WORLDS BEYOND: DETECTING AND CHARACTERIZING EXOPLANETS WITH PRECISION TECHNOLOGY.

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SENIOR RESEARCH SCIENTIST, JPL
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- Jason Wang
<table>
<thead>
<tr>
<th><strong>Age-old questions</strong></th>
<th><strong>Overarching scientific goals</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Where do we come from?</td>
<td>1. Characterize the diversity of planetary system architectures, compositions, and environments</td>
</tr>
<tr>
<td>Are we alone?</td>
<td>2. Understand the formation and evolution of planetary systems</td>
</tr>
<tr>
<td></td>
<td>3. Explore properties of exoplanets to identify potentially habitable environments (water)</td>
</tr>
<tr>
<td></td>
<td>4. Search for signatures of life on worlds orbiting other stars</td>
</tr>
</tbody>
</table>
SECOND COPERNICAN REVOLUTION

ALEKSANDER WOLSZCZAN AND DALE FRAIL,
PSR 1257+12 B AND C

MICHEL MAYOR & DIDIER QUELOZ, 1995,
DISCOVERY OF 51 PEGASI b
NOBEL PRIZE IN PHYSICS 2019
<table>
<thead>
<tr>
<th>Method</th>
<th>Percentage</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit</td>
<td>76.9%</td>
<td></td>
</tr>
<tr>
<td>Radial Velocity</td>
<td>18.8%</td>
<td></td>
</tr>
<tr>
<td>Microlensing</td>
<td>2.0%</td>
<td></td>
</tr>
<tr>
<td>Imaging</td>
<td>1.2%</td>
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</tr>
</tbody>
</table>

4352 CONFIRMED EXOPLANETS

- 1479 Neptune-like
- 1362 Gas Giant
- 1342 Super Earth
- 163 Terrestrial
- 6 Unknown
Sizes not seen in our solar system

Average Number of Planets per Star

Planet Size (Earth = 1)

1-1.4 | 1.4-2 | 2-2.8 | 2.8-4 | 4-5.7 | 5.7-8 | 8-11 | 11-16 | 16-23

NASA, Kepler mission
THE NEXT FRONTIER: CHARACTERIZING EXOPLANET ATMOSPHERES & SEARCH FOR BIOSIGNATURES

1. Is this star promising?
   - Use precursor information to establish target list

2. Is this a planet?
   - Multicolor point-source photometry and proper motion

3. Is the planet habitable?
   - Search for water

4. What is the star like? How active?
   - Characterize the star

5. Are there signs of life?
   - Constrain H$_2$O abundance, search for biosignatures
   - Check O$_2$ biosignatures aren’t false positives

6. Are the signs of life robust?
   - Extend spectrum to find additional features
   - Observe UV and longest λs

7. What is the atmospheric context?
   - Temporal signals

8. What is additional atmospheric context?
   - (e.g., seasons)

9. Are there time-varying signals?

Archean Earth: 4 billion years ago
- Haze
- CH$_4$
- H$_2$O
- CO$_2$

Proterozoic Earth: 2.5 billion years ago
- 1 percent present atmospheric level O$_2$
- 0.1 percent present atmospheric level O$_2$

Modern Earth: 541 million years ago
- O$_3$
- O$_2$
- H$_2$O
- CO$_2$
- CH$_4$
- H$_2$O
\[ L_{\text{firefly}} = \frac{A(\lambda)}{4} \left( \frac{R_p}{a} \right)^2 L_\odot \phi + \kappa(\lambda)B(\lambda, T_p)4\pi R_p^2 \]
Extreme contrast ratio relative to the star
$10^{-4}$ for self-luminous gas giants
$10^{-8}$ for temperate Earth-size planets orbiting late-type stars
$10^{-10}$ for temperate Earth-size planets orbiting Sun-like stars

Tiny angular separation
$0''.1$ (1 AU at 10pc)
"The rareness of total eclipses of the Sun, [...], the distances one has to travel to observe them have [...] led astronomers and physicists to seek for a method which enables them to study the corona at any time."
SOLAR CORONA CIRCA 1930 WITH THE FIRST CORONAGRAPH!

Lyot, circa 1930
"If we had the means of continually measuring the deviation of rays [...] so as to correct [...] the aberration pattern, we could expect to compensate [...] for any inherent imperfection of the optical figure."

HORACE BABCOCK IN 1953 - ADAPTIVE OPTICS
US ELT program recommended by Astro2020:

Direct imaging and high-resolution spectroscopy
“LUVEX” recommended by Astro2020

Direct imaging and characterization of Earth-size planets

Habitable Exoplanet Observatory (HabEx)

Large UltraViolet Optical InfraRed Space Telescope (LUVOIR)

NASA. JPL/Caltech. GSFC.
AXES OF MAWET’S GROUP RESEARCH

DIRECT IMAGING OF YOUNG SYSTEMS

DIRECT SPECTROSCOPY AT HIGH-R

NEW TECHNOLOGIES AND INSTRUMENTS
Constraining the Orbit and Mass of \( \varepsilon \) Eridani b with Radial Velocities, Hipparcos IAD-Gaia DR2 Astrometry, and Multi-epoch Vortex Coronagraphy Upper Limits (Llop-Sayson et al. 2021)

Orbital parameters

Predicting planet location for JWST
SURVEY OF PROTOPLANETARY DISKS USING THE KECK/NIRC2 VORTEX CORONAGRAPH (WALLACK ET AL. 2021)

ALMA PP disks

Constraints on PP mass
And accretion
KECK/NIRC2 L'-BAND IMAGING OF JOVIAN-MASS ACCRETING PROTOPLANETS AROUND PDS 70 (WANG ET AL. 2020)
DIRECT HIGH-RESOLUTION SPECTROSCOPY OF PLANETS
HIGH DISPERSION CORONAGRAPHY: MOLECULE MAPPING, SPIN, DOPPLER IMAGING, SIDESTEPS SPECKLE NOISE

Snellen et al. 2015, Mawet et al. 2017, Wang et al. 2017

**Diagram Description:**
- **Light of Star + Planet**
  - Blocks Most of Light from Star
- **Light of Planet + Residual Starlight**
  - Blocks Most of Light from Star
  - Light from Planet Becomes Detectable
- **Coronagraph**
- **High Resolution Spectrograph**
- **Optical Cable**
- **Raw Data from Spectrograph**
- **Matched to Ideal Model of Oxygen Spectrum**
- **Detection of Oxygen in Planet Atmosphere!**
The Benefits of HDC

Speckle chromaticity is not an issue at high-R
HIGH-RESOLUTION SPECTROSCOPY: MOLECULE MAPPING

HIGH-RESOLUTION SPECTROSCOPY: MEASURE PLANET SPINS, AND RVS

β Pic b, Snellen et al. 2014
HIGH-RESOLUTION SPECTROSCOPY: DOPPLER MAPPING


LUH16 B, Crossfield et al. 2014
Delorme et al. 2021, Wang et al. 2021

Fiber Positions

Star + Planet

Starlight Only

NIRSPEC

Order

Order

HR 8799 d

Flux (DN)

Data

Star+Planet Model

Star Model

Planet Model

Wavelength (micron)
TECHNOLOGY AND INSTRUMENT DEVELOPMENTS
Keck Planet Imager and Characterizer

Mawet et al. 2016, Delorme et al. 2018, Jovanovic et al. 2019,
Bond et al. 2019, Pezzato et al. 2019, Delorme et al. 2021 (submitted)

J.-R. Delorme
Charlotte Bond

Fiber Injection Unit
IR PWFS
What is KPIC?

- K, L, M band coronagraphy
- K and L band spectroscopy
  - $R \sim 35,000$
Fiber Bundle

Input side of the bundle

Input connector
KPIC Phase II Coming Soon!

High-order deformable mirror  Atmospheric Dispersion Corrector

Beam Shaping PIAA/Apodizers  Fiber Nulling Coronagraph
KPIC Phase II: Design

Main Goal: Increase efficiency, throughput and contrast.
High Order Deformable Mirror

KPIC Kilo DM currently tested at Caltech

Custom CaF2 Window
Throughput >97% H, K, L and M single pass
Coronagraph

Key points:
- Two types of coronagraphs: apodizer and a vortex in the vortex fiber nulling (VFN) mode.
- The apodizer will reduce leaked starlight into the fiber.
- The VFN will enable detection and spectroscopy of exo-planets at or within 1λ/D.

### KPIC Apodizer Concept

<table>
<thead>
<tr>
<th>Without Apodizer</th>
<th>With Apodizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pupil Plane</td>
<td></td>
</tr>
<tr>
<td>Focal Plane</td>
<td></td>
</tr>
</tbody>
</table>

### Apodizer and vortex currently tested at Caltech

Vortex fiber nulling concept

Ruane et al. 2018 & Encheverri et al. 2019
Atmospheric Dispersion Compensator

Key points:
- Custom ADC: J-H-K-L band -- Residual dispersion < 0.1 λ/D – Offset between bands < 0.1 λ/D
- Landed on the Mathar model (ALL OTHER MODELS ARE WRONG)
- This is significant for ELT ADCs – come talk to us for specifics

Tracking Camera Image

Elevation 49.26° – Target HR 8799

KPIC ADC 3D model
Phase Induced Amplitude Apodization

Key points: Improve the light injection into SM fiber

First Batch of KPIC PIAA Lenses

Injection Gain

# High Resolution Infrared Spectrograph for Exoplanet Characterization

## Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
<th>Notes</th>
<th>Limiting science case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>1.49-2.46(\mu)m</td>
<td>Single shot</td>
<td>All</td>
</tr>
<tr>
<td>Resolving power</td>
<td>&gt;100,000</td>
<td>Average over 1.49-2.46(\mu)m</td>
<td>KSP1</td>
</tr>
<tr>
<td>Sampling</td>
<td>&gt;2.5 pixels</td>
<td>Over 80% of spectral range</td>
<td>KSP3</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>&lt;50 mas</td>
<td>SMF, diffraction-limited</td>
<td>KSP2, KSP3, KSP4</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;3%</td>
<td>Over 1.49-2.46(\mu)m (from top of atmosphere)</td>
<td>All</td>
</tr>
<tr>
<td>Pt source sensitivity</td>
<td>(\sim) 15 mag (Vega)</td>
<td>S/N &gt; 30 per spectral resel in 1 hr</td>
<td>KSP2, KSP4</td>
</tr>
<tr>
<td>Instrument stability</td>
<td>&lt;0.3 m/s (1 year), excl. atm.</td>
<td>Calibration with gas cells (abs.) and LFC (rel.)</td>
<td>KSP1, KSP3</td>
</tr>
<tr>
<td>Mode 1</td>
<td>Single-object</td>
<td>High efficiency</td>
<td>KSP1, KSP3</td>
</tr>
<tr>
<td>Mode 2</td>
<td>High-contrast off-axis</td>
<td>HDC, VFN</td>
<td>KSP2</td>
</tr>
</tbody>
</table>

- Wavelength Range: 14,900 – 24,600 Å
- Echelle Blaze Angle (\(\theta_b\)): 76°
- Echelle ruling density (\(v\)): 13 lp/mm
- Pixel Size: 10 \(\mu\)m
- Sampling: 2.9 – 4.8 pix
- Spectral Resolution (\(R\)): 90K – 150K
- Linear Dispersion (\(\Delta \lambda / \Delta x\)): \(\sim\) 0.05 Å/pix
- Collimator Focal Length: 112 mm
- Camera Focal Length: 550 mm
- Aperture Stop Dia.: 28 mm
- N Fibers: 4
HISPEC EXOPLANET PHASE SPACE

Transit spectroscopy

Direct spectroscopy

Discovery/masses with PRV
KSP 1: ATMOSPHERES OF CLOSE-IN EXOPLANETS (50 NIGHTS)
KSP 2: CHEMODYNAMICS OF RESOLVED SUBSTELLAR COMPANIONS (50 NIGHTS)
KSP 3: EXOPLANET MASSES, ORBITS, AND DISCOVERY WITH NIR PRV (50 NIGHTS)
FRONT-END INSTRUMENT, ROBOTIC FIBER SWITCHING AND PERFORMANCE
Thirty Meter Telescope (TMT)
California (Caltech & UC), Canada, China, India, and Japan

MODHIS
Multi-Object Diffraction-limited
High-resolution Infrared Spectrograph

PSI
Planetary Systems Imager

TIO - R. Hurt (Caltech)
EARTH SPECTRUM
AT HIGH SPECTRAL RESOLUTION
Wang, Mawet, et al. 2017

Albedo spectra of an Earth-like planet.

Methods

- HDC simulation shows that the Keck Planet Imager and Characterizer (KPIC) can detect CO, H2O, and CH4 in the atmosphere of HR 8799 e even at moderate starlight suppression levels [1].

- At high levels of starlight suppression, HDC may provide sufficient SNR for Doppler imaging of planet surface.

HDC Simulation

Flow chart of simulation for an HDC instrument. The simulation pipeline provides guidance to set system requirements for an HDC instrument and understand the fundamental limit of the HDC technique.

Detection Significance

Starlight Suppression

HDC offers a promising way of searching for biomarkers in Proxima Cen b with ELTs.

Plots above show detection significance contours of J-band HDC simulation for Proxima Cen b (d=1.3 pc) [1]. Planet/star contrast is 1.6 x 10^-7. The simulation assumes 100 hour exposure at TMT.

HDC relaxes the starlight suppression requirement by a factor of 1000.

Plots above show detection significance contours of K-band HDC simulation for CO2 and CH4 in a hypothetical M dwarf planet in the habitable zone (d=5 pc) [1]. Planet/star contrast is 6.2 x 10^-9. The simulation also assumes 100 hour exposure at TMT.

- HDC significantly increases sensitivity due to its spatial and spectral filtering of starlight. The technique provides a new way for characterizing exoplanet atmospheres.
- KPIC (talk on Monday at 12:50PM) will be powerful in characterizing directly imaged gas giant exoplanets.
- An ELT HDC instrument can be used to search for biomarkers in the atmospheres of potentially habitable planets around M dwarfs.
- Caltech group led by Dr. Dimitri Mawet are advancing the HDC technique in simulation (P2052), observation, data reduction [2], system design (P3038), and lab demonstration [3] (P1024).
TECHNOLOGY DEVELOPMENTS IN THE EXOPLANET TECHNOLOGY LAB

Supported by JPL RTD, NASA ExEP, ROSES TDEM (2), APRA (1)


**Vortex Fiber Nuller** concept for Keck, TMT, HabEx and LUVOIR (Ruane et al. 2018, Echeverri et al. 2019)