Astro2020 Science White Paper

Astrophysics with the NASA Infrared Telescope Facility (IRTF)

Thematic Areas: ☒ Planetary Systems ☒ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☒Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract (optional):

Much frontline astronomical research can still be done on 3-4-m class optical-infrared telescopes. This paper highlights future key observing programs that can be efficiently done on IRTF by exploiting current and planned capabilities and that do not require larger and more expensive facilities. Key programs include spectroscopy to survey and monitor small solar system bodies and planet-forming disks, spectroscopy of planet and exoplanet atmospheres, measuring the fundamental properties of *Gaia* and *TESS* stellar targets, understanding icy grains through extinction studies, and expanding work on optical-infrared stellar libraries. Through flexible scheduling and short observing blocks IRTF is well-suited to monitoring programs and fast follow-up to target of opportunities. 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.

Introduction

The NASA Infrared Telescope Facility (IRTF)[2] is a 3.2-meter infrared telescope (useable aperture 3.0-meter) located at an altitude of approximately 13,600 feet near the summit of Maunakea on the island of Hawaii. IRTF is run under contract to NASA by the University of Hawaii. In a Memorandum of Understanding (MOU) between NASA and NSF, NASA funds telescope operations (about $6m per year) while NSF agrees to accept proposals for facility instruments (historically one new instrument or significant instrument upgrade every five years) and pays support costs (about $150k per year) for observing programs of interest to NSF. Observing time is open to the entire astronomical community. Under this MOU about 50% of observing time is reserved for observations of solar system objects and NASA spaceflight mission support, and the balance for observations outside the solar system. NASA's strategy in operating a dedicated ground-based observatory continues to be the support of NASA's missions and science goals[3].

Since 1998 IRTF has evolved from a telescope doing mostly imaging and photometry (74% in 1998) into a telescope doing mostly single object spectroscopy (95% in 2018) where augmented array format has been used to increase one-shot wavelength coverage or spectral resolving power (R). Due to the requirement for fast response with multiple instruments, wide field prime focus observations are not an option. The relatively small field of view at Cassegrain focus makes IRTF also less suited for wide field imaging or wide field multiplexed spectroscopy.

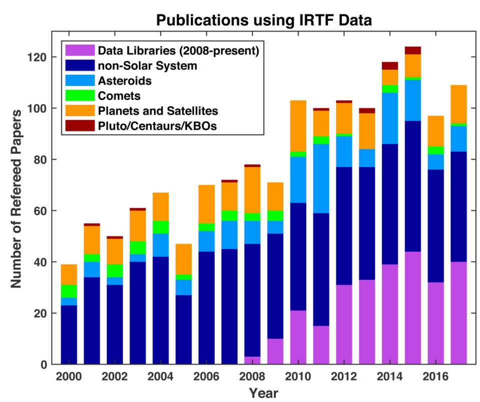

Figure 1. Publications by science category. Note the contribution from IRTF spectral libraries

Through a mixture of facility and visitor instrumentation IRTF offers a powerful suite of 0.5-26 μm imaging and spectroscopic (R=10-10^7) capabilities. Facility instruments cover the 0.5-5 μm range (R=10-10^5) while visitor instruments cover the mid-infrared (MIR) or 5-26 μm range (R=10-10^7). The MIR is particularly important for the study of planetary atmospheres but has been largely abandoned on other Maunakea telescopes. IRTF maintains a strong visitor instrument program, with the added advantage of providing a platform for technology development and student training. The telescope is classically scheduled but through remote observing and fast instrument changes IRTF typically executes up to four observing programs per night and is able to respond to target of opportunities (ToOs) within hours. IRTF *regularly* observes during daytime – a unique capability for an optical-infrared telescope but a critical capability for spacecraft mission support and comet apparitions. Starting in 2017, all data from facility instruments are archived at the Infrared Science Archive hosted by IPAC and are publically available. For a medium-sized telescope IRTF is scientifically still very productive, averaging over 100 refereed publications per year, about the same as Gemini North. One of the reasons for the high productivity is the IRTF's pioneering work on providing an efficient data reduction pipeline, Spextool (Cushing *et al*. 2004), for the facility spectrographs. Figure 1 shows the number of papers by scientific category published per year since 2000. Note the significant contribution from the IRTF stellar[4], brown dwarf[5], and asteroid[6] spectral libraries that are available online to the wider astronomical community.

Planetary Systems

The detection, characterization, and mitigation of potential asteroid impactors is one of the key functions of NASA, as recognized by the January 2016 creation of the Planetary Defense Coordination Office (PDCO) within the agency. IRTF plays a key role in the characterization of near-Earth objects (NEOs) and remains a vital asset in NASA's planetary defense efforts providing capabilities that are unduplicated with other NASA assets[7].

Small bodies – asteroids, comets, Centaurs, and trans-Neptunian objects (TNOs) – are the 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. For decades, the IRTF has been a vital asset for small body mission planning, mission support, planetary defense, and science in general. Missions enable extremely detailed and, in most cases, unprecedented measurements on individual targets, but the numbers visited by missions are limited. Most of IRTF's work on small solid bodies is currently done with the 0.7-2.5 µm R=100 mode of the facility spectrograph, SpeX, and supplemented with optical coverage from other telescopes when necessary, for definitive spectral characterization. A planned facility 0.4-4 µm integral field R=100 spectrograph (no slit losses), SPECTRE[8], will result in much improved efficiency (more targets) and sensitivity (smaller sizes). Covering 0.4-4 µm in one shot is needed to break the degeneracy in modeling Centaurs and TNOs (Protopapa *et al*. 2008) and accurately probe hydrated features in main belt asteroids. With this new capability IRTF will be uniquely positioned to play a leading role in ground-based remote sensing observations of small solid bodies for decades to come.

The IRTF's Mid-Infrared Spectrometer and Imager (MIRSI) is currently being upgraded to include an optical CCD channel that will enable it to directly measure asteroid albedos and sizes, and improve the albedo-composition correlation for the NEO population. MIRSI will be able to observe about 250 NEOs per year.

Comets are some of the least altered objects from the birth of the Solar System, providing the most direct means for determining the chemistry and conditions present during this formative period[9]. Thus, the study of comets is intimately connected to fundamental research in astronomy including the formation, evolution and chemical inventory of our Solar System, physical conditions and composition of circumstellar disks, and the chemistry of the interstellar medium. High-resolution spectroscopy at 2-5 µm is important for studying the composition of comets because of the simultaneous fluorescence emissions of water, organics and nitriles, information that is difficult or impossible to obtain from other methods, such as radio observations, especially for apolar molecules such as CH_4 and C_2H_2.

Several features position the IRTF as a powerful facility for observing comets: i) the *unique* ability to observe during daytime and at small solar elongation, ii) the fact that 50% of the entire observing time is allocated for observations of Solar System objects, iii) prompt response to new and active comets, and especially with iv) the new high-resolution immersion echelle spectrograph (iSHELL), which covers the 1-5 µm range, with improved sensitivity, high spectral resolving power (R=80,000), and broader spectral coverage per setting, compared with other instruments available elsewhere. In particular, at R=20,000-100,000 the 2-5 µm range will remain competitive with space-based instruments (there is no JWST equivalent) due the lower thermal background and increased complexity and larger size of high-resolution spectrographs. Observations to date suggest the presence of two distinct chemical groups in both principal dynamical reservoirs (Kuiper Belt, Oort Cloud). Owing to the large fraction of time reserved for solar system studies at IRTF, iSHELL can characterize upwards of 100 comets during the next decade and be able to establish statistically significant population ratios for chemical groups in each dynamical reservoir.

With the high resolution ($R \approx 10^5$) spectrographs iSHELL (1-5 μm) and TEXES (5-26 μm), IRTF will continue to do fundamental work on the chemistry, dynamics and magnetospheric physics of planetary atmospheres (e.g. the recent measurement of Jupiter's water abundance by Bjoraker *et al.* 2018). The observations provide context for spacecraft missions and monitor atmospheric changes over the decades-long seasons of the outer planets that are not otherwise measurable.

In the last few years, the extraordinarily exciting field of exoplanet characterization has emerged. Understanding the nature and evolution of planets both young and old requires knowledge of their atmospheres, densities, and dynamics. High spectral resolution techniques are particularly powerful as they use the large RV variability amplitude to detect signals from the planet directly, allowing for the measurement of specific chemical species such as CO and H_2O at 2-4 μm (Snellen *et al.* 2010). Such work is key to distinguish between hot start and cold start models. Chemical abundance measurements will allow for the determination of the C/O ratio. This parameter is a sensitive tracer of where in the disk a planet formed because the abundance gradients in disks depend strongly on the freeze out temperatures (snow lines) of different molecules. NASA's *TESS* mission is expected to find relatively bright exoplanets that will be accessible with iSHELL. Consequently, iSHELL will be a key player in these studies over the next decade or longer.

Star and Planet Formation

Disks around young stars have been imaged at optical (e.g. *HST* and VLT+SPHERE), mm (e.g. SMA and ALMA), and infrared wavelengths (e.g. Haisch *et al*. 2005). The dust in the inner disks dissipates on a timescale of a few Myr (e.g., Wyatt 2008). However, due to predictions of grain growth during planet formation, it is not clear that emission from the small dust grains provides an adequate picture of protoplanetary disk evolution. Additional disk tracers, in particular, the gas which accounts for most of the disk mass, are required. Observations of optical emission lines suggest that disk gas in the inner few AU dissipates *more rapidly* than the dust (Fidele *et al.* 2010), contrary to most models. A more direct tracer of the disk gas in the inner few AU around young stars is CO emission, particularly the 4.5-5.0 μm fundamental lines (Banzatti *et al*. 2015). iSHELL, with its one-shot 4.5-5.2 μm wavelength grasp and high efficiency is a strategic resource for this work. Measurements of both dust and gas masses as a function of stellar age should provide critical insights.

A more direct understanding of the distribution of disk gas within individual disks can also be obtained using the technique of spectro-astrometry (SA). 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 (Pontoppidan *et al.* 2011) and natal gas giant planets (Brittain *et al*. 2013). The capability of iSHELL for carrying out SA has been demonstrated on the Herbig Ae/Be star HD 179218 (Brittain *et al*. 2018), for which an SA 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 and makes it competitive with current instrumentation on 8-m class telescopes. 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.

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? Simultaneous 0.4-4.0 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 mag). Low resolution 0.4-4 μm spectroscopy with IRTF's future instrument SPECTRE would be superior to broad band photometry because of its ability to separate the stellar signal from the dust and ice signals for individual sightlines (higher spatial resolution). The simultaneity of the observations in SPECTRE's wide wavelength range also guarantees the accurate relative calibration needed for this work.

Stars and Stellar Evolution

Gaia, LSST and *TESS* will produce powerful datasets for determining fundamental properties (masses, radii, ages) of low-mass stars and substellar objects, that are critical to test interior and atmosphere models (Huber *et al*. 2012). Absolute flux calibrated spectroscopy is vital for effective temperature scales by constraining bolometric fluxes (Mann *et al*. 2015), which is especially critical in the *Gaia* era where T_{eff} will dominate uncertainties to calculate radii. This does not need high resolution but does need broad wavelength coverage, so a concept like SPECTRE (where there are no slit losses and systematic errors are minimized) would be well suited for accurate measurements of T_{eff}, bolometric luminosity and radius, when coupled with precise parallax data. Since *Gaia* works in the optical it will be relatively insensitive to low-mass astrometric binaries, which can be followed up with SPECTRE's IFU for resolved spectrophotometry. *TESS* will measure rotation periods for members of nearby moving groups for which *Gaia* and LSST will measure parallaxes. However, the absolute RV precision of *Gaia* will be poor for these stars, limiting membership confirmation. Combining *vsin(i)* (long term near-infrared RV precision better than 0.5 km s^{-1} with iSHELL) and rotation periods can empirically constrain radii, which are necessary for testing low-mass stellar structure models. IRTF will also continue to play an important role in the characterization of exoplanet hosts as a path to understanding the exoplanets themselves; work that was started with *Kepler* (e.g. Crossfield *et al*. 2015) and that will continue with *TESS* and IRTF (absolute flux calibrated spectroscopy and metallicities).

The 0.8-5 μm *R*=2000 IRTF Spectral Library (Cushing *et al*. 2005, Rayner *et al*. 2009) has proved a valuable community resource. 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 is currently being extended by Villaume *et al*. (2017) to include a wider range of metallicities and hotter stars for improved modeling of unresolved galaxy populations. The library will have a long-lasting legacy, particularly in the "big data" era of large galactic spectroscopic and astrometric surveys such as *Gaia*.

The Role of IRTF in the 2020s

Unlike some other similarly sized telescopes (e.g. Mayall/DESI, UKIRT/UKIDSS and Blanco/DECam), IRTF will continue to do classical observing, providing the opportunity for new ideas and fast follow-up to new discoveries. IRTF operations are funded by NASA, which has programmatic needs for NEO characterization and mission support. However, all these needs are currently accommodated through the TAC peer-reviewed process and are not mandated. By exploiting current and planned new capabilities, IRTF is well positioned to make significant contributions to the fields of planetary systems, star and planet formation, and stellar science during the coming decade. The following key science areas have been identified and discussed above:

1. *Planetary Systems*
   - 0.4-4 μm survey of small solid solar system bodies (SPECTRE)
   - NEO diameter measurements through optical and 10 μm photometry (MIRSI)
   - Chemical characterization of comets (iSHELL)
   - Continuing synoptic studies of planetary atmospheres (iSHELL and TEXES)
   - Characterizing exoplanet atmospheres of bright *TESS* discoveries (iSHELL)
2. *Star and Planet Formation*
   - Probing the lifetime of gas and dust in planet-forming disks (iSHELL)
   - Using spectro-astrometry to understand spatial gas distribution in disks (iSHELL)
   - Probing the properties of icy dust grains through 0.4-4 μm extinction studies (SPECTRE)
3. *Stars and Stellar Evolution*
   - Survey the fundamental properties of *Gaia*, *TESS*, LSST targets with flux calibrated 0.4-4 μm spectroscopy (SPECTRE)
   - Extend work on near-infrared spectral libraries to include a wider range of metallicities and hotter stars for improved modeling of unresolved galaxy populations (SpeX).

All these programs can be executed efficiently and cost-effectively on IRTF and without the need for larger telescopes. The 1-5 μm *R*=80,000 and one-shot wideband 0.4-4 μm *R*=100 capabilities also complement JWST.

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