THIRTY METER TELESCOPE
PLANETARY SYSTEMS IMAGER

DIMITRI MAWET, ON BEHALF OF THE TMT-PSI TEAM
TMT-PLANETARY SYSTEMS IMAGER

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SCIENCE CASES - EXOPLANETS

- Exoplanet demographics on Solar system scales (0.5 AU to >5AU)
- Exoplanet characterization from Earth-like planets, Super-Earths, Mini-Neptunes, Ice and Gas giants
  - Orbital configuration/dynamics
  - Atmosphere composition, clouds/hazes
  - Energy budget, climate
  - Spin, Weather
  - Moons, rings
- Biosignatures on Habitable Earth-size planets around M/K stars
  - H₂O, O₂, CH₄ trifecta
A REAL GIANT PLANET IN ORBITS AROUND STARS, AND SUCH GROUND-BASED CAMPAIGNS SHOULD BE CONTINUED WITH DILIGENCE. NOT ONLY WILL THEY PROVIDE A CENSUS OF OUTER GIANT PLANETS, THEY WILL ALSO PROVIDE TARGETS FOR SUBSEQUENT CHARACTERIZATION STUDIES. THE PRECISION OF THE RV TECHNIQUE HAS STEADILY IMPROVED TO THE POINT WHERE THE DETECTION OF EARTH-MASS PLANETS IN SHORT-PERIOD ORBITS AROUND BRIGHT STARS IS NOW POSSIBLE (E.G., THE ROCKY EARTH-SIZE PLANET KEPLER-578b). EFFORTS ARE UNDERWAY TO IMPROVE THIS PRECISION EVEN FURTHER, POTENTIALLY ALLOWING ROUTINE DETECTIONS OF SHORT-PERIOD EARTH-MASS PLANETS AROUND A RANGE OF HOST STARS. DEVELOPING THIS CAPABILITY IS NOT ONLY IMPORTANT FOR SURVEYING NEARBY SYSTEMS DOWN TO LOW MASSES, BUT ALSO FOR PROVIDING CRUCIAL MASS MEASUREMENTS FOR PLANETS DETECTED BY TRANSIT SURVEYS, SUCH AS THE TESS MISSION (DISCUSSED IN SECTION 2.2). IN PRINCIPLE, IT MAY BE POSSIBLE TO IMPROVE RV PRECISION TO THE POINT WHERE THE DETECTION OF EARTH-MASS THEIR FREQUENCY. RV MEASUREMENTS MIGHT THEN YIELD CRUCIAL MASS MEASUREMENTS FOR EXOCEORTHS DETECTED BY THE DIRECT IMAGING MISSIONS OF THE FORMATIVE AND VISIONARY ERAS (SEE SECTION 2.3). RECOGNIZING THE IMPORTANCE OF THESE GROUND-BASED EFFORTS, NASA HAS INVESTED IN THIS LINE OF RESEARCH, WITH RECENT EXAMPLES BEING THE ETA-EARTH SURVEY AND THE KEPLER FOLLOW-UP PROGRAM ON THE KECK I GROUND-BASED TELESCOPE.
Small Planets Come in Two Sizes

Number of Planets per 100 Stars

Size Relative to Earth (Radius)

Kepler-22b
Kepler-452b
“Fulton gap”

Fulton et al. 2017
1 in 4 M-type stars has a rocky planet in its Habitable zone

Dressing & Charbonneau 2015

Proxima Centauri b
Artist rendition (ESO/M. Kornmesser)
BLIND SEARCH VS TARGETED CAMPAIGN
RV, TESS AND GAIA

- Plethora of new RV machines coming online, many now expanding to the near-IR
- TESS Launch imminent (Spring 2018)
  - All-sky transit mission
  - More exoplanet demographics
  - Expected to detect a few super-Earths in 100-day orbits around nearby stars
  - Remember single-transits
- GAIA expects to find $>>10,000$ Jupiters orbiting FGKM and WDs <100 pc, many with orbits (and masses!)
- $\sim2,600$ detections of Jupiter mass planets incl. $\sim500$ accurate orbits (assuming $\eta_{\text{Jup}}\sim3\%$ from RV)
- Some detectable with ELTs @ 1e-8 contrast
- Astrometric trends from 1-70 MJup companions. BDs detectable with current ExAO

Sozzetti 2015
Planets that formed on orbital configurations similar to the solar system might be expected to have multiple zodiacal belts or asteroid belt analogs. Such belts have the potential to reveal morphological signs of which planets form, tracing their subsequent migration.

Other science cases include:

- 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 habitability. Indeed, planetary metallicities and/or abundance ratios (e.g. C/O) may indicate the semi-major axes at which planets form and how they subsequently migrate.
- Investigating correlations between the locations and properties of different planets within a planetary system, including the potential influence of Jupiter-mass planets, is key to understanding planet formation, evolution, and ultimately the potential mechanisms for the delivery of water to the nascent Earth.
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OTHER SCIENCES

• Solar system science:
  • Volcanic Eruptions on Io
  • Organics in Comets
  • Asteroid Multiples
  • Planetary Atmospheres

• Galactic Astrophysics:
  • Stellar Multiplicity
  • Stellar Evolution
  • Inner Regions of Circumstellar Disks
  • Ice Lines in Disks
  • Dust streamers in Interacting Binaries
  • Compact Objects

• Extragalactic Astrophysics:
  • Inner Regions of Quasar-Host Galaxies
  • Spatially Resolved Spectra of Nearby Galaxies
HOW-TO: DIRECT REMOTE SENSING

- Fill out parameter space not probed by indirect techniques ➔ Direct imaging
- Orbital properties (SMA, e, i) ➔ Astrometry
- Bulk properties (Mass, $T_{\text{eff}}$, log g) ➔ Multi-λ Photometry
- Atmosphere’s composition, spin, inhomogeneities ➔ Spectroscopy (LRS, HRS)
- Cloud morphology, particle sizes and composition ➔ Polarimetry
- Planet-disk co-evolution ➔ Disk imaging (scattering, emission)
Habitable Zones within 5 pc (16 ly)

- **Inner Working Angle**
- **Contrast floor**

Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

O. Guyon
COMPLEMENTARITY WITH JWST

- Major impact in transit spectroscopy of short-period planets
- High-contrast imaging of self-luminous planets at larger separations
- Limited low-resolution spectroscopy

Morley et al. 2015
COMPLEMENTARITY WITH WFIRST CGI, HABEX/LUVOIR

- Launch >2024
- 0.4-1.0 um, R~70 spectroscopy
- Inner working angle 0.2"
- Discovery and characterization of nearby giant planets, several Neptunes
- Coronagraph may or may not have significant science program
- An opportunity for TMT for Reflected-light spectroscopic follow-ups of Jupiters/Neptunes at 100-500K Teff.
- Technological synergies
- And HabEx and LUVOIR
FEATURES OF THE PSI CONCEPT

• Ability to address a wide range of science goals
  • Including non-exoplanet science

• Modularity
  • Core capabilities support different science instruments
  • Upgrade paths to accommodate new technology
  • Fiber feeds allow straightforward use of instruments deployed and tested on smaller telescopes

• Relatively compact
  • Diffraction-limited, narrow field-of-view optics
  • Allows for phased development and deployment
Science case requires broad wavelength coverage
IMAGING GAS GIANTS, MINI-NEPTUNES AND ROCKY PLANETS

1 l/D IWA coronagraph, SNR=5 in broadband (400nm) @ 800nm
Speckle-noise limited with predictive control
No chromatic effects (WFS and science at 800nm)
HIGH DISPERSION CORONAGRAPHY AS A TOOL TO DETECT BIOSIGNATURES WITH TMT
1) LIGHT OBSERVED

- Light of Star + Planet
- Light of Planet + Residual Starlight

2) LIGHT PROCESSED WITHIN TELESCOPE

- Coronagraph: Blocks Most of Light from Star
- Optical Cable: Isolates Light from Planet

3) DATA ANALYZED

- High Resolution Spectrograph
- Raw Data from Spectrograph
- Matched to Ideal Model of Oxygen Spectrum

4) EXCITING RESULT

THE GOAL:

Detection of Oxygen in Planet Atmosphere!
HDC SIMULATIONS FOR GSMTS

EARTH-LIKE PLANET CHARACTERIZATION

Wang et al. 2017
HIGH DISPERSION CORONAGRAPHY

Mawet et al. 2017
FIBER INJECTION UNIT FOR THE KECK PLANET IMAGER AND CHARACTERIZER

## TECHNOLOGY GAPS - HARDWARE

<table>
<thead>
<tr>
<th>Items</th>
<th>Requirements</th>
<th>Actors/Partners</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Density Deformable Mirror</td>
<td>120×120, fast, large stroke (6 μm), low defective actuator count</td>
<td>BMC, NG, ALPAO, IRIS AO, TNO, Phys Inst, Xinetics, Northrop Gruman</td>
<td>R&amp;D initiated by ALPAO, ESO, BMC, synergies with space, Could be realized with woofer + tweeter setup</td>
</tr>
<tr>
<td>Low-noise detectors</td>
<td>&lt;1 e− ron, energy resolving, fast (ms), both for optical and IR</td>
<td>E2V (EMCCD), FLI, Nüvü, Leonardo/UH (IR-APD), UCSB/JPL (optical/NIR MKIDs)</td>
<td>Synergies with WFIRST-CGI, HabEx/LUVOIR</td>
</tr>
<tr>
<td>Coronagraph for segmented, obscured apertures</td>
<td>&gt;20%BW, small IWA, high throughput</td>
<td>UoA/Subaru, NASA AMES, Princeton, Caltech, JPL, Leiden, ABC/NAOJ, Hokkaido U</td>
<td>Solutions exist, need lab/on-sky demos</td>
</tr>
<tr>
<td>Low order wavefront sensor (LOWFS)</td>
<td>Fast, out of band, sensitive, sensor fusion</td>
<td>UoA/Subaru, NASA AMES, UCSC, HIA, U of T</td>
<td>Now in operation, telemetry management not unified</td>
</tr>
<tr>
<td>Real Time Controller</td>
<td>Fast, large scale SVD (predictive control)</td>
<td>UoA/Subaru, MicroGate, GreenFlash, JPL, KAUST, Osaka Univ.</td>
<td>Requirements TB refined</td>
</tr>
<tr>
<td>Fibers (single/multi-mode, bundles)</td>
<td>Low-loss, cryogenic, feedthroughs, photonic lanterns, high-density high fill factor bundles</td>
<td>LVF, Corning, Caltech, JPL, fiberguide, ABC/NAOJ, U Tokyo</td>
<td>Synergies with RV and highly multiplexed spectro</td>
</tr>
<tr>
<td>Polarimetric devices</td>
<td>Fast switching high efficiency modulators, achromatic waveplates</td>
<td>Leiden, Caltech/JPL, Subaru</td>
<td>New tech. Available: e.g. polarization gratings</td>
</tr>
<tr>
<td>Dichroics/ADC</td>
<td>High efficiency, large bandwidth, cryogenic</td>
<td>Asahi Spectra</td>
<td>Microstructures promising</td>
</tr>
</tbody>
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Table 1. Key technologies for TMT PSI — high priority HARDWARE needs. Actors/Partners will expand with our collaboration.
## TECHNOLOGY GAPS - SOFTWARE

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<tr>
<td>Extreme AO</td>
<td>2 kHz, 100 µs lag for $I = 9$, $120 \times 120$ elements</td>
<td>UoA/Subaru, LLNL, Stanford, JPL, NRC</td>
<td>~2 kHz loop frequency, assuming predictive control</td>
</tr>
<tr>
<td>Focal plane WFS/C</td>
<td>Control amplitude speckles, NCPAs</td>
<td>JPL/Caltech, NRC</td>
<td>Eliminates non-common paths from control</td>
</tr>
<tr>
<td>Predictive AO control</td>
<td>Achieve 100 µs-level temporal lag on $I = 9$ sources</td>
<td>LLNL, Victoria, Stanford, UoA/Subaru</td>
<td>Improves sensitivity, critical for M dwarfs</td>
</tr>
<tr>
<td>Sensor fusion</td>
<td>Integrated control algorithms making use of all sensors/telemetry</td>
<td>Princeton, JPL/Caltech, UoA/Subaru</td>
<td>Improves sensitivity, addresses WF chromaticity</td>
</tr>
<tr>
<td>Post-processing</td>
<td>Bridge the gap between raw contrast and astrophysical contrast, work at the photon noise limit</td>
<td>LAOG, Berkeley, Caltech, Stanford, STScI, UCLA, NRC</td>
<td>Machine learning techniques (supervised learning), coherent differential imaging</td>
</tr>
</tbody>
</table>

**Table 2.** Key technologies for TMT PSI — high priority SOFTWARE needs. Actors/Partners will expand with our collaboration.
KEY TECHNOLOGIES NEED RAPID MATURATION FROM PAPER CONCEPTS TO SYSTEM INTEGRATION

Paper concept (TRL 1)  Lab demo (TRL 3)  On-sky demo (TRL 5)

Return on investment for ground-based instruments is more rapid.
But we need more investments!
Figure 4. A timeline showing an implementation phasing scenario for PSI. Current R&D efforts seek to advance the technologies in Tables 1 and 2. While the improvement in IWA and contrast enabled by the aperture of TMT will open many science opportunities in exoplanet characterization, advancing the achievable contrast through these areas will help maximize the return of PSI and allow evolution of the instrument architecture. The final design of PSI-Red corresponds to the end of the technology R&D phase. The optimization of PSI-Blue is more dependent on technical development, so its design begins later, and its integration and testing phase overlaps with the scientific use of PSI-Red. Not shown is the development of instrumentation associated with the 8–13 µm channel.