ASTROPHYSICS AT THE IRTF

The NASA Infrared Telescope Facility (IRTF) is a 3.0-meter infrared telescope located at an altitude of approximately 13,600 feet near the summit of Maunakea on the island of Hawaii. Observing time is open to the entire astronomical community, with 50% of the time reserved for observations of solar system objects 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 (Hasan 2018).

1. Star and Planet Formation (Presentations: Brittain 2018, Flagg 2018, Johns-Krull 2018, Newton 2018, Plavchan 2018, Sitko 2018)

The IRTF has played a critical role in astronomers' understanding of the later stages of star formation and the evolution of pre-main sequence stars; however, many open questions remain that the IRTF can contribute significantly to. While our understanding of planet formation is not as complete, the IRTF also plays an important role and is very well-positioned to contribute significantly in this area over the next decade.

1.1. Planet Forming Disks Around Newly Formed Stars

Planets form in circumstellar and circumbinary disks around young stars. While some disks have been imaged at optical (e.g., *HST* and VLT+SPHERE) and mm (e.g., ALMA) wavelengths, the vast majority have been studied via their infrared emission (e.g. Strom *et al.* 1989, Skrutski *et al.* 1990, Simon & Prato 1995, Haisch *et al.* 2001, Haisch *et al*. 2005) with pivotal contributions from the IRTF. *M*- and *L*-band observations are particularly powerful and have established that virtually all stars form surrounded by a protoplanetary disk and that these disks dissipate on a timescale of a few Myr (Wyatt 2008).

The disk emission traced comes from small, sub-micron dust grains found in the inner 2-3 AU around a young star. Some models predict significant growth of the dust grains during the process of planet formation, thus it is not clear that evidence for emission from 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 to form a complete picture of protoplanetary disk evolution. Indeed, some models for giant planet formation require that substantial amounts of disk gas survive until rocky cores of ~10 M are built up from small grains. Initial work on the timescale over which the disk gas survives relies on estimates of the fraction of stars in clusters that are still accreting as diagnosed by optical emission lines such as H-alpha (Fidele *et al*. 2010). Work to date suggests that the disk gas dissipates *more rapidly* than the dust, contrary to most models. What is needed is a more direct tracer of the disk gas in the inner few AU around young stars. CO emission, particularly the 4.5-5.0 μm fundamental lines, provides an effective signpost for this gas (Banzatti *et al*. 2015). iSHELL, with its 1.05-5.3 μm wavelength grasp and high efficiency is a strategic resource for this work. A plot analogous to dust emission versus disk age but based on a disk gas tracer for comparison will provide critical insights.

More detailed understanding of the distribution of disk gas within individual disks can also be obtained using spectro-astrometry. Spectro-astrometry (SA) is the measurement of the centroid of the point spread function (PSF) of a spectrum as a function of velocity (i.e. wavelength). With proper correction for artifacts and good signal-to-noise ratio, the centroid 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 forming gas giant planets (Brittain *et al*. 2013). The capability of iSHELL (Rayner *et al*. 2016) for carrying out SA has been demonstrated on the Herbig Ae/Be star HD 179218 (Brittain *et al*. 2018), for which a SA fidelity of 0.44 mas was achieved (0.13 AU at the distance of HD 179218). The power of the spectral grasp of iSHELL on IRTF provides a significant advantage when stacking multiple transitions and makes it competitive with current instrumentation on 8-m class telescopes. Some of the more interesting, and little explored, SA-based science could come from repeated observations of the same source (e.g., the proposed orbiting proto-planet in HD 100546, Brittain *et al*. 2018); hence, the availability of remote observing and flexibility in scheduling with the IRTF is key for facilitating investigations of this nature.

1.2. Searching for Planets Around Young Stars

A requirement for testing models of planet formation, and for characterizing the timescales for formation and migration, is to detect and study newly formed planets, including those still embedded in the disks from which they form. Of paramount importance is getting reliable mass estimates for the young planets discovered around young stars, achievable with radial velocity (RV) measurements. Masses determined from imaging rely on models, which are uncertain because we do not know which ones (the so-called hot start or cold start) are most appropriate. Small variations in model selection can drive order of magnitude differences in the estimated planet masses. Concrete progress requires RV detections of planets around young stars; however, these stars show a host of phenomena related to accretion and magnetic activity such as starspots, that can mask or even mimic RV detections of companions (e.g. Saar & Donahue 1997, Huelamo *et al*. 2008, Prato *et al*., 2008, Johns-Krull *et al*. 2016). Fortunately, most of these astrophysical effects are significantly reduced when observations are made at longer wavelengths such as the *H* or *K* bands (Huelamo *et al*. 2008, Prato *et al*. 2008), and may be reduced even more at even longer wavelengths. Despite all the challenges facing RV planet detection around young stars, a few high-quality candidates are now known (John-Krull *et al*. 2016, van Eyken *et al*. 2012, Donati *et al*. 2016, David *et al*. 2016, Yu *et al*. 2017). Infrared RVs have played an important role in discovering and vetting these candidates. Evidence for two RV-detected young planet candidates emerged in optical data after filtering the observations using methods such Doppler imaging and/or Gaussian process regression to remove the starspot-related contamination. Given that the amplitude of such spot-induced contamination is significantly lower at *K* (by at least a factor of four, Mahmud *et al*. 2011), such techniques applied to RV measurements with iSHELL offer the promise of identification and characterization of substantially lower mass planets around young stars. To truly understand planet formation, this type work will be required and will rely on instruments such as iSHELL, positioning the IRTF at the forefront of planet formation studies for the next decade.

1.3. Exoplanet Characterization

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. Ground-based observations of exoplanetary atmospheres using both broad band (Croll *et al*. 2015) and high spectral resolution infared observations are invaluable (e.g. Birkby *et al*. 2013, Birkby *et al*. 2017). The 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. Such data offer the ability to study in detail the abundances, chemistry, and temperature structure (e.g., the presence of thermal inversions) of planetary atmospheres. This work in turn facilitates the exploration of fundamental problems in planet formation. For example, for young planetary systems in which RV measurements can provide masses, direct detection of the planetary spectrum permits a measurement of the planetary flux relative to the host star. 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, given the different abundances expected in the disk as a function of distance from the central star and the resulting freeze out of molecular gas into ices. As we push to even lower mass planets around bright stars, an expected outcome of NASA's *TESS* mission, atmospheric characterization will allow explorations of habitability. With its large wavelength grasp, high efficiency, and high spectral resolution, iSHELL will be a key player in these studies over the next decade or longer.

1.4. Discussion and Future Needs

iSHELL is a powerful and important resource for both star and planet formation research, as well as general exoplanet studies. In the near-term, improvements in telescope image quality (e.g. the proposed low order active optics system) should be a priority to optimize the performance of iSHELL on the IRTF. The increased sensitivity in terms of the amount of light through the slit will improve both the efficiency of observations and expand the number of objects accessible to high-resolution IR spectroscopy. A direct benefit also exists for spectro-astrometry because the SA accuracy is directly proportional to the PSF. The availability of remote observing and flexibility in scheduling with the IRTF are key for facilitating investigation of sources that require many repeated observations.

2. Stellar and Substellar Astrophysics (Presentations: Burgasser 2018, Huber 2018, Villaume 2018)

2.1. IRTF in the Era of *Gaia*, LSST and *TESS*

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). IRTF can provide key complementary information to achieve that goal (Mann *et al*. 2015). *Gaia* will discover a significant number of low-mass astrometric binaries, which enable mass measurements through orbital monitoring. *Gaia* will be relatively insensitive to resolved brown dwarf companions which can be followed up over longer timescales using IRTF, ideally with an AO-assisted IFU with resolved spectrophotometry (and hence classification). *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)* and rotation periods can empirically constrain radii, which are necessary for testing low-mass stellar structure models. Both opportunities can be realized with high-resolution IR spectroscopy as enabled by iSHELL on IRTF. IRTF should 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*.

2.2. Brown Dwarf Science

IRTF, and especially SpeX (Rayner *et al*. 2003), has had a very significant role in the early development of brown dwarf science[1]. Many of the key science objectives of the field as it moves forward - measurement of the low-mass IMF of young associations (Theissen *et al*. 2018), discovery and characterization of mass-yielding binaries (Dupuy *et al*. 2018), atmospheric model testing and abundance determination (Souto *et al*. 2017), and characterization of clouds and weather (Schlawin *et al*. 2017)- can be achieved on IRTF with investments in new instrumentation. Examples include the capability for simultaneous optical and infrared spectroscopy (atmosphere characterization, including magnetic- and weather-induced variability - a concept such as SPECTRE (Connelly 2018) would provide this, wide-field imaging/astrometry (distances, variability), AO imaging (spectrophotometric monitoring of resolved binaries), and simultaneous or "fast switching" instrumentation to acquire multiple datasets for transient events. Developments in data access and analysis could also increase science yield. Continued development of the IRTF archive[2], providing more than raw data files (the Keck Observatory Archive is a good model); and moving reduction software away from the IDL platform (for broader accessibility and to capitalize on developments in community code development) are encouraged. Additional support for different scheduling modes, such as low cadence "queue" observations could realize new science in astrometry, weather, binary orbits, magnetic/accretion events, and other areas.

2.3. Spectral Libraries

The IRTF Spectral Library[3] (Cushing *et al*. 2005, Rayner *et al*. 2009) constructed with SpeX, has proved a valuable resource for the astronomical community. It has found a variety of applications: physics of cool stellar and substellar atmospheres, classification of optically embedded and cool stars, improving stellar population synthesis models, and synthetic photometry. Simple stellar populations, which are used to constrain, for example, the IMFs

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[1] http://pono.ucsd.edu/~adam/browndwarfs/spexprism/library.html

[2] https:/irsa.ipca.caltech.edu/Missions/irtf.html

[3] http://irtfweb.ifa.hawaii.edu/~spex/IRTF_Spectral_Library

of integrated stellar populations in galaxies, are ultimately limited by the accuracies of stellar libraries, including flux-calibrated spectra. Most of these are currently based on optical spectra, but NIR libraries are notoriously incomplete at low metallicities (< -0.5 dex) which are important for extragalactic stellar populations. Work by Villaume *et al*. (2017) extending the IRTF Spectral Library over a wider range of metallicities will have a long-lasting legacy impact, in particular in the "big data" era of large galactic spectroscopic and astrometric surveys such as *Gaia*.

Serious consideration should be given to constructing a complementary high resolution (R=80,000) 1-5 μm with iSHELL. It would prove a valuable resource for stellar physics. Lebzelter *et al*. (2012) have produced a 1-5 μm library of 20 stars across the Hertzsprung-Russell Diagram using CRIRES[4] (R≈100,000) on VLT (Käufl *et al*. 2004). When selecting bright stars an iSHELL survey should prove more efficient requiring about 17 setting to cover the 1-5 μm range compared to 200 for CRIRES (in original long slit configuration). A survey on IRTF (20 degrees north) would also complement the survey on VLT (25 degrees south).

2.4. Discussion and Future Needs

Flux calibration: Discussion highlighted the importance of SpeX for effective temperature scales by constraining bolometric fluxes, 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 would be well suited for this if it is possible to obtain good flux calibration. Some discussion focused on how flux calibration can be achieved; issues with "misclassified" standards suggests the need for a curated library of A0 stars (Vacca *et al*. 2003). There was discussion about removal of telluric emission and absorption (Vacca *et al*. 2003, Villaume *et al*. 2017). The planetary spectrum generator (PSG – Villanueva *et al*.[5]) at GSFC was discussed and demonstrated. PSG can be used to generate high-resolution spectra of planetary bodies.

Multi-mode instrumentation: Instrumentation that spans multiple wavebands (cf., current SpeX+MORIS) was seen as potentially competitive/complementary with facilities such as VLT/Xshooter (Vernet *et al*. 2011), GROND on the MPG/ESO 2.2-m telescope(Greiner *et al*. 2008), Gemini/SCORPIO (formerly OCTOCAM, de Ugarte Postigo *et al*. 2016), etc. SPECTRE (Connelley 2018) satisfies low-resolution optical-infrared band spectroscopy. A wide-band optical-NIR capability at high spectral resolution might also be useful (e.g., iSHELL plus an optical echelle). Simultaneous NIR+MIR observations could also be considered. Rapid switching of instruments was not seen as strongly motivated for stellar science.

Time domain photometry & spectroscopy: There is increased interest in synoptic photometry and low/high resolution spectroscopy for various science investigations (multiplicity, magnetism, exoplanets, and weather), and both flexible observing modes and high precision local time determination are desirable.

Multi-object spectroscopy (MOS) and high-resolution spectroscopy: The current hot topic in stellar astrophysics / galactic archeology are the large-scale multiplexed surveys such as

[4] https://www.eso.org/sci/facilities/paranal/instruments/crires.html
[5] http://psg.gsfc.nasa.gov

SDSS[6], AAT/GALAH[7], etc. One of the best current surveys is the MOS/APOGEE survey at R~20,000[8]. The consensus was that multi-object spectroscopy was not an area of competitive advantage for IRTF due to its small field of view. A better approach is to focus on high-resolution spectroscopy that galactic archeology surveys do not provide and which iSHELL now fills; this also addresses issues in ultracool atmosphere characterization, kinematics/multiplicity, exoplanetary detection, etc. High-resolution spectral capabilities in the optical and MIR should also be considered.

AO-assisted spectroscopy: There was general agreement that resolved spectroscopy with AO would be an advantage for IRTF; a low-resolution IFU (i.e. SPECTRE) may be a capability IRTF could capitalize on.

Software tools: There was support for scriptable and interactive reduction pipelines based on open-source software (i.e. a move away from IDL) and community-based development (e.g. github). Further development of the IRTF archive toward a Keck-like data repository that hosts raw data and basic reduced spectra (and possibly user-contributed data products) was encouraged.

Spectropolarimetry: Magnetism studies in the infrared would highly benefit from high-resolution spectropolarimetry in *H* & *K* bands (Ti I, Fe I, FeH), which would be broadly useful for many classes of stars (Johns-Krull 2018).

3. Extragalactic Astrophysics

At about 5% of the total time request the demand for extragalactic observing time on IRTF is relatively small, which is not too surprising given the relative faintness of extragalactic targets on a 3-m telescope compared to the larger facilities available to the community. One area where IRTF remains competitive is for compact point-like sources such as quasars and AGNs (powered by supermassive black holes), and supernovae. Increasingly, all-sky surveys are efficient at selecting large samples of objects the brightest of which are accessible for study at low to medium spectral resolution with SpeX on IRTF.

3.1. Quasars and AGNs

Extragalactic IRTF programs include observations of old and young quasars, where accretion diagnostics (O[III] and FeII emission lines) are redshifted (z~3) into the *H* and *K* bands can test for a correlation between quasar age and accretion measure (e.g. Ross *et al.* 2015). Another example is a program to investigate recent evidence that suggests a possible connection between radio brightness and quasar dust reddening. This is surprising since radio emission from AGNs is not expected to relate to dust located kiloparsecs away from the black hole. The near-infrared (NIR) wideband coverage of SpeX is needed to confirm quasar nature of these objects. A reddening correlation would provide constraints for feedback and co-evolution of AGN with galaxies.

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[6] https://www.sdss.org/surveys/
[7] https://galah-survey.org/survey_design
[8] http;//www.sdss.org/dr12/irspec

AGNs are thought to contain a circumnuclear dusty torus that explains the two types of AGN emission emerging from accretion onto a black hole as due to orientations effects (Antonucci & Miller 1985). However, the geometry of the hypothesized dust torus is currently too small to be resolved by imaging (point-like in the NIR). A promising technique is to constrain the size and geometry of the dust torus by reverberation – measuring the time with which the dust responds to ionizing flux from the accretion disk by measuring coronal emission lines in the NIR over the course of several weeks (Landt *et al*. 2015). The wideband NIR medium resolution available with SpeX and the ability to schedule multiple observing blocks for synoptic monitoring makes this a promising project for IRTF.

3.2. Supernovae

SN Ia cosmology is currently limited by systematic uncertainties and understanding these explosions is needed to reduce these systematics. SN Ia from different progenitor systems can have different redshift evolution properties (e.g. Hoeflich *et al*. 2017, Blondin *et al*. 2017), complicating the interpretation of the cosmic expansion history. NIR spectroscopy provides a unique probe of SN Ia physics with several important advantages over optical observations: NIR lines are stronger, isolated, and produced by ions often unavailable in the optical. Low to medium resolution NIR spectral diagnostics can be used to distinguish i) peculiar events, ii) unburned carbon, and iii) embedded hydrogen and helium, and lead to a better understanding of the underlying uncertainties. With the advent of all-sky surveys such at the All-Sky Automated Survey for Supernovae[9] (ASAS-SN) bright SN Ia events are more accessible to IRTF and SpeX with on average eight discoveries caught early within 80 Mpc each month (Holoien *et al*. 2017). Findings from these types of observations will inform the designs of the dark energy experiments onboard *WFIRST*.

3.3. Discussion and Future Needs

Most extragalactic science goals can be met with low and medium resolution NIR spectroscopy with SpeX. No particular needs have been identified for a new instrument although SPECTRE (Connelley 2018), the proposed three-channel low-resolution IFU spectrograph, will be of value for some extragalactic programs. Since all the viable science programs are for compact sources significant gains in the accessible number of targets can be made by improving the image quality and getting more light through the spectrograph slits. In the near-term gains of up to 0.5 magnitudes are achievable with the planned low-order active optics system for focus and collimation control. In the long-term gains of between 1-2 magnitudes are possible with an AO system. Flexible scheduling to allow synoptic monitoring will remain important.

[9] http://www.astronomy.ohio-state.edu/asassn/index.shtml

4. Emerging Topics (Presentations: Becklin 2018, Bosh 2018, Lau 2018, Mumma 2018)

4.1. Time Domain Astronomy

There are several ways in which observations at observatories including the IRTF are dependent on the time domain: (i) time critical observations, events that occur at a specific time, (ii) high time resolution observations (also requiring highly accurate timing fidelity), obtaining data at high rates (from a few seconds to 100 Hz or faster) for observations of stellar occultations, near-Earth objects, exoplanet transits, or stellar activity, (iii) repeated observations with a specified observing cadence (e.g. 30 minutes once a night for 10 nights) for observations of objects with short observing windows (comets, Mercury) or to monitor activity to watch for changes (cataclysmic variables), and (iv) rapid response observing to respond to targets of opportunity quickly (supernovae, gravitational-wave transients, various activity with solar system objects). Some of these needs impact the scheduling of telescope time (time-critical, repeated observations, rapid response).

All-sky synoptic survey telescopes such as PanSTARRS[10], ATLAS (Tonry *et al*. 2018), ASAS-SN and particularly LSST[11], will revolutionize time domain astronomy in the next decade. LSST is scheduled to start formal operations in 2023. The main "wide-fast-deep" survey covers 18,000 deg^2 of the sky within the declination range $-62° > \delta > 2°$ once every few days in the filters *ugrizy*. Within the main survey, two visits per 9.6deg^2 field (in either the same or different filters) are acquired in each night to allow identification of moving objects and rapidly varying transients. A Northern Ecliptic Spur mini *griz* survey ($\delta < 30°$, once every five nights) completes coverage of the ecliptic survey for small solar system bodies. Of main relevance to IRTF is the identification of astrophysical transients and the cataloging small solar bodies. Detection of on average 10^7 events (transients and moving objects) is expected per night. LSST is developing a community alert system for rapid dissemination, follow-up and event characterization[12]. Participating facilities include SOAR, Gemini, Blanco and Las Cumbres Observatory Global Telescope Network. Formal participation by IRTF could be considered.

GATTINI-IR (Moore et al. 2014) is a wide-field J-band survey telescope that will survey the observable sky to mag 15.5 every night, detecting IR transients. Individual fields are 5×5 arcmins with 8.6 arcsec pixels and so follow-up will be needed using larger telescopes, such as IRTF, with better spatial resolution and infrared spectroscopy for further characterization. The GATTINI-IR case includes supernovae, classical novae, massive YSO outbursts and the electro-magnetic counter parts gravitational wave events. A precursor program carried out during the warm *SPITZER* mission discovered a new class of eSPecially Red Intermediate luminosity Transient Events (SPRITES). The most interesting of these will be followed up with Guaranteed Time Observations on *JWST*.

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[10] http://pswww.ifa.hawaii.edu/pswww/
[11] https://www.lsst.org/
[12] https://www.noao.edu/meetings/lsst-tds/presentations/Blum_LSSTFollowUpSystem.pdf

4.2. Synergies with Other Telescopes

Collaborating with other telescopes and facilities was discussed. Possibilities include building complementary instrumentation, and developing and sharing instruments and other resources such as data reduction pipelines. The most promising synergy is with SOFIA and this is fully discussed in the following section on Mission Support.

4.3. Discussion and Future Needs

SPECTRE, the proposed 0.4-4 micron low resolution IFU spectrograph is ideal for transient follow up and occultation studies. The IFU allows for point and shoot positioning without the need for fine positioning for a slit and with no slit throughput losses.

IRTF is classically scheduled and most observers now use IRTF remotely. This has allowed for efficient scheduling of the telescope in blocks as short as one hour to accommodate synoptic monitoring and target of opportunity programs. In response to alerts from coming all-sky surveys IRTF needs to consider even more flexible telescope scheduling. One option is to employ queue observing but this would require more staff and is not considered a goal. Without queue observing accommodating more ToO programs could be arranged by padding the schedule with ToO observing blocks (say several blocks per month) and with agreement from classical remote observers to reschedule at short notice or have more experienced telescope operators execute well defined observing programs.

If a ToO interrupt requires a change of instrument this can take up to 30 minutes since this has to be done manually on IRTF. However, aside from increased efficiency, no strong scientific motivation for rapid instrument changes has been identified. Since instruments need to be manually moved into position remote operation of IRTF is not possible without major changes to the telescope multiple instrument mount and instrument optics.

5. Astrophysics Mission Support (Presentations: Becklin 2018, Hasan 2018, Rayner 2018)

Strategic support of current NASA flight missions is needed to achieve their science goals, enhance their scientific output, and provide data for mission planning. IRTF also provides preparatory data for planned missions and potential future missions and supports NASA's general science objectives and programmatic needs in the fields of exoplanets, stellar and substellar, galactic and extragalactic astrophysics (Hasan 2018).

5.1. Astrophysics Missions

IRTF support of NASA's future astrophysics missions is also key. In the near term IRTF will support the *K2* and *TESS* missions. IRTF has already played an important role in characterizing exoplanet hosts with SpeX for *K2* and will do the same for *TESS*. The proposed new instrument, SPECTRE, is ideal for exoplanet host spectral and luminosity measurements. TESS is likely to discover nearby and bright (K<5) exoplanet hosts harboring planets that can be characterized at high spectral resolving power with iSHELL by resolving out telluric contamination. Further exoplanet characterization can be done with radial velocity measurements made using iSHELL's gas cell ($\geq 10\ ms^{-1}$).

All-sky surveys and big data from facilities such as PanSTARRS (optical), Gattini-IR (*J* band, Moore *et al*. 2014) and the upcoming Large Synoptic Survey Telescope (optical) are becoming increasingly important. Potential NASA flight missions such as the *SPHEREx*[13] 1-5 μm all-sky R=40-140 spectral survey may also contribute. Ultimately these surveys will supply targets for NASA's flagship missions such as *JWST* and *WFIRST*. Observing time on these facilities will be orders of magnitude more expensive than IRTF. With its flexible suite of instrumentation IRTF can follow-up these targets in their own right but also perform triage before following up with *JWST* or *WFIRST*. Transients need to followed up fast and efficiently so some redesign of IRTF scheduling will need to be considered. Coordination with other facilities expected to be very active in transient follow-up, such as the Gemini telescopes, should also be expected.

Another important NASA facility is SOFIA. Lacking airplane cavity turbulence, the image quality on IRTF is typically a factor of 3-4 better at wavelengths shorter than about 20 μm. The cost of SOFIA per hour is 50 times more than IRTF. Therefore, IRTF should be used when the atmospheric transmission allows, except for objects not visible from Maunakea (e.g. solar system occultations). SOFIA and IRTF are highly complementary because together they cover most of the infrared wavelength range, and both have high spectral resolution capabilities (e.g., TEXES and iSHELL at IRTF versus EXES[14] and the future HIRMES[15] instruments on SOFIA). Their high spectral resolution instruments complement much lower spectral resolution instruments on space-based observatories, such as *JWST*, and are also particularly popular for solar system studies. There are other synergies between IRTF and SOFIA. IRTF has been used as a test bed for SOFIA instruments (EXES) and the facilities have shared data reduction pipeline development and should continue to do so.

5.2. Discussion and Future Needs

The proposed 0.4-4 μm R≈100 integral field spectrograph (SPECTRE, Connelley 2018) is an ideal instrument for exoplanet host characterization in support of the *K2* and *TESS* missions. SpeX is somewhat limited by slit losses that complicate flux calibration. This source of systematic error is removed with the use of an IFU in SPECTRE. The wide band coverage of SPECTRE makes it ideal for follow-up to discoveries made by survey missions such and *SPHEREx*.

Future missions are also better supported with improved spatial resolution and expanded spectral coverage. In the near term the proposed low-order active optics system will

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[13] http://spherex.caltech.edu/

[14] http://irastro.physics.ucdavis.edu/exes

[15] https://science.nasa.gov/technology/technology-stories/HIRMES-High-resolution-Mid-infrared-Spectrometer-SOFIA

improve image quality through focus and collimation control. IRTF is effectively diffraction limited at wavelengths longer than about 5 μm but in the long term an AO capability at shorter wavelengths would be a significant enhancement (with an adaptive secondary and LGSAO)

The upgraded MIR spectrograph and imager (MIRSI, Kassis *et al*. 2008) will be online in 2018. MIRSI will now include an optical channel enabling simultaneous MIR and optical photometry primarily to measure NEO albedos and therefore diameters but the return of thermal imaging to IRTF will have astrophysical applications. Finally, TEXES provides a valuable R≈5,000-100,000 8-26 μm capability but which is only currently available as a visiting instrument. Building a replacement or converting TEXES into a fully-supported facility instrument with remote observing and a user data reduction pipeline is highly desirable.

6. Summary of Astrophysics Future Needs

6.1. Science

Of primary importance is that IRTF continues to support NASA flight missions, provide data for mission planning, and supports NASA's general science objectives and programmatic needs in the fields of exoplanets, stellar and substellar, galactic and extragalactic astrophysics. Important current missions include *K2* and *TESS* where IRTF will play an important role in characterizing exoplanet hosts with low- to medium- resolution optical-NIR spectroscopy with SpeX and later with SPECTRE. Flux calibrated spectroscopy is vital for effective temperature scales by constraining bolometric fluxes, which is especially critical in the *Gaia* era where T_{eff} will dominate uncertainties to calculate radii. *TESS* is likely to discover nearby and bright (K<5) exoplanet hosts harboring planets that can be characterized at high spectral resolving power with iSHELL. Further exoplanet characterization can be done with radial velocity measurements made using iSHELL's gas cell ($\geq$ 10 ms^{-1}) particularly for young planets to test timescales for planet formation and migration. With its flexible suite of 0.4-26 μm instrumentation IRTF can follow-up interesting targets identified in all-sky surveys in their own right but also perform triage before following up with flagship facilities such as *JWST* and *WFIRST*. Another important NASA facility is SOFIA. SOFIA and IRTF are highly complementary because together they cover most of the infrared wavelength range, and both have high spectral resolution capabilities that complement much lower spectral resolution instruments on space-based observatories, such as *JWST*.

As measured by thermal emission from dust protoplanetary disks are thought to dissipate on timescales of a few Myr. However, gas accounts for most disk mass and so for a clearer picture of protoplanetary disk evolution the timescale of gas dissipation needs to be measured. Current work on optical emission lines indicates that disk gas dissipates more rapidly than dust, contrary to models. Fundamental CO line emission at provides a more direct tracer of disk gas in the inner few AU around young stars. With its high resolving power and wide wavelength grasp (many fundamental CO lines) iSHELL is ideal for this work. A more detailed understanding of the distribution of disk gas within individual disks can also be obtained using the technique of spectro-astrometry (SA), which has already been demonstrated with iSHELL on IRTF using the fundamental CO lines at 5 μm. SA can probe spatial information about disk gas at milli-arcsecond scales - orders of magnitude better than the diffraction limit. iSHELL will be a strategic resource for work on protoplanetary gas disks.

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. IRTF can provide key complementary information to achieve that goal; imaging to resolve *Gaia* low-mass binaries and iSHELL RV spectroscopy to measure *vsin(i)* and rotation periods that can empirically constrain radii, which are necessary for testing low-mass stellar structure models. Many of the key brown dwarf science objectives - measurement of the low-mass IMF of young associations, discovery and characterization of mass-yielding binaries, atmospheric model testing and abundance determination, and characterization of clouds and weather, can be achieved on IRTF with investments in new instrumentation, such as SPECTRE. Examples include the capability for simultaneous optical and infrared spectroscopy (atmosphere characterization, including magnetic- and weather-induced variability) and spectrophotometric monitoring of resolved binaries.

The medium-resolution 0.8-5 μm IRTF Spectral Library has proved a valuable resource for the astronomical community, finding applications in the physics of stellar atmospheres, stellar classification and stellar population synthesis. The library is currently being extended to include a wider range of metallicities and hotter stars for improved modeling of unresolved galaxy populations. Serious consideration should be given to constructing a complementary high resolution 1-5 μm with iSHELL. It would also prove a valuable resource for stellar physics. Despite its relatively small aperture IRTF remains competitive with larger telescopes for observations of compact point-like sources such as quasars and AGNs (powered by supermassive black holes), and supernovae. Increasingly, all-sky surveys are efficient at selecting large samples of objects the brightest of which are accessible for study at low to medium spectral resolution on IRTF.

6.2. Needed Capabilities

At the workshop there was general agreement that IRTF should proceed with measures to improve image quality to be seeing limited at *K*: a low-order active optics system followed by efforts to improve the dome thermal control. The primary goal being to improve throughput of the slit-fed spectrographs. Caution was expressed about the deployment laser guide star adaptive optics (LGSAO) for high-resolution imaging on IRTF because of the lack of in-house expertise and the large resources required. Even then IRTF would not be competitive with AO imaging on larger telescopes (except perhaps in the optical). Nevertheless, the high Strehl resulting from LGSAO can increase the point source sensitivity of spectrographs by up to 2 magnitudes. The consensus was that LGSAO, ideally with an adaptive secondary mirror, should be a long-term goal.

The case for SPECTRE, the proposed three-channel 0.4-4 μm R~100 (~8″x 8″) IFU spectrograph, was enthusiastically received. There was strong support from groups working on NEOs and small bodies, exoplanet characterization, occultations and transients. The consensus of many workshop participants was that IRTF should proceed with the development of SPECTRE as the next facility instrument.

There was strong support for the visitor instrument program on IRTF and in particular for MIR instruments. TEXES, the high-resolution MIR spectrograph, is very popular with observers and the possibility of taking over TEXES as a facility instrument was discussed. This would increase availability but would require extra staff to support it. Upgrades could include remote observing and the development of a data reduction pipeline (possibly in collaboration with SOFIA/EXES). Building a replacement for TEXES could also be considered. In the MIR observing conditions typically do not change significantly until about 10 am and so adding a regular extra sunrise to 10 am observing shift should be considered.

Workshop participants highly valued the ability to quickly change (in less than 30 minutes) between instruments both to support flexible observing schedules and to react quickly to target of opportunity requests. Apart from the increase in observing efficiency no strong science driver was identified for instant instrument changes. Since instruments need to be manually moved into position remote operation of IRTF is not possible without major changes to the telescope multiple instrument mount and instrument optics.In response to alerts from coming all-sky surveys IRTF needs to consider even more flexible telescope scheduling. One option is to employ queue observing but this would require more staff and is not considered a goal. Without queue observing accommodating more ToO programs could be arranged by padding the schedule with ToO observing blocks (say several blocks per month) and with agreement from classical remote observers to reschedule at short notice or have more experienced telescope operators execute well defined observing programs.

Building on the success of the Spextool data reduction pipeline for SpeX and iSHELL there was support for scriptable and interactive reduction pipelines based on open-source software (i.e. a move away from IDL) and community-based development (e.g. *github*). Further development of the IRTF archive toward a Keck-like data repository that hosts raw data and basic reduced spectra (and possibly user-contributed data products) was encouraged. Shared software development with SOFIA is encouraged.

References

Antonucci, R., Miller, J. S., 1985, ApJ, 297, 621
Banzatti, A., & Pontoppidan, K. M. 2015, ApJ, 809, 167
Becklin, E. E. 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Birkby, J. L., de Kok, R. J., Brogi, M., *et al*. 2013, MNRAS, 436, L35
Birkby, J. L., de Kok, R. J., Brogi, M., Schwarz, H., & Snellen, I. A. G. 2017, AJ, 153, 138
Blondin, S. *et al*. 2017, MNRAS, 470, 1, p.157-165
Brittain, S. D., Najita, J. R., Carr, J. S., *et al*. 2013, ApJ, 767, 159
Brittain, S. D., Carr, J. S., & Najita, J. R., 2018, PASP, 130, 074505
Brittan, S.D. 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Burgasser, 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Croll, B., Albert, L., Jayawardhana, R., *et al*. 2015, ApJ, 802, 28
Crossfield *et al*. 2015, ApJ 804, 10
Connolley 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Cushing *et al*. 2005, ApJ 623, 1115
David, T. J., Hillenbrand, L. A., Petigura, E. A., et al. 2016, Nature, 534, 658
de Ugarte Postigo *et al*. 2016, Proc. SPIE, Volume 9908, id. 990840
Donati, J. F., Moutou, C., Malo, L., *et al*. 2016, Nature, 534, 662
Dupuy *et al*. 2015, ApJ 805, 56
Fedele, D., van den Ancker, M. E., Henning, T., Jayawardhana, R., & Oliveira, J. M. 2010, A&A, 510, 72
Flagg 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Greiner *et al*. 2008, PASP 120, 403
Haisch, K. E., Jr., Lada, E. A., & Lada, C. J. 2001, ApJL, 553, L153
Haisch, K. E., Jr., Jayawardhana, R., & Alves, J. 2005, ApJL, 627, L57
Hasan, H. 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Hoeflich, P. *et al*. 2017, ApJ 846, 58
Holoien, T. W.-S *et al*. 2017, MNRAS, 464, 3
Huber *et al*. 2012, ApJ 760, 32
Huber, 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Huelamo, N., Figueira, P., Bonfils, X., et al. 2008, aap, 489, L9
Johns-Krull, C. M., McLane, J. N., Prato, L., et al. 2016, ApJ, 826, 206
Johns-Krull 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Käufl, H.U. *et al*., 2004, SPIE 5492, 1218
Kassis, M., Adams, J., Hora, J., Deutsch, L., Tollestrup, E., 2008, PASP, 120, 1271
Landt, H. *et al*. 2015, MNRAS, 454, 3688
Lebzelter *et al*. 2012, A&A 539, A109
Mahmud, N. I., Crockett, C. J., Johns-Krull, C. M., Prato, L., Hartigan, P., Jaffe, D. T. 2011, ApJ, 736, 123
Mann *et al*. 2015, ApJ 804, 64
Moore, A.M. *et al*. 2014, https://arxiv.org/ftp/arxiv/papers/1608/1608.04510.pdf
Newton 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Plavchan 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Pontoppidan, K. M., Blake, G. A., & Smette, A. 2011, ApJ, 733, 84
Prato, L., Huerta, M., Johns-Krull, C. M., Mahmud, N., Jaffe, D. T., Hartigan, P. 2008, ApJL, 687, L103
Prato, Carr, Johns-Krull,2018,
http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Rayner *et al*. 2016, SPIE, 9908E, 84R

Rayner *et al*. 2003, PASP 115, 362
Rayner *et al*., 2009, ApJS 185, 289
Rayner 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Ross, N. P., *et al*. 2015, MNRAS, 453, 3932
Saar, S. H., & Donahue, R. A. 1997, ApJ, 485, 319
Schlawin *et al*. 2017, 849, 163
Simon, M., & Prato, L. 1995, ApJ, 450, 824
Sitko 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Skrutskie, M. F., Dutkevitch, D., Strom, S. E., et al. 1990, AJ, 99, 1187
Smette *et al*. 2015, AA 576, A77
Souto *et al.* 2017, ApJ 835, 239
Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451
Tonry, J.L. *et al*. 2018, https://arxiv.org/abs/1802.00879
Theissen *et al*. 2018, ApJ 853, 75
van Eyken, J. C., Ciardi, D. R., von Braun, K., et al. 2012, ApJ, 755, 42
Vacca *et al*. 2003, PASP 115, 389
Vernet *et al*. 2011, A&A 536A, 105
Villaume *et al*. 2017, ApJS 230, 23
Villaume 2018, http://irtfweb.ifa.hawaii.edu/meetings/irtf_future_2018/Presentations/
Wyatt, M. 2008, ARAA, 46, 339
Yu, L., Donati, J.-F., Hebrard, E. M., et al. 2017, MNRAS, 467, 1342