool stars, stellar population synthesis, and synthetic photometry. Simple stellar populations, which are used to constrain, for example, the IMFs of integrated stellar populations in galaxies, are ultimately limited by the accuracies of stellar libraries (van Dokkum & Conroy 2010). Most of these are currently based on optical spectra, but near-infrared libraries are notoriously incomplete at low metallicities (< 0.5 dex) which are important for extragalactic stellar populations. The library was extended by Villaume *et al*. (2017) to include a wider range of metallicities and hotter stars for improved modeling of unresolved galaxy populations (e.g., see Figure 38). The library will have a long-lasting legacy, particularly in the "big data" era of large galactic spectroscopic and astrometric surveys such as *Gaia*. Data is publicly available through download form the IRTF website[14].

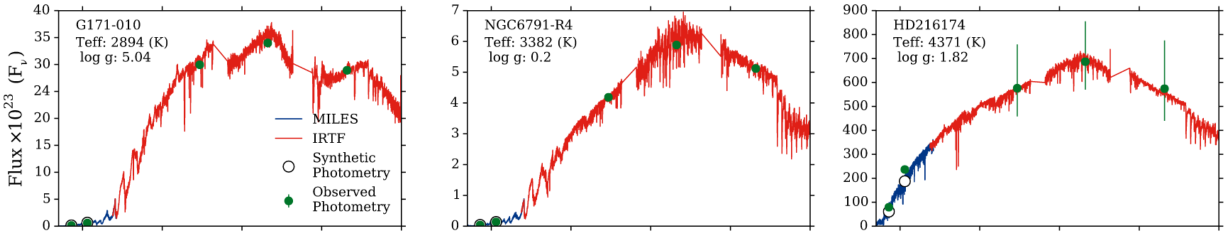

Figure 38. Example spectra from The Extended IRTF Spectral Library: expanded coverage in metallicity, temperature and surface gravity. IRTF spectra (red) are combined with optical Medium Resolution Isaac Newton Library of Empirical Spectra (MILES, blue). Villaume et al. 2017.

In addition to the R=2000 IRTF Spectral Library, Burgasser and collaborators (Burgasser 2014 and references therein) have constructed the SpeX Prism Library (SPL)[15]. The SPL contains over about 2000 R~100 spectra observed since SpeX first light in 2000. It contains mostly M, L and T dwarfs (or ultracool dwarfs - UCDs), which are easily characterized by their broad molecular absorption features, but also giant stars, subdwarfs, white dwarfs, carbon stars, novae and supernovae, extrasolar giant planets and galaxies. A significant fraction of the spectra has been contributed by members of the IRTF community. Prism spectra are well-matched in sensitivity to wide-field red optical and infrared imaging surveys such as 2MASS, DENIS, SDSS, UKIDSS, Pan-STARRS and WISE. As such, SpeX has been a discovery machine for late M, L, T and Y dwarfs identified in imaging surveys. The sources span most of the visible sky from IRTF ($-50° \leq \delta \leq 68°$), with notable gaps around the Galactic plane (see Figure 39).

The SPL has enabled a broad range of stellar, brown dwarf and exoplanet science. The many atomic and molecular absorption features that characterize UCD spectra are shaped by several factors, including photospheric temperature, elemental composition, and pressure-sensitive opacity effects and can be used to model UCD atmospheres. Increasingly, the SPL and prism observations are being used to analyze the spectra of directly-imaged exoplanets to characterize their physical and atmospheric properties.

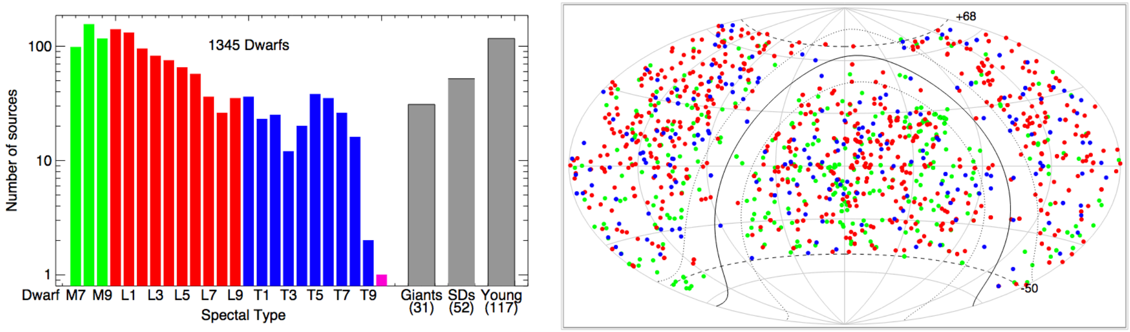

Figure 39. Distributions of SPL spectra by spectral type and class (*left*) and in equatorial coordinates (*right*). UCDs are color coded by spectral type: late-M dwarfs (green), L dwarfs (red), T dwarfs (blue) and Y dwarfs (purple). Burgasser 2014.

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[14] http://irtfweb.ifa.hawaii.edu/~spex/observer/

[15] https://cass.ucsd.edu/~ajb/browndwarfs/spexprism/library.html

An excellent example is the recent UH PhD thesis of Zhoujian Zhang (now Sagan fellow at UT at Austin). 'ZJ' is conducting surveys to search for giant planets and brown dwarfs that are wide-orbit companions to low-mass stars. The large, well-defined sample of these benchmarks is used to explore the formation of the outer architecture of extrasolar planetary systems and to test our understanding of ultracool atmospheres of giant planets (Zhang et al. 2022, see Figure 40).

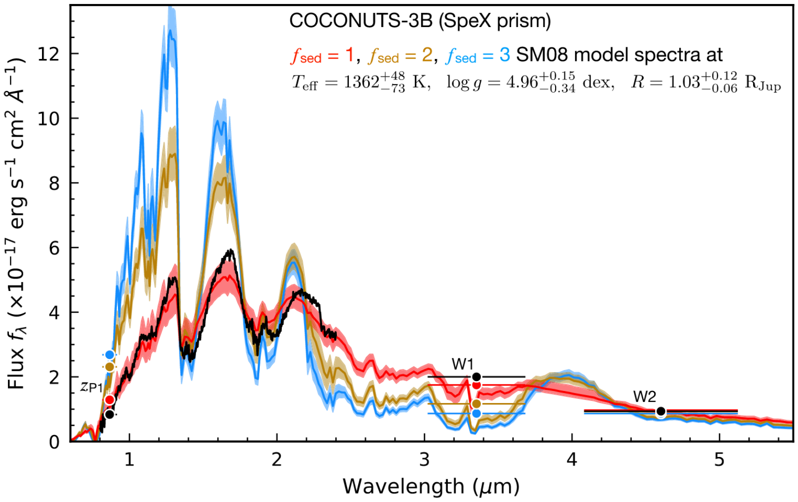

Figure 40. SpeX prism spectrum of COCONUTS-3B (black) compared to the evolution-based atmospheric model spectra. The spectral energy distribution of COCONUTS-3B can be best matched by atmospheric models retaining ample condensate clouds in its photosphere. Zhang et al. 2022.

The SPL is also a valuable resource for characterizing and simulating UCD populations, to design effective search (and rejection) strategies for wide-field imaging programs, predict yields in deep surveys; and connect observable distributions in spectral type or effective temperature to the underlying substellar mass function and birth rate.

In contrast to the broad molecular features in UCDs, atomic and isotopic lines of stars are best studied at high resolving power with iSHELL. Following on from the work of Johns-Krull (2007) on the magnetic field of classical T Tauri stars using CSHELL, Flores et al. (2019) are comparing the atmospheres of young stars to benchmark dwarf and giant stars, to measure magnetic fields in young stars by Zeeman splitting ($\Delta\lambda\propto\lambda^2$). Magnetic fields are thought to be one of the fundamental drivers of the evolution of pre-main-sequence stars, playing a very important role in the star-disk interaction. The large one-shot wavelength range of iSHELL together with high resolving power allows access to more photospheric lines in a single setting and enables simultaneous and consistent stellar parameter measurements (e.g., see Figure 41).

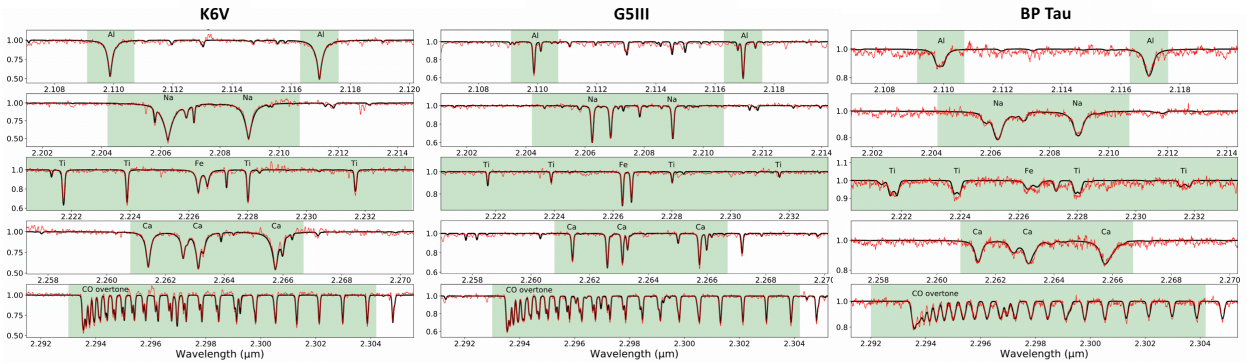

Figure 41. iSHELL R=50,000 spectra at 2.1-2.3 µm of a dwarf (*left*), giant (middle) and young star (*right*) showing the observed (black) and modeled spectra (red). The excellent discrimination of spectral features and the resolved line profiles are ideal for spectral modeling. Flores et al. 2019.

Stellar observing programs with iSHELL include measuring the abundances of light elements that provide insight into the chemical evolution of the Milky Way Galaxy and its stellar populations. Understanding the formation of light elements provides an opportunity to constrain nucleosynthesis. For the coolest stars, the optical spectra are dominated by molecular lines, limiting the extent to which chemical compositions can be determined owing to blending. At NIR wavelengths there are spectral windows that are relatively free of molecular absorption. Furthermore, the reduced effects of extinction in the NIR compared to the visual range allow us to access more distant stars.

M dwarf stars are cool, low mass main-sequence stars that are best observed in the NIR. They are the most abundant stars in the Milky Way galaxy, making up over 70% of the population by number and now are thought to host at least two exoplanets per star. To accurately measure radii and equilibrium temperatures of these exoplanets and determine if they are in the habitable zone, we need to know the host star properties, specifically mass, radius, and effective temperature, to equal accuracy. Double-lined eclipsing binary stars are the best laboratories for measuring fundamental stellar properties, without relying on stellar evolution models. With a standard radial velocity precision of 0.5 km/sec iSHELL is ideal for this work. Several IRTF programs are pursuing these observations.

6.2 Protoplanetary Disks and YSOs

The advent of high-resolution infrared spectroscopy with CSHELL on IRTF had a big impact on the science of protoplanetary disks. Most notable was the first kinematic evidence for Keplerian rotation in the disk of WL16 by Carr et al. (1993). CSHELL *R*=20,000 (13 km s^{-1}) CO overtone spectra at 2.3 μm is best fit by a Keplerian disk (see Figure 42). CO overtone emission probes very warm (≥2000 K) dense gas very close to the star (≤0.2 AU or ≤0.03″ for nearby star-forming regions at 150 pc). These are scales currently impossible to image. Najita et al. (2003) extended this work to CO fundamental emission at 5 μm with CSHELL and NIRSPEC on Keck. CO fundamental emission is sensitive to cooler and less dense gas out to a few AU of the star – the region of terrestrial planet formation also probed by precision radial velocity searches for extrasolar planets.

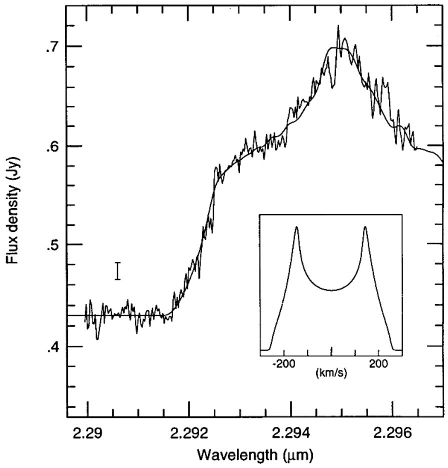

Figure 42. WL 16 spectrum overlaid with the best-fit model profile (*V sin i* = 140 km s^{-1}). The inset the line profile as it would appear for a single O emission line. Carr et al. 1993.

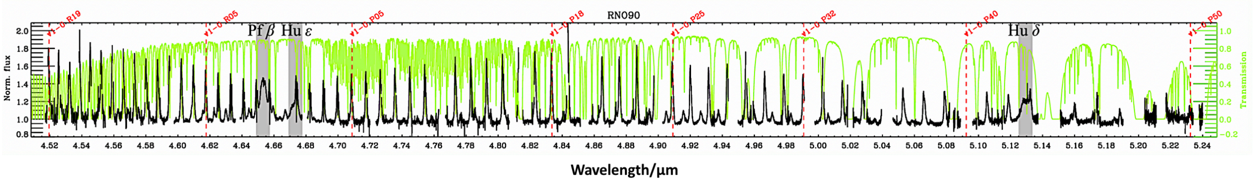

Figure 43. The one-shot coverage of the iSHELL spectroscopic survey of planet-forming disks, measuring >50 ^{12}CO and ^{13}CO emission lines (black). Telluric atmospheric transmission at the summit of Maunakea (4200 m) is also shown (green). Banzatti et al. 2022.

Ground-based observations in the 5 μm region are complicated by significant telluric absorption (see Figure 43). Fortunately, IRTF is on the best ground-based site of an optical-infrared telescope to minimize telluric absorption. This, coupled with the high resolving power of iSHELL (*R*=90,000 at 5 μm) and large one-shot wavelength coverage, makes iSHELL an ideal instrument for CO fundamental observations. Banzatti et al. (2022a, 2022b) are conducting an *M*-band spectroscopic survey of planet-forming disks with iSHELL, covering more than 50 lines from the R and P branches of ^{12}CO and ^{13}CO for each of multiple vibrational levels, and providing unprecedented information on the excitation of multiple emission and absorption components. The large number spectral lines of ^{12}CO (*v*=1 and *v*=2), and separately of ^{13}CO (*v*=1-0), can be stacked to significantly improve S/N, and provide the highest-quality line profiles to study gas kinematics (line shape, centroid, and width – see Figure 44). The velocity-resolved kinematic profile of CO spectral lines locates the emitting regions in the disk, seeing emission within the dust sublimation radius and as far as tens of AU in some disks, therefore tracing gas over the entire region of observed exoplanets (0.01-10 AU). Some of the disks observed show evidence of kinematic (line profile) variability on timescales of a decade, possibly connected to planet formation.

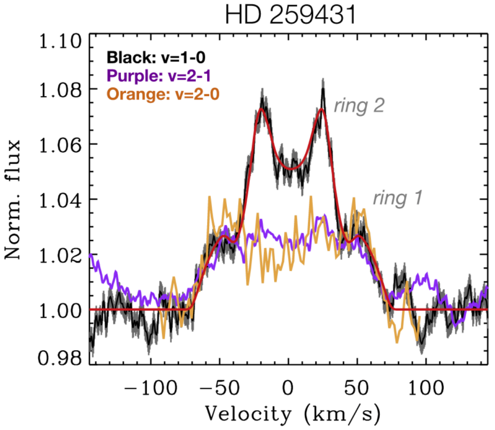

Figure 44. Two Keplerian rings of CO emission observed in HD 259431 (radii 0.2 AU and 1.0 AU). Banzatti et al. 2022.

A more direct understanding of the distribution of disk gas within individual disks can also be obtained using the technique of spectro-astrometry (e.g., Whelan & Garcia 2008). With proper correction for artifacts and good signal-to-noise ratio, the spatial centroid of spectral lines can be measured to a small fraction of the PSF and provide spatial information about the disk gas on milli-arcsecond scales – an order of magnitude better than the 2.2 µm diffraction limit on a 30-m telescope. This method can provide verification of Keplerian rotation in disks and enable the identification of non-axisymmetric disk structures that may point to the presence of disk winds and natal gas giant planets. The capability of iSHELL for carrying out spectro-astrometry has been demonstrated on the Herbig Ae/Be star HD 179218 (Brittain *et al*. 2018, see Figure 45), for which a spectro-astrometry fidelity of 0.44 mas on the 5 µm CO fundamental lines was achieved (0.13 AU at the distance of HD 179218). The power of the spectral grasp of iSHELL on IRTF provides a big advantage when stacking multiple emission lines. In addition, due to the IRTF's flexible scheduling in short blocks, variability in disk structure can be monitored on timescales of months and years.

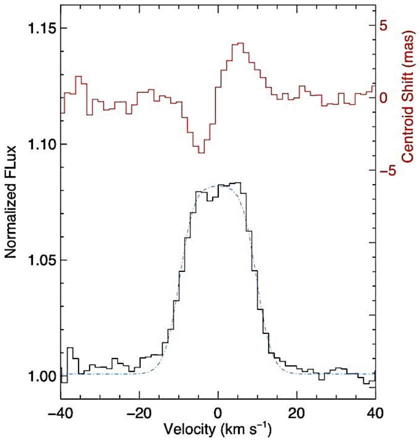

Figure 45. Stacked profile of v=1–0 CO lines and spectro-astrometric signal, indicating a sensitivity to spatial scales of a few mas compared to measured 560 mas PSF at 5 µm. Brittain et al. 2018.

6.3 Exoplanets

Small, cool planets represent the typical end-products of planetary formation. Studying the architectures of these systems, measuring planet masses and radii, and observing these planets' atmospheres during transit directly informs theories of planet assembly, migration, and evolution. To fully characterize exoplanets detected during *Kepler* and *TESS* transit surveys it is necessary to also characterize the exoplanet host star. IRTF is a contributor to these important observations. A good example of this process are the observations of Crossfield et al. (2015) required to characterize the cool star hosting three small planets. The host star was spectrally typed as M0V by comparison by stars from the IRTF Spectral Library (see Figure 46) with additional line indices to estimate temperature (3900 K) and metallicity ([Fe/H] = –0.3). Using the SpeX [Fe/H] empirical calibration of Mann et al. (2013) results in a host star radius of 0.561±0.068 $R_\odot$ and a mass of 0.601±0.089 $M_\odot$. Using these values and the resulting orbits, the three planets have radii of 2.1, 1.7 and 1.5 $R_\oplus$, and equilibrium temperatures of 470 K, 350 K and 280 K, respectively. Since the host is bright (*K*=8.5) this system is a good candidate for *JWST* characterization.

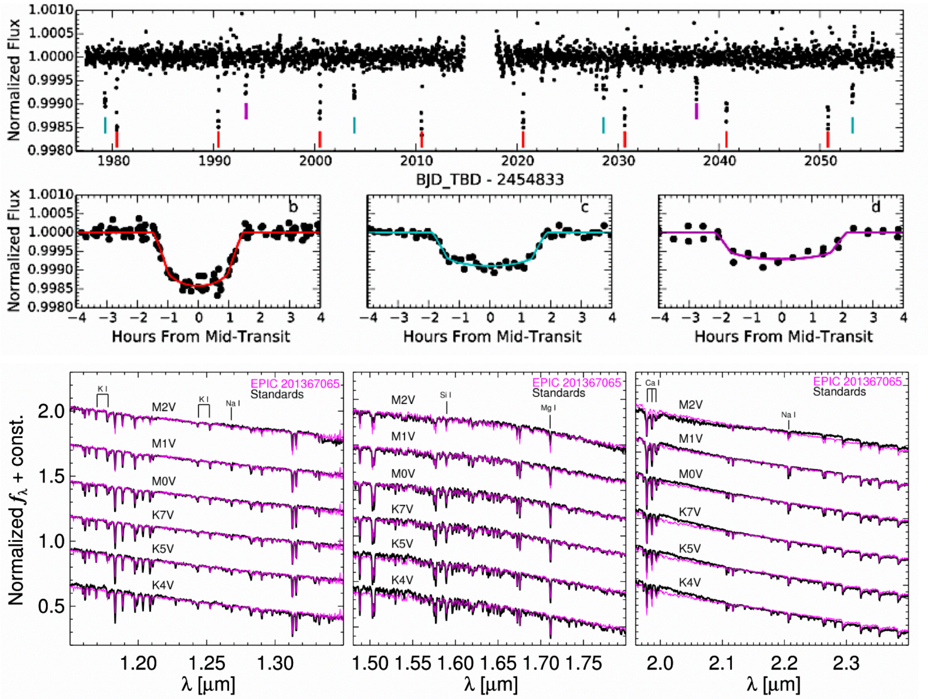

Figure 46. Characterization of K2-3 system planet host as M0V using SpeX. Crossfield et al. 2015.

As mentioned previously, precise and accurate parameters for late-type (late K and M) dwarf stars are important for characterization of any orbiting planets, but such determinations have been hampered by these stars' complex spectra and dissimilarity to the Sun. Further highly-cited work using SpeX by Mann et al. (2015) exploited an empirically calibrated method to estimate spectroscopic effective temperature (T_{eff}) and the Stefan–Boltzmann law to determine radii of 183 nearby K7–M7 single stars with a precision of 2%–5% (see Figure 47). The improved stellar parameters enabled development of model-independent relations between T_{eff} or absolute magnitude and radius, as well as between color and T_{eff}. Using the 0.4-4.2 μm coverage and ability to resolve binaries with its IFU, future observations of *Gaia* stars with SPECTRE can provide the ultimate benchmark sample for testing stellar models (see section 15).

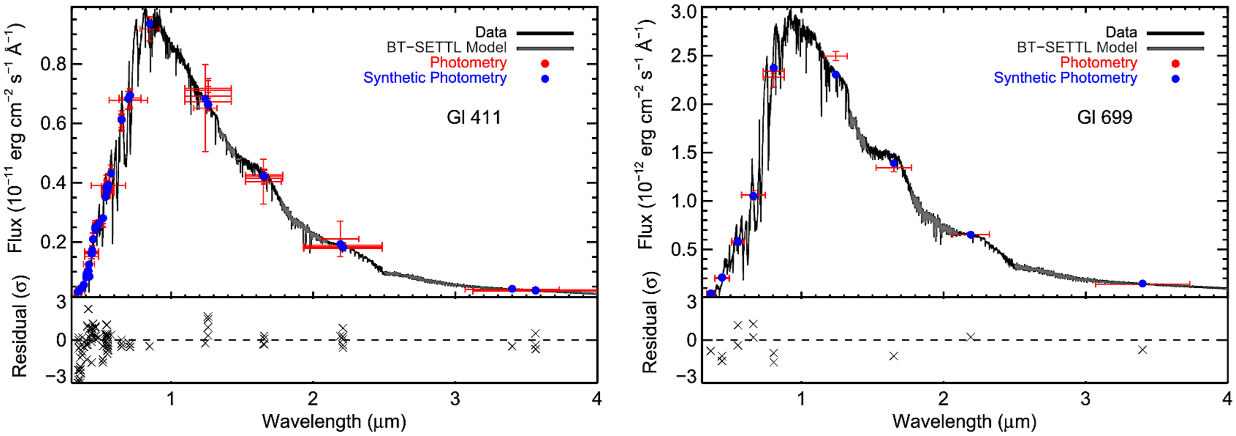

Figure 47. Examples of visible and SpeX spectra, models and photometry of cool dwarfs used to establish model-independent relations between T_{eff} or absolute magnitude and radius, as well as between color and T_{eff}. Mann et al. (2015).

iSHELL is not a precision RV-optimized infrared spectrograph. It is mounted at Cassegrain focus and optics are moved to change observing modes, and so it is not optimized for stability. Nevertheless, using the methane gas cell provided by Peter Plavchan's group, iSHELL is proving productive for some RV studies of young stars. RV observations are made with the gas cell inserted into the beam, imprinting wavelength calibrated absorption lines onto stellar spectra. Good examples are the observations of AU Mic. AU Mic is a pre-main sequence star with a spatially resolved edge-on debris disk. iSHELL RV observations by Plavchan et al. (2020) have helped confirm the presence of the transiting planet AU Mic b (see Figure 48). Observations of a planet co-existing with a debris disk offer the opportunity to test the predictions of current models of planet formation and evolution.

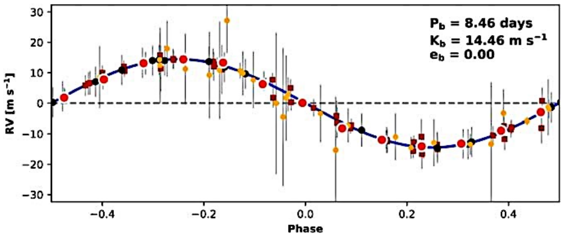

Figure 48. RV measurements phased to the orbital period of AU Mic b. The data come from three spectrographs: iSHELL (yellow circles), HIRES (black circles) and HARPS (red squares). The 1σ uncertainties for iSHELL are about 15 ms^{-1}. Plavchan et al. 2020.

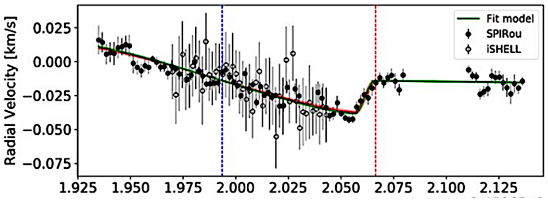

Figure 49. Simultaneous fit to the SPIRou RVs and iSHELL RVs of the model of the Rossiter-McLaughlin effect from Martioli et al. (2020). The vertical dashed lines show the predicted transit center (blue) and end (red). iSHELL did not observe the end of the transit. Martioli et al. 2020.

By observing AU Mic b in transit, Martioli et al. (2020) combined SPIRou/CFHT and iSHELL RV observations to measure the Rossiter-McLaughlin effect (see Figure 49). The analysis shows that the orbit of AU Mic b is prograde and aligned with the stellar rotation axis with a sky projected spin–orbit obliquity of 0°±16°. The aligned orbit of AU Mic b indicates that it formed in the protoplanetary disk that evolved into the current debris disk around AU Mic. Martioli et al. (2020) conclude that the agreement between the data sets from these two different instruments using independent techniques for data analysis is "remarkable" and shows that both instruments are stable and can provide short-term RVs with precisions of a few ms^{-1} for an active star.

6.4 Interstellar Medium

A fundamental first step in the formation of pebbles, rocks, and planetesimals is the coagulation of dust grains in dense molecular clouds. Dust coagulation is expected to be intimately linked to the formation of ice mantles, because ice-coated grains are stickier than bare grains (e.g., Ormel *et al*. 2011). Grain growth in dense clouds is evident from a flattening of extinction curves (Chapman *et al*. 2009) and suppressed depth of the 9.7 μm silicate band (van Breemen *et al.* 2011). But grain growth and ice formation has not been directly observationally linked. What are the time scales for grain growth under various conditions of ice formation and destruction (e.g., radiation fields, turbulence)? What grain sizes are formed? What is the relation with cloud depth?

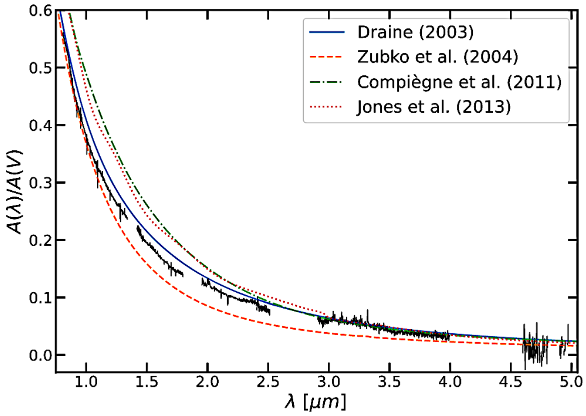

Figure 50. Average diffuse NIR extinction curve compared to previous work. Decleir et al. 2022.

Measuring interstellar extinction curves is another application of the IRTF Spectral Library and resulted in a recent paper by Decleir et al. (2022, see Figure 50). A finding is that most of the variation in the observed sample can be linked to the ratio of total-to-selective extinction, a rough measurement of the average dust grain size.

A related important topic is the formation of ices on grains in dense molecular cloud cores. UH PhD student, Lauri Chu, obtained 2-5 μm spectra of background stars seen through several small and dense molecular cores (Chu et al. 2020, see Figure 51). For the first time CO ice and CH_3OH were detected in dense cores without star formation, indicating that complex organic molecules can form abundantly before stars form. This work is being used to plan an extended observing campaign with *JWST*.

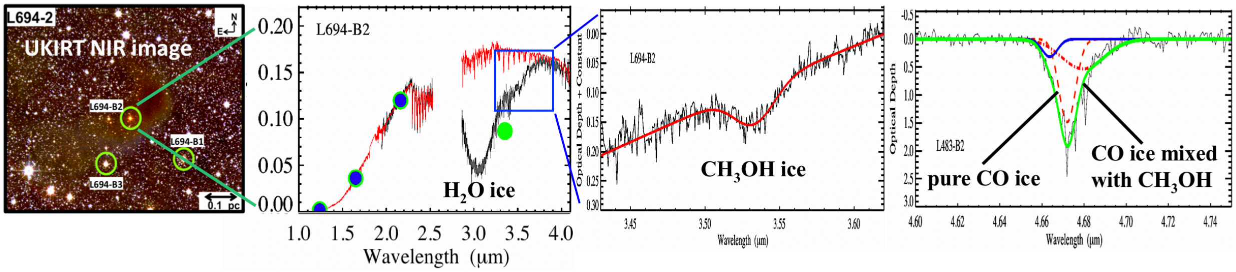

Figure 51. Spectra (black) showing the onset of complex organic molecule formation in a dense molecular cloud core. Spectra are compared to theoretical ice models. CH_3OH, a key indicator of complex molecule formation, is abundantly present (~10% relative to H_2O ice). Chu et al. 2020**.**

We anticipate significant further progress with the proposed new instrument, SPECTRE. Simultaneous 0.4-4.2 μm low resolution spectroscopy of reddened field stars constrains the grain sizes (from the shape of the derived extinction curve, with the shortest wavelengths being most sensitive to total extinction and the longest wavelength to the largest grains) and constrains the presence of ice mantles (from the 3.0 μm ice band) at the important diffuse to dense cloud transition (A_V= 0-6 magnitudes). Low resolution 0.4-4.2 μm spectroscopy with SPECTRE would be superior to previous observations because of its ability to separate the stellar signal from the dust and ice signals for individual sightlines. The simultaneity of the observations in SPECTRE's wide wavelength range also guarantees the accurate relative calibration needed for this work.

6.5 Galactic and Extragalactic Transients

Due to IRTF's relatively small aperture compared to some of its neighbors on Maunakea, the telescope is not competitive for most extragalactic observations. The exceptions are for point source observations: low-resolving power NIR observations (SpeX prism) of quasars and supernovae, and medium-resolving power SpeX cross-dispersed observations of bright active galactic nuclei (AGNs). Until recently these projects comprised only about 5% of awarded telescope time. Recently, however, extragalactic observing time has increased to about 15% of awarded telescope time. This is primarily due to follow-up of transient objects identified in all-sky surveys by Pan-STARRS, ATLAS and ASAS-SN – UH and UH related assets, and gravitational wave (GW) events. We do not expect a significant increase once the Rubin Observatory comes online in 2023 since many of these targets will be fainter than those already being found by the UH survey telescopes (see Figure 52). The exception is the early detection of flyby NEOs (see section 3.3) and transients identified in infrared sky surveys (see below).

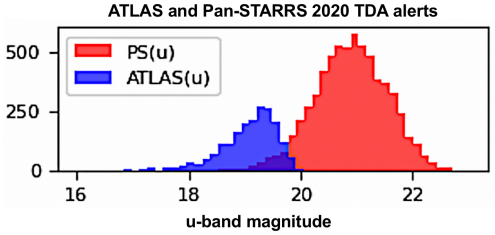

Figure 52. Time Domain Astronomy (TDA) alerts from ATLAS and Pan-STARRS in 2020. Events include SN Ia, classical novae, infrared dippers and YSOs. SpeX and SPECTRE sensitivities are well-matched to the brighter ATLAS alerts.

Currently, three types of exotic galactic and extragalactic transients are being followed up with SpeX in the NIR. The reasons why the NIR is favored for these events is due to i) interstellar extinction (e.g., galactic classical novae, white dwarf mergers and embedded tidal disruption events), ii) self-enshrouding events creating local dust (e.g., stellar mergers and obscured supernova), and iii) fundamental bound-bound absorption in the visible (binary neutron star mergers and neutron star black hole mergers). Unlike the merger of two black holes, the merger of two neutron stars (NS) produces electromagnetic radiation. These so-called kilonovae are powered by high-speed (>0.1 c) mass outflows that also trigger gamma ray bursts. Following GW localization there is need for rapid follow up of these events to understand their physics. Another type of event is the nuclear flaring of AGNs. AGNs host supermassive black holes (SMBH) that emit luminous flares due to the tidal disruption of a star and subsequent return of debris to the SMBH. In addition, core-collapse supernovae (CCSN) play significant roles in the chemical evolution of their host galaxy. Nebular phase NIR spectroscopy tracks features that allow us to measure CCSN mass to test chemical evolution models of the SN ejecta and better understand the demise of massive stars. These events can be classified with the $R \approx 100$ prism mode but, brightness permitting, resolving powers of $R \geq 1000$ with SpeX are needed for a fuller understanding.

6.6 Following up Infrared Sky Surveys

Despite the large number of optical transient survey instruments commissioned (or soon to be) over the past decade (e.g. ZTF, ATLAS, Pan-STARRS and Rubin Observatory), there have been few comparable efforts in the infrared. Time-domain infrared surveys offer a key window into a host of astrophysical phenomena, especially in the age of multi-messenger (electromagnetic, neutrinos, gamma rays and gravitation waves) astrophysics. In addition, the infrared variability of embedded young stars on time scales of hours to days, months and years can tell us much about how stars acquire their mass, and how the structure and composition of protoplanetary disks evolve. Examples of classes include "dippers" (McGinnis *et al.* 2015), Herbig AeBe stars (Wagner *et al*. 2015), and eruptive variable protostars (e.g., FUor, MNor, EXor). The latter are thought to trace the episodic mass accretion process, a key aspect of star formation (Kenyon & Hartmann 1995).

Several infrared sky surveys will come online within the next few years building on the Palomar Gattini-IR *J*-band survey (De et al. 2020). Some of these surveys exploit the newly-developed commercial indium-gallium-arsenide (InGaAs) sensors. The first of these, the Wide-field Infrared Transient Explorer (WINTER) had first light in October 2022 (Lourie et al. 2020). WINTER is a robotic *Y*, *J*, short-*H* time-domain survey instrument which operates behind a dedicated 1.0 m aperture telescope at Palomar Observatory. With a FOV of about 1 deg^2 WINTER is the first seeing-limited instrument dedicated to systematic infrared time-domain searches and will survey the available Northern sky every two weeks. IRTF (3.2 m diameter) is well-matched to spectroscopic follow up with SpeX and SPECTRE infrared transients found with WINTER.

7 OBSERVING FLEXIBILITY FOR FAST RESPONSE

There are currently two pathways for obtaining target-of-opportunity (ToO) observations with IRTF: formal proposals for ToO programs that undergo TAC review and ranking, and less formal requests for Director's Discretionary Time (DDT).

ToO proposals are submitted in response to the semi-annual Call for Proposals, and must contain the same level of scientific and technical justifications as other observing proposals, plus specific criteria under which a ToO interrupt would be initiated. To limit the potential impact of these interrupts on classically scheduled observing programs, the time blocked out for ToO observations each semester is limited to 24 hours for the top-ranked Solar System and 24 hours for top-ranked non-Solar System programs, with each ToO interrupt being no longer than three hours. To initiate a ToO interrupt, the program investigator must contact the IRTF Director, who will communicate the interrupt request to the telescope operator and classically scheduled observer. Whenever possible, unused engineering time (18 nights per semester) is offered to the observer whose time was interrupted.

The second method for obtaining ToO observations is to submit a DDT request. These requests can be made at any time, usually as a phone call or email describing the need for a limited set of observations, and explaining why this request was not submitted during the last proposal cycle. Most of these requests are granted time that is usually taken from scheduled engineering slots not needed by the IRTF staff for engineering purposes.

There is significant difference in the use of these two pathways for obtaining ToO observations at IRTF. While it is typical for the time requested in formal, TAC reviewed ToO proposals to be over-subscribed (the requested hours for ToO's is larger than the 24 hours available for both Solar System and non-Solar System programs), typically only one to two interrupts are triggered per year, meaning that most of the time blocked out for ToO observations goes unused (and remains with the classically scheduled observer). By contrast, we typically receive more than ten DDT requests per year, spanning a wide range of subjects across both Solar System studies and Astrophysics. We find that a high percentage of the observations obtained under DDT have contributed to rapid publications.

Many observing proposals submitted to IRTF contain some time domain component, whether it is monitoring temporal changes in specific targets (like planetary atmospheres or studies involving radial velocities or variable stars), or projects where the target is only observable for a short time (like supernovae or NEOs). The flexible scheduling of IRTF, due in part to our remote observing capabilities and fast instrument changes, allows for many time-domain programs to be intertwined in a classical observing schedule. IRTF currently schedules up to five programs per night, and we believe this is approaching a limit of observing efficiency within the classical scheduling framework.

Accommodating a larger number of ToO and time-domain programs may require changes to the scheduling and observing strategies used at IRTF. Queue observing would not be practical without a major increase in IRTF personnel to support this mode of operation. (Gemini Observatory operates a queue but Keck and Subaru do not. In an informal poll of IRTF observers queue observing is not viewed favorably.) A more likely change would be to schedule dedicated time blocks (e.g., perhaps one first-half and one second-half night per week) during which several ToO and time-domain programs can merge observing target lists and share observing responsibilities. This approach would be relatively easy to schedule, and would have the least impact on the IRTF staff and on the other classically scheduled observing programs.

8 DATA MANAGEMENT, ARCHIVING, AND CURATION

It is NASA Science Mission Directorate (SMD) policy, consistent with Federal policy and the NASA Plan for Increasing Access to the Results of Scientific Research, that scientific information produced from SMD-funded scientific activities be made publicly available to the extent legally permitted[16,17]. IRTF works to this policy.

Beginning in 2017 all observing data from SpeX and iSHELL, the two main facility instruments, are archived and curated at the IPAC Infrared Science Archive (IRSA), which, as of 2019 includes figures and signal-to-noise values of extracted, but not flux calibrated spectra[18]. Currently, this raw data is made available at IRSA after a proprietary period of 12 months. We do not yet have the ability to archive fully reduced data since data reduction with the Spextool data reduction package (Cushing et al. 2004) requires user interaction to run the package (the code is publicly available through download from the IRTF website[19]). However, Burgasser and Cushing et al. have a funded Astrophysics Data Analysis Program (ADAP) grant to convert Spextool from the IDL original coding language to Python (open source pySpextool). This work will also include the development of a batch mode and allow reduced data to be archived.

Data from the recently recommissioned IRTF facility instrument, MIRSI, is not yet available at IRSA. We plan to make raw data from MIRSI available at IRSA soon, once the instrument is in its final recommissioned configuration (a science grade array will be installed in 2023) and once the data headers are modified to meet the required archiving requirements.

IRTF has one FTE employee to manage the backup and archiving of data, and transfer of data to IRSA. Oversight and consultation are provided by the IRTF Deputy Director.

Legacy SpeX data (50,000 sources and 30 Tb of data) covering the period 2001-2016 is archived at the IRTF website since the original (2000) data headers (metadata) do not meet the requirements for formal archiving at IRSA. This data is still made publicly available through a more limited search capability[18]. Once pySpextool becomes available the legacy SpeX data will be re-reduced and archiving transferred to IRSA.

With the development of SpeX, IRTF pioneered the delivery of a data reduction package as part of the instrument development program (Cushing et al. 2004). Efficient data reduction is critical to the scientific productivity of the telescope. In recognition of this and future needs, we hired a data reduction specialist as a new scientific staff member in 2017. Recent software developments include automated real-time spectral extraction and signal-to-noise tools for observing with SpeX and iSHELL, and work on telluric modelling using atmospheric models (Villanueva et al. 2018) to eliminate or reduce the time needed to observe telluric standard stars. A Beta version is currently available to observers. As part of a just approved graduate student PhD thesis project, we are also just starting work on the data reduction code for SPECTRE, the proposed new three-channel IFU spectrograph for IRTF.

The 0.8-5 μm R=2000 IRTF Spectral Library of several hundred stars observed using SpeX (MLT dwarfs: Cushing *et al*. 2005, FGKMSC stars: Rayner *et al*. 2009) has proved a valuable community resource. The library was extended by Villaume *et al*. (2017) to include a wider range of metallicities and

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[16] https://science.nasa.gov/researchers/science-data/science-information-policy

[17] https://science.nasa.gov/science-red/s3fs-public/atoms/files/SMD-information-policy-SPD-41a.pdf

[18] http://irtfweb.ifa.hawaii.edu/research/irtf_data_archive.php

[19] http://irtfweb.ifa.hawaii.edu/~spex/observer/

hotter stars for improved modeling of unresolved galaxy populations. Burgasser and collaborators (Burgasser 2014 and references therein) have also constructed the SpeX Prism Library (SPL). The SPL contains over 2000 spectra, mostly ultracool dwarfs, but also giant stars, subdwarfs, white dwarfs, carbon stars, novae and supernovae, extrasolar giant planets and galaxies. All three of these 'stellar' libraries are publicly available online (see section 7.1). In addition, thousands of SpeX prism spectra of asteroids and NEOs from the MITHNEOS (Binzel et al. 2019) are also available online (see section 6.1).

The facility instrument designs SpeX (Rayner et al. 2003), MIRSI (Kassis et al. 2008), and iSHELL (Rayner et al. 2022) are documented in open source peer-reviewed journals. Although not required by NASA rules, it is IRTF policy to make all IRTF hardware designs and software available on request if allowed by ITAR regulations.

9 RESEARCH PRODUCTIVITY

9.1 Research Paper Metrics

The number of observing proposals submitted to the IRTF TAC and the resulting oversubscription in requested observing time for the period of 1998-2022 is shown in Figure 53. Of note is the significant jump in the number of proposals following the commissioning of new facility instruments – SpeX in 2000B and iSHELL in 2016B. Overall the number of observing proposals submitted over the period 2000-2022 has remained roughly the same at 100 per semester. Note the steady decrease in oversubscription over the same period, from about 2.5 in 2000 to about 1.5 in 2022. This is probably due to a combination of more available national and international observing resources, and the significant increase in IRTF observing efficiency due to more efficient instruments (e.g., see Figure 1) and more flexible scheduling.

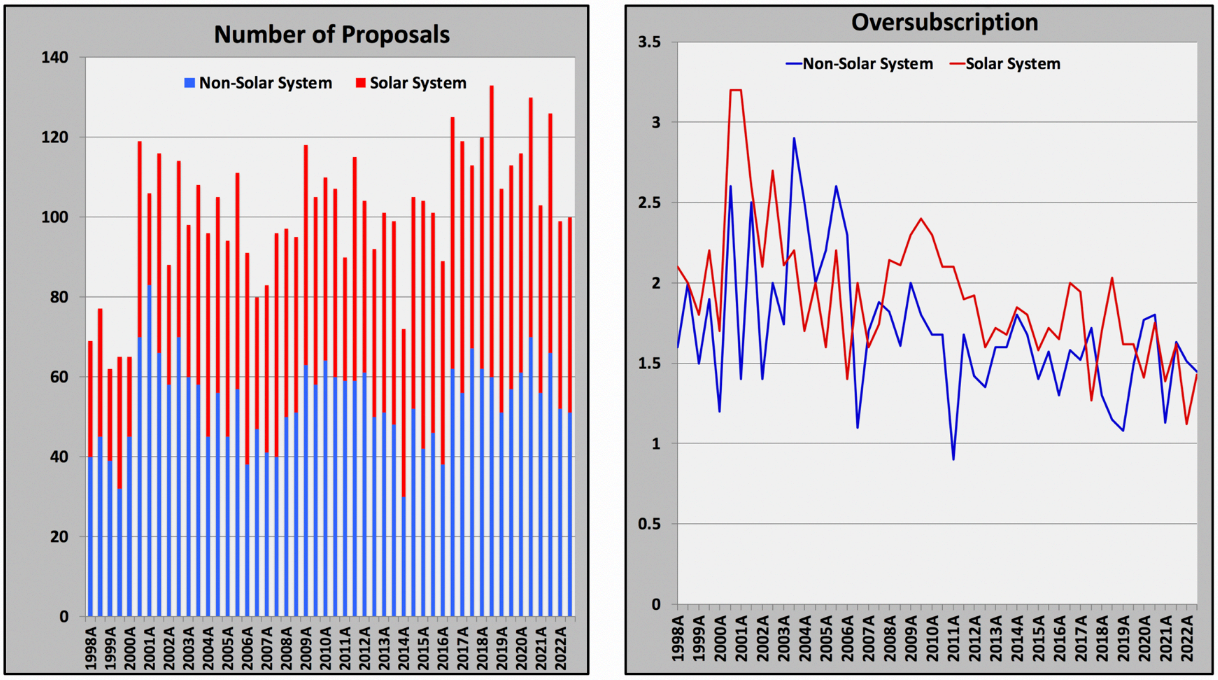


Figure 53. (*Left*) The number of observing proposals submitted to the IRTF TAC 1998-2022. (*Right*) oversubscription in requested observing time over the same period. Non-solar system proposals (blue), solar system proposals (red). Note the jumps in the number of proposals when SpeX (2000) and iSHELL (2016) were commissioned.

Over the same period there has been a significant increase in the number of IRTF publications, from 40 in 2000 to 100 in 2021 (see Figure 54). The bibliographic information comes from NASA's Astrophysics Data System (ADS) database. A large part of the increase from about 2008 is the use of data from the IRTF spectral libraries (see sections 6.1 and 7.1). The division of papers between solar system and non-solar system has remained about the same (one third solar system). Given the relative size of the ground-based non-solar system and solar system communities this division is to be expected.

The primary scientific output of a telescope is the collection of papers published in refereed journals based on data from that telescope. A telescope's productivity is measured by the number of papers published, while its scientific impact is the sum of each individual paper's impact as measured quantitatively by the number of citations that the paper receives. The bibliographic metrics and methodology used in this section are from Dennis Crabtree (e.g., Crabtree 2018). These are the metrics used by most Maunakea Observatories. The raw data is from the SAO/NASA ADS database.

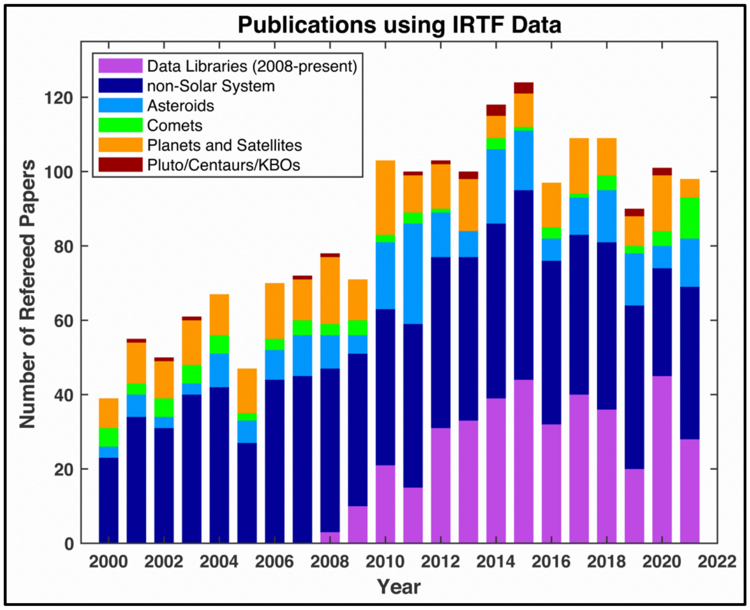


Figure 54. Publications using IRTF data 2000-2021, color-coded by science topic. Note the significant use of open-source IRTF spectral libraries beginning in 2008. In proportion about one third of papers are from the ground-based solar system observing community, as expected given the relative size of the ground-based solar system and astrophysics communities.

A paper accumulates citations as it ages. The accumulating citation counts for papers makes it very difficult to compare papers published in different years. A paper with 40 citations after one year is likely to be having more impact than a paper with 40 citations after 12 years even though they have the same number of citations at the time that the citation counts were checked. To account for this age effect in the raw citation counts, Crabtree determines a paper's impact factor. A paper's impact is determined by dividing the number of citations to the paper by the median number of citations to all Astronomical Journal (AJ) papers published in the same year. For example, assume the median AJ paper in 2005 has 15 citations. A 2005 paper with 45 citations has an impact factor of 3.0. This approach treats the median AJ paper as a standard measuring stick against which to measure all papers.

The Dennis Crabtree metrics (updated from Crabtree 2018) for the total number of papers per telescope and the total impact (scaled for number of citations) for the period 2016-2020 are shown in Figure 55. (Any paper that includes data from that telescope is counted.)

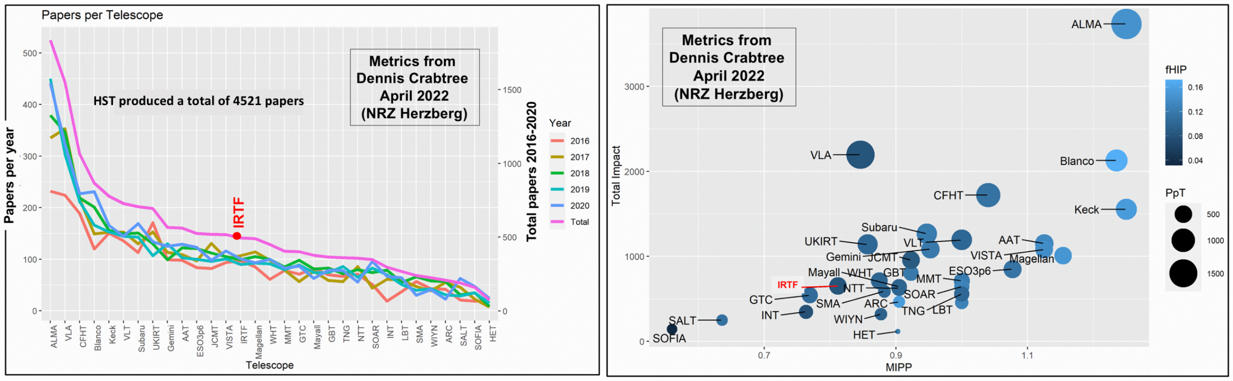


Figure 55. Dennis Crabtree metrics (updated from Crabtree 2018) for the total number of papers per telescope (*left*, note MIPP scale starts at 0.6) and the total impact (*right*) for the period 2016-2020. MIPP is Median Impact Per Paper.

For a relatively small telescope IRTF is very productive (about the same number of papers per year as produced by other 4-8-m class telescopes). Although still impressive, this plot under represents IRTF productivity given that in contrast to the other facilities 50% of observing time goes to solar system observers that comprise a much smaller part of the ground-based observing community. By contrast the Dennis Crabtree metrics for the total number of solar-system only papers per telescope and the total impact (scaled for number of citations) for the period 2016-2020 are shown in Figure 56. Clearly, IRTF is the premier ground-based observing facility for solar system science.

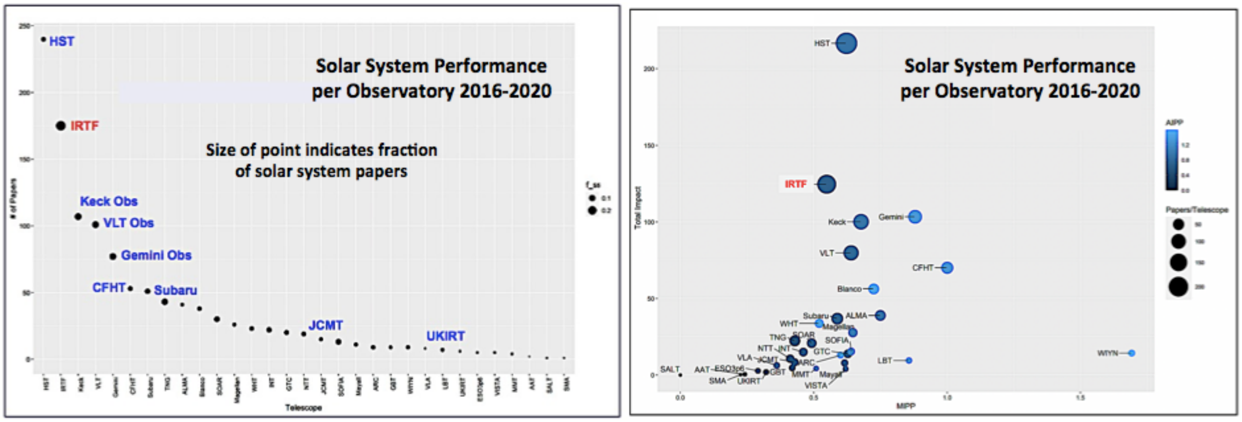
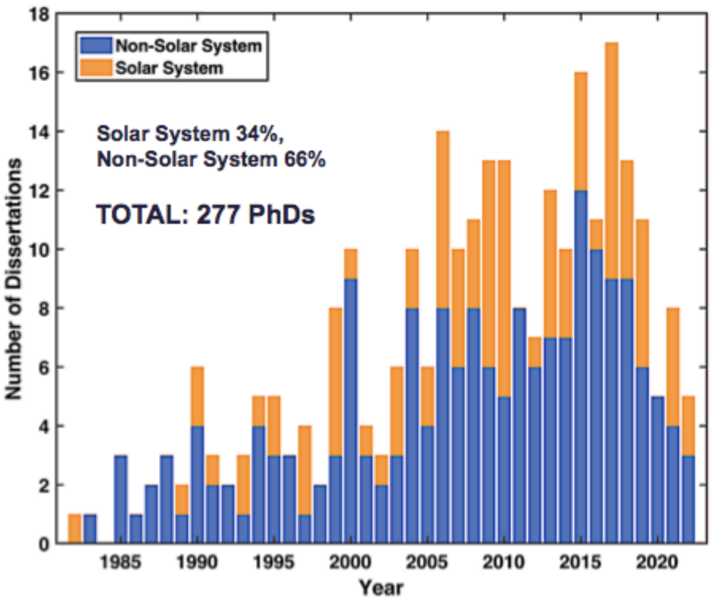


Figure 56. Dennis Crabtree metrics for the total number of solar system papers per telescope (*left*) and the total impact (*right*) for the period 2016-2020. Note that Keck Obs., VLT Obs. and Gemini Obs., represent the **sum** of two, four and two telescopes respectively.

Over the operating life IRTF a total of 277 PhD dissertations have been awarded to students using IRTF data, at least in part, for their dissertations (see Figure 57). The division between solar system and non-solar system topics is nearly identical to that seen for refereed publications in the IRTF bibliography (one-third of publications are solar system).



88 institutions have awarded PhDs using IRTF data

University of Hawaii at Manoa	35
University of Arizona	17
University of Texas at Austin	15
University of California, Los Angeles	10
Observatoire de Paris	9
State University of New York, Stony Brook	8
The University of Toledo	8
New Mexico State University	7
Cornell University	6
Harvard University	6
University of Florida	6
Georgia State University	5
Massachusetts Institute of Technology	5
University College London	5
University of Central Florida	5
Boston University	4
California Institute of Technology	4
Columbia University	4
Pennsylvania State University	4
Rensselaer Polytechnic Institute	4
University of Colorado at Boulder	4
University of Minnesota	4
University of Missouri, St. Louis	4
University of Tennessee, Knoxville	4
University of Wyoming	4

Figure 57. (*Left*) PhDs awarded to students each year using IRTF data since first light in 1979. The data for the last couple of years are incomplete. (*Right)* List of the top 25 awarding institutions.

9.2 Cost Effectiveness of IRTF Compared to Other Facilities

Perhaps the best way to assess the cost reasonableness or cost effectiveness of IRTF compared to other facilities is to estimate the cost per published research paper. (See section 11 for budget details and for a comparsion of overhead rates.) We have done this by simply dividing the yearly telescope operations' cost by the number of published papers per year as determined independently by Denis Crabtree for many astronomical facilities (see Figure 55 and Crabtree 2018). These estimates use the audited operating budgets as made available by all the facilities listed in Table 2. They do not include facilty construction costs. The cost per paper is also divided by the estimated median impact per paper (effectively the number of citations) since some papers are scientifically more valuable than others.

Table 2. Cost per paper per year compared for Maunakea facilities, SOFIA and HST

FACILITY	Operating budget (2019) per year	Number of telescopes	Average number of papers per telescope (2019)	Cost per paper	Median impact per paper (Crabtree metric)	Impact scaled cost per paper
SOFIA	$100M	1	25	$4M	0.55	§7M
HST	$98.3M	1	905	$109K	1.00	§109K
Keck	$28M	2	160	$93K	1.25	§69K
Gemini	$21M	2	120	$88K	0.95	§93K
Subaru	$13M	1	152	$86K	0.95	§91K
CFHT	$8M	1	170	$45K	1.05	§43K
IRTF	$6M	1	110	$55K	0.82	§67K

§: arbitrary currency

The operating budgets also do not include the costs of building new instruments, which are typically built by collaborating institutions, or are funded separately by NSF, for example. The only facility that made these costs available to us was CFHT and so these costs are not included in Table 2. CFHT estimates about $1.8M per year averaged over the past ten years. For IRTF the amount is about $0.5M per year averaged over the past ten years. The instrument budgets for Keck, Gemini and Subaru are most likely significantly more than CFHT and IRTF. However, retiring old instruments and replacing them with new, state-of-the-art, instruments, is an important ingredient in maintaining scientific productivity. IRTF also receives small budget supplements for various unplanned facility upgrades (task orders). For example, dome resurfacing and data archiving over the last ten years. On this basis the cost per paper for CFHT and IRTF are comparable and significantly less than Keck, Gemini and Subaru.

These cost estimates do not include the programmatic value to the organization funding the facility (e.g. the programmatic value of mission support and planetary defense to NASA in the case of IRTF).

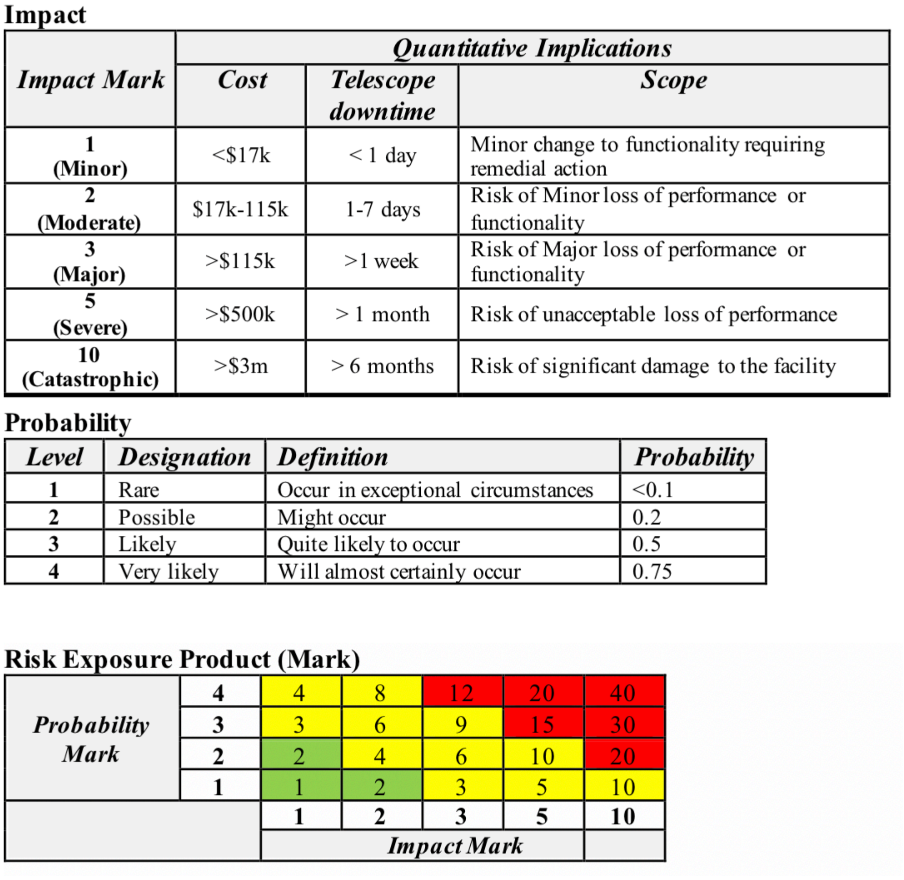
10 ENGINEERING RISK ASSESSMENT

The objective of risk management is to improve the probability of project success, not just measured in terms of specification but also in time and cost. It does that by anticipating problems, identifying opportunities and then taking cost-effective actions to minimize the impact of problems and maximize opportunities. Here we briefly describe how IRTF manages a systematic process of identifying, analyzing and responding to such known project risks.

Methods and assessment of technical risks to the IRTF facility are presented here. The methods used are those employed by the UK Astronomical Technology Centre (ATC) for Gemini and European Southern Observatory (ESO) instrumentation projects.

10.1 Risk Management Process

All IRTF technical staff have an important role in risk management as it is only by the successful and continuous identification of risks that the process can succeed. Risks are discussed at weekly meetings of the summit technical staff (the ‘day crew’) and all the Hilo- and Honolulu-based engineering and science staff. The appointed risk owners are the Observatory Manager (the day crew lead), the Senior Engineer (Hilo) and the IRTF Director (Honolulu). Ultimately, the IRTF Director owns the top ten risks and continuously monitors them.



Impact

Impact Mark	*Quantitative Implications*		
	Cost	*Telescope downtime*	*Scope*
1 (Minor)	<$17k	< 1 day	Minor change to functionality requiring remedial action
2 (Moderate)	$17k-115k	1-7 days	Risk of Minor loss of performance or functionality
3 (Major)	>$115k	>1 week	Risk of Major loss of performance or functionality
5 (Severe)	>$500k	> 1 month	Risk of unacceptable loss of performance
10 (Catastrophic)	>$3m	> 6 months	Risk of significant damage to the facility

Probability

Level	*Designation*	*Definition*	*Probability*
1	Rare	Occur in exceptional circumstances	<0.1
2	Possible	Might occur	0.2
3	Likely	Quite likely to occur	0.5
4	Very likely	Will almost certainly occur	0.75

Risk Exposure Product (Mark)

Probability Mark	**4**	4	8	12	20	40
	3	3	6	9	15	30
	2	2	4	6	10	20
	1	1	2	3	5	10
		1	**2**	**3**	**5**	**10**
		Impact Mark				

Figure 58. Risk impact-probability assignment and numeric scoring.

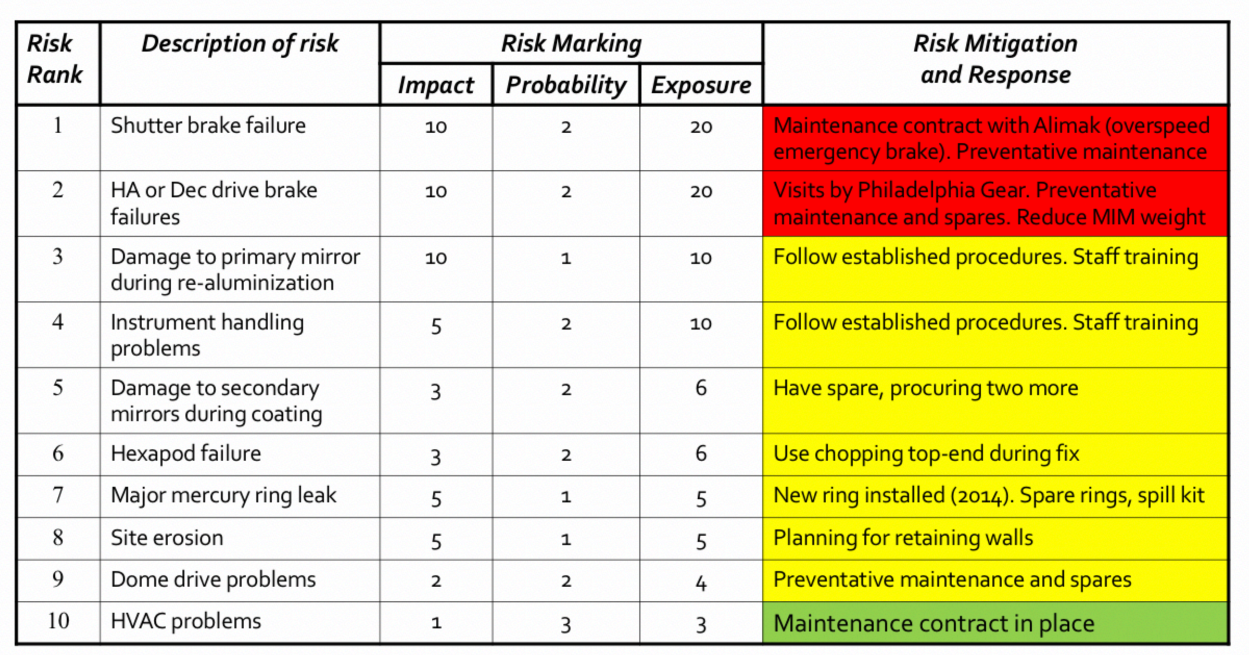
Together with weekly technical meetings, risks are identified through a process of review of past and current project risks, analysis of known design issues, reviews of ongoing facility maintenance and performance, and cause and effect analysis.

Following risk identification, the risks are scored following the standard impact-probability methodology. This process assigns a numeric score to the impact of an identified risk and a numeric score to the probability of occurrence (see Figure 58).

10.2 Risk Register

Th current top ten IRTF technical risks are given in the Risk Matrix (see Figure 59). Once identified and ranked, the objective of risk response planning is to implement cost effective risk reduction actions that reduce the probability and effect of the risk. There are different types of action to be invoked depending on the risk exposure to the project:

- *Avoidance*: This is where proactive measures are taken to avoid risk
- *Mitigation*: Measures are taken to reduce probability or impact of the risk to an acceptable level should it occur
- *Transfer*: The risk is transferred to a third party who is better placed to manage the risk should it occur (e.g. a vendor adds cost to mitigate risk)
- *Acceptance*: Accept the risk on the basis that it is most unlikely to happen. It is beyond the IRTF's control or too expensive to avoid (e.g. loss of the completed instrument)



Risk Rank	*Description of risk*	*Risk Marking*			*Risk Mitigation and Response*
		Impact	*Probability*	*Exposure*	
1	Shutter brake failure	10	2	20	Maintenance contract with Alimak (overspeed emergency brake). Preventative maintenance
2	HA or Dec drive brake failures	10	2	20	Visits by Philadelphia Gear. Preventative maintenance and spares. Reduce MIM weight
3	Damage to primary mirror during re-aluminization	10	1	10	Follow established procedures. Staff training
4	Instrument handling problems	5	2	10	Follow established procedures. Staff training
5	Damage to secondary mirrors during coating	3	2	6	Have spare, procuring two more
6	Hexapod failure	3	2	6	Use chopping top-end during fix
7	Major mercury ring leak	5	1	5	New ring installed (2014). Spare rings, spill kit
8	Site erosion	5	1	5	Planning for retaining walls
9	Dome drive problems	2	2	4	Preventative maintenance and spares
10	HVAC problems	1	3	3	Maintenance contract in place

Figure 59. The top ten risks in the IRTF Risk Matrix.

In addition, some risks are difficult to assess. These include budget, schedule, and bureaucratic risks. Examples include the effects of the current nation-wide difficulties in hiring and replacing staff, and recent bureaucratic delays in getting tax compliance for vendors in the State of Hawaii.

10.3 Contingency Management Plan

The IRTF contract with NASA includes a contingency budget of up to $2.5M in the form of an Indefinite Delivery, Indefinite Quantity (IDIQ) contract (see SOW in Appendix 1). IDIQ covers IRTF facility needs that cannot be determined or that are very unlikely to occur at the time the five-year contract with UH is agreed.

11 MANAGEMENT AND BUDGET

11.1 Management

The organizational structure of IRTF is shown in Figure 60. IRTF staff work in three locations: at the UH IfA office on the Manoa campus of UH in Honolulu, Oahu; at the UH IfA office in Hilo, Hawaii Island; and at the telescope on the summit of Maunakea, Hawaii Island.

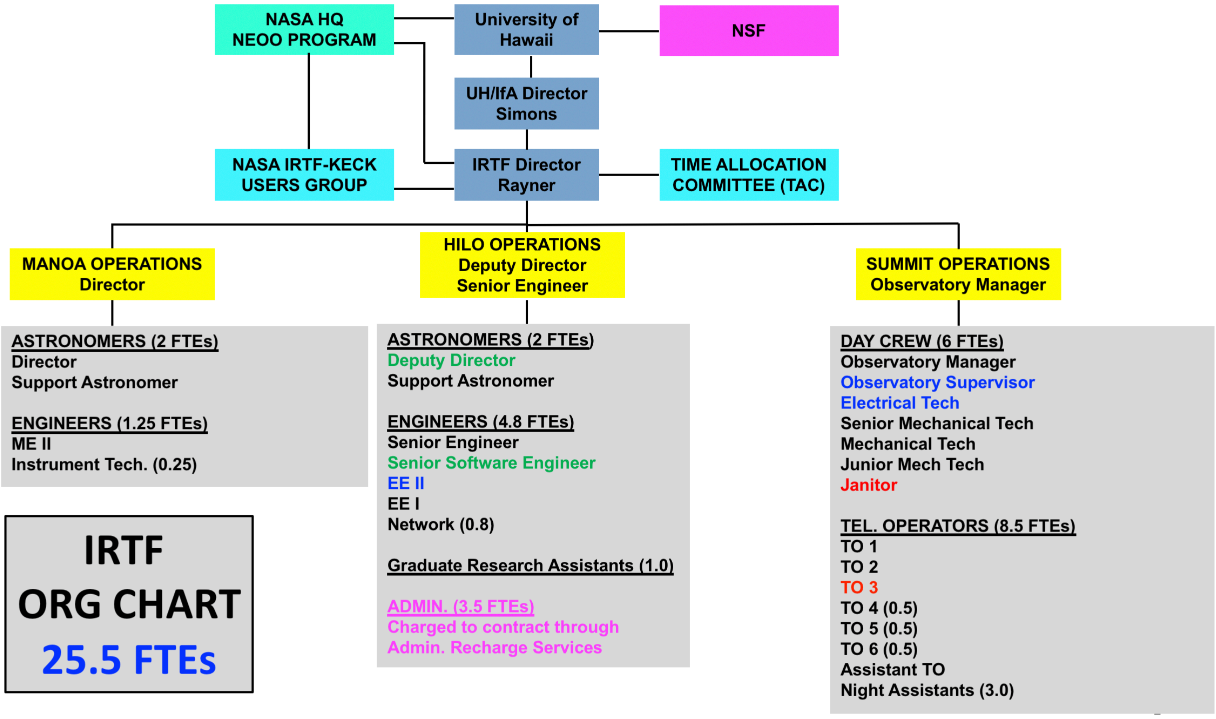


Figure 60. The IRTF Organization Chart. Positions in red are unoccupied due to long-term medical leave. Positions in blue are open and are being recruited. Positions in green are upcoming retirements.

The day crew commute daily from the Hilo office to the telescope, a round trip of about 70 miles (two hours). They work 40-hour weeks Monday to Friday. Their function is to maintain the telescope in operating condition. For emergency telescope repairs the day crew work overtime at night and weekends as needed. Nighttime operations are conducted by one Telescope Operator (TO) assisted by an Assistant TO or a Night Assistant. Since most observing is now done remotely we operate a two-person rule at the summit for safety. TOs work 12-hour shifts (dusk till dawn) typically lasting three nights, and sleep during the day at the Hale Pohaku (HP) mid-level facility. TOs also work daytime observing shifts when scheduled. Both the day crew and the TOs pick up vehicles in Hilo and drive to the summit. IRTF maintains a fleet of several vehicles under contract to the General Services Administration (GSA).

The engineering staff in Hilo also support telescope operations as needed (remotely or physically at the telescope), maintain and repair facility instruments and other telescope systems, maintain telescope and instrument software, and are involved in the planning, design and construction of new instrumentation. It is unusual for an operational staff to also design and build facility instrumentation but this is probably why IRTF instruments interface so well with the telescope and are easy for observers to use.
IRTF staff astronomers (three support astronomers and the Director) support observers during nighttime and daytime observing as needed and are always on-call to help observers. Since most observing is now

done remotely, observing support is now also done remotely (and works very well). The staff astronomers individually specialize in instrumentation, data reduction, and observatory operations (telescope scheduling and TAC organization). They also have about 25% of their time available for their own scientific research, and teaching if they so choose.

Administration support for the telescope is through a mixture of G-funds (i.e., state funds) and Administrative Recharge Services (ARS). The ARS costs charged to the IRTF contract supports 3.5 FTEs. There are no administration positions directly paid for by the IRTF contract.

Each work site has a lead manager. The Observatory Manager at the summit, the Deputy Director and Senior Engineer in Hilo, and the Director in Manoa, with overall management residing with the IRTF Director. Historically, the IRTF Director (and previously the IRTF Division Chief) has remained in Manoa for better communication with the IfA Director, IfA faculty, and IfA administration (particularly HR for recruitment). Originally the IfA Director was the PI of the IRTF grant or contract with NASA, with the IRTF Division Chief running telescope operations and managing IRTF staff. This changed in 2000 when the IfA Director agreed to make the Division Chief the Director and PI of the grant or contract.

On NASA matters the IRTF Director takes direction from Kelly Fast, the IRTF Program Officer at NEOO/PDCO, and on UH matters from Doug Simons, the IfA Director. IRTF staff meets with the NASA IRTF-Keck Users Group (NIKUG) in the spring (Washington DC) and fall (Hilo) of each year. The IRTF Program Officer in consultation with other NASA representatives selects the NIKUG members, which includes several IRTF and Keck users, and representatives from NASA and NSF. As a NASA committee the NIKUG report ‘findings’ to the Program Officer and IRTF Director. In consultation with the Program Officer the Director usually follows the recommendations of the NIKUG.

The NASA contract with UH includes several reporting requirements and plans - small business subcontracting reporting plan and reporting requirement, safety and health plan and reporting requirements, and cyber security requirements and plan.

As will be clear from the Organization Chart in Figure 60, maintaining and recruiting staff is currently one of our biggest challenges. Hiring is done through UH HR and has become increasingly difficult following the pandemic. This seems to be a nation-wide problem.

11.2 Budget Explanation

The budget for IRTF operations covering the current five-year contract (2019-2024) is $30.3m (see Appendix 6 for September 2022 status). A further maximum contingency (Indefinite Delivery Indefinite Quantity) of $2.5M is for unplanned major repairs is included. The Statement of Work (SOW, see Appendix 1), defining NASA expectations is the starting point for budget negotiations between NASA (the Program Officer and Contracting Officer) and UH (the IRTF Director and Administrative Officer).

The SOW has not changed significantly over the past several budget cycles and the number of staff required to execute the SOW and operate the telescope is well understood (the number of FTEs and their nature, see Figure 60). The total direct labor is about 53% of the budget. Another major item is the cost of services provided by the University (Administrative Recharge Services, Computer Recharges and indirect costs of 26%) totaling 15% of the budget. In preparing the budget request the IRTF Director consults with IRTF engineering staff over needs for equipment, materials and supplies (including software and licensing), facility and instrument repair and maintenance. Additional items include the IRTF’s contribution to Maunakea Support Services (mountain infrastructure), utilities, GSA vehicle fleet operation and servicing, travel costs, and HP lodging costs.

All extramurally funded award budgets of the UH must include indirect costs using the approved Facilities and Administrative rate. The indirect cost rate used for this contract is 26% which is the UH, Organized Research, **Off**-Campus rate approved by the Department of Health and Human Services (DHHS) in its current rate agreement. This rate is applied to contract modified total direct costs which consists of all direct costs excluding equipment, Job Order System Services and Mauna Kea Support Services costs. By comparison, the UH Organized Research, **On**-Campus rate is 45.5%. The lower off-campus rate of 26% applies to the IRTF contract as project activities are predominantly performed at a facility which is not owned by UH and therefore facility maintenance and utilities are not supported by indirect costs but rather are supported directly by the contract funding instead. The comparable indirect cost rate used by the University of Arizona, the University of California, Santa Cruz, and the W.M. Keck Observatory is 26%, 26% and 65%, respectively.

Formally, the budget is prepared and tracked by the responsible UH Administrative Officer (AO) with input from the IRTF Director. NASA funds the contract in increments at their discretion (typically with payments every six months) with regular communication between the NASA Contracts Officer and the UH AO.

12 COMMUNITY INPUT AND FEEDBACK

There are several ways that IRTF receives input from the community. IRTF staff meets with the NASA IRTF-Keck Users Group (NIKUG) in the spring (DC) and fall (Hilo) of each year. The IRTF Program Officer in consultation with other NASA representatives selects the NIKUG members, which includes several IRTF and Keck users and representatives from NASA and NSF. As a NASA committee the NIKUG report 'findings' to the Program Officer and Director. The format is a day-long meeting consisting of IRTF staff presentation to the NIKUG including questions and discussions. Presentations are also given by the Program Officer for PDCO matters, and the IfA Director for UH and Maunakea matters. The Washington DC meeting also includes Q&A with the heads of the Astrophysics and Planetary Science Divisions, plus a presentation from a representative of NSF. The NIKUG then meets in closed session before giving verbal feedback to the IRTF Director. The Hilo meeting also includes an extra day for the NIKUG to visit the summit and the telescope. Following the meeting a formal written document is sent to the IRTF Director and the Program Officer. In consultation with the Program Officer the IRTF Director usually follows the recommendations of the NIKUG. The Program Officer and the IRTF Director also meet monthly.

Figure 61. IRTF booth at a recent DPS meeting with IRTF staff taking animated input from a long-time user.

IRTF staff also have a booth (virtual for the past couple of years) at DPS and AAS meetings (see Figure 61). These meetings are well attended by IRTF users and provide us with an opportunity to have discussions with users in person. We also take the opportunity to advertise IRTF capabilities and attract new users, particularly students who might not otherwise be familiar with IRTF.

We also attend the annual Maunakea Users Meeting. At this meeting all the Maunakea telescopes give brief presentations on their activities over the past year. This is an opportunity to keep up-to-date with technical developments at the other Maunakea telescopes and apply lessons learned to IRTF. The IRTF Director also attends monthly meetings of the Maunakea Directors to keep appraised of political issues and community issues (e.g., COVID procedures and protocols) and give input. An IRTF staff member also attends meetings of the Maunakea Support Services (MKSS) Oversight Committee. (The IRTF Director currently chairs this committee.) IRTF pays a subscription to MKSS to manage the mountain infrastructure (road maintenance above HP, snow clearing, rangers, HP food and lodgings service etc.).

A nightly log of telescope operations, written by the on-duty TO, is emailed to the technical staff at the end of nightly telescope operations. The day crew and support astronomers respond as needed. Observers can provide feedback to the Director on the performance of the telescope, instrumentation and staff through a confidential online form.

In 2018 we organized an IRTF 'Future Directions Workshop' to take input from the astronomy community about planning for future IRTF operations and needed new capabilities. The workshop was held at the Biosphere 2 research facility in Oracle, Arizona, and was attended by about 50 astronomers (see Figure 62). All the presentations are available on the IRTF website[20]. In summary, efforts to improve telescope image quality, pointing and tracking were encouraged. For telescope operations and scheduling

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[20] http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/

there was interest in limited partial queue observing, fast turnaround of observing proposals (i.e. more DDT), and a better approach to long-term multiyear observing proposals. Although adaptive optics was regarded as a powerful capability for IRTF there was significant concern expressed about the extra resources needed to develop and maintain an AO capability to the detriment of other IRTF capabilities. The continued development of data reduction tools was highlighted. The development of a 0.4-4.2μm *R*=150 IFU spectrograph (SPECTRE) was strongly endorsed as a key part of an emphasis on critical capabilities for planetary defense (see section 3.5). There was also strong support for mid-infrared capabilities that are well aligned with IRTF's planetary role, capabilities which were perceived as being abandoned at other Maunakea facilities.

We anticipate holding another community workshop within the next few years.

Figure 62. Attendees at the 2018 IRTF Future Directions Workshop help at the Biosphere 2 research facility in Oracle, Arizona.

13 EDUCATION AND COMMUNITY OUTREACH

13.1 Education and Training

Figure 63. IRTF graduate students Kenji Emerson (*left*) and Ellen Lee (*right*) with their pre-thesis project – ‘Opihi (see section 1.2).

IRTF has a long history of funding and training both undergraduate and graduate students. Several current employees were former UH undergraduate students and worked as interns and student workers at IRTF. This includes our Senior Engineer, Observatory Manager, Network Engineer and two Telescope Operators. In addition, several other former IRTF interns and student workers are employed at other Maunakea telescopes. Over summer 2022 we had a mechanical engineering student intern with us in Honolulu. Former IRTF graduate student, Mike Connelley, is now an IRTF staff astronomer. The IRTF budget includes funding for two full-time graduate students. Our current graduate students are Kenji Emerson and Ellen Lee. Ellen and Kenji are working on instrumentation for IRTF and have an opportunity to develop as future instrumentalists (see Figure 63).

UH participates in NSFs Research Experiences for Undergraduates (REU) program and every summer IRTF hosts groups of REU students for a visit to the summit and the telescope. These are rewarding experiences for everyone concerned and frequently former REU students return to UH IfA as graduate students.

One of the significant benefits of remote observing is the ability for remote participation by groups of people. Recent examples include classes of school students hosted by observers during their observing runs (see Figure 64).

Figure 64. (*left*) Astronomers Emma Thomas and Henrik Melin from the University of Leicester, UK, host a class of 10-year-olds from London, during their iSHELL run observing Uranus’ aurorae**.** (*right*) Astronomer Nathan Roth, explaining iSHELL’s GUI to Andre Watson from Bishop McNamara High School, Washington DC, during observations of 67P/Churyumov-Gerasimenko.

We have recently created two new positions of Assistant Telescope Operator. This position is targeted for members of the local Hawaii Island community that are not otherwise qualified to be a Telescope Operator, which requires a technical degree. Since most observing is now done remotely we require a ‘second body’ to accompany the TO at the telescope for reasons of safety. These ‘Night Assistant’ (NA) positions require no formal qualifications and are typically occupied temporarily by UH undergraduate students and casual hires. Following discussions with the NAs it became clear that with the right training that we could provide them with the opportunity to apply for TO positions at IRTF. The first ATO was hired six months ago and is proving to be a great success.

13.2 Outreach

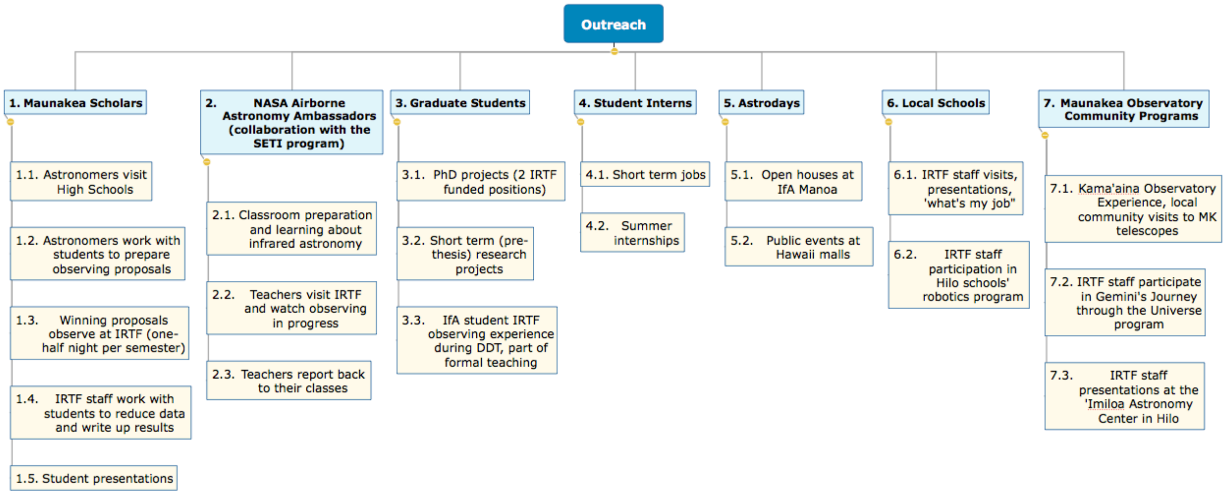

Figure 65. Outreach activities at IRTF

Unlike some of the larger telescope facilities on Maunakea such as Keck, Gemini, Subaru, and the Canada-France-Hawaii Telescope (CFHT), IRTF does not have funding for outreach and funded positions for outreach staff. Outreach is not a requirement in the SOW. Nevertheless, we still organize our own outreach activities and fully participate in community-wide Maunakea Observatory activities. Outreach activities are summarized in Figure 65. It should be noted that some of these programs are only now restarting following interruption by the pandemic.

IRTF participates in the Maunakea Scholars program[21], a program created in 2015 and managed by CFHT. Maunakea Scholars is an innovative program designed to bring Hawaii's public high school students into the observatory community by allocating observing time on world-class telescopes to local students. Every telescope on Maunakea and the Las Cumbres Observatory on Maui participates.

The participating schools range from urban Honolulu to the most rural and remote schools in the state (ethnicity: Asian 37%, Black 3%, Hispanic 8%, Native Hawaiian 10%, White 27%, other 15%). Maunakea Scholars partners with the ʻImiloa astronomy and culture center in Hilo to help ground the program in a cultural context focused on Maunakea. This helps students understand the importance of Maunakea as a site revered across Polynesia for its cultural roots. High school students work with telescope science staff to develop observing projects, which then compete for telescope time with other students. (The observing time allocated is up to the facility but it typically scales inversely with telescope size.) IRTF contributes one night per year. Students, with the help of science staff, take and reduce data, and write up and present the results. Projects winning observing time on IRTF are listed in Table 3.

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[21] https://maunakeascholars.com/

Table 3. Maunakea Scholars observing programs awarded time on IRTF 2016 – 2019

Year	*Observing Project*	*Students*	*School*
2018-2019	Climate Change in our Solar System	Gretchen Silen Megan Villafuerte	Honoka'a HS, Hawaii
	Tracing the Makings of a Comet	Kaitlin Villafuerte	Honoka'a HS, Hawaii
	Life on Titan	Sean Koyamatsu	Kalani HS, Oahu
	Stars	Akoni Williams	Waiakea HS, Hawaii
	WHh Stars: Precursors to LBV Stars?	Jean Claude Dumaslan	Waipahu HS, Oahu
2017-2018	Measuring Jupiter's Bands	Kaitlyn Tsuba Jenny He	Kalani HS, Oahu
	Brown Dwarf Spectroscopy	Alyssa Zhang	Kalani HS, Oahu
	Does the orbit of Sag A effect the Surrounding Stars	Elijah Kogler Noah Kolona	Kapolei HS, Oahu
	Jupiter's Red Spot	Issac Pauole Jacob Pauole	Waiakea HS, Hawaii
2016-2017	Possible Life on Titan	Annika Wiley Marie-Claire Ely Kaitlin Villafuerte	Honoka'a HS, Hawaii

The Maunakea Scholars program is part of a larger effort to engage with the local and Hawaiian communities. Several hundred people regularly attend the IfA 'Astrodays' in Manoa, Oahu, and on Hawaii Island. These events take place a few times a year and involve public lectures, physics and astronomy demonstrations, and activities for children. IRTF staff also attend career fairs at local schools.

Outreach currently does a better job of reaching more privileged communities than underserved minority populations in Hawaii, especially children. It is clear we need to improve outreach to underserved children.

Figure 66. Two teachers from the Airborne Astronomy Ambassadors meeting with the TO (Dave Griep) during their visit to the telescope in August 2022.

IRTF is collaborating with the SETI Institute on the NASA Airborne Astronomy Ambassadors program[22]. This program is a professional development and STEM immersion experience for high school teachers that formerly included flying on SOFIA. Following the demise of SOFIA, the program was transferred to IRTF this year. As a pilot scheme, group leaders visited IRTF in August 2022 to witness telescope operations and nighttime observing (see Figure 66). The first two cohorts of teachers visited IRTF and the 'Imiloa center in October 2022. Once back at their high schools the teachers conduct ten-day immersion physics and astronomy classes for their STEM students incorporating their experiences at IRTF. NASA's Science Mission Directorate is funding this program through 2025 with the goal of bringing NASA science to the classroom.

All Maunakea Observatories participate in the 'Kama'ãina Observatory Experience' (KOE)[23]. The KOE is a free monthly community event that provides residents with an opportunity to visit the summit, tour

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[22] https://www.seti.org/aaa

[23] http://kamaainaobservatoryexperience.org/

the telescopes, and attend lectures about the culture and environment of Maunakea. At the summit IRTF visitors are given a brief lecture about telescope operations and science programs, are shown the control room, the instruments and primary mirror, and see the telescope slew. The KOE was introduced in October 2015 during a speech by President Barack Obama at the White House Astronomy Night in Washington, D.C.

IRTF staff have organized and run an underwater robotics program for schools in Hilo under the auspices of the Marine Advanced Technology Education (MATE) Center[24] for several years and plan to continue. MATE's mission is to use marine technology to inspire and challenge students to learn and creatively apply STEM to solving real-world problems. Class sizes are typically 20 students and meet once a week in Hilo, and occasionally at the IfA, Hilo. The total participation across the state is about 100 students. There is one regional competition each year and winners go onto national competitions. The Hilo cohort won through to the national competition in 2018. IRTF staff have observed students with few technical skills become confident with using a wide range of skills, proficient in problem solving, and learn team building skills. This program is ongoing.

The NASA Science Mission Directorate has a citizen science program to encourage collaborations between scientists and interested members of the public. Long-time IRTF observer, Glenn Orton, participates in this program. He recently posted some 5 µm Jupiter images to his Facebook site and received contemporaneous visible CCD 'lucky imaging' (very short exposures to 'freeze' the seeing) from Japanese amateur Shinji Mizumoto, aiding scientific interpretation of the IRTF images (see Figure 67).

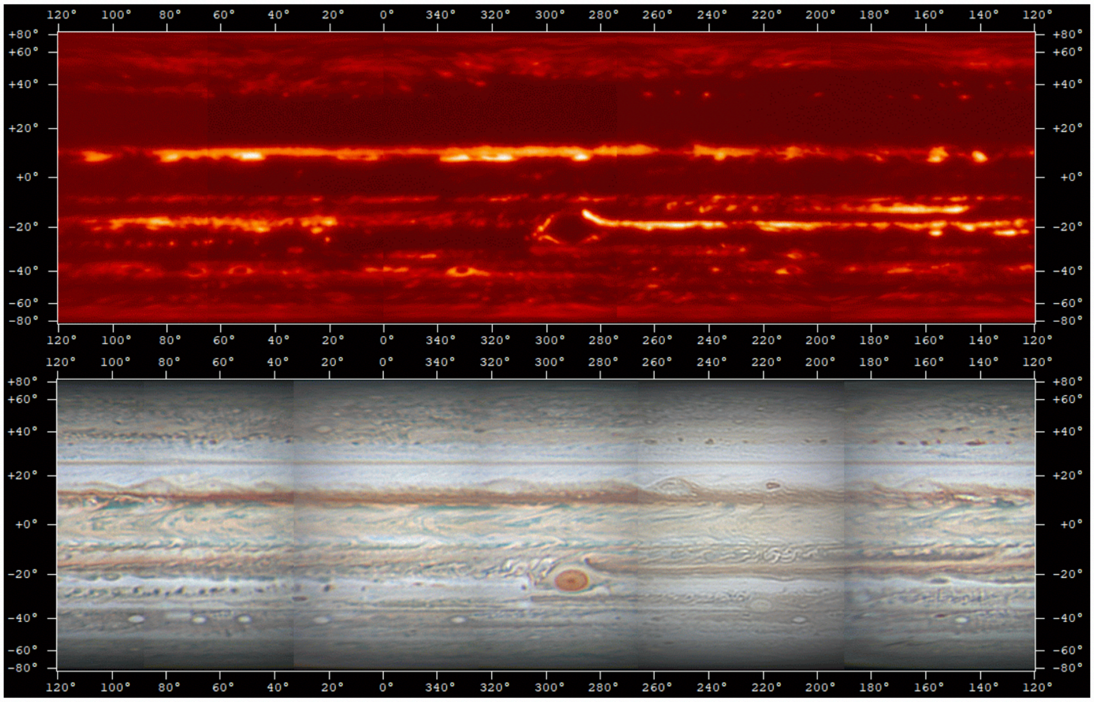

Figure 67. (*top*) IRTF 5 µm image map of Jupiter with contemporaneous visible image map from citizen scientist Shinji Mizumoto (*bottom*).

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[24] https://www.marinetech.org/mission/

14 CARBON FOOTPRINT

We have estimated IRTF's greenhouse gas (GHG) emissions expressed in metric tons of CO_2 equivalent (tCO2e) using the *carbonfootprint.com* online tool. We have not had time to do a formal audit of travel logs, vehicle logs, and electricity usage for this report. However, we are confident that our estimates are reasonably accurate, as explained in the following. We follow a methodology like that employed at Keck (McCann et al. 2022) and CFHT (Flagey et al. 2020). The three main sources of GHG emission are air travel, gasoline vehicle usage, and electricity.

14.1 Air Travel

About ninety percent of all observing is now done remotely (see Figure 2). Prior to the introduction of remote observing we would have on average have about 100 three-night observing runs per year, each with two observers. Most of these observers would come from the US mainland (200 return air flights, say Denver to Kona). Making this calculation for 2020 gives 10% of 300 tCO2e per year, or 30 tCO2e per year.

Prior to the pandemic IRTF staff would average about 100 return air flights per year between Honolulu and Hilo, or about 1.0 tCO2e per year, and 15 return US mainland flights (for conferences and meetings etc., again say Denver to Honolulu) for about 23 tCO2e per year.

Therefore, the total carbon footprint for air travel is about 54 tCO2e per year in 2022, compared to about 324 tCO2e per year before remote observing.

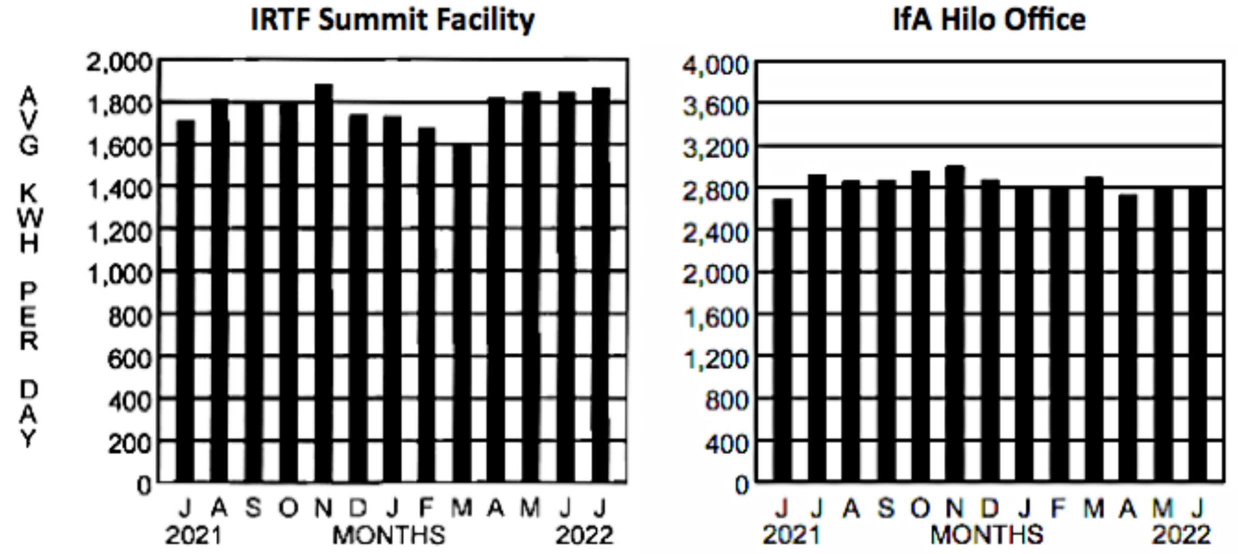

Figure 68. The Hawaiian Electric company billing for the IRTF summit facility and the UH/IfA Hilo office. The IRTF portion of the Hilo office electrical usage is about 25%.

14.2 Vehicle Use

IRTF has a fleet of eight gasoline vehicles for transfer of people and equipment between Hilo and the telescope at the summit of Maunakea. The standard vehicle is a 4WD Ford Explorer and we make on average four round-trips (70 miles) every day of the year for about 45 tCO2e per year in 2022. (Staff vehicle use during other trips is small by comparison.)

14.3 Electricity Use

Electrical usage at the telescope and at the IfA office in Hilo is shown in Figure 68 (Hawaiian Electric billing). The average use is 1800 kWh per day (260 tCO2e per year) at the summit and about 25% of 2800 kWh per day (121 tCO2e per year) at the UH/IfA Hilo office, for a total carbon footprint of 381 tCO2e per year. Neither facility currently uses solar panels.

14.4 Comparison with Keck and CFHT

Table 4 compares the carbon footprint per facility in the three major categories for the Keck Observatory (both Keck 1 and 2), CFHT and IRTF. The carbon footprint for Keck and CFHT are taken from McCann et al. (2022) and Flagey et al. (2020) respectively.

Table 4. Carbon footprint comparison

	Keck	CFHT	IRTF
Air travel	295	191	54
Gasoline vehicles	117	48	45
Electricity	1581	509	381
Total (tCO2e per year)	**1993**	**748**	**480**

Both CFHT and particularly Keck have bigger summit facilities and significantly more staff than IRTF and so it is difficult to conclude much from these comparisons. Both the Keck and CFHT electrical usage estimates are offset using solar panels both at the summit and base facility for Keck, and at the base facility for CFHT. UH and IRTF have not installed solar panels at their facilities. Probably the most significant difference is the relatively low IRTF carbon footprint for air travel due to remote observing. It should be noted that the CFHT and IRTF carbon footprints per employee are similar at 16 and 17 tCO2e per year per employee respectively.

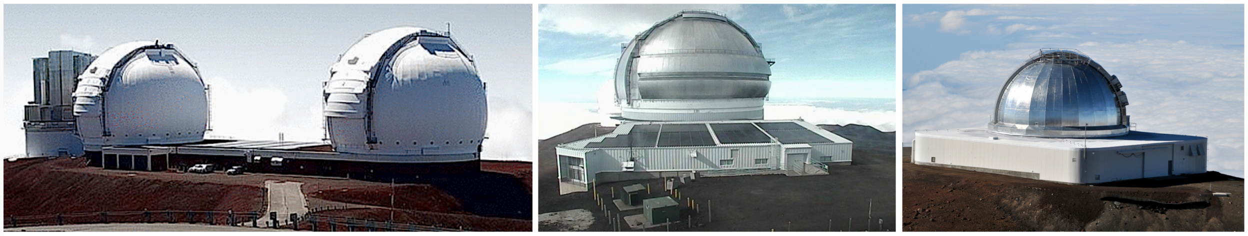

Figure 69. The solar panels on the roofs of Keck (*left*) and Gemini North (*middle*). The solar panels at Gemini North provide on average 650 kWh per day. There is little room for solar panels on the roof of IRTF (*right*).

The Paris Climate Accords recommend reducing an individual's average carbon footprint to about 3 tCO2e per year to stay below 2°C warming. It is difficult to see how IRTF can reduce air travel much more. Electrifying the gasoline vehicle fleet will help but a significant reduction in the electrical use at the summit and base facilities is needed (80% of the total, 54% from the summit facility). Keck and Gemini North have solar panels on the roof their summit buildings (see Figure 69). Unfortunately, the flat building roof at IRTF is small and solar panel placed there would suffer damage from ice falling off the dome. The heaviest user of electrical power at the summit is the HVAC system required to cool the dome, mirror and instrument helium compressors. Installing more energy efficient HVAC components and more energy efficient systems are the most viable options to reduce the IRTF's carbon footprint but this will require future investment.

15 FUTURE DIRECTIONS 2023-2032

In addition to maintaining the current IRTF capabilities for planetary science - a dedicated planetary telescope, flight mission support, planetary defense, flexible scheduling, daytime observing, observing campaigns, and unique instrumentation, we are planning important new capabilities and upgrades for the next decade. These are primarily to enhance the IRTF's role in planetary defense and to add capability for primitive body studies, and to exploit all-sky surveys to follow up on transient objects. Much frontline astronomical research can still be done productively on 3-4-m class optical-infrared telescopes by exploiting current and planned capabilities and that do not require larger and more expensive facilities.

New capabilities and science

Through remote-enabled flexible telescope scheduling and short observing blocks IRTF, is well-suited to monitoring programs and fast follow-up to target of opportunities (see sections 6 and 7). Planetary seasons and dynamical processes in planetary atmospheres last decades in the outer solar system, requiring long-term monitoring. In fact, for time domain observations IRTF covers the range from milliseconds (occultations) to decades, enhanced by almost year-round observations of planets through daytime observing. Rather than executing large programs, the peer review of observing proposals through the TAC process will continue to provide the opportunity for new ideas and follow-up of new discoveries. Telescope scheduling can also easily accommodate programmatic requests from NASA. To accommodate the expected increase in ToO and time-domain programs in coming years we anticipate scheduling dedicated time blocks of up to one night per week depending upon demand.

We continue to make incremental improvements to the delivered image quality of the telescope. The performance is limited by the original design: un-lightweighted Cer-Vit 201 primary mirror (6,100 kg) and a mercury ring radial support. The facility HVAC system keeps the mirror at a temperature within one K of the nighttime temperature for seeing control but the mercury ring support imparts focus drifts and some astigmatism as the telescope pointing changes. Although the image quality is good (median about 0.8″ FWHM at 2.2-μm) we are planning active focus and tip-tilt control with the FELIX off-axis wavefront sensor by 2023, eventually followed by active (slow) control of the wavefront with an adaptive secondary mirror (ASM, see section 1.3). These improvements will enhance sensitivity of all the Cassegrain-mounted instruments.

IRTF will continue to encourage the deployment of PI-lead instruments on the telescope, both for the purposes of science (through the TAC) and for R&D. Since 1990 about 20 different visitor instruments have been used at the telescope. In the immediate future the ASM project has the potential to significantly enhance telescope image quality, and demonstrate the TNO technology for adaptive secondary mirrors at other telescopes. In the long term equipping IRTF with AO is potentially a powerful capability but attendees at the community workshop expressed concern about the extra resources needed to develop and maintain an AO capability to the possible detriment of other IRTF capabilities (see section 12). Independently of the telescope itself, the high altitude of the facility is also advantageous for other experiments (e.g., the ClO monitor and the LIDAR experiment, see sections 1.2 and 1.3).

The ‘Opihi wide-field finder scope (see section 1.2) has just been commissioned and we expect its first use by observers in 2023. Its main purpose is for the recovery of newly found NEOs with large positional uncertainties. In addition, ‘Opihi can be used by observers as an extinction monitor, to bootstrap absolute photometry to SpeX observations, and as a general visible wavelength context camera.

For the overall science productivity of IRTF it is important to continue to equip the telescope with state-of-the-art instrumentation (e.g., see Figure 53). Probably our most important future project is the development of the new 0.4-4.2 μm R=150 integral field spectrograph, SPECTRE. It is being designed primarily as a capability for planetary defense to characterize NEOs, other small solar system bodies and potentially interstellar objects (see sections 1.3 and 3), and as a capability for fast characterization of variable objects discovered by transient sky surveys (see section 6.6). The one magnitude improvement is sensitivity will result in a factor of ten increase in the number of small bodies observable with $R \approx 100$ accurate spectrophotometry. Without the need for precise placement on a slit the IFU also enables very efficient 'point and shoot' observing. The wide-band coverage of the IFU will be unique and valuable to map extended targets such as Uranus (a future flagship-class mission target), and spatially resolve the big pixels of the soon-to-be-launched SPHEREx[25] all-sky 0.75-5 μm survey telescope.

SPHEREx will obtain spectra of millions of objects, and SPECTRE will be able to efficiently follow up these observations at a spatial resolution ten times better and a spectral resolution four to ten times better at wavelengths up to 4.2 μm, and extend the spectra down to the visible *U*, *B*, and *V* bands. One of the three main science topics of the SPHEREx mission is interstellar and circumstellar ices, and hundreds of thousands of new ice targets will be detected, the majority of which are bright enough for SPECTRE follow up at higher spatial and spectral resolution. The sensitivities of SPHEREx and IRTF/SPECTRE are well matched.

Precise and accurate information on the masses, radii, luminosities, and ages of stars is fundamental to nearly all areas of astrophysics: e.g. exoplanet composition (e.g., Weiss & Marcy 2014), variations in the initial mass function (e.g., van Dokkum & Conroy 2010), and cosmic expansion (e.g. Pietrzynski et al. 2013). These fields now regularly demand stellar properties to better than 5% accuracy. Asteroseismology and interferometry can provide information at the required precision but the number of targets is very limited. *Gaia* astrometry of binaries can measure masses to the required precision however masses alone are of limited use. To realize the full potential of *Gaia* binaries, we need comparably precise measurements of L_*, T_{eff} and R_* as well as age and metallicity, where possible. For stars with 2500 K$<T_{eff}<$6000 K, flux-calibrated spectra provide strong constraints on T_{eff} from the drop-off in the blue (Wien tail). By providing spatially-resolved flux-calibrated 0.4-4.2 μm spectra of thousands of *Gaia* binaries these capabilities will be uniquely provided by SPECTRE, providing the ultimate benchmark sample for testing stellar models and deriving empirical relations between fundamental parameters and observables (see section 6.3 and Figure 47). Overall, accurately flux-calibrated spectra would synergistically enhance the utility of the *Gaia* binary sample.

Both SpeX and SPECTRE will be very productive capabilities to follow up the transient sources found by the current optical (e.g., ATLAS) and coming infrared (e.g., WINTER) ground-based sky surveys (see section 6.5 and 6.6).

The 5-30 μm wavelength range is a niche for solar system observations on IRTF having largely been abandoned by other telescopes on Maunakea. The 5-20 μm camera, MIRSI, was successfully recommissioned in 2021 (see section 1.2). Its performance is currently limited by its engineering quality array and the lack of a chopping secondary capability. However, we have an MOU with NOIRLab for the transfer of a science grade array that is no longer needed from Gemini South's MIR camera (T-ReCS). We plan to install the science array in 2023. We are also adding a chopping capability to the hexapod secondary mirror. With these two upgrades we expect an improvement in 10 μm sensitivity of 1-2 magnitudes. The addition of an optical CCD channel enables MIRSI to directly measure asteroid albedos and sizes using their blackbody curves and improve the albedo-composition correlation for the NEO population. Estimates suggest that with the upgrades MIRSI will be able to measure the sizes of about 250 NEOs per year. Due to its unique and important role in the science of planetary atmospheres, we are considering converting the high-resolution 8-26 μm spectrograph TEXES

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[25] https://spherex.caltech.edu/

(see section 1.2 and 5.3) from a visitor instrument to a facility instrument on IRTF. Ideally, this would require hiring another support astronomer.

The high-resolution 1-5 µm spectrograph iSHELL is also a critical capability for planetary science (see sections 1.2, 5 and 6) – productive research programs on the Martian atmosphere, Jovian water, and the chemical inventories of comets, will continue over the next decade. The unique capability of extended daytime observing on IRTF is critical for the perihelion passage of comets and to monitor planets almost year-long with iSHELL, TEXES and SpeX. A particularly exciting observing program just underway with iSHELL and TEXES is to probe the conditions in planet-forming disks at the sites of terrestrial planet formation (Banzatti et al. 2022a, and Banzatti et al. 2022b). These observations are important to interpret the spectrally-unresolved (also kinematically-unresolved) JWST spectra (see Figure 6).

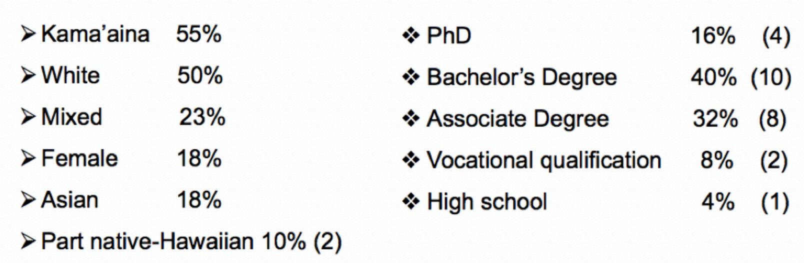
As a research facility it is important for us to give observers the tools to efficiently produce publishable data. With Spextool we have achieved this for our two main facility instruments, SpeX and iSHELL (see section 1.2). We are also in the process of converting Spextool from IDL to Python (pySpextool), which has become the community standard. The new version Spextool will also have a batch mode so that reduced data, rather than raw data, can be archived and curated at IRSA (see section 8). One of our support astronomers' main tasks is facility instrument data reduction.

We expect that most of these capabilities can be supported within the current a budget of about $6M per year (in 2022 dollars). The exception is the development of new facility instrumentation which we believe is required to keep the IRTF scientifically productive. Funding for the proposed SPECTRE instrument will be requested from NSF or NASA at an estimated cost of $4M.

Diversity and Outreach

We recognize the importance of supporting efforts to improve diversity and increase outreach at IRTF. Table 5 provides an indication of the race, gender and educational makeup of current IRTF staff. This is probably at least as diverse as any other Maunakea telescope facility.

Table 5. The race, gender and educational makeup of IRTF staff in 2022 (25 FTEs). We define Kama'aina as an individual that went to high school in Hawaii.



➢ Kama'aina	55%	❖ PhD	16%	(4)
➢ White	50%	❖ Bachelor's Degree	40%	(10)
➢ Mixed	23%	❖ Associate Degree	32%	(8)
➢ Female	18%	❖ Vocational qualification	8%	(2)
➢ Asian	18%	❖ High school	4%	(1)
➢ Part native-Hawaiian	10% (2)			

Although we strive to make IRTF as diverse as possible we are not currently as reflective of the local community as we would like to be. Part of the problem is finding individuals that are qualified for open IRTF positions. This illustrates the importance of continuing and improving upon our efforts in education and outreach for the local community (see section 13). A consensus that recently developed during Maunakea staff listening sessions was that all staff should be allowed about 2% of their paid time (one week per year) for outreach.

As enacted on July 7, 2022, in State of Hawaii Act 255, creating the new Maunakea Stewardship and Oversight Authority (MKSOA)[26] that is intended to replace the UH Center for Maunakea Stewardship (CMS)[27] in 2028, astronomy is now a policy of the State of Hawaii. The act requires MKSOA to promote astronomy, including education, training, employment, and professional employment opportunities for state residents. We will take this opportunity to create IRTF positions specifically for local residents (e.g., the Assistant Telescope Operator positions as discussed in section 13.1) and engage local teachers in outreach programs such as the Airborne Astronomy Ambassadors program (see section 13.2). To help with these and outreach efforts in general it also makes sense to add an outreach person to the IRTF staff.

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[26] https://www.capitol.hawaii.gov/sessions/session2022/Bills/GM1358_.PDF

[27] https://hilo.hawaii.edu/maunakea/stewardship/

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Note: Supporting documenets can be found on the IRTF website:
http://irtfweb.ifa.hawaii.edu/meetings/senior_review_2022/

These documents include recent powerpoint presentations to the NASA IRTF-Keck Users Group (the NIKUG) by IRTF staff, feedback reports from the NIKUG to IRTF, IRTF white papers to the astrophysics and planetary decadal panels, and various other documents that might be of interest to the Indpendent Review Panel.

1 APPENDIX: STATEMENT OF WORK 2019-2024

STATEMENT OF WORK
OPERATION OF
THE INFRARED TELESCOPE FACILITY (IRTF)

1.0 INTRODUCTION

This Statement of Work (SOW) delineates the services required to support the operation, maintenance, and development of the telescope system for the Infrared Telescope Facility (IRTF). NASA Headquarters is responsible for the general operational oversight of the IRTF. This is for the on-site operation of the IRTF, associated instrumentation, and observing programs. Over one hundred teams of astronomical researchers use the IRTF each year. These teams come from U.S. and foreign universities, NASA centers, other U.S. Government research centers, and research organizations.

1.1 BACKGROUND ON THE INFRARED TELESCOPE FACILITY (IRTF)

The NASA Infrared Telescope Facility (IRTF) is a 3-meter infrared telescope located at altitude of approximately 13,600 feet near the summit of Mauna Kea on the island of Hawaii. The IRTF was established by NASA in 1979 primarily to provide infrared observations in support of NASA's programs, and is the only U.S. ground-based national observatory dedicated to infrared astronomy. The IRTF consists of a large building that serves as a dome enclosure, control rooms, instrument rooms, equipment rooms, ready rooms, and associated support rooms, and a small building that houses a fan exhaust room. The telescope system consists of a telescope control station, a telescope control and guidance system with display, and computerized instrumentation and data collection facilities. NASA funds the operation of the IRTF; new focal plane instrumentation is developed by the Contractor primarily through instrumentation proposals to the National Science Foundation (NSF).

The astronomical observing time on the IRTF is allocated as follows: 75% of the total observing time is defined as available observing time; 15% of the total observing time is allocated to the University of Hawaii as a condition of the site lease agreement; and 10% of the total observing time is allocated to the scientific staff of the IRTF Contractor as engineering time to ensure high quality performance of the telescope and auxiliary instrumentation. Available observing time is for use by visiting scientists during periods of approved object availability on all nights of the year. The available observing time is open to the entire astronomical community; however, 50% of the available IRTF observing time is reserved for studies of solar system objects. The balance of available IRTF time is for astrophysical observations of the interstellar medium, stars and galaxies. A list of recent publications of observations, for information purposes, is publicly available at the IRTF Web site (http://www.ifa.hawaii.edu) for this procurement.

A physical description of the IRTF, including building, telescope, and auxiliary equipment, is provided as an attachment. This description includes a facility layout, instrumentation list, and other information determined by NASA as necessary for general understanding of work requirements.

A mid-level facility at Hale Pohaku (Onizuka Center for International Astronomy), which is owned by the University of Hawaii and operated by Mauna Kea Support Services, is located at approximately 9,200 feet approximately 34 miles from Hilo, Hawaii. Hale Pohaku (HP) is used as an astronomical support and acclimatization facility for the IRTF and other telescopes on

Mauna Kea. A description of HP is provided as an attachment. The description provided is determined by NASA as necessary for general understanding of work requirements.

2.0 CORE CONTRACT REQUIREMENTS

The Contractor shall provide the necessary engineering, operations, maintenance, and administrative services to operate and support the continual development of the telescope systems for the NASA Infrared Telescope Facility (IRTF). The scope of this SOW is based on the operation of the IRTF as an astronomical facility for all days of the year with the exceptions of Christmas Eve, of Christmas Day, and of New Year's Eve.

2.1 Management

The Contractor shall provide a Director who shall be the Government's primary point of contact for project direction to the Contractor. This Director shall be responsible for:

1. Ensuring appropriate Contractor personnel resources are provided to operate the IRTF in a state of observational readiness.

2. Providing detailed direction and administration of all Contractor personnel furnished for the required tasks.

3. Assuring the technical and scientific quality of performance and manpower schedules.

4. Preparing and maintaining a staffing plan and developing written procedures for utilization and assignment of Contractor staff to: (1) perform the immediate day-to-day needs for the maintenance and operation of the facilities; and (2) provide design and develop improvements and upgrades to the facility. These procedures will describe the Contractor's method of assigning duties and responsibilities for the various tasks and categories of support listed in this SOW.

5. Developing a plan for coordinating with the Contracting Officer's Representative (COR) on means of resolving conflicting priorities to satisfy the daily, near-term operations and the longer-term development tasks.

6. Assuring the work under this contract conforms to current NASA Headquarters' guidelines and policies.

The Contractor shall provide administrative support for the operations and tasks described in all sections of the Statement of Work.

2.2 Staff Requirements

The Contractor staff shall work with visiting scientists and NASA employees, and will be considered as a part of the research supported teams. Therefore, the Contractor staff must be capable of working with a variety of people in non-routine, often challenging, situations.

Most work functions are normally performed on 40-hour work week. However, nighttime operations require a different type of shift that is specified through and agreement with the telescope operator union. All overtime operations must be approved by the Director. The Contractor is responsible for maintaining continuity and coverage on ongoing work activities at all times.

Contractor personnel who routinely are present at the summit of Mauna Kea must be physically qualified to work at 13,600 feet for periods up to 12 hours. These personnel shall be assigned specific emergency duties and shall, in addition, maintain currency in American Red Cross Standard First Aid training (which includes CPR).

3.0 SPECIFIC TASKS

3.1 Operational and Maintenance Support

The Contractor shall operate and maintain the IRTF, its building, telescope, and auxiliary instrumentation as a visitor and remote observing facility. The Contractor shall be responsible for providing the following:

3.1.1 Adequate staffing to operate the IRTF at a fully functional level, including the telescope, instrumental and computer systems and their interfaces. The Contractor shall plan, organize, schedule and operate activities under this contract. The Contractor must successfully manage and coordinate software, hardware, electronic, optical, and mechanical technical personnel in order to provide for a smooth and efficient operation of the IRTF.

3.1.2 Precise or refined adjustments of telescope and associated optical and computer systems, including detectors, support systems, and air conditioning systems. Maintain, and where possible, surpass the design specifications of these systems. Improve existing facility instrumentation, computer systems and physical plant in ways that will enhance the capabilities of the facility for astronomical observations. The Contractor shall evaluate the performance of the entire telescope system on an annual basis and address this evaluation in the annual report of each contract year. (The requirement in 3.4.7 can serve as that reporting.)

3.1.3 Maintenance of the entire facility; including the facility instrumentation, computer systems, auxiliary instrumentation, control systems, associated infrastructure (electrical, hydraulic, HVAC, plumbing, computers, interfaces with the Mauna Kea computer LAN, etc.) and physical plant [roads (through Mauna Kea Support Services), buildings, and approximately seven existing GSA leased vehicles] in a fully operational and safe condition. This will include updating of documentation (operators manuals for facility instrumentation as well as the telescope and computer systems), preliminary and extended data reduction procedures, and documenting and carrying out an active preventative maintenance program on instrumentation, telescope, and associated support systems.

3.1.4 Design, fabrication and commissioning of new state-of-the-art facility instrumentation. Requirements for the observing instrumentation will be determined in consultation with NASA. Development of such instrumentation will be primarily funded by the National Science Foundation (NSF) under separate grant agreements with the Contractor.

3.1.5 Continued development of and completion of the existing upgrade projects and instruments.

3.2 Visiting Scientist Support

The Contractor shall provide support for visiting scientists during the period of approved object availability on all days/nights of the year. The term "visiting scientist" is defined as a scientist and other team members whose observing proposal has been approved independently by the Telescope Allocation Committee (TAC) and to whom observing time on the IRTF has been awarded. The Contractor, in consultation with the NASA, will select a Telescope Allocation Committee (TAC), which is composed of approximately eight or more peers from the infrared astronomical community who have expertise in solar system and astrophysical disciplines. Peer review regulations shall apply to TAC members with respect to the review of proposals in which they may have a conflict of interest, such as home institution and/or scientific collaboration. The Contractor shall be responsible for chairing, coordinating and supporting the travel and functions of this committee, as outlined in paragraph 3.4.2 hereunder. Visiting scientist support shall include the following:

3.2.1 Local ground transportation of personnel to and from local Contractor

offices/headquarters, the mid-level support facility at Hale Pohaku, and the summit, as well as local ground transportation of associated equipment (if any) to and from the local airport closest to Contractor offices/headquarters, the mid-level support facility at Hale Pohaku, and the summit.

3.2.2 Full housing and three meals daily for up to two observing team members at the mid-level facility (HP) for up to two days before their observing run (for the altitude acclimatization and any instrument preparation), during their observing run, and one day after the completion of their observing run. Additional support may be provided to instrument teams at the discretion of the Director.

3.2.3 Assistance in the installation of facility and user equipment at the telescope including any required telescope configuration changes or interfacing of computer systems, (assuring the operation of facility instruments).

3.2.4 Provision of electronic and computer hardware technician support. The Contractor personnel must be able to quickly recognize and analyze operational failures of telescope systems and facility instruments; recommend and perform repairs or work-arounds during installation or an observing period. If the repairs require specialized personnel who are not at the summit, the Contractor shall make all reasonable attempts to carry out these repairs before the next observing session. When appropriate this support may be accomplished by personnel who are not on-site, but have telecommunications/LAN links available and can provide this support via those links.

3.2.5 Observer orientation including up to date telescope, instrument and computer manuals and provide the necessary introduction and assistance at the telescope for an observing run by the instrument scientist or equivalent. This orientation and assistance shall ensure efficient and safe operations of valuable observatory equipment.

3.2.6 Assistance by a telescope operator during the observing run, primarily in the operation of the IRTF telescope, associated IRTF instruments, and IRTF computer systems and networks.

3.2.7 Provision of cryogens (liquid nitrogen and liquid helium) and replacement of closed-cycle coolers when needed for the facility IRTF instruments. Visiting observers using their own instruments shall be provided with liquid nitrogen. Visiting observers using their own instruments shall be provided with liquid helium at the discretion of the Director.

3.2.8 Provision of supplemental work areas or laboratory space for visiting scientists and their associated instrumentation at the summit facility. The Contractor shall provide support of this laboratory space to include: (1) maintenance of these areas and the equipment, supplies and tools located in them; and (2) planning and implementation of improvements to these areas and the equipment used in them, as appropriate. The equipment involved includes vacuum systems, leak detectors, cryogenic transfer lines and dewars, hand tools, electronic test equipment and tools, and a few machine tools. Such supplemental work areas may include offices and laboratory areas, as necessary, and shall be sufficient to house facility instruments.

3.2.9 Provision of preliminary and extended data reduction software shall be made available to visiting scientists, including non-linear detector response and flat-fielding. Support shall be provided to visiting scientists in the use of this software. All software procedures shall be documented and maintained by the Contractor.

3.2.10 Provision of access to the Internet at HP and the summit facilities, including maintenance and updating of the existing homepage, IRTF online server and file system which is available to the general astronomical community via the Internet.

3.2.11 The Contractor shall provide a service observing program when such observations can be performed by the Telescope Operator. Such programs would be done at the discretion of the Director and the availability of manpower.

3.2.12 Proposals that have requested remote observing will be supported provided the observer has the required Internet bandwidth and hardware. The Contractor shall provide the capability on the IRTF-side with the instructions for the visiting astronomer(s) for real-time communications with the telescope operator through reliable means and for real-time communications with the instrumentation to be used through a secure Internet connection.

3.3 Engineering Support

The Contractor shall be responsible for design of custom hardware, including instrumentation funded through NSF grants, and software for the observatory. The designs may be for complex systems composed of mechanical, vacuum, cryogenic, pneumatic, refrigeration, electronic, computer or optical subsystems or components. While Standard Commercial Equipment is used whenever practical, most engineering tasks will require unique and innovative solutions for one-of-a-kind systems.

The Contractor shall provide design for new systems, upgrades to existing systems, and design analysis for IRTF telescope systems. The engineering shall include conceptual planning, the development of specifications, and detailed design for fabrication and installation. All design work shall be in accordance with NASA, industry, or Mil Standards as approved by the COR, including standards for drawings, parts lists, and materials selections.

In addition to engineering design for new systems or system upgrades, the Contractor shall provide engineering support to solve complicated troubleshooting or maintenance problems and shall support scientists in solving integration or other experiment problems.

3.3.1 Engineering Supervision

The Contractor shall schedule, coordinate and review all design activities performed under this contract. The activities which must be successfully managed and coordinated include electrical/electronic and mechanical/structural engineering, design and drafting, software development, and the testing of hardware and software. The Contractor shall be responsible for maintaining proper documentation of the work.

3.3.2 Electrical/Electronic Engineering

The Contractor shall provide competent electrical and electronic engineering support for the design and analysis of both analog and digital hardware. This will include design of new, custom hardware as well as modifications to existing facility hardware. The electrical/electronic engineering tasks under the contract may involve the design and fabrication of telescope subsystems controlled by microprocessors or computers.

3.3.3 Mechanical/Structural Engineering

The contractor shall provide competent mechanical engineering support of the analysis and/or design of mechanical systems associated with the IRTF. These mechanical systems may stand alone or may be integrated into complex systems involving optical, electronic, servo, etc., subsystems. Some engineering tasks will require use of finite-element stress analysis.

3.3.4 Software Engineering, Development, and Maintenance

The Contractor shall provide systems and software engineering, development, and maintenance for the IRTF. The Contractor shall be required to develop and maintain appropriate applications and systems software. Disciplines that may be required in providing programming support for the IRTF include astronomical coordinate systems and spherical astronomy, Fourier analysis, servo-control systems, graphics display techniques and interface, database management, microprocessor applications, data and interface software and maintenance.

3.3.5 Electromechanical Design

The Contractor shall be responsible for design of items such as equipment upgrades and modifications, wiring changes, electronic racks and chassis. Many assignments will require considerable initiative, resourcefulness and drafting expertise.

3.3.6 Documentation

The Contractor shall maintain original copies of all facility documentation for hardware and software changes to telescope systems and instruments. Examples of facility documentation are engineering drawings, software listings, test reports, design reports, systems analyses, equipment logs, component data sheets, and manuals.

3.4 Management and Administrative Support

To provide the following management and administrative functions in support of the IRTF and its facilities, the Contractor shall provide for the following:

3.4.1 Prepare all financial, administrative, maintenance reports specified under this contract.

3.4.2 Semi-annually, publicize availability of observing time, receive and evaluate proposals for observing time through the Telescope Allocation Committee (TAC), and schedule observing runs.

3.4.3 For the users of the IRTF, post updates to the IRTF website containing information pertinent to telescope, instruments, telescope time and schedule.

3.4.4 As either requested and/or approved by the COR, prepare and submit proposals to the National Science Foundation (NSF) in order to acquire new instrumentation for the IRTF on a timely basis, as opportunities and funding permit, with the understanding that such proposals would be subject to the NSF proposal review process.

3.4.5 Maintain the scientific stature of the IRTF Contractor staff through individual astronomical research programs using the IRTF and other facilities, if necessary. Such research may include non-solar system, as well as solar system observations.

3.4.7 Plan, prepare, and present materials and presentations on IRTF operations and scientific results for the semiannual NASA Keck/IRTF Management Operations Working Group, or "Users Group," meetings (one annual meeting at the IRTF facility in Hawaii and one annual meeting in Washington, D.C) in coordination with the chairperson of the MOWG. Such materials and presentations shall be designed to make the meetings informative and productive, and may serve as a reporting avenue to NASA.

3.4.8 The Contractor may submit an augmentation proposal which recommends appropriate extra-contractual investments by NASA in capital equipment, major maintenance items and unique opportunities related to the IRTF facility.

3.4.9 A proposal requesting support for observers carrying out astrophysical programs ("IRTF Visitor Support") shall be submitted to the National Science Foundation (NSF).

3.5 Future Development Support

3.5.1 Develop and deliver to the COR within six months of the start of the contract, a long range (5 year), strategic plan to maintain the current IRTF status as a Center of Excellence in infrared astronomy.

3.5.2 Continually adapt and apply new optical, electronic and detector technologies and operating modes into existing instrumentation.

3.5.4 Continue to develop ongoing alternative observing strategies, such as service observing and remote observing programs, which may be needed to address needs of the multi-faceted cadre of current and future NASA missions.

3.5.5 Outline and deliver plans for maintaining and improving the scientific expertise of the IRTF Support Astronomers, who are the vital, human links between the stable of IRTF related instruments and scientific publications.

3.6 Data Archiving

3.6.1 The Contractor shall maintain and support the data archiving activities established for preserving science-quality astronomical data acquired with IRTF facility instruments, and relevant metadata, in NASA public data archives (i.e., NASA's Infrared Science Archive). This includes the internal data management to facilitate the processing and delivery of the data to the archive, including the formatting of data, the capturing of metadata, and the storage and preservation of telescopic and engineering data.

3.6.2 The Contractor shall, to the extent possible and practical, make legacy data (data acquired prior to the public data archiving activities and not incorporated into the archive) available upon request.

4.0 Indefinite Deliverable Indefinite Quantity (IDIQ) PORTION REQUIREMENTS

The Contractor shall provide any major maintenance repairs to the IRTF outside of the normal routine maintenance covered in the core contract. For example, this may include major repairs to the facility building or telescope structure.

The Contractor shall provide, at the request of NASA, any operations services outside of the normal routine operation services covered in the core contract. This may include mission critical observations or observations of a programmatic rather than scientific nature.

The Contractor shall provide, at the request of NASA, any data management services outside of the normal routine data management services covered in the core contract. This may include enhanced data archival activities not included in the baseline activities, such upgrades to archiving activities, upgrades to access management, or upgrades to usage statistics reporting.

The Contractor shall provide, at the request of NASA, any instrument development deemed of strategic importance and not already covered through grant agreements between the Contractor and the National Science Foundation following proposal through available competitive opportunities. This may include instrumentation to meet particular flight mission support needs or programmatic needs for NASA.

The Contractor shall, at the request of NASA, manage any increase in the sub-lease payment amount that may result from an updated or new Maunakea sub-lease agreement between NASA and the University of Hawaii.

2 APPENDIX: PROGRAMS AWARDED IRTF OBSERVING TIME IN 2022A

Near-Earth Objects

Observations of Near Earth Objects with the new MIRSI+MOC: Diameters and albedos (**MIRSI/MOC**)

Investigating the regolith properties of NEAs: Thermophysical modeling constrained by IRTF/SpeX observations and shape information (**SpeX**)

Characterization of NASA Janus mission target 1996 FG3 (**SpeX**)

IRTF NEO Rapid Response: Close Encounters of the Asteroid Kind (**SpeX/MORIS**)

Spectral Measurements of Spacecraft Mission Candidates and Potentially Hazardous Asteroids (**SpeX/MORIS**)

Main-belt / Trojan asteroids

Mapping Water in the Outer Asteroid Belt (**SpeX**)

Near-Infrared Spectroscopy of Outer Main Belt Asteroids (**SpeX**)

SpeX validation of the high abundance of olivine-rich asteroids from Gaia spectra (**SpeX/MORIS**)

Understanding Space Weathering in the Koronis Asteroid Family (**SpeX/MORIS**)

NIR spectroscopy of the Polana family: Exploring the small members (**SpeX/MORIS**)

Searching for Red Outer Solar System Materials in the Middle & Outer Main Belt (**SpeX/MORIS**)

Constraining the connection of the primordial family to other asteroid families in the inner Main Belt (**SpeX/MORIS**)

Observational Campaign of the Gefion Asteroid Family [GAF] (**SpeX/MORIS**)

Major planets / satellites

Global mapping of H2O, HCl, trace gases and their isotopic signatures in the Martian atmosphere. (**iSHELL**)

D/H ratio in water vapor: key diagnostic to water history on Venus (**iSHELL**)

Search for variation of minor species in Venus' Atmosphere (**iSHELL**)

Mapping of Methane and Searching for Other Organic Molecules During Northern Late Summer/Early Fall on Mars (**iSHELL**)

High-cadence imaging measurements of Jupiter's mid-infrared auroral emission (**MIRSI**)

Mid-Infrared Characterization of Evolving Atmospheric Processes in Jupiter During Juno Perijoves 41-43 and Potential *JWST* Observations (**MIRSI**)

Near-Infrared Characterization of Evolving Atmospheric Processes in Jupiter During Juno Perijoves 41-43 and Potential *JWST* Observations (**SpeX**)

Unraveling the carbon, nitrogen, and sulfur chemical systems operating on the Galilean moons Ganymede and Callisto: What species and processes form the 4.6-micron band? (**SpeX**)

Investigating Titan's Northern Summer meteorology through cloud monitoring with IRTF SpeX (**SpeX**)

Water in the Moon (**SpeX**)

High Cadence Imaging of Io's Volcanos to Understand Volcanic Outbursts and The Periodicity of Loki (**SpeX/iSHELL**)

Investigating the composition of dark material on the Saturnian moons Tethys, Dione, Rhea, and Iapetus: Rich in ammonia and organics? (**SpeX/MORIS**)

Spectral Image Cubes of Venus in Support of *Akatsuki* Observations (**SpeX/MORIS**)

Are Jupiter Irregular Satellites and Ceres-like Asteroids Related? (**SpeX/MORIS**)

The role of long-lived Waves and Instabilities in the Atmospheric Super-rotation of Venus. (**SpeX/MORIS/MIRSI/MOC**)

The thermal structure of Venus' mesosphere from high resolution observations of CO2 lines (**TEXES**)

Studying Io's Seasonal Atmosphere and Investigating Volcanic Emissions (**TEXES**)

Characterizing Jupiter's Deep Belt/Zone Structure in the era of the *Juno* mission and the *JWST* observations (**TEXES**)

IRTF-TEXES spectroscopy of Jupiter's mid-to-high latitudes: support for the *Juno* mission (**TEXES**)

Thermal mapping of SO2 and HDO at the cloud top of Venus (**TEXES**)

Saturn since *Cassini*: seasonal progression with IRTF and JWST (**TEXES**)

Comets

A Study of Parent Volatile Compositions and Searching for Seasonal Effects in Short-period Comet 19P/Borrelly (**iSHELL**)

Characterizing the Parent Volatile Composition and Outgassing of a Target-of-Opportunity Comet (**iSHELL**)

Study of the composition and outgassing behavior of comet C/2021 O3 [PanSTARRS] at small heliocentric distances (**iSHELL**)

Investigation of CO vs H2O driven outgassing in comet C/2017 K2 [PanSTARRS] (**iSHELL**)

The exceptional passage of comet C/2021 O3 [Pan-STARRS]: investigations of its volatile and isotopic composition at near-IR wavelengths. (**iSHELL**)

Deciphering Cometary Outbursts (**SpeX/MORIS**)

Temporal variability of the physical properties of water-ice grains in cometary comae. (**SpeX/MORIS**)

Centaurs / TNOs / KBOs

Occasional Triton spectra 2020-2023 for rotational and seasonal variability (**SpeX**)

Temporal Evolution of Pluto's Surface in Late Spring (**SpeX**)

Stellar occultations by Pluto and Quaoar (**SpeX/MORIS**)

Do all outbursts of active Centaur 29P/Schwassmann-Wachmann 1 look alike? (**SpeX/MORIS**)

Makemake's visible and compositional variability (**SpeX/MORIS**)

Stellar

Hidden Binaries in the Beta Pictoris Moving Group (**iSHELL**)

Magnetic field measurements of M dwarf stars using high-resolution near-infrared iSHELL spectra (**iSHELL**)

C/O ratio of M stars with T-dwarf companions (**iSHELL**)

Pinpointing the Common Envelope Phase with Precise Masses for HZ 9 (**iSHELL**)

Catching the Wind: Uncovering the peculiar mass loss histories of Symbiotic X-ray binaries with iSHELL spectroscopy (**iSHELL**)

A ToO study of young stars with major eruptions (**SpeX**)

LAERTES: L-Band Accretion Estimator Reconnaissance of TTS Emission Spectra (**SpeX**)

The Mass Function of the Galactic Halo Down to the Hydrogen Burning Mass Limit (**SpeX**)

Infrared spectroscopy to support an optical interferometric study of symbiotic stars (**SpeX**)

Retrieving Physical Parameters of a Volume-Limited Sample of Brown Dwarfs (**SpeX**)

Calibrating Brackett alpha as a protostellar mass accretion tracer (**SpeX**)

SpeX spectroscopy of Luminous Red Novae (**SpeX**)

Characterizing New Nearby Ultracool Dwarfs with IRTF/SpeX (**SpeX**)

Characterizing the Ultracool TESS Targets: Investigating the Role of Gravity in Planet Hosts (**SpeX**)

Probing the Local IMF with Backyard Worlds (**SpeX**)

Characterization of brown dwarfs in the feedback driven star-forming region IC1396 using SpeX (**SpeX**)

New Cold Compact Source Discoveries in the Galactic Plane (**SpeX**)

Benchmark Brown Dwarf Systems (**SpeX**)

Determining stellar embryo properties from present day observations of young stars (**SpeX/iSHELL**)

An Infrared Perspective on a Stellar Mass-loss Mystery in Symbiotic X-ray Binaries with SpeX and MIRSI (**SpeX/MIRSI**)

Eruptions from Young Stars: Following the next outburst from V347 Aurigae (**SpeX/MORIS**)

Synoptic SpeX Observations of RS Ophiuchi -- The 2021 Event (**SpeX/MORIS**)

Studying the Formation and Dissipation of Transient Decretion Disks in Newly Discovered Be Stars (**SpeX/MORIS**)

SpeX 'Snapshots' of V1391Cas and V140Cas - Novae in the Dust and Coronal Emission Line Phase (**SpeX/MORIS**)

IRTF SpeX Time Domain Observations of the RW Aurigae A Classical T Tauri 'Planet Eating' System (**SpeX/MORIS**)

What darkens Chi Cyg? Investigating the dynamics of the variable S-type star via TiO and SiO high-resolution mid-IR observations (**TEXES**)

Exoplanets

An iSHELL survey of M-band CO spectra from Protoplanetary Disks (**iSHELL**)

Transit Spectroscopy of a Nearby Young Exo-Neptune (**iSHELL**)

Observing asymmetry and potential variability due to embedded companions in the ro-vibrational CO emission of HD 36112 and V380 Ori. (**iSHELL**)

Discovering the youngest free-floating planets: spectroscopic confirmation of candidate young brown dwarfs and planetary mass objects in Taurus and Barnard 5 (**SpeX**)

Characterizing the Variable Debris Disk Around HD 166191 (**SpeX/MIRSI**)

Coordinated IRTF/SpeX and Subaru/SCExAO observations of Stars with Planet-Building Disks (**SpeX/MIRSI**)

Galactic / Interstellar medium

SpeX IR Spectroscopy of Candidate Obscured Stars With Ice Absorption Spectra (**SpeX**)

Spectroscopy of 20 Myr-old Stars with Circumstellar Disks (**SpeX**)

Variation of SiO Rovibrational Lines in Asymptotic Giant Branch Stars (**TEXES**)

Extragalactic

The first near-IR spectroscopic campaign contemporaneous with a *Hubble Space Telescope* UV campaign to map the dust in the torus and accretion disk in the AGN Mrk 817 (**SpeX**)

Infrared Spectroscopic Reverberation Mapping of two GRAVITY/VLTI-targeted Active Galactic Nuclei (**SpeX**)

Improving SN Ia IR K-Corrections for Dark Energy, Peculiar Velocities, and the Hubble Constant (**SpeX**)

Disentangling radiating particle properties and jet physics from M87 multi-wavelength variability (**SpeX/MORIS**)

Nuclear Transients Through the Lens of SpeX (**SpeX/MORIS**)

SpeX NIR spectroscopy of Infant Type Ia supernovae (**SpeX/MORIS**)

Probing Mass Loss and Chemical Evolution in Core-Collapse Supernovae with Near-Infrared Spectroscopy (**SpeX/MORIS**)

3 APPENDIX: PROGRAMS AWARDED IRTF OBSERVING TIME IN 2022B

Near-Earth Objects

Observations of Near Earth Objects with MIRSI and MOC (**MIRSI/MOC**)

Constraining thermal properties of Near-Earth Object with MIRSI (**MIRSI/MOC**)

Investigating the regolith properties of NEAs: Thermophysical modeling constrained by IRTF/SpeX observations and shape information. (**SpeX**)

How dusty is the *DART* impact? Following Dimorphos' ejecta evolution (**SpeX/MORIS**)

Near-Infrared Spectral Observations of High Priority Near-Earth Objects (**SpeX/MORIS**)

IRTF NEO Rapid Response: Close Encounters of the Asteroid Kind (**SpeX/MORIS**)

Main-belt / Trojan asteroids

Mapping Water in the Outer Asteroid Belt (**SpeX**)

3 micron mapping of asteroid [2] Pallas during its 2023 opposition (**SpeX**)

NIR Investigation of the Trojan Asteroid Eurybates, its Collisional Family, and the three L4 Lucy Mission Targets (**SpeX/MORIS**)

Searching for Red Outer Solar System Materials in the Middle & Outer Main Belt (**SpeX/MORIS**)

NIR spectroscopy of the Polana family: Exploring the small members (**SpeX/MORIS**)

Understanding Space Weathering in the Koronis Asteroid Family (**SpeX/MORIS**)

Major planets / satellites

Grand Prix at Uranus: Measuring Ion flows at the Southern Aurora (**iSHELL**)

Water Clouds and Volatiles on Jupiter Concurrent with *JWST* and *Juno* (**iSHELL**)

iSHELL Observations of Uranus' K-band H2 Emission Spectrum (**iSHELL**)

Probing the sources and sinks of HCl on Mars (**iSHELL**)

Mid-Infrared Characterization of Evolving Atmospheric Processes in Jupiter During *Juno* Perijoves 44-48 and Potential HST and *JWST* Observations (**MIRSI**)

The origin of recent polar brightening on Uranus (**SpeX**)

Occasional Triton spectra 2020-2023 for rotational and seasonal variability (**SpeX**)

Investigating Titan's seasonal meteorology through cloud monitoring with IRTF SpeX (**SpeX**)

The Moon's three micron band: Behavior during partial and total eclipse (**SpeX**)

Titan's Stratospheric Winds from an Occultation before Equinox (**SpeX/MORIS**)

Investigating the origin of Nereid and the spectral hints of NH_4-bearing minerals on its surface (**SpeX/MORIS**)

Near-Infrared Characterization of Evolving Atmospheric Processes in Jupiter During *Juno* Perijoves 44-48 and Potential *JWST* and *HST* Observations (**SpeX/MORIS**)

Investigating CO2 cycles on the Uranian moons: Radiolytic production and migration to low latitude cold traps? (**SpeX/MORIS**)

Studying Io's Seasonal Atmosphere: Approach to Perihelion (**TEXES**)

Evolution of Jupiter's polar stratosphere: supporting *Juno's* extended mission (**TEXES**)

Characterizing Jupiter's Deep Belt/Zone Structure in the era of the *Juno* mission and the JWST observations (**TEXES**)

Saturn's northern summer with IRTF and *JWST* (**TEXES**)

Investigating nitrile chemistry on Titan (**TEXES**)

Comets

Compositional measurements as comet C/2017 K2 [Pan-STARRS] transitions from hypervolatile to water dominated activity. (**iSHELL**)

Compositional Study and Seasonal Variability of Newly Discovered Comet C/2022 E3 [ZTF]. (**iSHELL**)

Characterizing the Parent Volatile Composition and Outgassing of a Target-of-Opportunity Comet (**iSHELL**)

Deciphering Cometary Outbursts (**SpeX/MORIS**)

Temporal variability of the physical properties of water-ice grains in cometary comae. (**SpeX/MORIS**)

Centaurs / TNOs / KBOs

Temporal Evolution of Pluto's Surface in Late Spring (**SpeX**)

Stellar occultations by the large trans-Neptunian objects Quaoar and 55638 (**SpeX/MORIS**)

Rotationally resolved spectroscopy of the dwarf planet [136199] Eris (**SpeX/MORIS**)

Stellar

Spectro-astrometry of the planet-forming regions of circumstellar disks (**iSHELL**)

The Disk Eclipse of R Aqr (**iSHELL**)

High resolution spectral survey of RW Aur A (**iSHELL**)

Telling them apart: Identifying the first chemical differences between R Coronae Borealis and dustless Hydrogen-deficient Carbon stars (**iSHELL**)

Discovery of an Exceptionally Short-Period Very Low Mass Binary (**iSHELL**)

From active to inactive magnetic dynamos in pre-main-sequence stars (**iSHELL**)

Fluorine Abundances in AGB Carbon Stars (**iSHELL**)

Using iSHELL to Explore Chemical Inheritance and Evolution in Young Stellar Objects (**iSHELL**)

Precision Fundamental Properties of M Dwarf Stars using Eclipsing Binaries from *TESS* (**iSHELL**)

LAERTES: L-Band Accretion Estimator Reconnaissance of TTS Emission Spectra (**SpeX**)

Constraining the Effects of Large Cool Spots on the Early Evolution of Sun-like Stars (**SpeX**)

Understanding Mass Accretion and Outflow Variations Triggered by Binary Orbital Motion (**SpeX**)

Studying the Formation and Dissipation of Transient Decretion Disks in Newly Discovered Be Stars (**SpeX**)

In search of the missing stellar mergers: A systematic search for mid-infrared outbursts near the Galactic plane (**SpeX**)

Spectroscopy of 20 Myr-old Stars with Circumstellar Disks (**SpeX**)

IRTF Observations of Large-scale Wind Structure and Mass-loss in Wolf-Rayet Stars (**SpeX**)

Characterizing the Ultracool *TESS* Targets: Investigating the Role of Gravity in Planet Hosts (**SpeX**)

Time-dependent dust heating and reverberation in the disk of the highly accreting classical T Tauri star DR Tau (**SpeX**)

A Survey for Members of the 32 Ori Association (**SpeX/iSHELL**)

High-resolution IR observations of TiO and SiO in Mira-type variables at different stellar phases (**TEXES**)

Monitoring the molecular absorption of the torus in the PPN CRL618 (**TEXES**)

Exoplanets

Observing variability in the ro-vibrational CO emission of the multi-star system V892 Tau (**iSHELL**)

Star Spots on the Planet-hosting Star HD189733 (**iSHELL**)

Searching for the Companions to Brown Dwarfs Showing the Cyclotron Maser Instability (**iSHELL**)

NIR Radial Velocity Follow Up of Exoplanet Candidates Orbiting Young Stars (**iSHELL**)

An iSHELL survey of M-band CO spectra from Protoplanetary Disks (**iSHELL**)

Characterizing Cool Hosts of Candidate Transiting Exoplanets with IRTF/SpeX (**SpeX**)

Probing the Formation of Directly Imaged Exoplanets via Robust Atmospheric Characterization (**SpeX**)

Running Out of Gas near the End of Planet Formation (**SpeX**)

Galactic / Interstellar medium

Cosmic-ray ionization rates inferred from H3+: testing predictions of cosmic-ray transport theories (**iSHELL**)

Tracking the kinematic ridge features of the Milky Way disk with Cepheids (**iSHELL**)

Extragalactic

Infrared Spectroscopic Reverberation Mapping of a GRAVITY/VLTI-targeted Active Galactic Nucleus (**SpeX**)

Improving SN Ia IR K-Corrections for Dark Energy, Peculiar Velocities, and the Hubble Constant (**SpeX/MORIS**)

Rapid SpeX Follow-up of a New Kilonova (**SpeX/MORIS**)

A SpeX View of Luminous Nuclear Transients (**SpeX/MORIS**)

Probing Mass Loss and Chemical Evolution in Core-Collapse Supernovae with Near-Infrared Spectroscopy (**SpeX/MORIS**)

SpeX NIR spectroscopy of Infant Type Ia supernovae (**SpeX/MORIS**)

Disentangling radiating particle properties and jet physics from M87 multi-wavelength variability (**SpeX/MORIS**)

4 APPENDIX: EXCERPTS FROM THE NASEM PLANETARY SCIENCE AND ASTROBIOLOGY DECADAL SURVEY 2023-2032

Excerpts from the Planetary Science and Astrobiology Decadal Survey 2023-2032 are reproduced here to illustrate planetary science areas that IRTF observations directly or indirectly addresses. The relevant chapter and page of the excerpted text are given (e.g. **1-4** for chapter 1- page 4).

1 Planetary Defense

1-4 Planetary defense is an international cooperative effort to detect and track objects that could pose a threat to life on Earth. As such its motivations are more concerned with human health and safety rather than the advancement of scientific understanding. The threat posed by extraterrestrial bodies to Earth and its inhabitants was amply demonstrated in 2013, when a 20-m diameter asteroid detonated at an altitude of some 23 km over the Siberian city of Chelyabinsk. The resulting explosion released nearly 450 kt (~2 petajoules) of energy and caused non-fatally injuring to more than 1,600 people. This event highlighted the fact that Earth travels around the Sun amidst millions of small objects in similar orbits that sometimes cross Earth's orbit (see, for example, NASEM 2018c). Planetary science and exploration provide knowledge and tools to detect, track, and characterize such objects, key inputs to developing realistic detection and mitigation strategies against these natural disasters. Starting in the 1990s, Congress and presidential administrations have directed NASA to take a lead role in planetary defense and that role has grown in the past decade. NASA, NSF, and other government agencies collaborate in activities in support of planetary defense. This decadal survey is the first to include planetary defense in its charter.

1 The Relationship Between Ground and Space-Based Research

1-4 Planetary science is a multidisciplinary endeavor and is conducted by a synergistic combination of ground- and space-based activities. No one type of research approach (e.g., spacecraft missions, telescopic observation, and theoretical studies) is more or less important that the others. All research approaches and techniques have a role to play if progress is to be made in addressing key scientific issues.

Today, ground and space-based telescopic observations continue to provide key support to robotic space missions, e.g., by characterizing targets in advance of spacecraft encounters, and ongoing observations provide data between missions as well.

1 Support for Planetary Science and Astrobiology

1-5 The primary purpose of NSF-AST is to support research in ground-based optical, infrared, and radio astronomy. NSF-AST provides access to world-class research facilities and supports the development of new instrumentation and next-generation facilities. NSF-AST also supports basic research in planetary astronomy.

2 Outer Solar System Small Bodies

2-39 Ground-based observations have also led to the notable discovery of rings around some small bodies. In 2014, Chariklo, a 250-km body, was the first Centaur shown to have rings, detected through stellar occultations. Since then, rings have been discovered around the dwarf planet Haumea, and the Centaur Chiron is suspected to have rings as well.

9 Q6.6a What Processes Are Important in Controlling the Trace Gas Composition of the Martian Atmosphere?

9-24 CH4 has been reported in Mars's atmosphere from ground-based spectroscopic measurements (Mumma et al. 2009) and mass spectrometer measurements made by NASA's *Curiosity* rover (Webster et al. 2018). These measurements suggest that CH4 is present at ppbv levels and that its concentration exhibits both spatial and temporal variations, with maximum values up to ~7 ppbv. But ESA's *Trace Gas Orbiter*, which should be capable of detecting CH4 levels of ~10 ppt, found no evidence for it (Korablev et al. 2019). What is the resolution to this conundrum?

16 Dual Anonymous Peer Review

16-16 **Finding:** DAPR mitigates bias in proposal selections. The process by which it was achieved at STScI is a model for improving other procedures and policies.

16 Inclusion of URC Members in Initiatives to Improve the Diversity of the Community

16-21 **Finding:** NASA's engagement programs have supported the increased representation of women in planetary science over time, but to date have had a lesser impact on URCs (Section 2). Measures to increase participation of URC students in NASA's student and early-career fellowship funding programs, and in fellowship programs that facilitate engagement of NASA-funded PS&AB researchers with faculty URCs, are crucial to improving racial and ethnic diversity in PS&AB.

18 NEO Characterization

18-9 Spectral similarities between a NEO and specific meteorite compositions can be used to estimate an object's mineralogical makeup. NASA's Infrared Telescope Facility in Hawai'i has made key contributions to the spectral characterization of NEOs, and continuing such efforts is important for refining mineralogic classifications. These classifications are then used to infer bulk densities, physical strengths, and assumptions about internal structure, albeit with significant uncertainty, since porosity is not known.

18-10 **Finding:** Meteor, fireball, and bolide events offer naturally occurring opportunities to characterize atmospheric energy deposition processes, elucidate the mechanical properties of NEO materials, and investigate the break-up process. Such knowledge informs and assists planetary defense activities related to NEO characterization, mitigation, and modeling.

Unique perspectives can also be gained from fireball and bolide events if they can be subsequently linked to a recovered meteorite. One of the most insightful examples of this paired knowledge stemmed from the airburst of 2008 TC3, which delivered the Almahata Sitta meteorites to Sudan (Jenniskens et al. 2009). The roughly 4-meter 2008 TC3 asteroid was discovered about 19 hours prior to impact and observed by numerous telescopes worldwide. After its explosion as a bright fireball, a dedicated field search collected numerous meteorites. These meteorites revealed a surprising degree of mineralogical and compositional diversity, illuminating the potential compositional heterogeneity exhibited by a single NEO. This event demonstrated the scientific value of linking and interpreting telescopic observations of small NEOs prior to Earth impact.

18 NASA-NSF Cooperation

18-12 Recommendation: As the steward of ground-based observatories with NEO observing capabilities, NSF should support and prioritize critical planetary defense observations of NEOs at its ground-based facilities.

18 Next Steps for Planetary Defense Demonstration Missions

18-21 Data from ground-based planetary radars, ground-based telescopes, and the few in situ missions conducted to date (e.g., *NEAR*, *Hayabusa*, *Hayabusa2*, and *OSIRIS-REx*) suggest that the NEO population is very heterogeneous, varying from unconsolidated "rubble piles" to heavily fractured bodies with some degree of physical integrity. Knowing a NEO's characteristics is crucial because the efficacy of any deflection method depends on the body's mass, cohesiveness, and associated physical properties. For example, an intended deflection may disrupt a loosely-bound NEO into multiple objects, and inadvertently increase the probability of impact (albeit with smaller pieces).

20 NASA Telescope Facilities

20-2 Observatories (on the ground and in space) provide both unique discoveries and essential support for planetary missions as well as the continuing search for and characterization of exoplanets by providing spatial, temporal, and spectral context for observations from spacecraft. Both ground and space-based facilities support the major subsets of the survey's 12 key science questions by providing essential monitoring of dynamic or unique solar system phenomena, including atmospheres (Q7, Chapter 10), comets (Q1, Q2, and Q3, Chapters 4-6), cryovolcanic/plume activity (Q5, Q6, and Q8, Chapters 8-9 and 11), occultations (Q4, Chapter 7), and many more, all varying on timescales of hours to multiple decades. Changes over long timescales are challenging for a visiting spacecraft, so telescope observations fill the gaps between missions. There are excellent synergies between planetary missions and ground/space-based observatories, such as Earth-based support campaigns, which encompass both professional facilities (multi-spectral from radio to X-ray) and amateur observers (in visible and near-infrared).

Ground-based facilities have the benefit of longevity, and their capabilities can increase over time as science instruments can be upgraded, repaired, or replaced. These instruments have relaxed mass and size constraints compared to spacecraft instrumentation, delivering capabilities such as high spectral resolution, spectral multiplexing, and the strong light-gathering power of large apertures. Currently, NASA/IRTF devotes 50 percent of its time to solar system studies, but all other facilities rely on competitive proposals each semester, with limited NASA/ESA guidance on priorities for spacecraft mission science support. Observatories may also consider offering the possibility of long-term status for monitoring programs, extending over multiple cycles with mutually agreed renewal procedures.

20-3 **Finding:** Planetary science at NASA-funded observatory facilities benefits from a proposal mechanism for spacecraft mission support, for example, the Keck 2022A call for mission support proposals, as well as multi-cycle programs.

20-3 **Finding:** To enable planetary observations, Astrophysical telescope assets need to continue to include tracking non-sidereal rapidly moving objects, with dynamic range accommodations for both bright and faint targets.

20 Future Facilities

20-14 Recommendation: NSF-supported, ground-based telescopic observations provide critical data to address important planetary science questions. The NSF should continue (and if possible expand) funding to support existing and future observatories (e.g., NOIRLab, ALMA, TMT, GMT, ngVLA) and related PI-led and guest observer programs. Planetary astronomers should be included in future observatory plans and development to maximize the science return from solar system observations.

22 Telescopic Observations

22-44 Telescopic observations from space- and ground-based observatories provide essential support for planetary science and astrobiology through synergies with data returned from flight missions (see Chapter 20 and references therein). Ground-based facilities have the benefit of longevity, and their capabilities can increase over time as science instruments can be upgraded, repaired, or replaced.

Recommendation: NSF-supported, ground-based telescopic observations provide critical data needed to address important planetary science questions. The NSF should continue and, if possible, expand the funding to support the existing and future observatories, provide guest observer programs, and include planetary astronomers in future observatory development to maximize the science return from solar system observations

5 APPENDIX: IRTF MISSION SUPPORT OBSERVING PROPOSALS FOR 2022

Semester 2022A (17 out of 100 proposals)

013 Spectral measurements of spacecraft mission candidates of PHOs
Low Δv mission accessible targets for composition and density

018 IRTF NEO rapid response to close flybys
Measure possible physical changes due to tidal effects on close approach. Measure spectral properties of possible falls (recovery). Low Δv mission accessible targets for composition and density

019 NIR characteristics of Jupiter's atmosphere during *JUNO* perijoves 41-43 and potential *JWST* observations
Combine with JUNO MWR for 3D maps, and JWST and HST observations

020 Pluto and Quaoar Occultations
Place *New Horizons* atmospheric observations in wider context

022 Characterizing Jupiter's deep belt/zone in era of *JUNO* and *JWST*
MIRI has a small FOV and saturates at >11 μm. TEXES gives global MIR temperature maps to complement MIRI spectroscopy

023 NIR spectroscopy contemporaneously with *HST* UV campaign to map dust in AGN Mrk 817
Reverberation mapping of dusty nucleus complementary to *HST* UV observations

028 Mapping Martian HCl and water
Elucidate *ExoMars TGO* measurements to identify sources and sinks in lower atmosphere

032 NIR spectroscopy of Polona asteroid family
Identify possible family of Bennu (NASA *Osiris-Rex*) and Ryugu (JAXA *Hyabusa 2*) mission sampled asteroid targets

033 Pluto temporal evolution
Context for *New Horizons* imaging and spectroscopy and tracing surface changes

034 Characteristics of NASA *JANUS* mission target 1996 FG3
Target of NASA *SIMPLEX JANUS* small cube-sat mission piggy-backing on *Psyche* (since delayed)

035 Jupiter MIR atmospheric evolution during perijoves 41-43
3D structure contemporaneous with *JUNO* MWR, *JWST* and *HST*

038 Waves and instabilities on Venus
Calibrate Akatsuki orbiter degrading LIR bolometer with MIRSI observations on IRTF

054 Saturn with IRTF and *JWST*
Supporting observations for *JWST* GTO. Small FOV MIRI N-band calibration and Q-band extended range to complement MIRI.

058 **Spectral image cubes of Venus in support of *Akatsuki* observations**
Support *Akatsuki* orbiter UVI and LIR camera observations by providing 0.8-2.5 μm global nightside maps

061 **TEXES MIR Jupiter auroral observations**
Support *JUNO* mission by providing auroral observations near-contemporaneously with *JUNO* flybys

078 **T Tauri stars with IRTF and *HST***
Brα observations contemporaneously with *HST* UV observations to probe accretion

085 **NEOs with MIRSI and MOC**
Simultaneous V- and N-band observations to measure NEO albedos and diameters (impact hazard characterization)

Semester 2022B (19 out of 100 proposals)

002 **Small NEO characterization**
Measure composition for impact hazard assessment and as possible PHO mission targets

005 **SpeX observations of the Didymos-Dimorphos system**
DART mission ground-based support observations to track system spectral changes post impact

006 **NIR spectroscopy of Polona asteroid family**
Identify possible family of Bennu (NASA *Osiris-Rex*) and Ryugu (JAXA *Hyabusa 2*) mission sampled asteroid targets

014 **Occasional Triton spectra 2020-2023 for rotational and seasonal variability**
Also, NIR Neptune atmosphere/cloud imaging of potential 'ice-giant' mission target

015 **Water clouds and volatiles on Jupiter concurrent with *JWST* and *JUNO***
High-resolution M-band spectroscopy along *JUNO* MWR ground tracks and to place *JWST* observations in context

016 **Mineralogy of *Hyabusa-2* extended mission target [98943] 2001 CC21**
Rotational spectral characterization to help design and plan flyby timing

020 **Investigating nitrile chemistry on Titan**
Could provide valuable input to *Dragonfly* 2034 mission to Titan

023 **NIR investigation of Trojan asteroid Eurybates, its collisional family, and the three L4 *Lucy* mission targets**
Mapping spectral variability will allow *Lucy* team to decode what spectral unit to target dirking flyby

024 **Characterizing Jupiter's deep belt/zone in era of *JUNO* and *JWST***
MIRI has a small FOV and saturates at >11 μm. TEXES gives global MIR temperature maps to complement MIRI spectroscopy

026 **How dusty is the *DART* impact?**
Characterize ejecta cloud evolution. Any change in weathered surface?

036 **Saturn’s northern hemisphere with IRTF and *JWST***
Important context for *JWST* MIRI. TEXES provides tropospheric temperatures

041 **IRTF NEO rapid response to close flybys**
Measure possible physical changes due to tidal effects on close approach. Measure spectral properties of possible falls (recovery). Low Δv mission accessible targets for composition and density

053 **Measuring ion flows at the southern aurora of Neptune**
Complement to *JWST* observations

066 **NIR characteristics of Jupiter’s atmosphere during *JUNO* perijoves 44-48 and potential *JWST* observations**
Combine with *JUNO* MWR for 3D maps, and *JWST* and *HST* observations

069 **NEOs with MIRSI and MOC**
Simultaneous V- and N-band observations to measure NEO albedos and diameters (impact hazard characterization)

072 **Temporal evolution of Pluto’s surface in late spring**
Context for *New Horizons* imaging and spectroscopy and tracing surface changes

074 **Evolution of Jupiter’s polar stratosphere: supporting *JUNO’s* extended mission**
Provides constraints to interpret *JUNO’s* UV data

092 **MIR characteristics of Jupiter’s atmosphere during *JUNO* perijoves 44-48 and potential *JWST* observations**
3D atmospheric structure contemporaneous with *JUNO* MWR, *JWST* and *HST* observations

095 **iSHELL and SpeX observations of comet C/2017 K2: organics, molecules and dust**
Context for *JWST* NIRSPEC to remove blinding at the lower spectral resolution of NIRSPEC and allow more accurate modelling

6 APPENDIX: BUDGET 2019-2024

9/20/2022 IRTF-Senior-Review-80HQTRD0030-Budget-Status-and-Cost-Summary

Operation and Maintenance of the IRTF
Fixed Priced Contract NASA 80HQTR19D0030
Budget Status and Cost Summary
For the five years ending June 30, 2024

Description	06/30/20 Total Costs Year 1	06/30/21 Total Costs Year 2	06/30/22 Total Costs Year 3	06/30/23 Projected Costs Year 4	06/30/24 Budgeted Costs Year 5	Total Costs 5 Years	Total Budget 5 Years	Projected Balance
Salaries & Wages	1,922,824	1,973,691	2,071,753	2,230,461	2,193,879	10,392,608	10,751,468	358,860
Fringe Benefits	877,346	819,962	822,571	932,653	1,079,207	4,531,739	5,316,196	784,457
Total Direct Labor	2,800,170	2,793,653	2,894,324	3,163,114	3,273,086	14,924,347	16,067,664	1,143,317
Job Order System Services	40,490	9,232	4,335	71,368	67,500	192,924	320,400	127,476
Equipment	78,591	240,221	169,834	103,792	0	592,438	516,057	(76,381)
Materials & Supplies (incl softwre & lic)	160,469	424,057	390,099	344,822	269,353	1,588,800	1,328,042	(260,758)
Travel (domestic & foreign)	40,027	1,865	38,604	74,146	82,983	237,625	405,333	167,708
Mauna Kea Support Services (infrastructure)	145,226	128,380	126,710	101,037	110,890	612,243	528,062	(84,181)
Mauna Kea Support Services (HP lodging)	74,916	80,252	153,726	180,000	105,306	594,200	501,468	(92,732)
Facility & Instrument Repair	41,832	94,131	83,432	412,682	26,182	658,259	505,880	(152,379)
Computer & Consultant Services	17,360	71,292	0	0	0	88,652	24,950	(63,702)
Utilities (elec, comm, water)	179,959	201,030	239,422	381,263	243,388	1,245,061	1,159,015	(86,046)
Vehicle (lease rent, repairs, insurance)	33,886	60,451	56,796	78,637	52,431	282,201	249,675	(32,526)
Publications	2,886	1,188	6,826	2,328	4,084	17,312	19,449	2,137
Professional Services (TAC, high alt exams)	3,040	5,537	6,651	12,712	16,537	44,477	78,749	34,272
Freight	6,487	2,996	2,532	6,174	6,888	25,077	32,800	7,723
Other management (job ad, subscrip, regis)	13,929	15,416	15,286	2,758	3,488	50,877	16,610	(34,267)
Admin Recharge Services	321,285	343,403	346,687	381,873	411,405	1,804,653	2,054,402	249,749
Computer Recharge Services	117,320	118,540	117,880	124,080	135,628	613,448	655,850	42,402
Subtotal - Direct costs	4,077,873	4,591,644	4,653,143	5,440,785	4,809,149	23,572,593	24,464,406	891,812
Indirect costs - MTDC, 26%	966,091	1,080,683	1,091,538	1,296,076	1,176,618	5,611,006	5,875,589	264,583
Total direct & indirect costs	5,043,964	5,672,327	5,744,681	6,736,861	5,985,767	29,183,599	30,339,995	1,156,395
Personnel FTE								
Manoa Operations								
Director	0.950	0.950	0.950	0.950	0.950			
Associate Astronomer	1.000	1.000	1.000	1.000	1.000			
Mechanical Engineer II	1.000	1.000	1.000	1.000	1.000			
Electronics Technician	0.000	0.000	0.250	0.250	0.000			
Job Order System Services	0.180	0.050	0.020	0.250	0.250			
Hilo Operations								
Astronomer	1.000	1.000	1.000	1.000	1.000			
Associate Astronomer	1.000	1.000	1.000	1.000	1.000			
Senior Software Engineer	0.900	0.900	0.900	0.900	0.900			
Computer Systems Support Spec (Archive)	1.000	1.000	1.000	1.000	1.000			
Senior Engineer	1.000	1.000	1.000	1.000	1.000			
Electronics Engineer II (vacant from 11/2020)	1.000	0.375	0.000	0.000	1.000			
Electronics Engineer	1.000	1.000	1.000	1.000	1.000			
Network System Engineer	0.800	0.800	0.800	0.800	0.800			
Graduate Research Assistant	0.625	0.625	1.000	1.000	1.000			
Summit Operations								
Observatory Manager	1.000	1.000	1.000	1.000	1.000			
Observatory Supervisor (LWOP)	0.000	0.000	0.000	0.000	1.000			
Lead Mechanical Technician	1.000	1.000	1.417	2.000	1.000			
Electrical Technician (vacant from 6/2021)	1.000	1.000	0.000	0.000	1.000			
Observatory Technician	1.000	1.000	1.000	1.000	1.000			
Observatory Support Technician	1.000	1.000	1.000	1.000	1.000			
Telescope Operator (full-time)	4.000	4.000	4.000	4.000	3.000			
Telescope Operator (part-time)	0.950	0.950	0.950	0.950	0.950			
Telescope Operator Assistant	0.000	0.000	0.750	1.000	0.000			
Observatory Night Attendant (part-time)	2.850	2.850	2.850	2.850	2.850			
Total	24.255	23.500	23.887	24.950	24.700			

Operation and Maintenance of the IRTF
Fixed Priced Contract NASA 80HQTR19D0030
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For the five years ending June 30, 2024

Description	**06/30/20 Total Costs Year 1**	**06/30/21 Total Costs Year 2**	**06/30/22 Total Costs Year 3**	**06/30/23 Projected Costs Year 4**	**06/30/24 Budgeted Costs Year 5**	**Total Costs 5 Years**	**Total Budget 5 Years**	**Projected Balance**
Equipment Cost Details								
Facility Equipment-Yr1-Movable counter weights, Yr2-welder, Yr4-Backup generator & other	45,744	8,771	-	53,388	-			
Cryodyne Refrigerator/Edwards Vacuum	10,392	-	-	-	-			
Helium leak detector/Agilent	22,455	-	-	-	-			
Logic Analyzer/Newcomb	-	9,980	-	-	-			
Array controller spares and spare boards	-	26,877	-	24,300	-			
Nicolet filter scanner	-	-	67,775	-	-			
IDA Storage server	-	-	-	26,104	-			
Servers and Instrumentation Support Eq	32,847	36,857	67,775	50,404	-			
FELIX Low Order Adaptive Optics Fabrication	-	72,462	-	-	-			
OPIHI Wide Angle Finder/in service May-22	-	122,131	15,521	-	-			
SPECTRE preliminary design	-	-	86,538	-	-			
Instrument Fabrication	0	194,593	102,059	0	-			
Total Equipment	78,591	240,221	169,834	103,792	0			
Materials & Supplies Details								
Facility Operations and Maintenance-liquid nitrogen/helium, spares, tools, safety, janitorial and Yr3-shutter fender assy	106,460	289,620	293,998	240,124	127,165			
Facility Network and Instrumentation	-	22,218	14,382	-	55,703			
Computer, Engineering and Lab	35,942	43,027	60,437	36,058	73,167			
Array controller spares and spare boards	-	57,690	-	51,337	0			
Software and Software Licenses	18,067	11,502	21,282	17,303	13,318			
Total Materials & Supplies	160,469	424,057	390,099	344,822	269,353			
Mauna Kea Support Services (infrastructure)								
Hale Pohaku Base fee and office services	25,727	16,106	18,867	7,963	8,161			
Visitor Information Station and Outreach	31,038	30,187	32,765	26,424	34,414			
Road Maintenance	33,375	18,369	22,233	24,585	25,199			
Snow Removal	3,138	9,319	10,019	8,012	8,212			
Weather Center and atmospheric monitor	28,117	29,380	36,849	29,427	30,162			
Communication Network	6,308	6,162	5,977	4,626	4,742			
Security and supplemental funding	4,092	4,113	0	0	0			
Community and Govt relations services	13,431	14,744	0	0	0			
Total Maunakea Infrastucture	145,226	128,380	126,710	101,037	110,890			
Mauna Kea Support Services (HP lodging)								
Total annual cost	74,916	80,252	153,726	180,000	105,306			
Average daily rate for lodging & meals	$146.15	$156.15	$184.38	$210.62	$162.26			
Number of lodging nights	513	514	834	855	649			
Facility & Instrument Repair								
Secondary mirror protected silver coating (Yr2), Primary mirror recoating (Yr4)	-	19,000	-	27,900	2,638			
Painting exterior and dome, shutter inspection and maintenance	-	-	-	268,680	-			
Maintenance of telescope motor, gear box, brake	4,365	-	11,673	35,586	-			
Maintenance of glycol chiller and ice wagon equipment including electrical work	2,104	53,743	35,026	12,000	-			
UPS maintenance and battery replacement	9,479	1,200	-	25,446	13,951			
Other maintenance (network, computer, crane inspection, cryo pump)	25,884	20,188	36,733	43,070	9,593			
Total Facility & Instrument Repair	41,832	94,131	83,432	412,682	26,182			