The Keck Planet Imager and Characterizer:

Nemanja Jovanovic on behalf of the team
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## KPIC Team

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[Logos of NASA, NSF, and Heising-Simons Foundation]
Science goals
Science motivation

Two key science themes:

1. **Direct imaging of exoplanets** – to detect and improve photometry and astrometry
2. **Spectral characterization of exoplanets** – R>30k
Motivation for high resolution spectroscopy

Radial Velocity
Spin
Doppler Imaging
Atmospheric Parameters

Spectrum
Cross Correlation Function (CCF)

Courtesy of J.-B. Ruffio
High Dispersion Coronagraphy (HDC)

Proposed by Sparks and Ford, Riaud & Schneider 2007, and Snellen et al 2015

See Wang et al 2017 & Mawet et al 2017
The Instrument and Status
Keck II adaptive optic system

Key points:
• DM 21x21 actuators.
• Facility WFS: Shack Hartmann in Visible.
• Most productive AO system in the world.

Facility instruments:
• NIRC2: High Resolution & high contrast infrared imager (coronagraphic capabilities).
• Nirspec: High Resolution spectrograph (Resolution > 37,000 in K band)
KPIC is a series of upgrades to Keck AO, NIRC2 and NIRSPEC:

- **NIRC2** – K, L, M band vortex masks, new Lyot stop, polarimeter
- **Keck AO** – A NIR Pyramid (Py) WFS, a fiber injection unit (FIU)
- **NIRSPEC** – A fiber extraction unit (FEU) to enable NIRSPEC to run diffraction limited
Planet Imager/Finder Mode

Key points:
- Will be facilitated.

Goals:
- Detect & image low mass companions.
Keck Infrared Pyramid (Py) WFS

SAPHIRA: infrared avalanche photodiode array
- High frame rate (1.5kHz).
- Low noise (<1e).

- Sensor wavelength: H-band
- 40 pixels across the pupil
- Correction:
  - Phase 1: 21x21 Keck DM
  - Phase 2: 32x32 Mems DM
- Real time control: CACAO
Planet Imager/Finder Mode

Key points:
• PyWFS is routinely outperforming the Shack Hartmann
• Achieving Strehl approaching 90% in L band

C. Bond et al JATIS, 2020
Planet Characterizer Mode
Planet Characterizer Mode
NIRSPEC

Key points:
• High resolution spectroscopy over the wavelength region 0.95 to 5.4 microns
• K band resolution: $\approx 37K$
• Modified to be fiber fed (single mode fibers)
Step 1: Star Acquisition Close AO Loop

Light from the telescope

Tracking Camera
NIRSPEC
Cal. Sources 1550 nm

Fiber Bundle

TTM
IR
JH
KLM

Tracking Camera Pick Off
Retro Reflector

Tracking Camera Image
Step 2: Retro Feed Calibration Fibers

Light from calibration source

Tracking Camera
NIRSPEC
Cal. Sources 1550 nm
Fiber Bundle
TTM
Retro Reflector

Tracking Camera Image
Step 3: Science Fiber Positions

Light from calibration source

Tracking Camera Image
Step 4: Optimize Star Light Injection

- Star alignment with science fiber
- Scan science fiber to optimize injection
Step 5: Blind Offset to Planet Position

Astrometry of the target

Requires accurate knowledge of the
- Plate scale
- Orientation and
- Distortion map

Apply a blind offset
Step 6: Compensating DAR

- Keck has no Atmospheric dispersion compensator
- Need to offset pointing to compensate for offsets between the tracking and science bands

Elevation 49.26° – Target HR 8799
Raw detector images (HR 8799)

Tracking camera - InGaAs
Imaging/Fiber Placement

Science detector - H2RG
Spectrograph

Starlight Only

Planet + Star

Wavelength ->

Planet + Star
Star Only

Planet + Star
Star Only
Overall Throughput of the System

Throughput measured on Kappa And (July 3rd 2020 – Elevation 64.6°)

- ~40% injection/propagation efficiency (other losses include sky, telescope, Keck AO, optics, NIRSPEC)
- Throughput is similar to NIRSPAO
Preliminary reductions exist for all the data on a Caltech machine (hcig1)
1D spectra, Line width, & wavelength calibration

Delorme et al, in review
Courtesy of J.-B. Ruffio and J. Wang
HR8799 bcde detections

First detections of HR 8799 d & e at R > 10,000
2x better detection of HR 8799 c with 4x less time than NIRSPAO

Wang et al 2021, in review
A survey is underway

On-going survey:
• ~20 companions detected
• Additional 12 nights already scheduled in 2021
KPIC Phase I

KPIC phase I modules implemented:

- **NIRC2**: K, L, M band vortex masks, new Lyot stop and a **polarimeter**
- **Keck AO**: A NIR Pyramid PyWFS and a fiber injection unit (FIU), Zernike WFS
- **NIRSPEC**: A fiber extraction unit (FEU)
KPIC-FIU Timeline

**KPIC-FIU Phase #1 – Currently on Sky**
- 2015 -- KPIC white paper
- December 2017 -- Design Review
- September 2018 -- KPIC install at Keck
- November 2018 -- First light without NIRSPEC
  - January 2019 -- First stellar spectra
  - May 2019 -- First Science night
- Since May 2019 -- 20+ science targets observed

**KPIC-FIU Phase #2 – Work in progress**
- May 2019 -- Design Review
- Summer 2021 -- Lab integration
- Winter 2021 -- Installation at Keck
Next Steps for KPIC
Phase II upgrades

Increase planet throughput and suppress star light

- High-order DM – 1k BMC
- Atmospheric dispersion compensator (ADC)
- Beam shaping optics (PIAA)
- Fiber nulling coronagraph

+LFC
FIU Phase II upgrades

Near final CAD of the phase II plate
Images from integration

ADC mechanism

OAP alignment

PyWFS pickoff mechanism

Coronagraph mechanism
**High Order Deformable Mirror**

**Purpose:** *enhanced wavefront control*
- More actuators and faster response time for better PyWFS correction
- For advanced focal plane wavefront control techniques

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

**Simulation of improved performance with the PyWFS and the 1kDM. Does not take into account temporal gains, only fitting.**
Phase Induced Amplitude Apodization

Key points: Improve the light injection into SM fiber

KPIC PIAA design

Design courtesy of Garreth Ruane

KPIC PIAA concept

First Batch of KPIC PIAA Lenses

Measured injection gain

Lab results for KPIC optics: Calvin et al, PASP, 2021

Coronagraphs

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 $1.5\lambda/D$.

Echeverri et al, SPIE, 11117-33 (2019)
**Vortex Fiber Nulling**

**Key points:**
- Planet throughput with charge 1 vortex mask can be as high as 20% at 0.8 lambda/D.
- 25% when combined with PIAA optics
- Assuming 1 mas tip/tilt residuals at Keck (3x improvement from the current performance), with a charge 1 vortex KPIC could directly characterize 20 previously uncharacterizable giant planets!!!

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*Echeverri et al in prep.*
Advanced wavefront control

Key points:
- Predictive control on the PyWFS – this will bring large gains in performance (McEwen et al. AAS, 233 (2019)).
- Speckle nulling in the focal plane through the fiber (Sayson et al JATIS, 5, 2019) to further suppress the unwanted starlight. Reduction in speckle noise floor by a factor of 2-3 even with static NCPA compensation (Mawet et al. AJ, 838 (2017)).
- Kalman filtering to implement the focal plane wavefront control.
Zernike Wavefront Sensor

Key points: Measure primary mirror co-phasing error

Keck pupil image – w/o ZWFS – On sky data

Segmented DM – with ZWFS – Lab data
Looking to future missions
**Key points:**

- LUVOIR and/or HabEx should include point spectrographs fed by SMFs to enable HDC.
- This characterization tool nicely compliments the IFS detection tool.
Pushing SMF WFC

Key points:
• Pairwise probing/EFC through a SMF has been demonstrated in the lab – Caltech ETL
• With an unoptimized testbed and a vortex coronagraph, we’ve demonstrated $>10^{-5}$

Llop-Sayson et al. JATIS, 2019
Pushing SMF WFC

**Key points:**
- Pushed the contrast in a high-performance testbed – HCST – Caltech
- Funded through a NASA SAT TDEM
- First 2 milestones achieved
  - $10^{-8}$ contrast at 780 nm in 1% polychromatic light
  - $3\times10^{-8}$ contrast at 780 nm in 20% polychromatic light

![Diagram of optical setup](image)

**Graphs:**
- Normalized intensity vs. iteration
- Stellar PSF (image)
Pushing SMF WFC

Coker et al. JATIS, 2019
Questions?

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