1. INTRODUCTION

The planetary science community has special needs for access to ground-based telescope facilities that are different from the requirements for stellar and extragalactic astronomy. Meeting these special needs necessitates having an observatory that is operated with additional capabilities. Solar system targets display a number of time-varying properties, including unpredictable and unrepeatable phenomena such as stellar occultations, atmospheric activity, cometary outbursts, planetary impacts, and comets and asteroids passing near the Earth. These require capabilities for highly responsive operations and the ability to observe phenomena from the visible to the mid-infrared, over many different intervals in the time domain. Also, the orbital properties of solar system targets routinely place them within small angular separation from the Sun, requiring daylight observations. At present and in the foreseeable future, these capabilities are provided by the NASA Infrared Telescope Facility (IRTF), the only observatory that is designed and operated to meet the broad needs of mission support and planetary science.

The IRTF is a 3.2-meter infrared telescope located at an altitude of approximately 13,600 feet near the summit of Maunakea on the island of Hawaii. The University of Hawaii operates IRTF under contract to NASA while NSF agrees to receive proposals for new facility instruments and support costs for observing programs of interest to NSF. Designed for maximum performance in the infrared, IRTF takes advantage of the high transmission, excellent seeing, minimal water vapor, and low thermal background that characterize the atmosphere above Maunakea. IRTF is operated as a national facility. Through peer review of proposals, observing time on the telescope is open to the entire astronomical community. To fully utilize IRTF in support of NASA programmatic objectives and science we have significantly increased the use of flexible scheduling, remote observing, daytime observing and target-of-opportunity programs, and as a result, significantly increased IRTF productivity[1]. Approximately 50% of available observing time is dedicated to solar system mission support and planetary observations. The remaining time is assigned to non-solar system science. Many of these non-solar system programs are also broadly related to planetary science, including such topics as studies of exoplanets and exoplanet hosts, brown dwarfs, astrochemistry, and star and planetary disk formation. Data from IRTF facility instruments is publicly archived at the IPAC Infrared Science Archive.

2. UNIQUENESS FOR NASA MISSIONS AND SOLAR SYSTEM RESEARCH

The IRTF provides five essential capabilities for NASA's Planetary Science Division:

2.1. 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[2]. The IRTF is NASA's primary asset for the characterization of near-Earth objects (NEOs). It provides capabilities that are unduplicated with other NASA assets.

[1] http://irtfweb.ifa.hawaii.edu/information/metrics/IRTF_metrics_200630.pdf
[2] https://www.nasa.gov/planetarydefense/supporting_documents

2.2. *Ground-based observations in support of planetary missions*

Many IRTF observing programs provide ground-based data supporting current and future spacecraft missions to solar system bodies. IRTF has supported almost all previous, current and planned future small body missions to help with mission design and maximize science return. Regular mission support observations were conducted for *Galileo*, *Cassini* and *New Horizons*. In fact, the flyby hemisphere of Pluto by *New Horizons* was selected in part from long-term HST imaging and IRTF near-infrared spectroscopy. Critically, IRTF can provide support during unplanned mission events. Recent examples include infrared images to track a major storm on Jupiter during a *Juno* spacecraft safing event (2016), and infrared imaging and spectroscopy of Venus to support the *Akatsuki* mission (2018). Support for *Akatsuki* (which includes NASA co-Is) was required since the spacecraft ended up in an unplanned highly elliptical orbit with failures of both near-infrared sensors. Both of these support opportunities required daytime observing (at 17 degrees solar elongation in the case of Jupiter) – a unique capability for a major ground-based optical-infrared telescope.

2.3. *Time domain observations (milliseconds to decades)*

Time-critical observations, such as stellar occultations by planetary rings and small bodies, and observing sequences timed to the orbital phase of satellites, are routine for IRTF. Long-term observing programs such as synoptic observations of Pluto, Triton, Titan and Io extend over decades and provide context for 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. Over 90% of IRTF users now operate remotely. Many solar system targets, such as asteroids, do not require long observing runs but do require short and irregular observing windows to track observing geometry (e.g. solar phase angle) changes over the course of their apparitions. IRTF regularly accommodates target of opportunity requests that are critical for observing new comets and cometary outbursts, for example. IRTF can respond within hours to NEO flyby alerts. Demand for rapid response capabilities is expected to increase dramatically with the advent of the Rubin Observatory synoptic survey telescope.

2.4. *Observing campaigns*

Dedicated IRTF observing campaigns are highly valued by the planetary community. IRTF responds to community and NASA HQ requests to schedule weeks-long observing campaigns (e.g., the SL9 Jupiter impact campaign, Deep Impact mission observations of comet Tempel 1, comet C/2012 S1 (ISON), comet C/2013 A1 (Siding Spring) and comet 46/P Wirtanen in 2018). Blocks of observing time for these campaigns is guaranteed but individual proposals are still peer reviewed.

2.5. *Unique suite of instrumentation*

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. The telescope has a Multiple Instrument Mount that allows instruments to be switched in about 20 minutes, greatly increasing the schedule flexibility.

SpeX is the IRTF's workhorse 0.7–5.4 μm spectrograph. First deployed in 2000, SpeX was upgraded with new detector arrays and array controllers in 2014. In its higher-resolution R~2000 cross-dispersed modes, SpeX is used in studies of planetary atmospheres and comets. In its 0.7–2.5 μm R~100 prism mode, SpeX is used for for compositional studies of NEOs, main-belt and Trojan asteroids, and the brightest Centaurs, TNOs and cometary comae. The addition of the dichroic-fed MIT Optical Rapid Imaging System (MORIS) CCD to SpeX in 2012 now makes *on-target* guiding on faint small bodies ($V \leq 20$) possible, an improvement of two magnitudes over the infrared guider (intended for red objects). *The one-shot wide-band spectral coverage, use of a highly efficient prism (no grating losses) and improved guiding makes IRTF competitive with 8-m class telescopes for small body studies, despite its modest size.*

MORIS is mounted to the optical port of SpeX and provides high-time resolution photometry at visible wavelengths (e.g., stellar occultations and light curves). Because of Hawaii's location on Earth, having this high-speed photometer provides an important capability for observing stellar occultation events over a longitude range for which there are no other ground-based observatories. *With MORIS and SpeX, the IRTF is one of the few observatories offering simultaneous optical and infrared observations, an important capability for planetary observations.*

High-resolution spectroscopy has proved to be an extremely effective niche for IRTF. High resolving power (R=20,000-100,000) in the infrared is required to separate and measure molecular species in planetary atmospheres and comets, and to discriminate against telluric contamination. At 1-5 μm these capabilities have been provided by the new facility instrument iSHELL (2016-present), and at 5-26 μm by the visitor instrument TEXES (2000-present). *For active new comets near the sun the daytime observing capabilities of iSHELL are likely to remain unique for the foreseeable future.*

Ultra-high resolving powers ($R > 10^6$) 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 (2000-present).

Infrared imaging with the facility 1-5 μm cameras and visitor mid-IR cameras have provided a several decades-long monitoring of the dynamical process 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.

The IRTF has a very successful visiting instrument program. The telescope has a visitor instrument port that can accommodate a variety of instrument types. After technical consultation and review by IRTF staff, PIs can apply through the TAC for observing time. Over two dozen different visiting instruments have been used on IRTF since the telescope was commissioned in 1979. Together with bona fide visitor science instruments (e.g., TEXES, HIPWAC and the prototype of MORIS) this program also provides a platform for new technical ideas and instrument development. Recent examples include the on-sky testing of EXES before it was deployed on SOFIA, and a laser comb and gas cells for high precision radial velocity calibration. One of the gas cells is now part of iSHELL.

3. PLANNED NEW CAPABILITIES 2023-2032

In addition to maintaining the current capabilities discussed above, 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. Potential future plans for IRTF were discussed at a community workshop in 2018.[3]

Foremost is SPECTRE, a proposed new facility instrument. SPECTRE is a three-channel 0.4-4 μm $R \approx 150$ Integral Field Spectrograph (IFS). For rigidity and ease of calibration there are no moving optics. The 7 x 7 arc-second field of the integral field unit (IFU) is optimized for point sources. By optimizing throughput for each channel, removing the slit losses of conventional spectrographs, and by having more area to accurately measure sky background, the IFS significantly improves sensitivity, and enables absolute flux-calibrated spectrophotometry. SPECTRE's *unique* ability to simultaneously monitor the entire 0.4-4 μm spectral region, and probe weak absorption bands associated with volatile-bearing minerals, will provide a new capability in exploring the volatile inventory and history of NEOs and primitive solar system bodies. The one magnitude gain in sensitivity compared to our current capability with the SpeX prism mode will significantly increase the population of small bodies observable on IRTF. Without the need for precise placement on a slit the IFU also enables very efficient 'point and shoot' observing. An important part of the project is a purpose-built data reduction pipeline for ease of publication. SPECTRE also offers unique capabilities for the rapid characterization of astrophysical transients. SpeX will be used for follow up spectroscopy at higher spectral resolution.

The 5-20 μm Mid-Infrared Spectrometer and Imager (MIRSI) is currently being refurbished and converted from a visitor instrument into a facility instrument. The addition of an optical CCD channel will enable MIRSI to directly measure asteroid albedos and sizes using their blackbody curves and improve the albedo-composition correlation for the NEO population. Current estimates suggest that MIRSI will be able to observe about 250 NEOs per year. We are also adding a chopping capability to the current hexapod secondary mirror so that MIRSI can be switched in at short notice without the need to change the telescope top end. This, in addition to the replacement of MIRSI's original liquid nitrogen and liquid helium dewar with a closed-cycle cooler, means that MIRSI will always be available for rapid response to target-of-opportunity NEO observations.

To improve telescope image quality and sensitivity, we are building a new off-axis CCD guider (FELIX) incorporating a 3 x 3 Shack-Hartman sensor for slow (~0.1 Hz) low-order wavefront correction. Corrections for focus and alignment will be sent to the hexapod-mounted secondary mirror. We expect to deploy FELIX in 2021. In the longer term, we plan to replace the telescope secondary mirror with an adaptive mirror for correction of higher order telescope aberrations, and for use eventually with an adaptive optics system.

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

4. ADVANCING PLANETARY SCIENCE 2023-2032

4.1. *Planetary Defense*

A full understanding of the impact risk posed by hazardous NEOs is predicated on knowing the physical properties of the NEO population. Important parameters include composition, spin rate, albedo, density and size. Impact hazard assessment models estimate that for small diameter NEOs (<100 m), those with metallic composition cause the most significant damage. In contrast, for NEOs larger than absolute magnitude H = 22 (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. IRTF's role in constraining the compositions and sizes of NEOs is critical for these impact hazard assessments. Physical parameters for asteroids are often correlated - for instance, an asteroid in the C spectral class can safely be assumed to have an albedo less than 10%, with a composition similar to carbonaceous chondrites, and a density of <2000 kg/m^3. Combining a measured size of an NEO with estimates of density and macroporosity derived from its spectral classification provides an estimate of the object's mass.

SpeX observations have contributed to our greater understanding of the relationship between spectral class and other physical properties, while simultaneous lightcurve measurements with MORIS can infer shape information. With 1000s of calibrated 0.7-2.5 µm prism spectra, the IRTF/SpeX MIT-Hawaii NEO Spectroscopic Survey (MITHNEOS) is the largest publicly available database of NEO spectra. The IRTF's flexible scheduling allows for observations of targets near peak observability as well as rapid turnaround target-of-opportunity observations of newly-discovered close-approach NEOs.

With the proposed instrument SPECTRE, spectral features would be recorded across the entire 0.4-4 µm range in a single shot, removing uncertainties resulting from assembling spectra taken with different instruments at different epochs. The 0.4-4.0 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. The one magnitude increase in sensitivity will allow measurements of smaller or more distant NEOs, and faster mapping of NEOs over rotational phase. Spectrophotometry from SPECTRE together with NEO size measurements from the upgraded MIRSI will advance IRTF's role in NEO characterization for planetary defense.

For NEOs, a key capability of IRTF is its ability to routinely track at high non-sidereal rates (up to 60″/sec, i.e., four times the sidereal rate). Such capabilities are not available at most observatories around the world. Due to the lack of accurate ephemerides for the most newly discovered small NEOs, the IRTF has plans to work in collaboration with the Mission Accessible NEO Survey team (PI Moskovitz) to develop tools for targeting NEOs with large ephemeris errors. This will enhance the rapid response opportunities for IRTF to characterize these NEOs, some of which can potentially impact Earth and be recovered as meteorites. The four known Earth-impacting NEOs were discovered less than 24 hours prior to impact. Targeting such objects will also be aided by the addition of a 17-inch wide-angle finder (0.5 degree) with a CCD camera to the telescope.

4.2. *The Origin of Primitive Bodies*

Small 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 in which they formed. SpeX, has been a true workhorse instrument in characterizing small bodies both in the R~100 prism mode (0.7-2.5 µm) and in the R~2000 cross-dispersed modes (0.9-5.4 µm). SPECTRE will add very significant new capability and replace the SpeX prism mode for most primitive small body studies.

The spectra of rocky asteroid surfaces contain broad solid-state mineral absorption bands that require low-resolution measurements over a wide spectral range. Full analysis of an asteroid spectrum relies on accurate (compositional and thermophysical) modeling of its continuum, the determination of which will be greatly enhanced by SPECTRE's capability for calibrated spectrophotometry over the wide wavelength range from 0.4-4 µm. SPECTRE will make possible precise studies of spectral variations of asteroids tied to changing observing geometries, surface particle properties, and surface exposure ages. Understanding these effects is key to interpreting the composition and surface properties (e.g. regolith grain size) of asteroids based on their spectral signatures. Studies facilitated by SPECTRE's extended wavelength coverage and improved sensitivity ($V \leq 20$) will provide a fuller understanding of asteroid collisional evolution, NEO source regions and the link between asteroids and meteorites.

The 3-4 µm spectral region is home to key absorption features due to OH and water in minerals on airless surfaces, minerals of intense interest when studying the origin of the solar system and evolution of the inner planets and their volatile inventories. In addition, absorptions due to organic materials (3.3-3.4 µm) and ammoniated minerals (3.1 µm) have been detected in asteroid spectra. The presence of a 0.7 µm feature appears to be correlated with the presence of a 3 µm band, though temporal variations in the strengths of both the 0.7 and 3 µm bands have been noted and need to be further investigated. SPECTRE's ability to simultaneously monitor these two spectral regions, and probe additional weaker absorption bands associated with volatile-bearing minerals, will provide a new capability in exploring the volatile inventory and history of asteroids.

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. While gases released by cometary bodies are best studied at the high spectral resolutions provided by iSHELL, the solid ices and dust that constitute most small bodies in the outer solar system are best detected at lower spectral resolution and over a broad spectral range. The capability of SPECTRE to detect water ice absorption bands at 1.5, 2.0 and 3.0 µm is a key to understanding the nature of cometary nuclei. The relative strengths and shapes of these bands, together with the slope of the reflectance spectrum, provide information on aggregate porosities, ice-to-dust ratios, grain sizes and abundances.

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. Longer wavelength observations (2.4-4 μm) will only be possible for the brightest targets, such as Pluto and the largest Centaurs.

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 can probe atmospheres (hazes, pressure etc.) and the particle sizes of ring systems (diffraction and scattering as a function of wavelength). In addition to spectrophotometry, an important added feature of SPECTRE is the ability to continuously measure sky transparency with the wide field (3′) of its acquisition and guiding CCD, a critical capability for time series spectrophotometry.

As noted earlier, IRTF has played a vital role in providing ground-based support for small body missions. A good example of potential future opportunities is SPECTRE observations in support of the Trojan asteroid tour planned for the Lucy mission in 2027 to 2033. Using one of the Lucy targets as an example, SPECTRE can obtain high quality one-shot 0.4-4 μm spectra (50σ, $R \approx 100$) of 3548 Eurybates in less than one hour at opposition. Eurybates (diameter 64 km) has a rotation period of 9 hours and so successive observations will be able to spatially map Eurybates at sub-hemisphere resolutions. Observing across 0.4-4 μm is ideal to break any degeneracy in spectral features but covering 0.4-2.4 μm will also be very valuable. There are about 50 Jupiter Trojans brighter than Eurybates and so ground-truth Lucy observations can then be applied to a population of objects (and an order of magnitude more objects at 0.4-2.4 μm).

5. SUMMARY: IRTF IN THE NEXT DECADE

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. Funding for IRTF operations requires continued support from NASA. Funding for new IRTF facility instrumentation (i.e., SPECTRE) requires continued support from NSF.

Accessible information on the web:

IRTF home page http://irtfweb.ifa.hawaii.edu/
IRTF bibl.: https://ui.adsabs.harvard.edu/search/p_=0&q=bibgroup:"irtf"&sort=date desc, bibcode desc