Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Exploration Program - Updates

Gary Blackwood
Program Manager

June 13, 2015

ExoPAG 12
Chicago IL

NASA Exoplanet Exploration Program

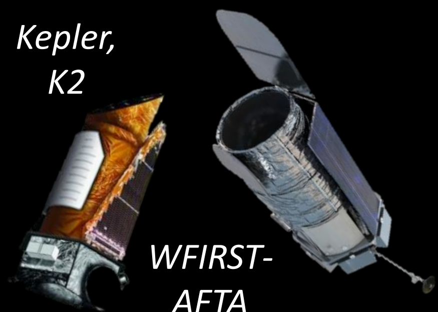
Serving the Science, and Community, by implementing NASA’s space science vision for exoplanets and astrophysics

Purpose described in 2014 NASA Science Plan

1. Discovering planets around other stars
2. Characterizing their properties
3. Identifying candidates that could harbor life

NASA Exoplanet Exploration Program

Space Missions and Mission Studies



Kepler, K2

WFIRST-AFTA

Probe-Scale:

Starshade

Coronagraph

Decadal Studies

Public Engagement

Supporting Research & Technology

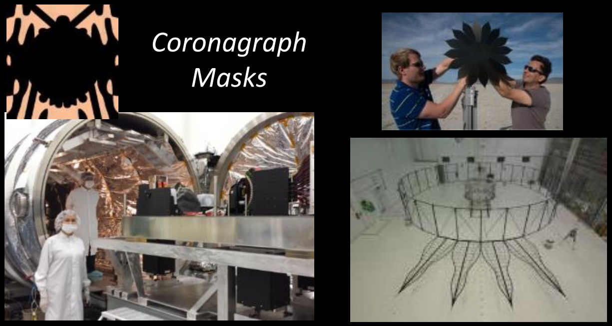
Key Sustaining Research

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

Extreme Precision Doppler Spectrometer

Technology Development



Coronagraph Masks

High Contrast Imaging

Deployable Star Shades

NASA Exoplanet Science Institute

Archives, Tools, Sagan Fellowships, Professional Engagement

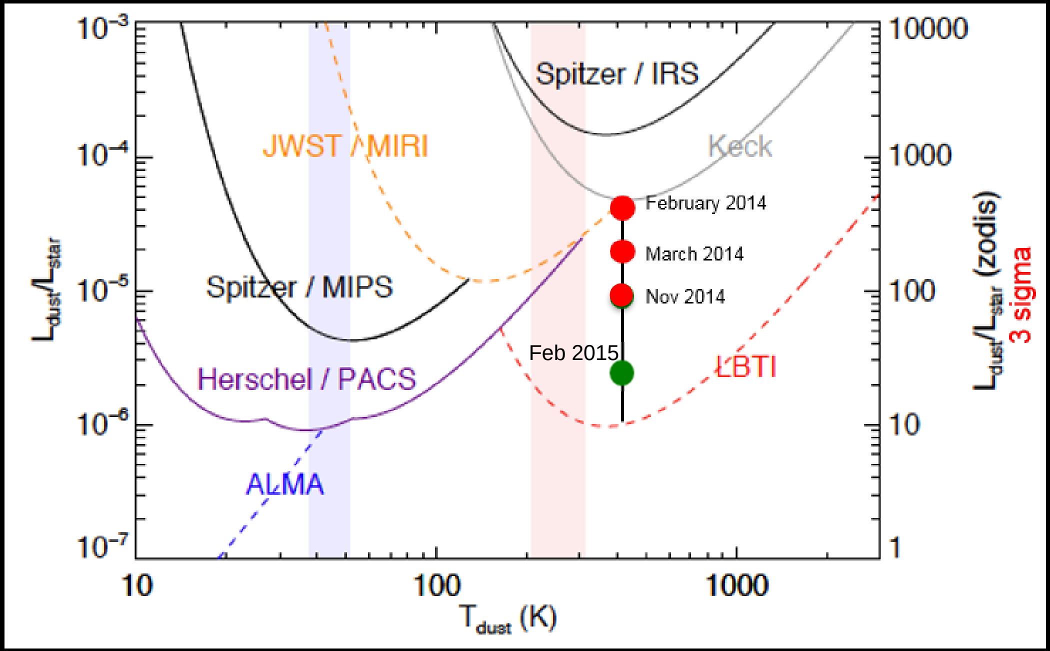
Large Binocular Telescope Interferometer

Measures exozodiacal dust in habitable zones

Phil Hinz, PI

THE UNIVERSITY OF ARIZONA

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/

M. Jeganathan

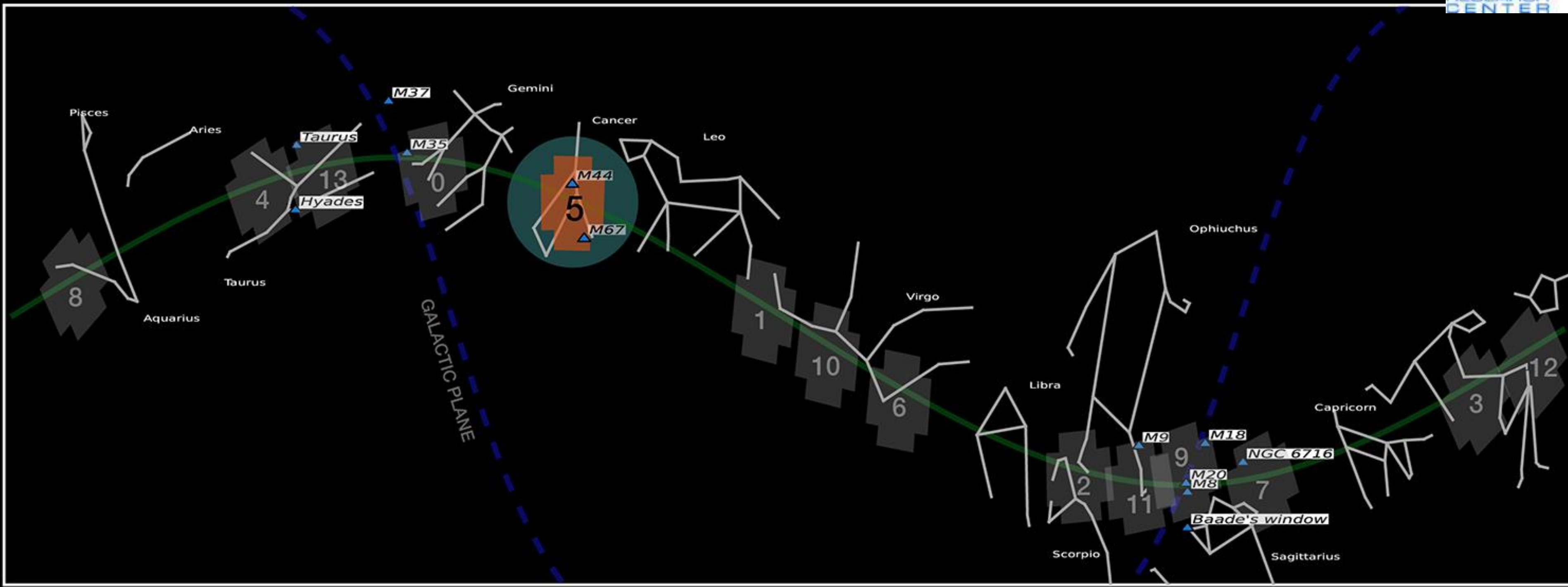
Kepler Closeout

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 ← Community — 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 ← Community — Sep 2016
  - Completeness and Reliability Products — Feb 2017

Kepler K2



Kepler Project, I. Heinrichsen

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

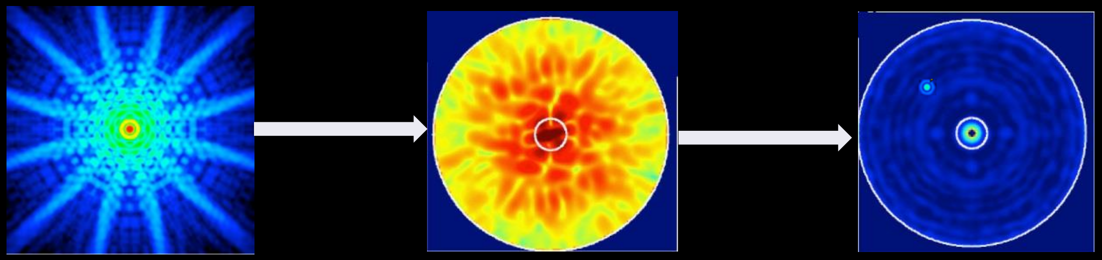
Microlensing Survey

- 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

No Mask | **With Mask** | **With Mask and Deformable Mirrors**



Coronagraph will develop the technologies for New Worlds Telescope mission

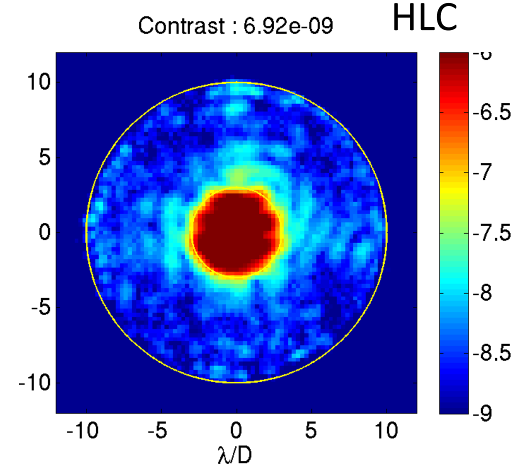
WFIRST Coronagraph Occulting Mask Technology

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

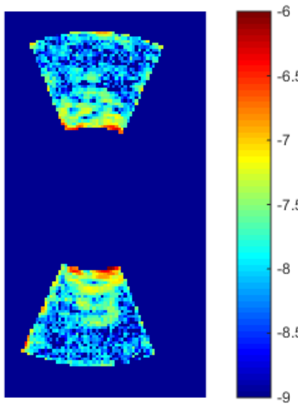
- **SPC (Shaped-pupil coronagraph)**
  - Successfully produced two-sided dark holes (2% bandwidth) using 2 DMs

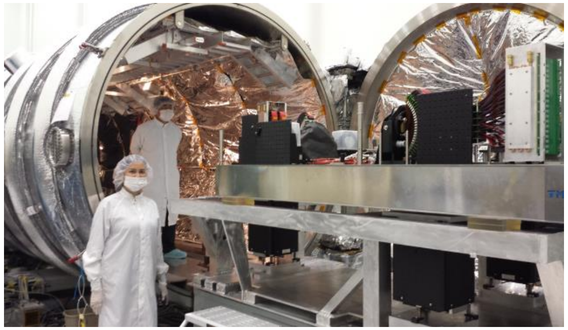
- **PIAA/CMC (backup): Focal plane mask fabricated.**
  - Recent designs show improved IWA performance

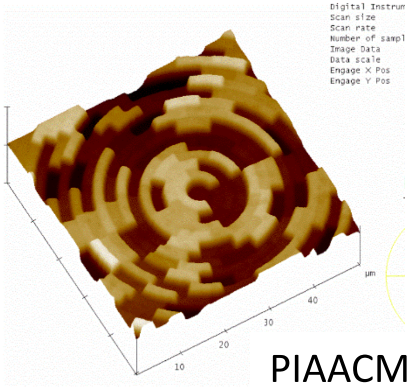
HLC



SPC







F. Zhao

PIAACMC mask
(atomic force microscope images)

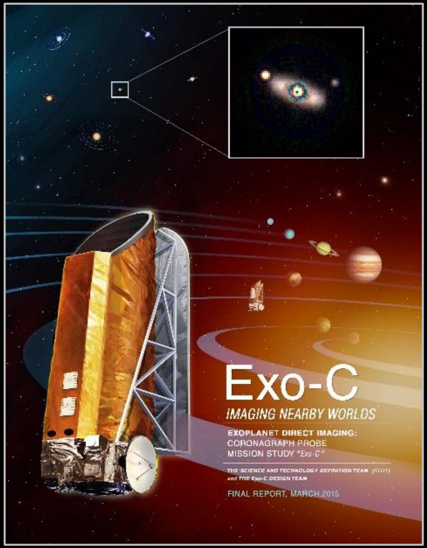
Exoplanet
Missions
Hubble
Spitzer
Kepler
TESS
JWST
WFIRST / AFTA
New Worlds Telescope
Habitable Exoplanet Imager
HabEx, LUV/O/IR
New Worlds, New Horizons
in Astronomy and Astrophysics
Report Release e-Townhall
Keck Center of the National Academies
August 13, 2010
What Exoplanet Direct Imaging missions 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

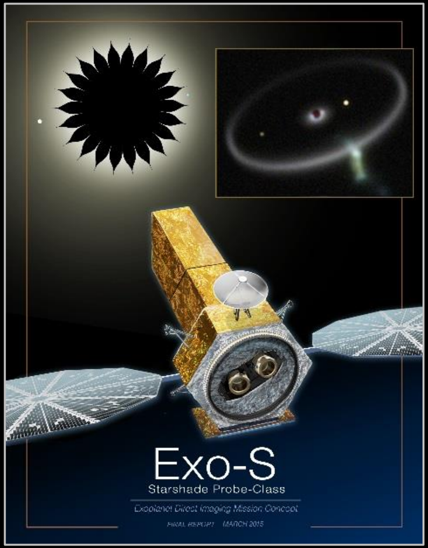
Ground rules:
- Compelling Science beyond ground capability at time of mission
- Feasibility: TRL 5 by end of Phase A, TRL 6 by end of Phase B
- $1B LCC confirmed by Aerospace CATE
- Launch 2024



Exo-C:

Internal Occulter (Coronagraph)

K. Stapelfeldt, STDT Chair, GSFC



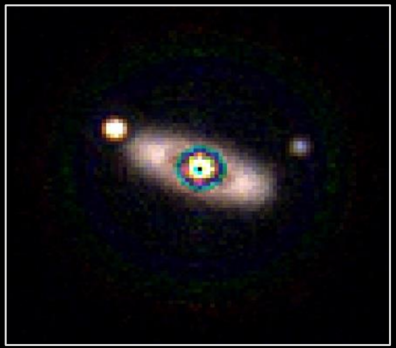
Exo-S:

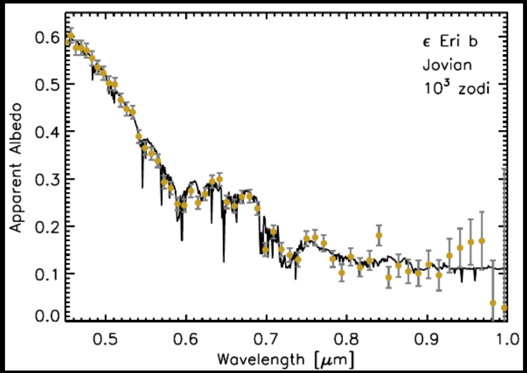
External Occulter (Starshade)

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





RV planet spectrum - ε Eridani

Exo-S Mission Concepts

Dedicated (Co-Launched) Mission

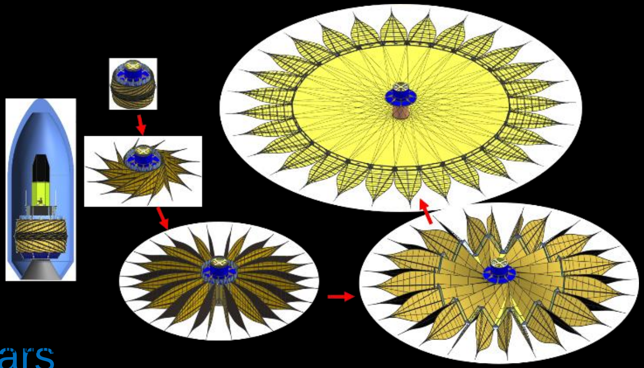
- Telescope: 1.1 m
- Retargeting: by the telescope s/c (SEP)
- $1.1B lifecycle cost

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

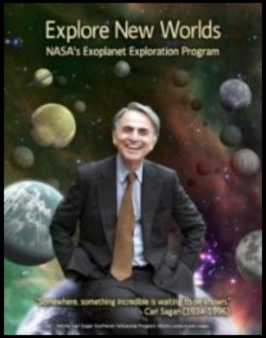
Coronagraph Technologist

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

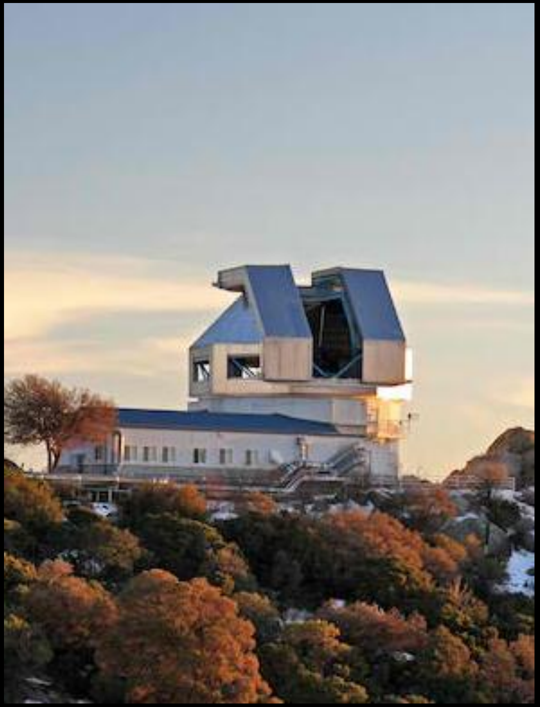
Leslie Rogers, **University of California, Berkeley**
Searching for Water in Distant Worlds

2015 Sagan Workshop, "Exoplanet System Demographics: Theory and Observations", Caltech, July 26–31.

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



3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

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: Probe 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:
  - **C**ompelling, **F**easible, **A**ffordable, **T**imely (**FACT**s)
  - 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

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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  - NASA Goddard Space Flight Center
  - NASA Ames Research Center
- Work also carried out by University of Arizona under a contract with the Jet Propulsion Laboratory.
- Work also carried out by Princeton University, University of Arizona and Northrop Grumman Aerospace Systems under contracts with the National Aeronautics and Space Administration.
- Contributions gratefully acknowledged from Karl Stapelfeldt and the Exo-C STDT, and by Sara Seager and the Exo-S STDT, Wes Traub, Nick Siegler, Feng Zhao, Steve Unwin, Keith Warfield, Ingolf Heinrichsen, David Imel, Muthu Jeganathan, Kevin Grady, Cathy Peddie.

Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Exploration Program
Organization Chart

Astrophysics Division, NASA HQ

Director – Dr. P. Hertz
Deputy Director/Program Director – A. Razzaghi

Exoplanet Prog. Exec. – J. Gagosian
Exoplanet Prog. Sci. – Dr. D. Hudgins

WFIRST Program Executive – J. Gagosian
WFIRST Program Scientist – Dr. D. Benford
Kepler / Closeout Program Exec – K. Chamberlain
Kepler / K2 Program Executive – J. Hayes
Kepler / K2 Program Scientist – Dr. D. Wallace
NExScI, Keck, LBTI Prog. Exec. – Dr. M. Perez
NExScI, Keck, LBTI Prog. Sci. – Dr. H. Hasan

Astronomy Physics & Space Technology Directorate, JPL

Director for – D. Gallagher
Deputy Director for – Dr. D. Coulter

730
Exoplanet Exploration Program Office

Program Manager – Dr. G. Blackwood
Deputy Program Manager - Vacant
Program Chief Scientist – Dr. W. Traub (3200)
Program Chief Technologist – Dr. N. Siegler

ExoPlanet TAC[1]

Dr. A. Boss
Carnegie Institute

7301
Program Science Office

Scientist - Dr. S. Unwin (312)
AFTA - Dr. D. Stern (326)
AFTA – Dr. G. Bryden (326)

7303
Program Engineering Office

Chief Engineer – Vacant
Program Engineer - K. Warfield
Export Tech Lia. – Dr. A. Abramovici (383)
Mission Assurance Manager – J. Mehta

Exoplanet Probe STDT - Starshade[1]

Dr. S. Seager, MIT

Exoplanet Probe Study Office

K. Warfield (312)

Exoplanet Probe STDT - Coronagraph[1]

Dr. K. Stapelfeldt, GSFC

731
Program Business Office

Manager – R. Lemus (731)
Resource Analyst – L. Scott (252)
Administrator – O. Pananyan (720)
Project Schedule Analyst – K. McClane (252)
Project Schedule Analyst – G. Luzwick (252)
Staff Assistant – K. Miller (730)
Staff Assistant - M. Rubio (730)

Mission Managers / Scientists

Kepler Mission Mgr – I. Heinrichsen (734)
Kepler Mission Sci – Dr. N. Gautier (326)
WFIRST Mission Mgr – I. Heinrichsen (730)
WFIRST Mission Sci – Dr. S. Unwin (312)

790
NASA Exoplanet Science Institute (Caltech)

Exec. Director –
Dr. C. Beichman (790)
Deputy Director – Dr. R. Akeson
Manager – Dr. D. Imel

Ground Observatories & Suborbital Activity (Caltech)

Manager – Dr. D. Imel
Keck Project Scientist –
Dr. R. Akeson

734
Kepler (ARC)

Project Manager (Phase E) – C. Sobeck
Project Scientist (Phase E) – Dr. S. Howell
Science PI – W. Borucki

733
Program Technology (JPL)

Manager – Dr. N. Siegler (383)

732
LBTI (Univ. of Arizona)
Manager – Dr. M. Jeganathan (383)
Principal Investigator – Dr. P. Hinz, U of A
Project Scientist – Dr. R. Millan-Gabet, Caltech

WFIRST/AFTA Study Office (GSFC)

Study Manager – K. Grady
Study Scientist – Dr. N. Gehrels

WFIRST/AFTA SDT[1]
Prof D. Spergel
Princeton University
Dr. N. Gehrels
GSFC

735
Extreme Precision Doppler Spectrometer

Manager – Dr. M. Jeganathan (383) (acting)
Proj Scientist – R. Capps (acting)
Concept Team A (TBD)
Concept Team B (TBD)

7302
Program/Project Communications (JPL)

Manager – M. Greene (183)
Web Manager – R. Jackson
Engagement Specialist – A. Biferno

747
JPL WFIRST/AFTA Project Office
Project Manager, B. Parvin , AD
Project Scientist: Dr W. Traub
Deputy Proj. Scientist: Dr. J. Rhodes
Telescope – B. Parvin (747)
Coronagraph – Dr. F. Zhao (383)
Technology – Dr. I. Poberezhskiy (383)
-- Dr. R. Demers (383)
Science Center – Dr. R. Cutri (Caltech)

WFIRST/AFTA TAC[1]

Dr. A. Boss
Carnegie Institute

[1]Reports to HQs APD

May 11, 2015
R. Lemus
Exoplanet Exploration Program

Coronagraph Key Milestones

MS #	Milestone	Date
1	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.	7/21/14
2	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	9/30/14
3	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.	12/15/14
4	Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	2/28/15
5	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.	9/15/15
6	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.	9/30/15
7	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.	8/25/16
8	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.	9/30/16
9	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.	9/30/16

WFIRST-AFTA Detector Technology Milestones

MS #	Milestone	Milestone Date
✓ 1	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.	7/31/14
✓ 2	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.	12/30/14
3	Produce, test, and analyze **full arrays with operability > 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.	9/15/15
4	Produce, test, and analyze final selected recipe in **full arrays demonstrating a yield of > 20%** with operability > 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.	9/15/16
5	Complete environmental testing (vibration, radiation, thermal cycling) of one SCA sample part, as per NASA test standards.	12/1/16