The Planetary Systems Imager for TMT

Astro2020 APC White Paper

Optical and Infrared Observations from the Ground

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1. Introduction

The Planetary Systems Imager (PSI) for the Thirty Meter Telescope (TMT) is a modular instrument suite centered on a high-performance adaptive optics (AO) system that enables a broad range of sensing and characterization capabilities, with a particular focus on high-contrast applications. Built on a core capability of wavefront control and starlight suppression, PSI combines science backends providing imaging, polarimetry, integral field spectroscopy, and high-resolution spectroscopic capabilities across a wide range of wavelengths (0.6–13 μm). This instrument is well suited to address major questions in the formation and evolution of planetary systems that will be relevant in the extremely large telescope (ELT) era, as recently examined in the NASEM Exoplanet Science Strategy report. Addressing these questions relies on our leveraging of the diffraction-limited resolution and light-gathering power of TMT, both of which will enable us to directly study gaseous, icy, and rocky planets at a range of effective temperatures. A design goal is to enable the detection of biomarkers in the atmosphere of planets in the habitable zones of nearby stars. Moreover, the instrument's sensing capabilities enable a wealth of other studies, from solar system to extragalactic astronomy.

2. Scientific Rationale

Over the past three decades instruments on the ground and in space have discovered thousands of planets outside the solar system. These observations have given rise to an astonishingly detailed picture of the demographics of short-period planets ($P \lesssim 30$ days), but are incomplete at longer periods where both the sensitivity of transit surveys and radial velocity signals plummet. Even more glaring is that the spectra of planets discovered with these indirect methods are either inaccessible (radial velocity detections) or only available for a small subclass (transit).

Direct detection can be used to discover and characterize the atmospheres of planets at intermediate and wide separations, including non-transiting exoplanets. Today, a small number of exoplanets have been directly imaged, and they represent only a rare class of young, self-luminous super-Jovian-mass objects orbiting tens to hundreds of AU from their host stars. Atmospheric characterization of planets in the <5 AU regime, where radial velocity (RV) surveys have revealed an abundance of other worlds, requires an extremely large telescope aperture (such as the TMT) in combination with an advanced AO system, coronagraph, and suite of spectrometers and imagers – this is the Planetary Systems Imager (PSI).

PSI will provide astrometry, photometry, and spectroscopy of an unprecedented sample of rocky planets, ice giants, and gas giants at a variety of ages. For the first time habitable-zone exoplanets will become accessible to direct imaging, as PSI has the potential to detect and characterize the innermost regions of nearby M-dwarf planetary systems in reflected light,* as well as in thermal emission around Sun-like stars. PSI's high-resolution spectroscopic capabilities will not only illuminate the physics and chemistry of exo-atmospheres, but may also probe rocky, temperate worlds for signs of life in the form of atmospheric biomarkers (combinations of H_2O, O_2 and other molecules). By completing the census of non-transiting worlds at a range of separations from their host stars, PSI will also provide the final missing pieces to the puzzle of planetary demographics.

2.1 Summary of Science Goals

- Detect and characterize the thermal emission of rocky planets, ice giants, and gas giants around nearby stars. Constrain the luminosities of these planets.

*cf. whitepaper to the Exoplanet Science Strategy committee of the U.S. National Academy of Science, Engineering, and Medicine: `https://goo.gl/nELRGX`

- Detect and characterize the abundances and abundance ratios of biomarker gases and other molecules in exoplanet atmospheres, including CH_4, CO, H_2O, NH_3, PH_3, as well as other more tenuous sources.
- Measure cloud depths, compositions, as well as constrain planetary spin rates and 2d distributions of clouds.
- Characterize the emission of light reflected by nearby gas giants, ice giants, and rocky planets at close separations from their host stars. Characterize the innermost regions of nearby M- and possibly K-dwarf planetary systems at equilibrium temperatures compatible with liquid water.
- Measure the albedos of nearby super-Earth rocky planets through detection of thermal emission and reflected starlight.
- Directly detect interactions between planets and their natal disks. Measure mass accretion rates of forming exoplanets, and resolve velocity structure of accretion.

2.2 Landscape and Demographics

Led by *Kepler*, transit surveys of the last decade have revealed that about half of all solar-type stars host planets with sizes between Earth and Neptune (1–4 R_{Earth}) and orbital periods less than a year, and that these planets are frequently found in closely packed multiple systems. The occurrence rate of such small planets declines at the shortest orbital periods ($P <$10 days), but is roughly flat in $\log P$ for periods between a month and a year (Winn & Fabrycky 2015, and refs. therein). Jovian worlds are known to be less common than terrestrial planets (Howard et al. 2010; Mayor et al. 2011), but their higher detectability means that they comprise the bulk of the presently detected population of long-period planets ($P >$ 1 year; NASA Exoplanet Archive). At the longest periods, current imaging surveys of young systems have found that very massive planets are rare (0.6% for 5–13 M_{Jup} and a =30–300 AU; Bowler 2016), but true Jupiter analogs are currently beyond reach.

As ongoing technical innovation propagates to the evolution of AO imagers on 8–10 m telescopes, new surveys will reveal both cooler and less massive (perhaps sub-Jovian at the youngest ages) planets at moderate separations from their host stars. While this new population could be characterized by our instrument, PSI will be able to exploit TMT's extremely large aperture to reach uncharted areas of the exoplanet distribution function. This is because the large increase in aperture both decreases the inner working angle (IWA; probing smaller separations) and increases the achievable contrast (even with equal wavefront control performance, as the power in wavefront error per λ/D element decreases with increasing telescope diameter). Unlike flagship space missions currently under consideration, the IWA of TMT/PSI will enable access to the habitable zones of hundreds of cool dwarfs. PSI can greatly contribute to the demographics of planets from 0.5 to beyond 5 AU, especially around stellar types that are not amenable to RV measurements and for face-on systems (see also Dressing et al. 2019, APC white paper). We note that with sufficient wavelength calibration, PSI spectrometers could directly measure RV parameters through the NIR, minimizing cadence needs by targeting short-period planets around low-mass stars.

2.3 Planetary Characteristics

Even more crucial than detecting planets with a variety of masses and separations is probing their bulk properties with spectroscopy. Indeed, the classic "core accretion" model of planet formation is supported by the enhanced metallicities and detailed compositions of the giant planets in our solar system and their correlation with planetary mass and semimajor axis. When spectroscopy is combined with atmospheric models it allows us to infer the atmospheric compositions of exoplanets.

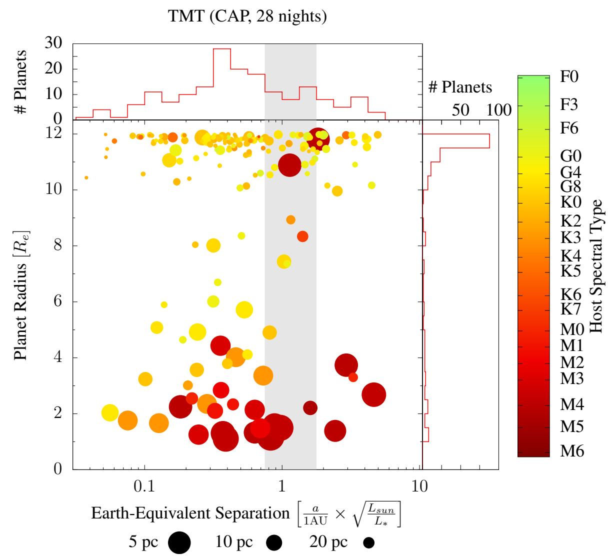

Figure 1. There are >100 *currently known* nearby planets potentially observable with PSI, ranging from temperate rocky planets to less observationally challenging giants. Shown are the detections of known planets with PSI in a survey spanning 28 nights of integration. The shaded region corresponds to an approximate habitable zone. Assumes a 1-λ/D IWA, speckle and photon noise arising from control of quasi-static aberrations and predictive control of the atmosphere at 0.8 μm. An empirical mass-radius relationship is used to derive planet radii. Albedos based on Cahoy et al. (2010) for larger planets, and the Earthshine spectrum (Turnbull et al. 2006) normalized to *EPOXI* measurements (Cowan & Strait 2013) for terrestrial planets ($R < 1.6 R_E$). Significant samples of both giant ($R_{Jup} = 11 R_{Earth}$) and rocky planets are detected across a range of T_{eq}, probing regions where condensates like H_2O, NH_3, and CH_4 are expected to play a major role in regulating planet formation.

Ongoing studies of giant exoplanet metallicity are beginning to explore whether core accretion is the dominant formation pathway for most exoplanetary systems. To date, however, observations of water or carbon abundance have been practical only for transiting hot-Jupiter planets and for self-luminous young giant planets discovered through direct imaging.

Over the next decade, the spectroscopic exploration of transiting planets will advance rapidly with the combination of *TESS* and *JWST*, including a potential sample of $\sim$100 giant planets and many more small planets (albeit biased towards planets with high effective temperatures and/or planets orbiting low-mass stars; Sullivan et al. 2015). TMT/PSI, however, will measure cooler planets and those orbiting earlier-type stars (Wang et al. 2019).[†] By probing different regimes of atmospheric chemistry than transit observations, we increase the parameter space spanned by our physical models, helping to identify their biases. Together, transit and direct methods will provide the spectroscopy of the diverse array of planetary targets that are needed to significantly further our understanding of planet formation.

In addition to composition, high-resolution spectroscopy can determine planets' rotation rates and cloud or continent distributions through Doppler imaging (Crossfield 2014). Photometry and polarimetry as a function of orbital phase can also constrain clouds, hazes, and surface features (e.g. Karalidi & Stam 2012). These science cases are enabled by TMT/PSI's unprecedented angular resolution, light-collecting power, and instrumentation. Moreover, PSI has the potential opportunity to detect biomarkers using a technique called high-dispersion coronagraphy (HDC; Wang et al. 2017). HDC takes advantage of high-resolution spectroscopy ($R >$50k) to overcome previous contrast limits from the ground (a raw planet-to-star contrast ratio of 10^{-5}) and in principle reach the sensitivities needed to characterize planets that are $\sim 10^8$ times fainter than their host stars (Lopez-Morales et al. 2019).[†]

TMT/PSI will be able to detect reflected light (and thermal emission) from many giant mature planets discovered through Doppler measurements (Figure 1), in addition to a sample of young, massive self-luminous planets (Bowler et al. 2019).[†] Moderate- or high-resolution spectroscopy

[†]Denotes an Astro2020 Science White Paper

of these planets can probe the depths of multiple water and methane features, allowing models to recover carbon or oxygen abundance (Lupu et al. 2016) and, in turn, enabling integrated studies of these abundances vs. planetary location, planetary mass, and stellar properties. Around nearer targets, PSI's sensitivity will reach down to sub-Neptune sized giant planets that will be discovered by upcoming Doppler and astrometric surveys. With the recent deprioritization of coronagraphic science on the *WFIRST* mission, 30-m class telescopes with AO are the only technique likely to characterize mature giant planets at AU-scale separations through at least the early 2030s.

Around nearby M dwarfs, PSI will be able to detect starlight reflected by rocky, temperate exoplanets in addition to ice and gas giants (Mazin et al. 2019).[†] For these stars, planets must orbit close-in to receive Earth-like radiance levels. While a boon for transit surveys due to the increased transit probability, the proximity of M dwarf habitable zones to the star poses a challenge for direct imaging because this zone typically lies well inside the IWA of 8-m telescopes. The small IWA of PSI makes it an ideal instrument for characterizing planets in this region. Only a small fraction will transit, and we await an understanding of the success of NIR-optimized RV surveys in discovering low-mass planets. Despite the uncertainties, Proxima Cen b, the TRAPPIST-1 planets, LHS 1140 b, Barnard's star b, and Teegarden's star b and c were all discovered in the last three years, and several more surveys targeting M dwarfs are beginning. PSI will be powerful not only in obtaining more complete and less biased statistics on planetary demographics through imaging surveys of low-mass stars, but also in characterizing these discoveries.

These observations will be among the first opportunities to detect biomarkers in the atmospheres of other worlds (Lopez-Morales et al. 2019).[†] Low-resolution spectroscopy at 10-μm can detect molecular species in rocky planets around nearby solar-type stars, while planets around faint M-type stars are the most favorable targets for spectroscopic follow up at shorter wavelengths with both PSI and *JWST* (in the case of transiting planets; Kasting et al. 2014). The abundant biomarker gas lines in these regions are of particular interest. For example, a simultaneous detection of oxygen (O_2) and methane (CH_4) would be highly suggestive of life (Des Marais et al. 2002). A detection of CH_4, however, is out of reach for *JWST* given the low concentration of CH_4 and the relatively high mean molecular weight / small scale height of an Earth-like atmosphere. Such measurements with PSI can potentially provide a strong case for life activities on nearby worlds: there are $\sim$20 M dwarfs within 5 pc that are observable by TMT, and there is at least one rocky planet per M dwarf (Dressing & Charbonneau 2015). Given the many nascent instruments that will undertake M-dwarf planet surveys in the near term, PSI will likely have access to a full census of characterizable planets in these nearest systems.

PSI will be able to detect thermal emission from warm (400–600 K) rocky planets around the nearest FGK stars (at 3–5 μm; Crossfield 2013), as well as somewhat cooler Earth-size rocky exoplanets around nearby Sun-like stars (at 8–13 μm; Quanz et al. 2015; Wang et al. 2019).[†] At the longest wavelengths, biomarkers such as H_2O, CH_4, O_3, and CO_2 can be identified with PSI using low-resolution integral field spectroscopy. The energy distribution can additionally be used to estimate surface temperature and cloud fraction. For $\sim$400 K super-earths around K-stars, PSI will be able to spectroscopically characterize both reflected light and 3–5 μm thermal emission for the same planets. The same will be true for some of the known, nearby, close-separation RV-detected rocky terrestrials, super-Earths, and warm giants (ice and gas) at 10 μm. Combining measurements of thermal and reflected light will make PSI the first instrument that is able to study the energy budget and climate of other worlds.

2.4 Planetary System Architectures

PSI will be able to place individual planets into formation context, both by investigating the correlation of planet properties with location, and by imaging circumstellar disks (e.g., Sallum et al. 2019).† The smaller IWA will allow PSI to peer into the inner regions of other systems that are inaccessible to today's telescopes.

In directly imaging dozens of exoplanets with previous RV detections and anticipated astrometric detections, PSI provides the spectroscopic and astrometric data (potentially combined with RV mass constraints) needed to investigate correlations between the locations and properties of different planets within a planetary system, including minor bodies. In the solar system, understanding such correlations has given us invaluable clues as to the system's formation history and dynamical evolution. For example, measuring the spatial locations and extent of the asteroid and Kuiper belts (as well as modeling their dynamical interactions with Jupiter) have been critical to understanding the potential mechanisms for the delivery of water to the nascent Earth. Tracing the architectures of extrasolar planetary systems – both planets and disks – is required to understand planet formation, evolution, and ultimately habitability. Indeed, planetary metallicities and/or abundance ratios (e.g. C/O) may indicate the semi-major axes at which planets form, tracing their subsequent migration.

Studying circumstellar disks can probe the full life-cycle of planetary systems: protoplanetary disks probe the earliest stages of planet formation when orbital architectures are still in flux, while debris disks reveal a system's long-term evolutionary state. The small IWAs afforded by TMT's aperture will allow us to probe true solar system planet analogs at separations of $\sim$1 AU out to 140 pc, where the nearest star forming regions are located (Fig. 2). For these nearest protoplanetary disks, PSI will image the gaps, spiral arms, and other asymmetries that trace planet-disk gravitational interaction, including down to terrestrial mass (Jang-Condell et al. 2019).† These structures' morphologies will help constrain the masses and orbits of forming planets. Furthermore, current telescopes are generally limited to imaging colder Kuipber-belt analog debris disk components, but PSI will access the separations at which zodiacal and asteroid belt analogs reside. Such belts can reveal morphological signs of unseen planets below PSI's detection limits and further contextualize system architectures. For both protoplanetary disks and debris disks, multi-wavelength photometry and polarimetry will constrain the properties (e.g. size distribution, porosity, composition) of $\sim$micron-sized dust. In protoplanetary disks, this dust represents the building blocks of planets, while in debris disks it is generated from collisional cascades of asteroid and comet-like parent bodies. By probing both types of disks we can trace the evolution of dust grains over the range of planet lifetimes, from their birth to their long-term evolutionary outcomes.

2.5 Other Science

Although PSI is optimized for characterization of exoplanets and disks, it will support a broad range of astrophysical science by expanding the capabilities of the TMT first generation instrument suite. PSI provides science cameras covering 0.5–5μm with imaging, polarimetry, and low/medium/high-resolution spectroscopy, all behind a high-performance AO system. PSI also has a channel for 10 μm imaging spectroscopy. Below we briefly discuss a few science areas where these capabilities will be broadly useful.

Volcanic Eruptions on Io — PSI's thermal integral field spectrograph (IFS) will monitor the locations, temperatures and areal extents of 10 times as many volcanoes as are visible with current telescopes (Chanover et al. 2019).†

Organics in Comets — IFS spectra of organic species in comets constrain the formation and survival pathways for species that are pervasive in SFRs and the ISM (Trilling et al. 2019).†

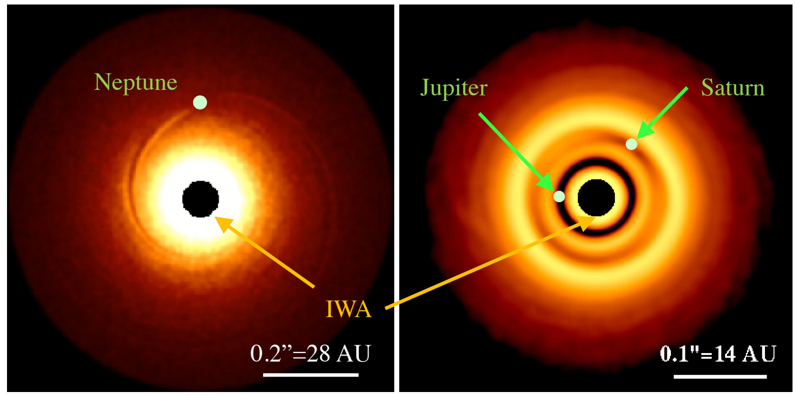

Figure 2. PSI can constrain the masses and orbits of forming planets by observing morphological features of cirucmstellar disks. Shown are 3D rad-hydro model predictions for PSI in H-band scattered light imaging, with spiral arms excited by a Neptune mass planet (left) and gaps opened by a Saturn and a Jupiter mass planets (right). Solar system planets are on their current orbits in a disk around a $1\,M_{\rm sun}$ star at 140,pc. The images assume an IWA of $2\,\lambda/D$. Images adopted from Dong & Fung (2017a,b).

Asteroid Multiples — PSI's diffraction-limited visible light imager will discover and monitor the orbits of asteroid multiples to constrain their masses and densities.
Planetary Atmospheres — High angular and spectral resolution spectroscopy at various wavelengths will probe the compositions and dynamics of weather and other variable phenomena on objects with dynamic atmospheres, such as Venus, Jupiter and Titan (Wong et al. 2019).†
Stellar Multiplicity — The combination of high-contrast imaging and high-resolution spectroscopy will allow PSI to measure the orbits of a wide range of binaries, in order to constrain the star formation process and test stellar evolution models in coeval systems.
Stellar Evolution — PSI will have the ability to resolve the AU-size scales of circumstellar environments of evolved stars (i.e., AGB stars, Wolf-Rayets) to study their stellar activity and dust formation processes, which play a major role in galactic chemical evolution.
Inner Regions of Circumstellar Disks — PSI will be able to spectro-astrometrically detect atomic and molecular lines in the inner parts of protoplanetary disks for studying evaporation, accretion, and winds (Jang-Condell et al. 2019).†
Ice Lines in Disks — PSI will obtain 2–4 μm IFS spectroscopy of protoplanetary and debris disks to image the broad 3.1-μm feature from water ice, a primary building block of planetary cores.
Dust streamers in Interacting Binaries — PSI will image dust flows connecting the components of Mira-like variables to constrain the evolution of interacting binaries.
Compact Objects — PSI can precisely measure masses of compact objects (black holes, neutron stars) and stars via astrometric microlensing.
Inner Regions of Quasar-Host Galaxies — PSI will deliver high-angular resolution images of the inner regions of local and high-redshift quasar-host galaxies, which will establish the co-evolution of galaxies and quasars. The sample could be greatly expanded with an LGS mode.
Spatially Resolved Spectra of Nearby Galaxies — PSI will be able to extend the spatially resolved SEDs of galaxies into the thermal infrared, probing PAH features and dust. Nearby AGN have tori with spatially resolved emitting regions that expand with wavelength. This sample also benefits from an LGS mode.

3. Technical Overview

3.1 Key Technical Requirements and Performance Goals

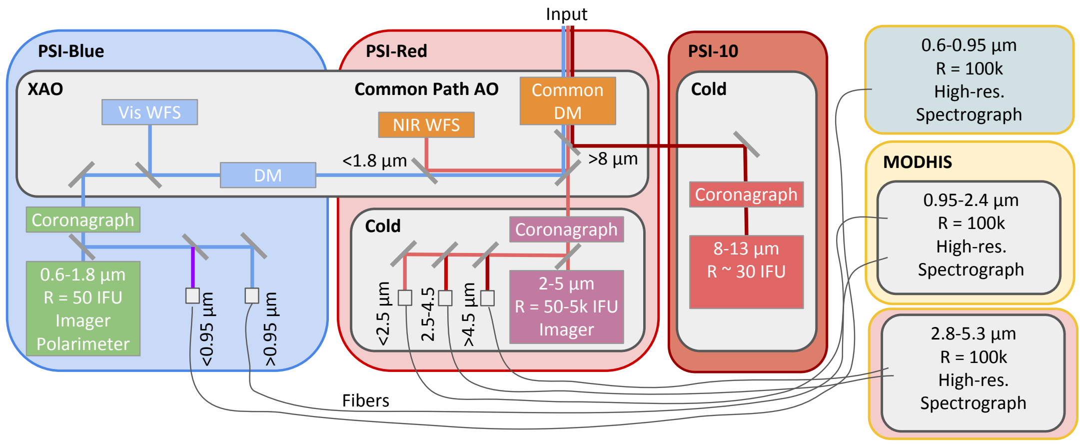

Figure 3. Conceptual layout of the PSI architecture. Not shown are atmospheric dispersion correctors and low-order wavefront sensors, as well as the coronagraphic IFS on the 10-μm channel.

- 10^{-5} at 1–2 λ/D raw contrast (0.6–1.8 μm)
- 10^{-8} at 1–2 λ/D final contrast (0.6–1.8 μm)
- 10^{-7} at 1–2 λ/D final contrast (2-5 μm)
- 10^{-7} at 1–2 λ/D final contrast (10 μm)
- Imaging and polarimetry (0.6–5.3 μm)
- R$\sim$200 integral-field spectroscopy (0.6–5.3 μm)
- R$\sim$30 integral field spectroscopy (8–13 μm)
- R$\sim$5k integral field spectroscopy (2–5.3 μm)
- R$\sim$100k spectroscopy (0.6–5.3 μm)

3.2 Instrument Architecture

Achieving the high contrast levels necessary for sensing and characterizing exoplanets and disks requires a multi-staged approach. The first stage provides precise wavefront control (achieved through AO), which then feeds to optics for suppressing the light from the host star (coronagraph). With the gain in raw contrast enabled by these modules, the light can then be fed to back-end instruments that are tailored toward the scientific measurements of interest as well as capabilities which enable further gains in wavefront control and starlight suppression. This can be accomplished both through feedback to the earlier stages (e.g. focal-plane wavefront sensing) and through post-processing. Experience to date shows care must be taken to minimize the degree and impact of aberrations and chromaticity with high-quality optics in the front-end (AO and coronagraph) relays, as well as by using lenslet-based integral field spectrometers (IFSs).

Our scientific interests span a broad wavelength range (0.6–13 μm). High-contrast science at the shorter wavelengths, from the optical to the blue end of the near-IR, is more technically demanding in terms of wavefront control than at longer wavelengths. Additionally, differences in background levels and detector technologies (in wavefront sensing and the back-ends) have driven us to a modular architecture that has different paths for light of different wavelengths. This architecture is based on a central core that feeds multiple instrument subsystems (Fig. 3). The design progresses from the mid-IR to the optical, splitting the light with dichroics into an 8–13 μm thermal module (“PSI-10”), a 2–5 μm section (“PSI-Red”) and a 0.5–1.8 μm optical and near IR section (“PSI-Blue”). Light is fed from the telescope to a set of preliminary optics then to a first-stage deformable mirror (DM) and IR wavefront sensor (WFS). This DM corrects the bulk of the turbulent phase errors, and will set the correction level of light feeding a set of cryogenic instruments optimized for $> 2\,\mu$m. Shorter wavelength light will be directed to the 0.5–1.8 μm optical section, beginning with a second DM and visible light WFS (sensitive to visible light, including the 589 nm Na LGS line) that is capable of correction for optical and near-IR wavelengths. A primary function of the second DM is the control of residual wavefront errors that more strongly affect shorter wavelengths. The light will then feed a set of instruments optimized for 0.6–1.8 μm science.

PSI-Red will share heritage with current mid-IR instruments and will operate from 2–5.3 μm. It will use an all-reflective design with a low-resolution IFS and imager, hosting a polarimeter and a high-resolution fiber-fed spectrograph. The primary IFS will use a lenslet array that fully samples an arcsecond-level field. Imaging will have a field of view driven by the limitations of the AO opto-mechanics. Both the IFS and imaging channels function simultaneously, allowing for advanced chromaticity-sensitive speckle suppression techniques to be employed in real-time speckle control and post-processing (e.g. Frazin 2019). The polarimeter will allow the measurement of the polarization states of both planets and disks, while at the same time suppressing speckles via polarimetric differential imaging. Further, atmospheric characterization at medium spectral resolution will be made possible via insertable slicing optics that geometrically rearrange a subset of lenslets into a pseudo-slit while using the same spectrograph optics as the primary lenslet channel. High spectral resolution characterization will be possible using a high-dispersion fiber-fed spectrographs. We have created a practical optical design concept for PSI-Red with these features based on the W. M. Keck Observatory instrument SCALES, currently in preliminary design.

PSI-Blue will be the result of an evolution of current instruments such as SPHERE, GPI, and SCExAO. It will operate from ~500 nm up to 1.8 μm, where thermal background arises. A faster and more sensitive wavefront control loop is needed to maintain sufficiently high contrast at these shorter wavelengths. This includes a wavefront sensor optimized for high sensitivity at high spatial frequencies along with a second tweeter DM. In addition, this channel must operate at higher bandwidth than those of PSI-Red due to the shorter decorrelation of the phase errors.

Shorter wavelengths not only offer superior angular resolution for accessing the inner regions of planetary systems, they also enable measurement of reflected and scattered light. For these reasons the blue-side instrument suite will include capabilities for low-resolution integral field spectroscopy, fiber-fed spectroscopy for detailed characterization at high R, and visible-NIR fast-switching polarimetry for the characterization of planet and dust disk scattering.

The main driver behind the long wavelength channel (PSI-10) is the characterization of planets' thermal emission. This is achieved through a coronagraph optimized for 8–13 μm operation feeding a low-resolution, narrow-field IFS. By splitting shortly after the first-stage DM, the number of non-cryogenic optics are minimized before the focal plane is sampled by the IFS lenslet array, minimizing thermal background and wavefront error.

Many of the technical research and development advances that must occur to achieve the most demanding contrast levels drive the blue-side requirements. We enumerate the challenges in §4; there is a companion APC whitepaper from Guyon et al. describing the necessary developments in more detail. We account for the greater blue-side development levels through careful phasing of the development and deployment activities. PSI-Red/10 will be deployed as a fully functional facility grade instrument. PSI-Blue hardware can be phased in installation (AO and back-end instruments that provide real time feedback, such as those acting as focal-plane WFS), but will likely require significant on-sky tuning of the AO control system before it will meet its more challenging specifications. Both instruments will be built in a modular fashion with well-defined optical, mechanical, electronic, and software interfaces. This modularity will enable upgrades of key components (deformable mirrors, wavefront sensors, ADCs, etc.) without a complete rebuild, as well as enabling contributions from all partners.

The above instrument concept presents unique advantages. While the science goals in reflected light are incredibly compelling, there is significant technical risk that needs to be retired before success is assured. The combination of arms operating at different wavelengths allows us to mine guaranteed science in the less technically demanding 2–13 μm bands, while simultaneously collecting photons from the same target in the 0.5–1.8 μm reflected-light channel. This will allow us to better understand the new telescope, its vibrations, and site-specific weather, and to begin implementing the software control systems that will enable us to reach final contrasts around 10^{-8} at 1–2 λ/D without using valuable telescope time for engineering.

3.3 Telescope and Observatory Architecture

PSI will primarily be deployed on a Nasmyth platform of TMT, including its adaptive optics system and the majority of its backend instrumentation and electronics. Cooling and power will be provided by facility infrastructure. The high-R SMF-fed spectroscopic capability of PSI in the 1–2.5 μm region will be provided by the MODHIS spectrometer (Astro2020 APC white paper Mawet et al.); the location of this spectrometer is still to be determined, but may be located away from the Nasmyth platform in a stable environment. PSI's short-wavelength high-R spectrometer ($< 1\,\mu$m) may be located in a similar environment, however long-wavelength high-R spectrometer capability will be co-located on the Nasmyth platform due to limitations from fiber losses.

The vibration dynamics of the telescope and the environment have proven to be essential to understand and control on current systems. As a segmented telescope, TMT will have the additional complication of coupled dynamics of primary mirror segments. While it is best to first minimize their amplitudes, the impacts of vibrations on raw contrast levels can be mitigated through the incorporation of additional sensing channels into (predictive) AO control schemes (this "sensor fusion" is noted in §4). On longer timescales, the PSI AO system will "offload" wavefront error onto the telescope primary and segmented mirror positioning systems. As such, PSI will necessarily integrate with the telescope sensing, telemetry, and control systems.

4. Technology Drivers and Roadmap

Optimizing the scientific impact of TMT PSI requires an active R&D program. There are many key technology development areas required; some of these developments are already underway in the high-contrast imaging community. Of paramount importance is the availability of laboratory and telescope test facilities to develop and proof-test these new technologies and techniques. Key technologies include high-density deformable mirrors, low-noise detectors, coronagraphs for segmented, obscured apertures, low-order wavefront sensors, real-time controllers, single- and multi-mode fibers and bundles, polarimetric devices, dichroics, and atmospheric dispersion correctors. Critical techniques include simulation capabilities, demonstrations of high-speed AO correction, focal-plane wavefront sensing and control, predictive control, sensor fusion, and differential imaging and other post-processing techniques. These technologies and the roadmap for achieving the requisite performance levels are described in a companion APC white paper from Guyon et al.

5. Organization, Partnerships, and Current Status

Currently the members of the PSI project are readying for conceptual design, developing simulation tools,[‡] developing precursor instrumentation (such as Subaru/SCExAO, Keck/HISPEC, Keck/SCALES), and furthering fundamental techniques and technologies outlined in §4. The MODHIS instrument, which provides high-resolution single-mode-fiber-fed spectroscopic capability for PSI, is currently planned to be ready at TMT first light.

[‡]https://github.com/planetarysystemsimager/psisim

As a TMT instrument, the PSI partnership seeks to span the partnership of the TMT International Observatory. For the U.S., this includes both UC and Caltech as partners, but other institutions as well (currently including UMich, UH, Notre Dame, Stanford, UAz, MIT, ARC). This is expected to evolve and expand with the TMT partnership. Planned partnerships span all TMT partner institutions. The PSI team also collaborates closely with with GMagAO-X team (Astro2020 APC white paper by Males et al.) given the two instrument concepts share common technologies.

6. Schedule

A notional schedule for the development of the instrument has its deployment occurring in 2030, shortly after the first light of TMT. The next major phase of the project is conceptual design. However, essential R&D (§4) for the more challenging requirements will be performed in parallel. Precursor instruments, such as Keck/HISPEC, Keck/SCALES, GPI upgrades, and Subaru/SCExAO and its instruments are in various stages of preparation in order to validate and demonstrate these technologies and techniques on current large telescopes.

Experience has shown that the deployment of high-contrast instrumentation requires significant tuning to optimize AO correction and the resulting contrast. These challenges are magnified as wavelength decreases; accuracy and speed become more critical to achieving performance goals. For these reasons we will stage the deployment of PSI, with the PSI-Red and PSI-10 channels deployed before the more challenging PSI-Blue. This will allow for science campaigns for exoplanet characterization in thermal emission to progress while the PSI-Blue wavefront control and suppression techniques are tuned over the first ∼2 years of operation. We expect PSI to entertain at least a 10-year lifespan given the potential for extended science campaigns across planets and host stars of different types. Moreover, the modularity of the instrument allows for upgrades as technological improvements become available (e.g. detectors, coronagraphs).

7. Cost Estimates

No reliable cost estimates have been obtained, given the project has not yet completed a conceptual design. The relevant scales for development costs are the upper end of the "Medium" or the "Large" category of ground-based instruments. The parallel cost of related technical research is also significant, especially for the PSI-Blue channel. Funding for PSI development and operations is expected to come from TMT and its members.

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