NASA Exoplanet Exploration Program
Serving the Science, and Community, by implementing NASA’s space science vision for exoplanets and astrophysics

Purpose described in 2014 NASA Science Plan

1. Discovering planets around other stars
2. Characterizing their properties
3. Identifying candidates that could harbor life
Large Binocular Telescope Interferometer
Measures exozodiacal dust in habitable zones

Phil Hinz, PI

LBTI Performance

- Demonstrated 12 zodi sensitivity for a solar twin at 10 pc
- **Successfully completed Operational Readiness Review (ORR) and now conducting Science Validation Phase**
- Level 1 requirement: 3 zodi (baseline) and 6 zodi (threshold) on 50 stars
- LBTI nulling data available to public at [http://nexsci.caltech.edu/missions/LBTI/](http://nexsci.caltech.edu/missions/LBTI/)

M. Jeganathan
Kepler Closeout
Harvesting the exoplanet yield from the mission

- **Uniform Processing of Q0-Q17 (using SOC 9.2)**
  - Long cadence light curves Dec 2014
  - Short cadence light curves Mar 2015
    - KOI Catalog Oct 2015
    - Occurrence Rate Products Sep 2015

- **Final Data processing of Q0-Q17 (using SOC 9.3)**
  - Pipeline Development Complete July 2015
  - Light curves Mar 2016
  - KOI Catalog Nov 2016
  - Occurrence Rate Products Sep 2016
  - Completeness and Reliability Products Feb 2017
Exoplanet Science Goals:

- Identify potentially-habitable planets around bright M-dwarfs near the Sun
- Observe hot planets around bright stars for follow-up transit spectroscopy
- Find small planets to aid measurements of masses, densities and compositions
- Determine if hot gas giants exist around young stars
- Detect and measure masses of free-floating planets using microlensing
WFIRST / AFTA
Exoplanet Science via Microlensing and Coronagraphy

Microlensing Survey
- Outer planet demographics
- Free-floating planets
- Completes census begun by Kepler

Exoplanet Direct Imaging
- Imaging and spectroscopy of exoplanet atmospheres down to a few Earth masses, R~70
- 0.4 – 1 μm bandpass
- ≤ 10\(^{-9}\) detection contrast
- 100 mas inner working angle at 0.4 μm

Coronagraph will develop the technologies for New Worlds Telescope mission
WFIRST Coronagraph Occulting Mask Technology

- **HLC (Hybrid Lyot Coronagraph)**
  - Successfully met $<10^{-8}$ narrowband raw contrast
  - Started broadband nulling

- **SPC (Shaped-pupil coronagraph)**
  - Successfully produced two-sided dark holes (2% bandwidth) using 2 DMs

- **PIAA/CMC (backup): Focal plane mask fabricated.**
  - Recent designs show improved IWA performance

F. Zhao

PIAACMC mask (atomic force microscope images)
What Exoplanet Direct Imaging missions are possible for Probe-Scale ($1B)?
Probe-Scale studies
High-Contrast Imaging

Purpose
• Establish science value for a medium-size exoplanet mission
• Motivate technology investments
• Candidates for next Decadal Survey

Ground rules:
• Compelling Science beyond ground capability at time of mission
• Feasibility: TRL 5 by end of Phase A, TRL 6 by end of Phase B
• $1B LCC confirmed by Aerospace CATE
• Launch 2024

Exo-C:
Internal Occulter (Coronagraph)
K. Stapelfeldt, STDT Chair, GSFC

Exo-S:
External Occulter (Starshade)
S. Seager, STDT Chair, MIT
Exo-C: Internal Coronagraph

- Visible Hybrid Lyot Coronagraph mask
- Design Reference Mission observes > 400 unique targets
  - Spectra or colors for ~30 planets
  - Access to a few super-Earths in HZ of their stars
- 1.4m aperture
- Cost: $1B life-cycle, validated by Aerospace CATE
- 3 year mission, Earth trailing orbit
- Exo-C’s scope, hardware, and expected cost are very similar to those of NASA’s Kepler mission
- A modest aperture can be very effective if coronagraphy requirements allowed to drive the mission and telescope design
Exo-S Mission Concepts

Dedicated (Co-Launched) Mission
- Telescope: 1.1 m
- Retargeting: by the telescope s/c (SEP)
- $1.1B lifecycle cost

Rendezvous Mission
- Telescope: WFIRST/AFTA 2.4 m is adopted
- Orbit: Earth-Sun L2
- Retargeting: by the starshade spacecraft
- Minimal impact to telescope to be “starshade ready”
- $0.6B lifecycle cost

Common to both:
- Starshade design (30 m vs. 34 m diameter)
- Formation-flying over ~35,000 km separation
- 3 Year Mission
- Science:
  - Spectra or colors for ~30 planets.
  - Access to several exo-Earths in HZ of their stars
Introducing new Exoplanet Exploration Program Office Members

Program Chief Technologist
Dr. Nicholas Siegler

Program Business Manager
Mr. Ramon Lemus

Coronagraph Technologist
Dr. Rhonda Morgan

TDEM Engineer
Mr. David Breda
Sagan Fellows – Class of 2015

Courtney Dressing, **Caltech**
*Characterizing Small Planets Orbiting Small Stars*

Daniel Foreman-Mackey, **University of Washington**
*Flexible and Robust Inference of the Exoplanet Population*

Jonathan Gagne, **Carnegie Institute for Science**
*Locating the Young, Isolated Planetary-Mass Objects in the Solar Neighborhood*

Paul Robertson, **Pennsylvania State University**
*Spotting Blue Planets Around Spotted Red Stars: Removing Stellar Activity from Radial Velocities of M Dwarf Stars*

Ty Robinson, **University of California, Santa Cruz**
*Bridging the Theory Gap: Developing a Novel Cloud Model for Exoplanets*

Leslie Rogers, **University of California, Berkeley**
*Searching for Water in Distant Worlds*

NASA/NSF Partnership for Exoplanet Research
Extreme Precision Doppler Spectrometer

• Scope:
  – Exoplanet-targeted Guest Observer program with existing instrumentation on WIYN using NOAO share (40%) of telescope time
  – Solicitation for facility-class extreme precision radial velocity spectrometer for WIYN telescope (commissioning goal: 2018)

• Motivation
  – Follow-up of current missions (K2, TESS, JWST)
  – Pathfinder observations inform design/operation of future missions

• Anticipated Timeline:
  – June 2015: Selection of study team(s)
  – July 2015: Begin 6-month concept phase
Looking Ahead: Program Activities

• Consistent Analysis of Exoplanet Yields for WFIRST, Probes (Traub, this afternoon)

• Exoplanet yield tool development to support both HabEx and LUVOIR studies

• CY15: P robe Extended Studies

• Exoplanets 20/20: celebration of anniversary

• Answering question of Starshade technology readiness for flight (TR6,7):
  – Starshade Readiness Working Group
  – Charter in development for APD DD approval
Decadal Large Mission Studies for Exoplanets
(Stating Program’s position. PAGs to recommend, APD DD to decide)

- The Exoplanet Program advocates for the exoplanet science (and technology investments) on both the Habitable Exoplanet Imager (HabEx) and the Large UV/Optical/IR Surveyor (LUVOIR)
- ExEP advocates study of these missions so Decadal Survey can make an informed prioritization in the name of the community
- Suggested criteria for successful reports:
  - **Compelling, Feasible, Affordable, Timely** (FACTs)
  - LUVOIR
    - Both Habitable Exoplanets and General Astrophysics as co-primary drivers
    - Compelling science guides the cost and necessary investments
  - HabEx:
    - Habitable Planet spectroscopy is primary science, plus general astrophysics
    - Astrophysics decadal budgets guide the compelling science
- The Exoplanet Program recommends that both the HabEx and LUVOIR concepts be matured
- The Exoplanet Program plans an Exoplanet Working Group (eXWG) to support both HabEx and LUVOIR mission studies: common tools, assumptions, figures of merit, technology evaluation and advocacy
Acknowledgements

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## Coronagraph Key Milestones

<table>
<thead>
<tr>
<th>MS #</th>
<th>Milestone</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than $10^{-3}$ and 20 μm pixel size.</td>
<td>7/21/14</td>
</tr>
<tr>
<td>2</td>
<td>Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.</td>
<td>9/30/14</td>
</tr>
<tr>
<td>3</td>
<td>First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm.</td>
<td>12/15/14</td>
</tr>
<tr>
<td>4</td>
<td>Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.</td>
<td>2/28/15</td>
</tr>
<tr>
<td>5</td>
<td>Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment.</td>
<td>9/15/15</td>
</tr>
<tr>
<td>6</td>
<td>Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.</td>
<td>9/30/15</td>
</tr>
<tr>
<td>7</td>
<td>Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.</td>
<td>8/25/16</td>
</tr>
<tr>
<td>8</td>
<td>PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.</td>
<td>9/30/16</td>
</tr>
<tr>
<td>9</td>
<td>Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.</td>
<td>9/30/16</td>
</tr>
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<td>MS #</td>
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<td>----------------</td>
</tr>
<tr>
<td>1</td>
<td>Produce, test, and analyze 2 candidate passivation techniques (PV1 and PV2) in banded arrays to document baseline performance, inter-pixel capacitance, and shall meet the following derived requirements: dark current less than 0.1 e-/pixel/sec, CDS noise less than 20 e-, and QE greater than 60% (over the bandpass of the WFI channel) at nominal operating temperature.</td>
<td>7/31/14</td>
</tr>
<tr>
<td>2</td>
<td>Produce, test, and analyze 1 additional candidate passivation technique (PV3) in banded arrays to document baseline performance, inter-pixel capacitance, and shall meet the following derived requirements: dark current less than 0.1 e-/pixel/sec, CDS noise less than 20 e-, and QE greater than 60% (over the bandpass of the WFI channel) at nominal operating temperature.</td>
<td>12/30/14</td>
</tr>
<tr>
<td>3</td>
<td>Produce, test, and analyze full arrays with operability &gt; 95% and shall meet the following derived requirements: dark current less than 0.1 e-/pixel/sec, CDS noise less than 20 e-, QE greater than 60% (over the bandpass of the WFI channel), inter-pixel capacitance ≤3% in nearest-neighbor pixels at nominal operating temperature.</td>
<td>9/15/15</td>
</tr>
<tr>
<td>4</td>
<td>Produce, test, and analyze final selected recipe in full arrays demonstrating a yield of &gt; 20% with operability &gt; 95% and shall meet the following derived requirements: dark current less than 0.1 e-/pixel/sec, CDS noise less than 20 e-, QE greater than 60% (over the bandpass of the WFI channel), inter-pixel capacitance ≤3% in nearest-neighbor pixels, persistence less than 0.1% of full well illumination after 150 sec at nominal operating temperature.</td>
<td>9/15/16</td>
</tr>
<tr>
<td>5</td>
<td>Complete environmental testing (vibration, radiation, thermal cycling) of one SCA sample part, as per NASA test standards.</td>
<td>12/1/16</td>
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